COST Action 726

Report of the "El Arenosillo"/INTA-COST Calibration and Intercomparison Campaign of UVER Broadband Radiometers

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Report of the "El Arenosillo"/ INTA-COST Calibration and Intercomparison Campaign of UVER Broadband Radiometers

"El Arenosillo", Huelva, Spain
15 August – 21 September 2007

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SUMMARY

This report compiles the main procedures and results of the El Arenosillo/INTA Calibration and Intercomparison Campaign of UVER Broadband Radiometers held in the observatory "El Arenosillo" in Spain from 15 August to 21 September 2007. This campaign was organized by the National Institute for Aerospace Technology (INTA) and the University of Extremadura, and was auspicied by the COST Action 726 "Long term changes and climatology of the UV radiation over Europe". Twenty-two UVER radiometers (9 Yankee-YES, 9 Kipp & Zonen, and 4 Solar Light) belonging to different institutions from Spain, Portugal, Poland and The Netherlands participated in the calibration campaign. As instruments of reference, the spectrophotometer Brewer #150 from the Spanish National Institute of Aerospace Technology (INTA) and the QASUME unit from the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC) were used. The methodology recommended by the Working Group 4 of the COST Action 726 was followed for the calibration of the broadband radiometers. It consisted of a characterization at the laboratory of the relative spectral and angular response functions of the radiometers, and an outdoors intercomparison with the reference instruments. The different terms of the equation of calibration were calculated for each radiometer and the results compared focussing mainly on the behaviour of different types of broadband radiometers. Radiometers showed an important variability between families and also within the same family. It is concluded the absolute need to individually characterize and calibrate each broadband radiometer.

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1 Introduction

The depletion in stratospheric ozone occurred in the last decades and caused mainly by the antropogenic emissions of chlorofluorocarbon has driven an increasing in the UV solar radiation that reaches the earth surface. This fact followed by the detrimental effects of UV radiation on the human health has brought into a high importance the monitoring of UV radiation at surface.

The availability of reliable values of UV radiation data for their spatially comparison and successful detection of trends requires highly reliable and precise measurements that can only be achieved by means of periodic and sound calibrations of the instruments. These precise calibrations require the laboratories to follow thorough protocols for calibration. Compatibility has to be achieved also between different laboratories.

In this framework, a calibration campaign of erythemal broadband radiometers took place at the calibration laboratory of "El Arenosillo", Huelva, Spain, from 15 August to 21 September 2007. This event was part of the COST Action 726 Working Group 4 activities as a continuation of a previous campaign held in Davos (Switzerland) in 2006 at the Physikalisch-Meteorologisches Observatorium Davos of the World Radiation Center (PMOD/WRC).

This publication is supported by COST.

2 Organisation

The calibration campaign was organized by the Atmospheric Sounding Station "El Arenosillo", belonging to the National Institute of Aerospace Technology (El Arenosillo/INTA), the University of Extremadura (UEx), the Physikalisch-Meteorologisches Observatorium Davos of the World Radiation Center (PMOD/WRC), and the COST Action 726 "Long term changes and Climatology of UV radiation over Europe".

The El Arenosillo/INTA and UEx jointly accomplished the calibration campaign. The El Arenosillo/INTA laboratory has broad experience in being responsible for calibration events. Thus, it is the host calibration centre for the Spanish Brewer network since 1999, for European Brewer calibration campaigns in cooperation with the Regional Brewer Calibration Centre in Europe (RBCC-E), and for Dobson calibration campaigns in cooperation with the Regional Dobson Calibration Centre for Europe (RDCC RA-VI). In addition, INTA funded the participation of the QASUME unit used, together with the Brewer #150, as the reference instruments for the outdoors intercomparison. The COST Action 726 funded the publication of this report and the two short-term-scientific-missions of Gregor Hulsen and Gregor Zablocky, who assisted INTA and UEx staff in the calibration procedure. Finally, the Spanish State Meteorological Agency (AEMET) provided specific meteorological information of interest during the whole campaign, such as the short and very short term weather forecast elaborated by its Forecast and Monitoring Group in Seville.

Figure 1: "El Arenosillo" Station, in Huelva, south-western Spain.

3 Location

The calibration campaign took place at the Atmospheric Sounding Station "El Arenosillo" of the National Institute for Aerospace Technology in South-Western Spain (37.10^{o}N, 6.73^{o}W, 50m a.s.l). This observatory is located at the Atlantic Coast, next to Huelva city, in the region of Andalusia. It is at the border of the Doñana National Park, within the pre-park area, which guarantees its natural environment. The surroundings of the station consist of pine trees which provide an uniform albedo spatially and temporally throughout the whole year. This constant behaviour of the albedo allows the comparison of results obtained in different times of the year.

The climate at "El Arenosillo" is characterized by very frequent sunny conditions, around 280 clear sky days per year, providing suitable conditions for intercomparison campaigns. Thus, this observatory has an extensive experience in radiometric studies and it has hosted many calibration and intercomparison campaigns of several different UV radiometers. It also offers interesting calibration facilitie, such as a big terrace with an open horizon (Figure 1). Additionally, the sounding station accounts for a well equipped laboratory where the spectral and angular characterizations of the erythemal radiometers were performed.

4 Participants

A total number of 22 UVER broadband radiometers participated in the calibration campaign. They correspond to four different models: YES UV-1 manufactured by Yankee Environmental Systems, UVS-E-T manufactured by Kipp & Zonen, and SL-501 and SL-501D manufactured by Solar Light. Table 1 shows the identity code, manufacturer, instrument, and institution it belongs to for each radiometer participating in the calibration campaign.

Table 1: Identity code, manufacturer, instrument, and institution it belongs to for each radiometer participating in the calibration campaign.

Code	*Manufacturer*	*Instrument*	*Institution*
BB101	YES	UVB-1 #030520	Instituto Nacional de Meteorología, Madrid
BB103	YES	UVB-1 #030526	Instituto Nacional de Meteorología, Madrid
BB105	YES	UVB-1 #941204	Instituto Nacional de Meteorología, Madrid
BB107	YES	UVB-1 #010906	Centro de Estudios Atmos. del Mediterráneo
BB109	YES	UVB-1 #010908	Universidad de Valencia
BB111	YES	UVB-1 #970829	Universidad de Barcelona
BB113	YES	UVB-1 #990608	Instituo Nacional de Técnica Aeroespacial
BB115	YES	UVB-1 #030521	Universidad de Granada, CEAMA
BB117	YES	UVB-1 #970839	Instituto Nacional de Meteorología, Izaña
BB201	Kipp & Zonen	UVS-E-T #010540	Universidad de Girona
BB203	Kipp & Zonen	UVS-E-T #000532	EUI Vitoria (GV)
BB205	Kipp & Zonen	UVS-E-T #020599	Kipp & Zonen B.V., The Netherlands
BB207	Kipp & Zonen	UVS-E-T #000392	Universidad de Extremadura
BB209	Kipp & Zonen	UVS-E-T #000518	Universidad de Extremadura
BB211	Kipp & Zonen	UVS-E-T #060625	Universidad de Extremadura
BB213	Kipp & Zonen	UVS-E-T #060634	Universidad de Extremadura
BB215	Kipp & Zonen	UVS-E-T #070638	Universidad de Extremadura
BB217	Kipp & Zonen	UVS-E-T #000409	Universidad de Extremadura
BB301	Solar Light	SL-501 (analog) #5806	Universidad de Barcelona
BB303	Solar Light	SL-501 (analog) #5775	MeteoGalicia
BB307	Solar Light	SL-501 (digital) #0935	IMWM, Poland
BB315	Solar Light	SL-501 (digital) #4358	Instituto Nacional de Meteo. e Geof. Portugal
BB317	Kipp & Zonen	CM11 #027771	Instituo Nacional de Técnica Aeroespacial
BB318	Kipp & Zonen	CM11 #060135	Universidad de Extremadura

Besides the UVER broadband radiometers, two pyranometers for measuring total solar radiation were co-located. These two instruments correspond to the model CM11 manufactured by Kipp & Zonen and provide information regarding the attenuation of the total solar radiation in the atmosphere. Since this attenuation is mainly due to absorption and scattering by aerosols and clouds, they give relevant information about the clearness of the atmosphere.

Additionally, the QASUME unit belonging to the PMOD/WRC, and the spectrophotometer Brewer #150 belonging to the El Arenosillo/INTA were considered as the instruments of reference for the outdoor intercomparison. The spectrophotometer Brewer #150 was compared to the QASUME unit during the campaign of the Regional Brewer Calibration Centre in Europe (RBCC-E),

5 Calibration methodology

This campaign followed a sound calibration procedure based on the methodology recommended by the Working Group 4 of the COST Action 726 (Webb, Gröbner, and Blumthaler 2006). Additionally, laboratory techniques and procedures have been contrasted with those used at the 2006 calibration campaign held at the PMOD/WRC (Gröbner et al. 2007).

5.1 Equation of calibration

The expression recommended by the COST Action 726 to convert raw signal of broadband radiometer into erythemal solar irradiance was used:

$$E_{CIE} = (U - U_{offset}) \cdot C \cdot f_n(\theta, O_3) \cdot \epsilon(T) \cdot COSCOR(\theta), \tag{1}$$

where:

- E_{CIE} is the erythemal UV irradiance (Wm^{-2}),
- U is the measured voltage signal given by the broadband radiometer (V),
- U_{offset} is the voltage signal offset obtained for dark conditions (V),
- C is the absolute calibration coefficient,
- $f_n(\theta, O_3)$ is the conversion function, which depends on the solar zenith angle (θ) and the total ozone column (O_3). It is normalized to unity at a solar zenith angle of 40° and total ozone column of 300 DU,
- $\epsilon(T)$ is a function which accounts for the effect of the temperature on the measurements[1],
- $COSCOR(\theta)$ is the cosine correction function.

[1] Since all the radiometers were stabilized at their reference temperature, this term was not considered.

5.2 Relative spectral response function

The relative spectral response functions of the radiometers were obtained at the laboratory, a dark room stabilised in temperature and humidity. The radiometers were previously temperature stabilised for at least four hours before performing any calibration measurement but not while measuring in order to prevent from electronic noise.

For the measuring process, a 450W Xe lamp was used as the light source. It was assembled to a double monochromator (Gemini 180 from Jobin Yvon) (Figure 2) configured to produce monochromatic light (2 nm FWHM). At the exit of the monochromator an integrating sphere optimized for the UV wavelengths was mounted, providing isotropic radiation coming out from the double monocromator. The radiometer to be characterized and a photodiode used as reference, were placed together to receive radiation from the integrating sphere.

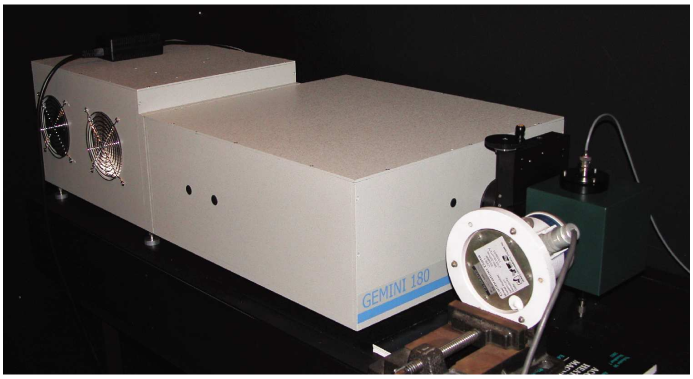
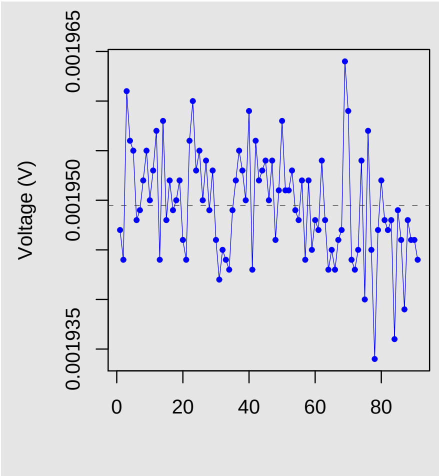


Figure 2: Relative spectral response facility at El Arenosillo Station.

The measuring process runs completely automatically being controlled by a software programmed in LabView code. The output signals from the broadband instrument and from the photodiode are read by an Agilent multimeter with $6\frac{1}{2}$ digits resolution. First, the dark signal (output voltage signal given by the radiometer under dark conditions, i.e, for no incoming radiation) was measured and its mean value was calculated (Figure 3). Subsequently, the double monocromator was used to scan the desired wavelength interval from 285 to 400 nm in steps of 1 nm. The simultaneous values measured by the photodiode and the radiometer, together with the well-characterised relative spectral response function of the photodiode allows to obtain the relative spectral response function of the radiometer (Figure 3).

The obtained measurements were analysed by visual inspection in order to prevent from undesired electronic noise. For some instruments the measurements at the labora-



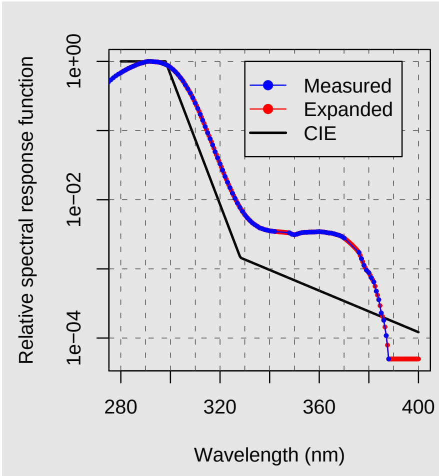


Figure 3: Dark signal and relative spectral response function of a Kipp & Zonen radiometer.

tory didn’t cover the whole wavelength range 285-400 nm. In these cases the final relative spectral response function was obtained by linearly extrapolating the measurements up to the wavelength 400 nm, where a value of 10^{-4} was considered. Although this extrapolation is needed for subsequent calculations, the complete procedure is not significantly sensitive to the methodology used to extrapolate, since it refers to wavelengths with a very low weight in the integrated UVER value.

Finally, values at an increment of 0.5 nm were estimated by linearly interpolating the obtained measurements.

5.3 Relative angular response function

The relative angular response function was obtained in the calibration laboratory by using an automatic device designed by INTA (Figure 4) and controlled by a software developed in Labview code.

A 1000W DXW halogen lamp ultra-stabilized was used as the radiation source. It was mounted on the top of a vertical support and perfectly aligned with the center of the radiometer input difusser by using a laser pointer. After setting up the instrument and the lamp, the system was covered with a black cloth to block any possible reflected radiation and, therefore, allowing only the pass of the direct radiation coming from the lamp. The procedure started with the measurements of the instrument offset. Afterwards, the radiometer was automatically rotated between -90^{o} and $+90^{o}$ (North and South) by steps of 2^{o} while the instrument voltage signal was monitored and registered for each

Figure 4: Device to measure angular response function.

position by an Agilent 6 $\frac{1}{2}$ digits resolution multimeter. The final relative angular response function was calculated as the average of both directions (Figure 5).

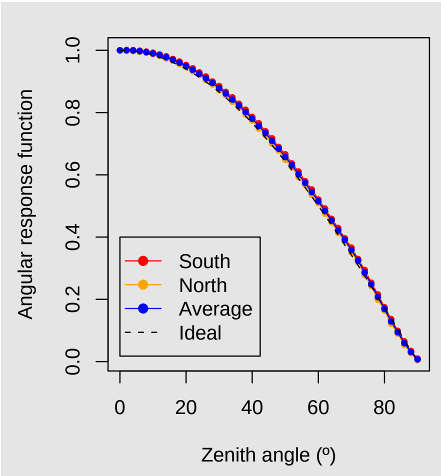


Figure 5: Relative angular response function of a Kipp & Zonen radiometer.

5.4 Cosine correction

The irradiance measured by the radiometer should follow the ideal angular response given by the cosine law. Deviations from this angular response produce systematic errors which depend not only on the solar zenith angle, but also on the partitioning of the solar radiation into direct and diffuse. The cosine correction function used to correct these deviations is based on the following expression:

$$COSCOR(\theta) = \frac{1}{f_b(\theta) \cdot r(\theta) + f_d \cdot (1 - r(\theta))}, \tag{2}$$

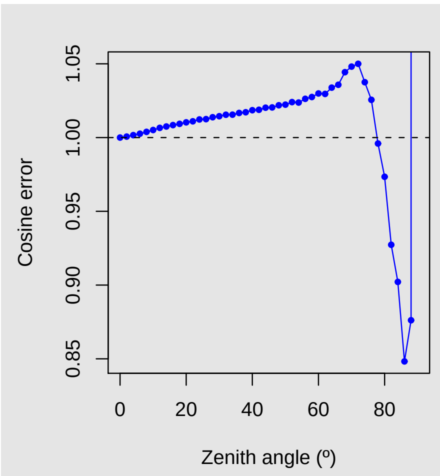
where $f_b(\theta)$ and f_d are the correction factors for the direct and diffuse solar radiation, respectively, and r is the ratio between the direct and the global effective irradiance. Thus, r and $1 - r$ represent the proportions of direct and diffuse components that compose the global irradiance.

5.4.1 Correction factor for direct irradiance

The correction factor for the direct irradiance, also known as cosine error, can be calculated from the measurements performed at the laboratory (Figure 6). It is defined as:

$$f_b(\theta) = \frac{U}{U(\theta = 0) \cdot \cos\theta}, \tag{3}$$

where U is the voltage signal measured for zenith angle θ.



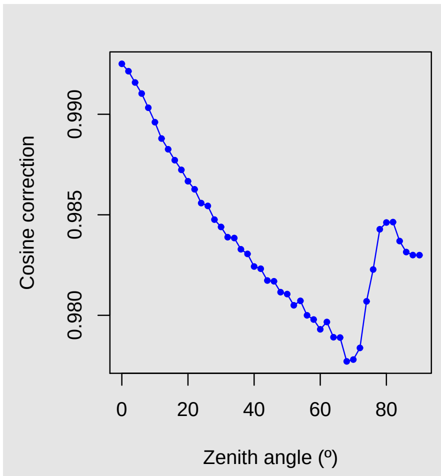


Figure 6: Correction factor for direct irradiance and cosine correction of a Kipp & Zonen radiometer.

5.4.2 Correction factor for diffuse irradiance

The correction factor for the diffuse irradiance can be calculated from the previously calculated correction factor for direct irradiance by means of the following expression (Bais et al. 1998):

$$f_d = 2\int_0^{\pi/2} f_b(\theta)\sin\theta\cos\theta d\theta. \tag{4}$$

In order to apply this correction, it is necessary to assume an angular response error of the instrument independent of the azimuth angle and an isotropic diffuse solar radiation field.

The first requirement is acceptable for UV radiation since, for solar zenith angles lower than 80$^{\text{o}}$, changes in azimuth angle cause variations in angular response errors within $\pm 1\%$ (Feister, Grewe, and Gericke 1997).

The second assumption is not generally valid. In the UVB the assumption of isotropic sky radiances was investigated by (Gröbner, Blumthaler, and Ambach 1996) and was found to be true within $\pm 2\%$. Similar results were also found by (Blumthaler et al. 1996). It is really difficult to evaluate the deviation of that approximation for different conditions: cloudy or partly cloudy skies, atmospheres with high aerosol load, etc., and, therefore, an isotropic diffuse solar radiation field is generally assumed (Blumthaler et al. 1996; Feister, Grewe, and Gericke 1997; Fioletov et al. 2002).

Therefore, both assumptions were taken into consideration in this calibration procedure.

5.4.3 Ratio direct to global irradiance

The ratio direct to global effective irradiance was estimated by means of the following expression:

$$r(\theta) = \frac{\int_{280nm}^{400nm} SRF(\lambda)E_b(\theta, 300DU, \lambda)d\lambda}{\int_{280nm}^{400nm} SRF(\lambda)E_g(\theta, 300DU, \lambda)d\lambda}, \tag{5}$$

where $SRF(\lambda)$ is the relative spectral response function of the radiometer, and $E_b(\theta, 300DU, \lambda)$ and $E_g(\theta, 300DU, \lambda)$ stand for the spectral direct and global irradiance, respectively, as calculated by a radiative transfer model considering a constant total ozone column of 300 DU. In this work, the UVSpec/LibRadtran version 2.2 atmosphere transfer code (Mayer and Killing 2005) has been used in order to estimate values of spectral direct and global UV irradiance. These spectral calculations were performed for wavelengths varying from 280 to 400 nm by steps of 0.5 nm, and solar zenith angle from 0$^{\text{o}}$ to 90$^{\text{o}}$ by steps of 5$^{\text{o}}$. The total ozone column was considered constant with a value of 300 DU since the ratio direct to global irradiance shows only a slight dependence on total ozone (Zeng et al. 1994).

It is important to note that the ratio direct to global effective irradiance had to be computed for each broadband radiometer since its calculation involves the actual spectral response of each instrument.

Once computed the correction factors for direct and diffuse irradiance and the ratio direct to global, the cosine correction function was calculated (Figure 6).

5.5 Conversion function

Radiative measurements from broadband radiometers depend on the relationship between its actual spectral response (SRF) and the nominal spectral response the radiometer was designed to simulate (in our case, the erythemal action spectrum CIE (McKinlay and Diffey 1987)). This ratio highly depends on the slant ozone amount, which is a function of the solar zenith angle and the total ozone column. The conversion function accounts for these dependences and is defined as follows:

$$f_n(\theta, O_3) = \frac{\int_{280nm}^{400nm} CIE(\lambda) E_g(\theta, O_3, \lambda) d\lambda}{\int_{280nm}^{400nm} SRF(\lambda) E_g(\theta, O_3, \lambda) d\lambda}, \tag{6}$$

where $E_g(\theta, O_3, \lambda)$ is the global irradiance at the earth surface as estimated by means of the UVSpec/LibRadtran version 2.2 atmosphere transfer code (Mayer and Killing 2005) with the solar zenith angle ranging from 0º to 90º by steps of 5º, the total ozone column from 200 to 500 DU by 20 DU, and the wavelength from 280 to 400 nm by 0.5 nm. Standard conditions for surface albedo, atmospheric pressure and aerosols, and cloud-free sky were considered for the calculations.

Once calculated, the conversion function (Figure 7) was normalized to unity at conditions of zenith angle of 40º and total ozone column of 300 DU. The factor resulting from this normalization was integrated in the absolute calibration coefficient.

5.6 Daily offset

The term U_{offset} in Equation 1 is the raw voltage signal measured under dark conditions. This value was calculated everyday as the average of the signal recorded during the period when the solar zenith angle was higher than 100°.

5.7 Absolute calibration coefficient

The absolute calibration coefficient was obtained using the spectroradiometer Brewer #150 as the instrument of reference. The intercomparison of broadband records against the spectroradiometer measurements requires preprocessing its spectral measurements in

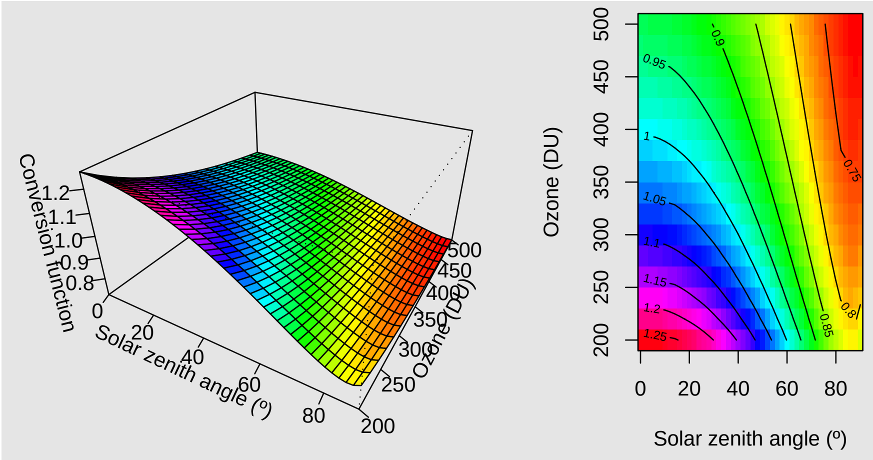


Figure 7: Conversion function of a Kipp & Zonen radiometer.

order to obtain effective weighted UV irradiance simultaneous to the broadband measurements. Firstly, the spectral range of the spectrophotometer measurements must be expanded from 363 nm (actual limit of its measurements) up to 400 nm, which is the upper limit of the wavelengths measured by the broadband radiometers. This calculation was performed by using a software developed by Martin Stanek at the Solar and Ozone Observatory of the Czech Hydrometeorological Institute (Stanek 2007). Secondly, the Brewer spectral irradiance has to be weighted by the actual spectral response of each broadband radiometer and integrated between 290 and 400 nm in order to obtain effective irradiance. In order to obtain simultaneous records of both type of instruments, the broadband radiometer voltages (which measures every 10 sec) were averaged along the one minute period corresponding to the Brewer scanning of wavelengths from 310 to 324 nm. This interval was chosen since it comprises the wavelengths where the UV spectral irradiance weighted by the CIE response function reaches the highest values.

The calibration coefficient of each broadband radiometer was obtained as the averaged ratio between the effective UV irradiance obtained by the Brewer spectroradiometer and the output voltage of the radiometer (Figure 8):

$$C = \frac{1}{n}\sum_{i=1}^{n}\frac{\int_{280nm}^{400nm} SRF(\lambda)E_i(\lambda)d\lambda}{(U_i - U_{offset})COSCOR(\theta)}. \tag{7}$$

In order to avoid systematic errors attributed to deviations of the angular response of broadband radiometers, only radiative and voltages values for SZA lower than 65° and cloud-free conditions were considered (Figure 9).

Finally, as mentioned for the normalization of the conversion function, the calibration

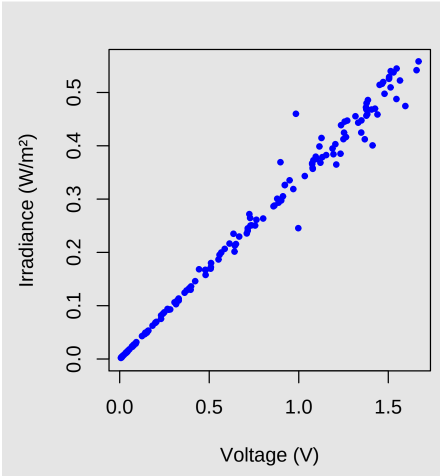


Figure 8: Effective UV irradiance as measured by Brewer versus voltage signal given by a Kipp & Zonen radiometer.

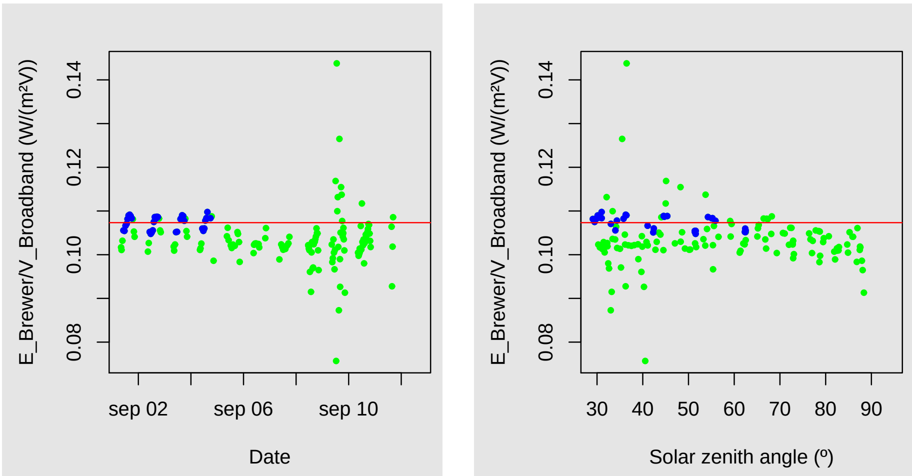


Figure 9: Calibration coefficient and its sensitivity with the solar zenith angle. Whole data (green points) and selected data for the calibration (blue points).

coefficient must be multiplied by the original value of the conversion function at 40º and 300 DU, being this product the definitive absolute calibration coefficient.

6 Campaign timetable and procedures

The radiometers arrived at El Arenosillo/INTA from 15 to 28 August, when they were registered and prepared to be studied at the laboratory. From 20 to 30 August the instruments were characterized at the laboratory obtaining their spectral and angular response functions.

Figure 10: Broadband radiometers installed on the terrace of El Arenosillo Station.

On 31 August all the instruments were installed at the terrace of El Arenosillo Observatory building for the outdoors intercomparison (Figure 10), near the spectrophotometer Brewer #150 which was to be used as the reference instrument. They were cleaned and correctly levelled to ensure the radiometers were horizontal. Also, their desiccants were checked to prevent from humidity inside the instruments. The radiometers were connected to an Agilent data acquisition unit (model 34970-A) (Figure 11) controlled by a computer with an appropriate software which provides real-time voltages data display.

The period of simultaneously measuring for the intercomparison extended from 1 to 11 September. During that period of time, radiometers were daily inspected and cleaned in order to prevent from dew on their domes or bodies. Since UV radiometers are temperature-stabilized at 25°C (Kipp & Zonen) or 40°C (YES, Solar Light), dew was only detected on the pyranometers for total solar radiation.

On 20 and 21 September 2007, once finished the calibration of the instruments, a seminar for operators of UV broadband radiometers was given. It consisted of several theoretical lessons and a final practical session focussed on examples and exercises developed

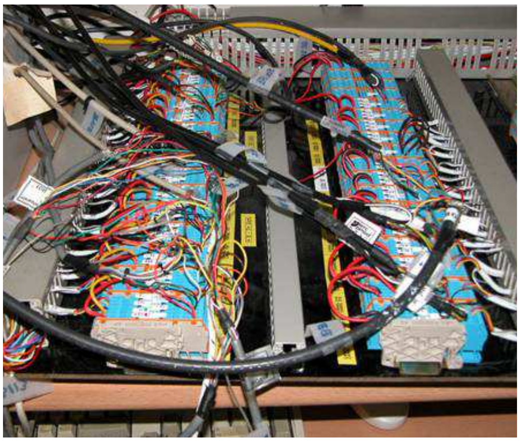


Figure 11: Output signals of radiometers connected to the data acquisition system terminal blocks.

using the real measurements and calibration parameters obtained for each radiometer.

7 Calibration report

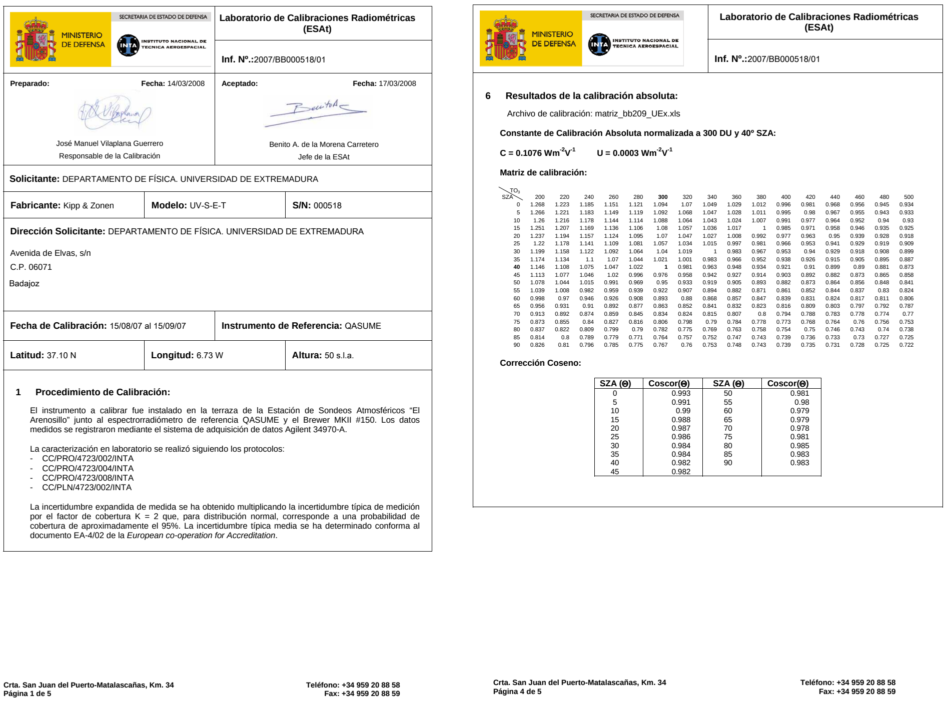
For each broadband radiometer, a specific calibration report was elaborated and provided to its operator. It briefly described the calibration procedure and gives the conditions in spectral, angular and absolute calibrations, the relative spectral response function, the conversion function, the cosine correction and the absolute calibration factor, along with their uncertainties (Figure 12).

8 Main results and discussion

In this section, the results of calibration campaign are presented. These results are organized in two subsections: by families of instruments and individually for each broadband radiometer participating.

8.1 General behaviour of the families of radiometers

Three types of broadband radiometers participated in this intercomparison: Kipp & Zonen (model UVS-E-T), Solar Light (model SL-501) and Yankee Environment System (model YES-UV-1). The behaviour of the three families of instruments is analyzed.



SECRETARIA DE ESTADO DE DEFENSA
MINISTERIO DE DEFENSA
INSTITUTO NACIONAL DE TECNICA AEROESPACIAL

Laboratorio de Calibraciones Radiométricas (ESAt)

Inf. Nº.:2007/BB000518/01

Preparado: **Fecha:** 14/03/2008

José Manuel Vilaplana Guerrero
Responsable de la Calibración

Aceptado: **Fecha:** 17/03/2008

Benito A. de la Morena Carretero
Jefe de la ESAt

Solicitante: DEPARTAMENTO DE FÍSICA. UNIVERSIDAD DE EXTREMADURA

Fabricante: Kipp & Zonen | **Modelo:** UV-S-E-T | **S/N:** 000518

Dirección Solicitante: DEPARTAMENTO DE FÍSICA. UNIVERSIDAD DE EXTREMADURA

Avenida de Elvas, s/n
C.P. 06071
Badajoz

Fecha de Calibración: 15/08/07 al 15/09/07 | **Instrumento de Referencia:** QASUME

Latitud: 37.10 N | **Longitud:** 6.73 W | **Altura:** 50 s.l.a.

1 Procedimiento de Calibración:

El instrumento a calibrar fue instalado en la terraza de la Estación de Sondeos Atmosféricos "El Arenosillo" junto al espectrorradiómetro de referencia QASUME y el Brewer MKII #150. Los datos medidos se registraron mediante el sistema de adquisición de datos Agilent 34970-A.

La caracterización en laboratorio se realizó siguiendo los protocolos:
- CC/PRO/4723/002/INTA
- CC/PRO/4723/004/INTA
- CC/PRO/4723/008/INTA
- CC/PLN/4723/002/INTA

La incertidumbre expandida de medida se ha obtenido multiplicando la incertidumbre típica de medición por el factor de cobertura K = 2 que, para distribución normal, corresponde a una probabilidad de cobertura de aproximadamente el 95%. La incertidumbre típica media se ha determinado conforma al documento EA-4/02 de la *European co-operation for Accreditation*.

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SECRETARIA DE ESTADO DE DEFENSA
MINISTERIO DE DEFENSA
INSTITUTO NACIONAL DE TECNICA AEROESPACIAL

Laboratorio de Calibraciones Radiométricas (ESAt)

Inf. Nº.:2007/BB000518/01

6 Resultados de la calibración absoluta:

Archivo de calibración: matriz_bb209_UEx.xls

Constante de Calibración Absoluta normalizada a 300 DU y 40º SZA:

$C = 0.1076\ Wm^{-2}V^{-1}$ **$U = 0.0003\ Wm^{-2}V^{-1}$**

Matriz de calibración:

SZA \ TO_3	200	220	240	260	280	**300**	320	340	360	380	400	420	440	460	480	500
0	1.268	1.223	1.185	1.151	1.121	1.094	1.07	1.049	1.029	1.012	0.996	0.981	0.968	0.956	0.945	0.934
5	1.266	1.221	1.183	1.149	1.119	1.092	1.068	1.047	1.028	1.011	0.995	0.98	0.967	0.955	0.943	0.933
10	1.26	1.216	1.178	1.144	1.114	1.088	1.064	1.043	1.024	1.007	0.991	0.977	0.964	0.952	0.94	0.93
15	1.251	1.207	1.169	1.136	1.106	1.08	1.057	1.036	1.017	1	0.985	0.971	0.958	0.946	0.935	0.925
20	1.237	1.194	1.157	1.124	1.095	1.07	1.047	1.027	1.008	0.992	0.977	0.963	0.95	0.939	0.928	0.918
25	1.22	1.178	1.141	1.109	1.081	1.057	1.034	1.015	0.997	0.981	0.966	0.953	0.941	0.929	0.919	0.909
30	1.199	1.158	1.122	1.092	1.064	1.04	1.019	1	0.983	0.967	0.953	0.94	0.929	0.918	0.908	0.899
35	1.174	1.134	1.1	1.07	1.044	1.021	1.001	0.983	0.966	0.952	0.938	0.926	0.915	0.905	0.895	0.887
40	1.146	1.108	1.075	1.047	1.022	**1**	0.981	0.963	0.948	0.934	0.921	0.91	0.899	0.89	0.881	0.873
45	1.113	1.077	1.046	1.02	0.996	0.976	0.958	0.942	0.927	0.914	0.903	0.892	0.882	0.873	0.865	0.858
50	1.078	1.044	1.015	0.991	0.969	0.95	0.933	0.919	0.905	0.893	0.882	0.873	0.864	0.856	0.848	0.841
55	1.039	1.008	0.982	0.959	0.939	0.922	0.907	0.894	0.882	0.871	0.861	0.852	0.844	0.837	0.83	0.824
60	0.998	0.97	0.946	0.926	0.908	0.893	0.88	0.868	0.857	0.847	0.839	0.831	0.824	0.817	0.811	0.806
65	0.956	0.931	0.91	0.892	0.877	0.863	0.852	0.841	0.832	0.823	0.816	0.809	0.803	0.797	0.792	0.787
70	0.913	0.892	0.874	0.859	0.845	0.834	0.824	0.815	0.807	0.8	0.794	0.788	0.783	0.778	0.774	0.77
75	0.873	0.855	0.84	0.827	0.816	0.806	0.798	0.79	0.784	0.778	0.773	0.768	0.764	0.76	0.756	0.753
80	0.837	0.822	0.809	0.799	0.79	0.782	0.775	0.769	0.763	0.758	0.754	0.75	0.746	0.743	0.74	0.738
85	0.814	0.8	0.789	0.779	0.771	0.764	0.757	0.752	0.747	0.743	0.739	0.736	0.733	0.73	0.727	0.725
90	0.826	0.81	0.796	0.785	0.775	0.767	0.76	0.753	0.748	0.743	0.739	0.735	0.731	0.728	0.725	0.722

Corrección Coseno:

SZA (Θ)	Coscor(Θ)	SZA (Θ)	Coscor(Θ)
0	0.993	50	0.981
5	0.991	55	0.98
10	0.99	60	0.979
15	0.988	65	0.979
20	0.987	70	0.978
25	0.986	75	0.981
30	0.984	80	0.985
35	0.984	85	0.983
40	0.982	90	0.983
45	0.982		

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Figure 12: Two pages of the calibration report for a Kipp & Zonen radiometer.

8.1.1 Spectral Response Function

Figure 13 shows the ranges of the relative spectral response function for the three types of radiometers as a function of the wavelength. There are notable differences between families, and even among the radiometers belonging to the same family. It is concluded that, in order to obtain reliable results, the relative spectral response function of each radiometer needs to be individually characterized. In order to suitably discuss the results the logaritmic scale used in Figure 13. Also it has to be noted that the lower variability within the Solar Light family is mainly due to the fact that it comprises only two instruments.

As it can be observed, for shorter wavelengths (from 300 to 330 nm), all radiometers overestimate the desired CIE spectrum. This overestimation is more pronounced in the case of the YES family. However, for larger wavelengths, YES and Solar Light families sharply decrease while Kipp & Zonen radiometers maintain high values far away from the desired behaviour.

These differences between the relative spectral response function and the CIE spectrum result in a conversion function $f_n(\theta, O_3)$. with values different from the unity.

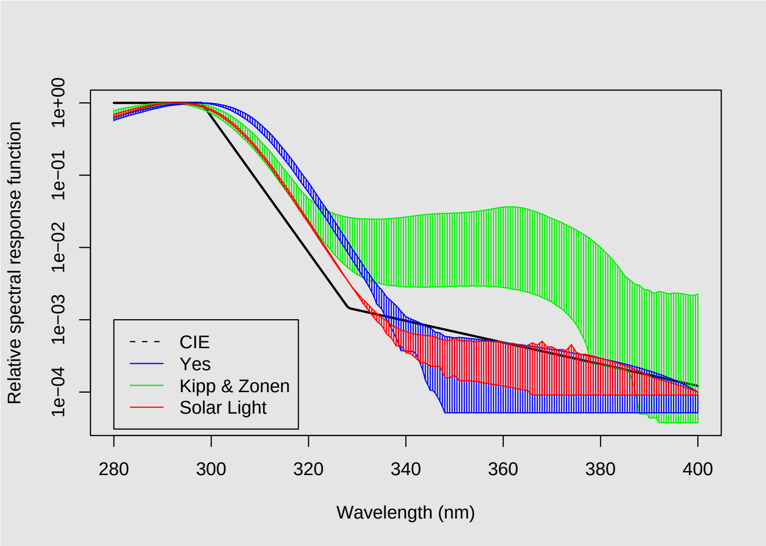

Figure 13: Ranges of the relative spectral response function for the different families of radiometers.

8.1.2 Angular response function

Figure 14 shows the ranges of angular response functions of the different families of radiometers obtained in the laboratory characterization. YES radiometers show a behaviour which is under the ideal response curve in the whole interval of the zenith angle. Solar Ligth instruments present a fairly good angular response up to 65°. Finally, the Kipp & Zonen family of radiometers shows the best angular response in the whole interval of the zenith angle. As mentioned before, the narrowest band of Solar Ligth instruments is mainly due to the low number of instruments involved, only two, significantly lower than the nine instruments in each of the other two families.

Similar behaviour can be observed in Figure 15 for the ranges of the cosine error for the three families of radiometers. The cosine correction, calculated as explained in section 5.4, is shown in Figure 16. The values range between 1.05 and 1.25 for YES instruments, between 0.93 and 1.02 for Kipp & Zonen, and between 1.00 and 1.07 for Solar Light.

8.1.3 Absolute calibration coefficient

It is essential to accurately know the absolute calibration coefficient of each instrument. The results have shown that they can be very different even within the same family and, frequently, they do not agree with those provided by manufacturers. The values obtained in this campaign show that the Solar Light instruments have coefficients that differ up to

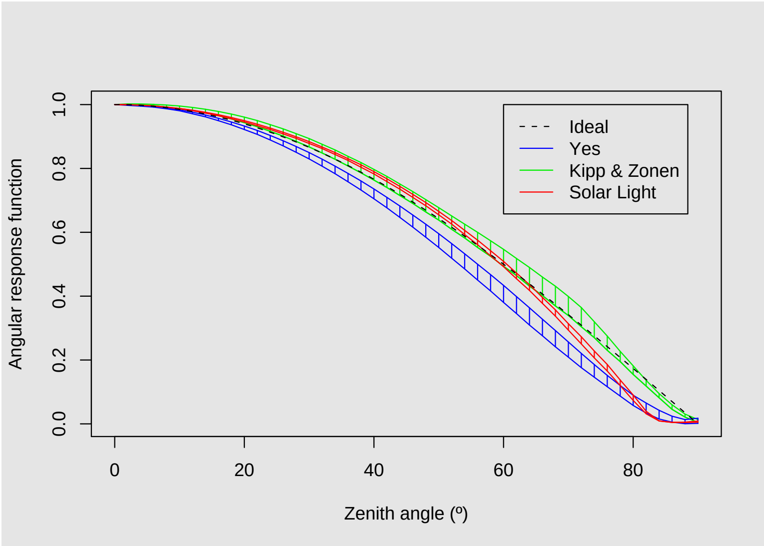

Figure 14: Ranges of the angular response functions for the different families of radiometers.

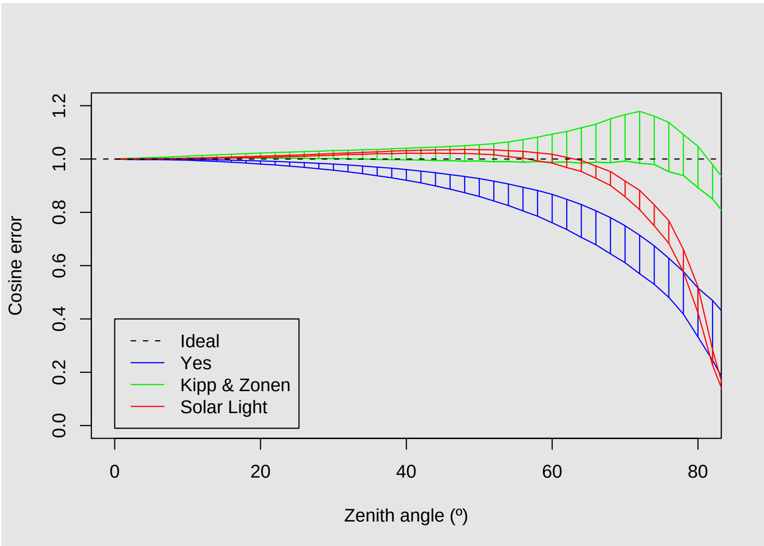

Figure 15: Ranges of the cosine error for the different families of radiometers.

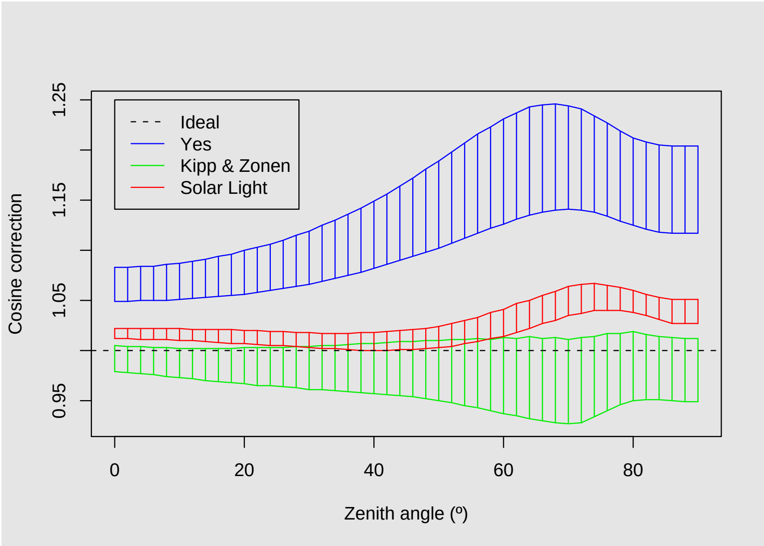

Figure 16: Ranges of the cosine correction for the different families of radiometers.

6%, up to 19% for Yankee-YES and up to 54% for Kipp & Zonen. However, it was observed that the temporal variability of the coefficient for a particular instrument was very low along the eleven days of campaign. Thus, the resulting relative standard deviations of absolute calibration coefficients ranged between 0.5% and 1.5%, pointing out the high stability of the calibration coefficients obtained.

8.1.4 Calibration uncertainty

Regarding to the uncertainty in the calibration, it depends on several factors. On one hand, it is conditioned by the uncertainty in the spectral irradiance measurements made by the reference instrument, that in this case is about $\pm 5\%$ for the Brewer spectroradiometer #150 used (Vilaplana 2004). On the other hand, additional uncertainty results from all the procedure steps that are required to obtain the final calibration function, including laboratory procedures (relative spectral response function and angular response measurements), radiative transfer model used and outdoors intercomparison.

Following the procedure described by (Hülsen and Gröbner 2007), the uncertainty of erythemally weighted irradiance obtained by a broadband radiometer can be calculated combining the uncertainty associated to calibration (absolute calibration coefficient and reference spectroradiometer uncertainties) and the uncertainty derived from the terms f_n and $COSCOR$ in conversion equation (1).

The calibration uncertainty can be calculated combining the variability of absolute calibration coefficient (between 0.5% an 1.5%, see section 8.1.3) with the reference spectroradiometer uncertainty (5%), resulting in a combined calibration uncertainty ranging between 5.0% and 5.2%.

The uncertainty in $f_n(\theta, O_3)$ depends on: (A) the measured relative spectral response function, (B) the radiative transfer model calculations and (C) the precision on $[O_3]$ estimation. According to (Hülsen and Gröbner 2007), an upper limit for these uncertainties can be considered as: 1% for (A), 1% for (B) and 1.2% for (C).

An important part of the total uncertainty depends on the accuracy of $COSCOR$ function. Considering the uncertainty of the cosine correction function (D) as the variability of its values, for this campaign, this variability ranged between 0.2% and 5.2%.

Combining the calibration uncertainty and those assigned to steps (A), (B), (C) and (D), the total expanded uncertainty ($k = 2$) results between 10.6% and 15.2%.

8.2 Individual results

This next section collects the results for the whole set of broadband radiometers participating in the campaign. Eight graphics are included for each instrument presenting: the individual relative spectral and angular response functions, the cosine error and cosine correction, the conversion function, the comparison of UVER irradiance as measured by Brewer #150 weighted by the SRF of the radiometer with the radiometer signal (needed to obtain the absolute calibration), and its sensitivity to the solar zenith angle.

8.2.1 YES broadband radiometers

(BB101) YES UVB-1 #030520

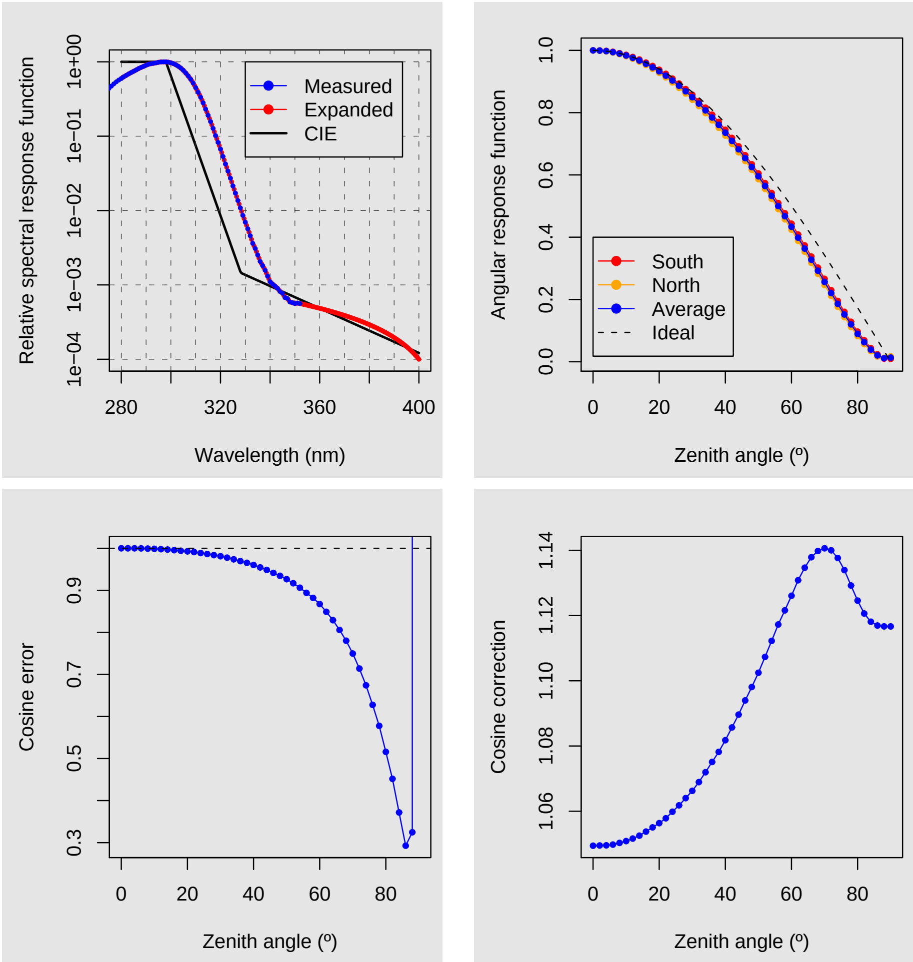

Figure 17: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB101) YES UVB-1 #030520

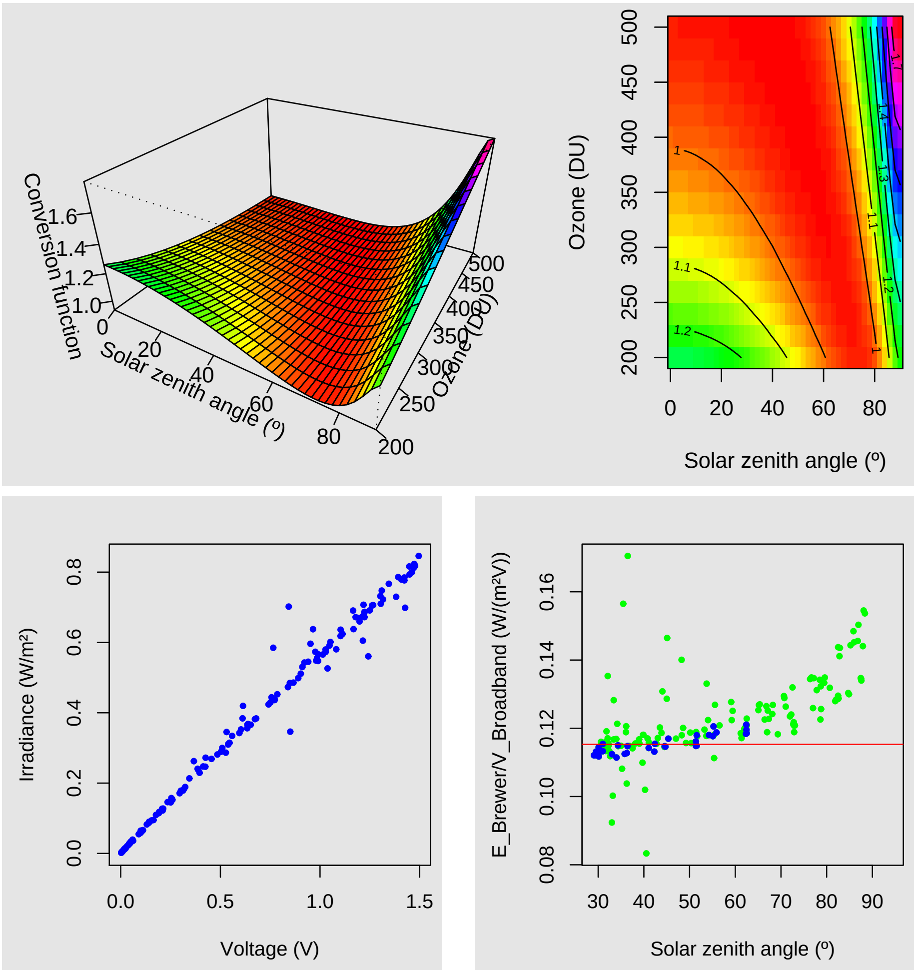

Figure 18: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB103) YES UVB-1 #030526

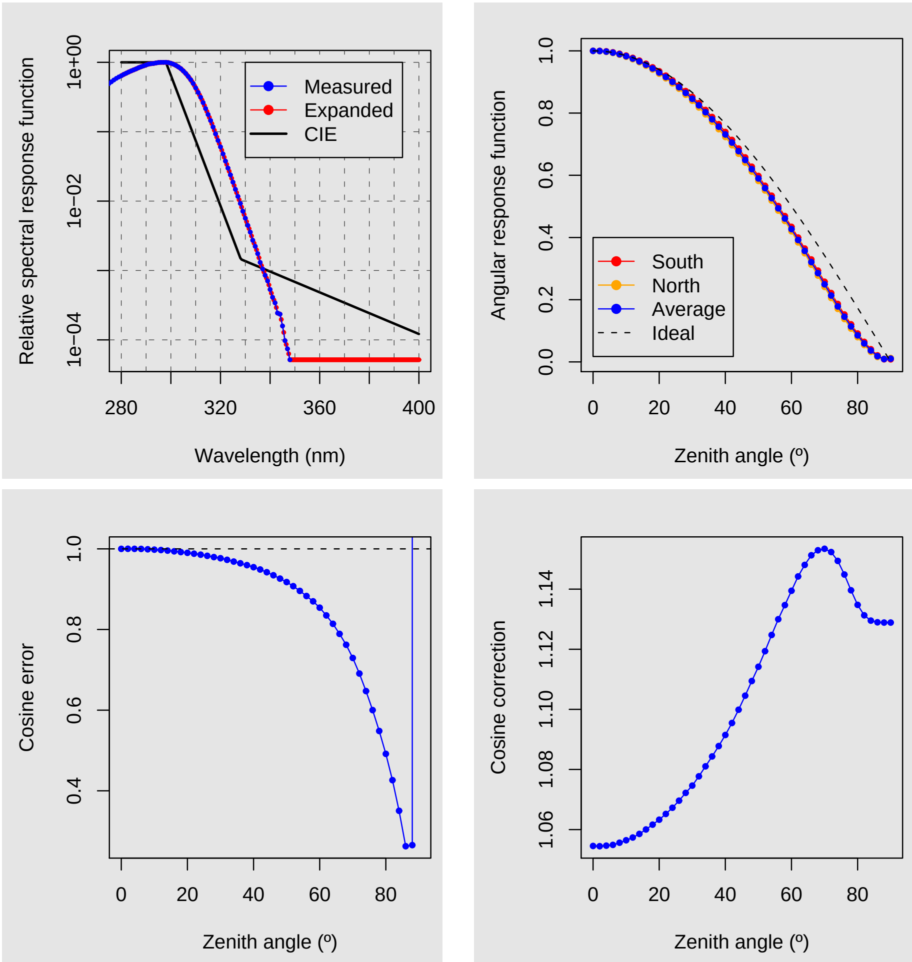

Figure 19: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB103) YES UVB-1 #030526

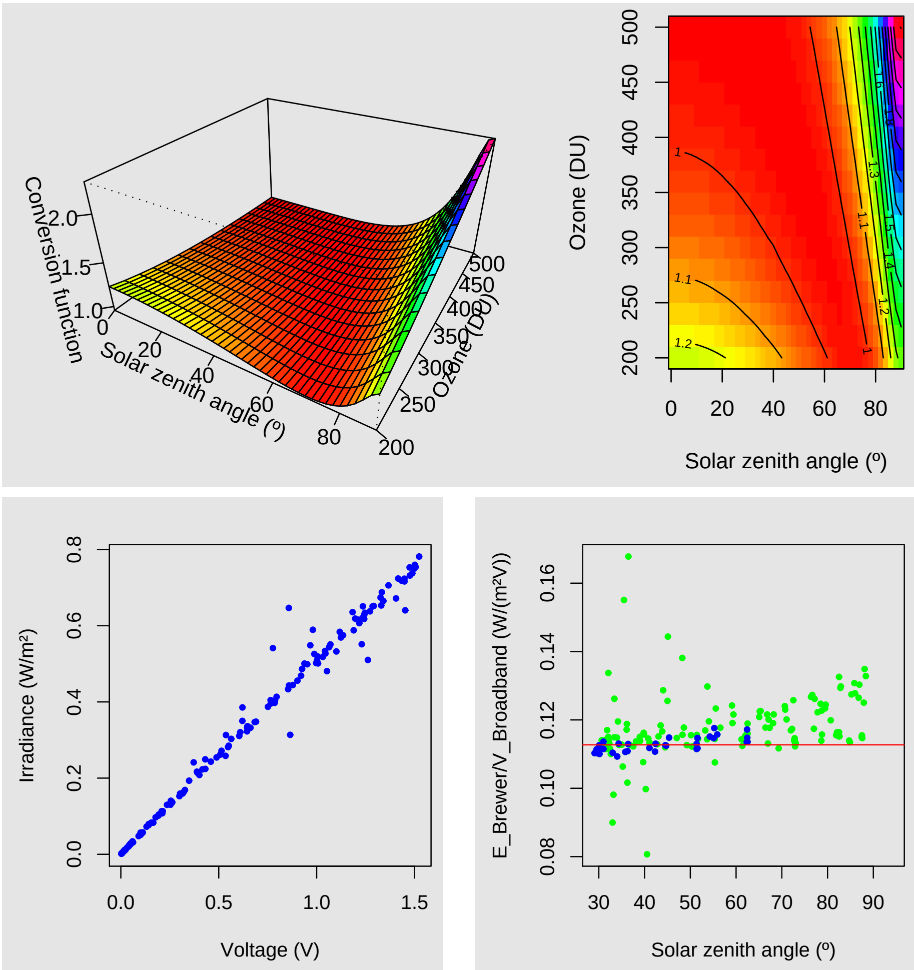

Figure 20: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB105) YES UVB-1 #941204

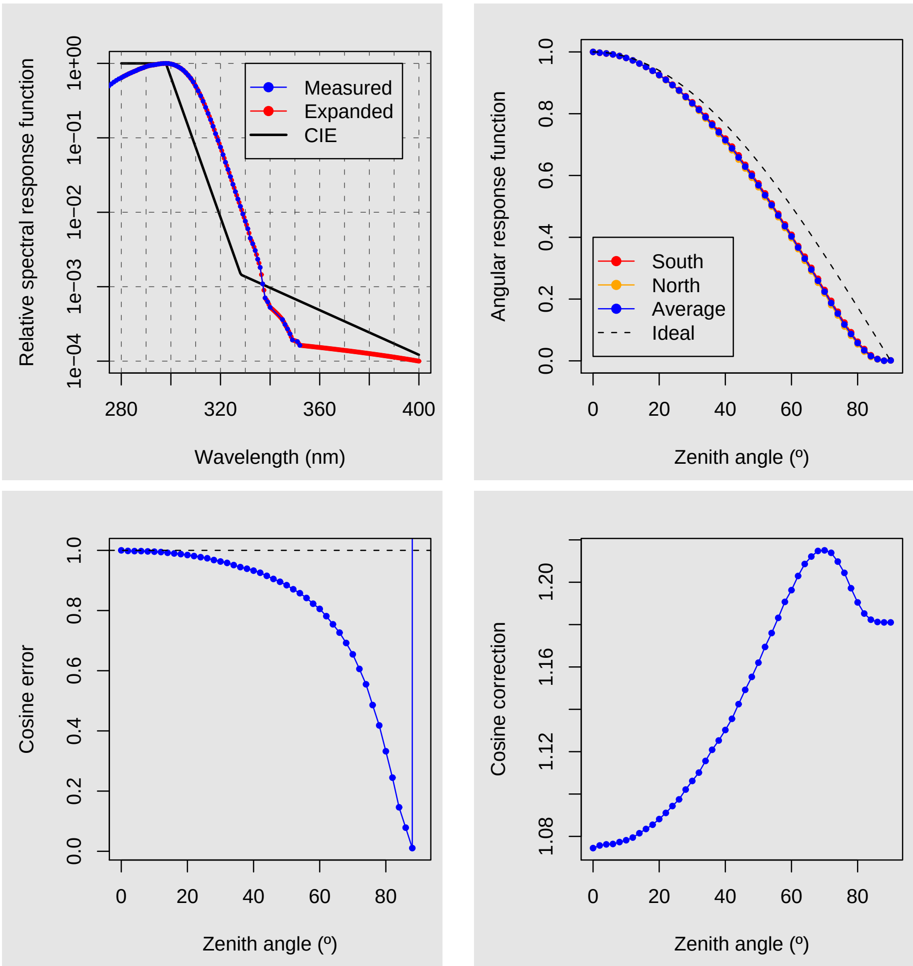

Figure 21: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB105) YES UVB-1 #941204

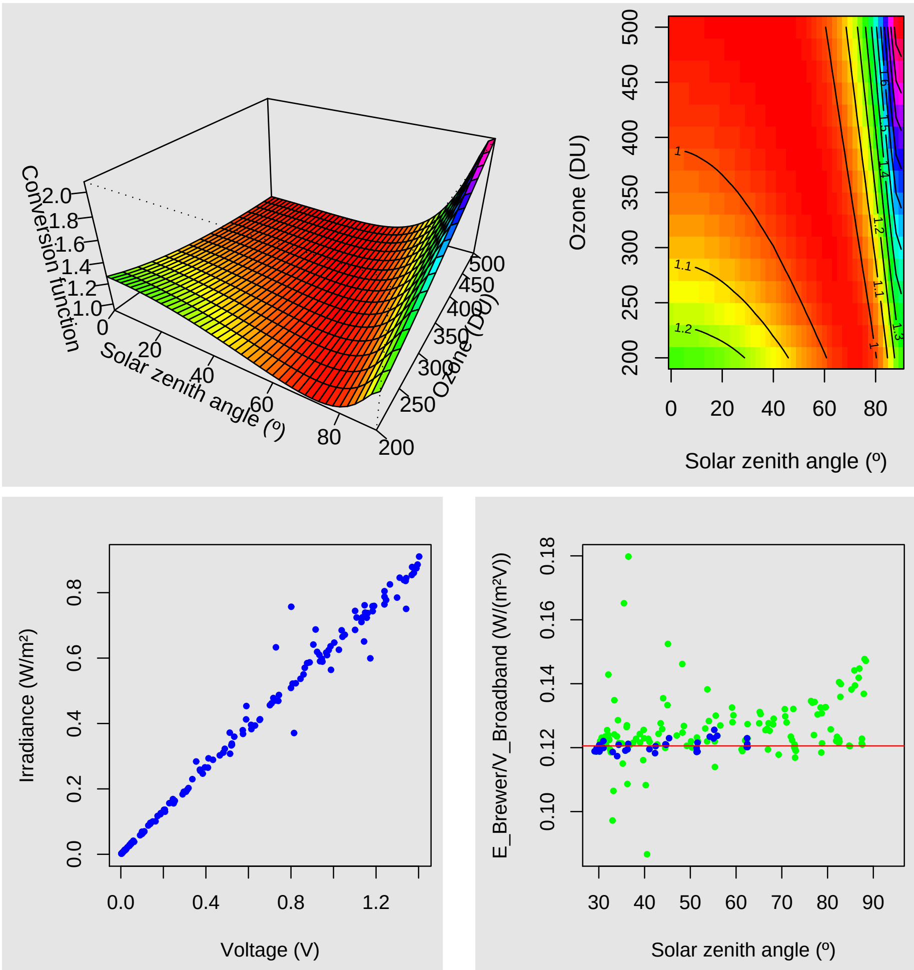

Figure 22: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB107) YES UVB-1 #010906

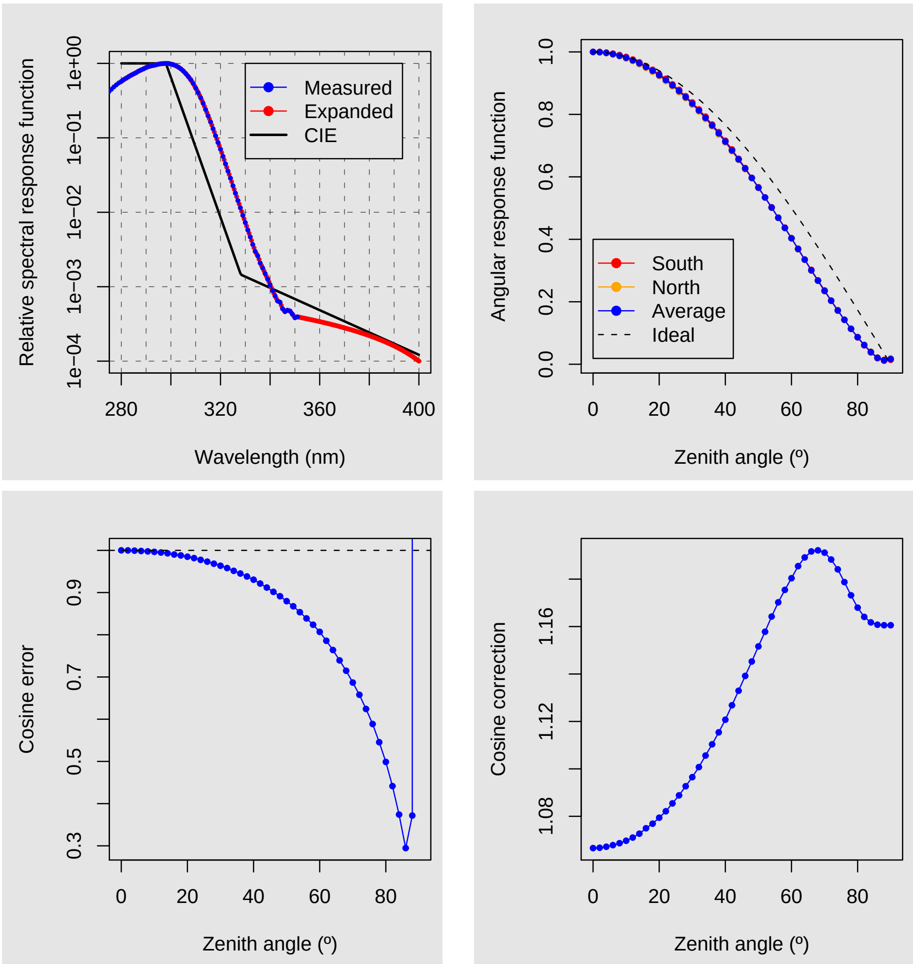

Figure 23: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB107) YES UVB-1 #010906

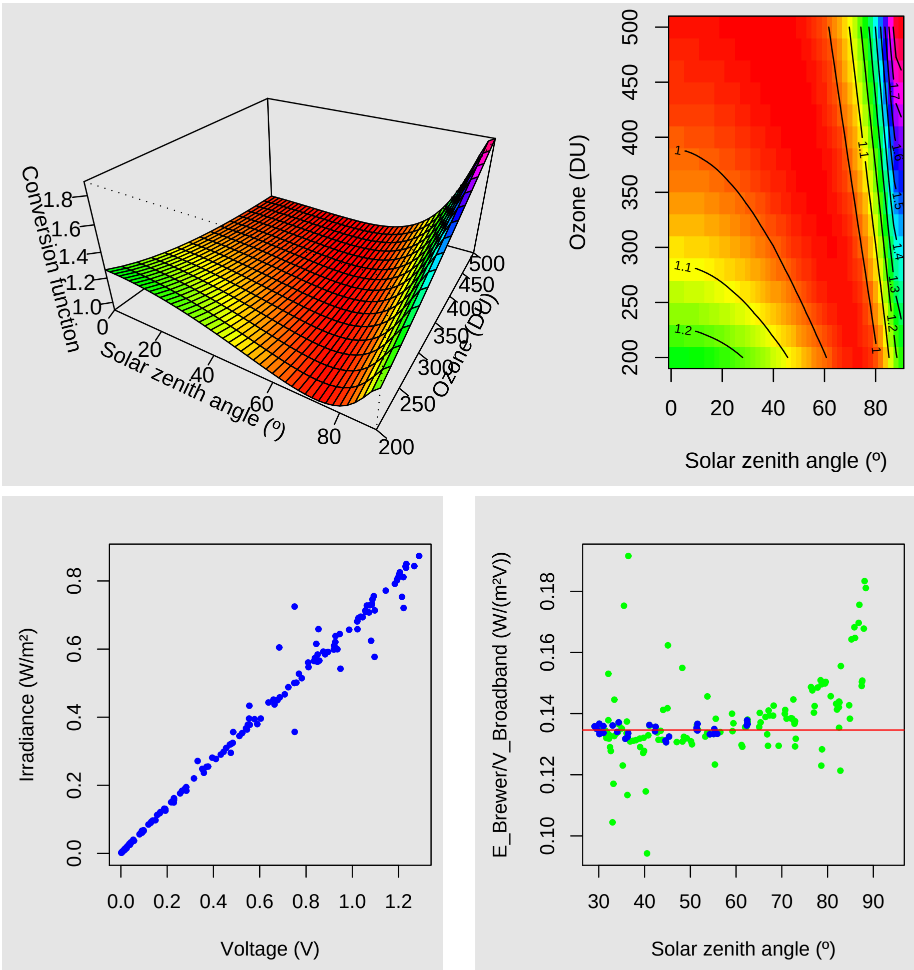

Figure 24: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB109) YES UVB-1 #010908

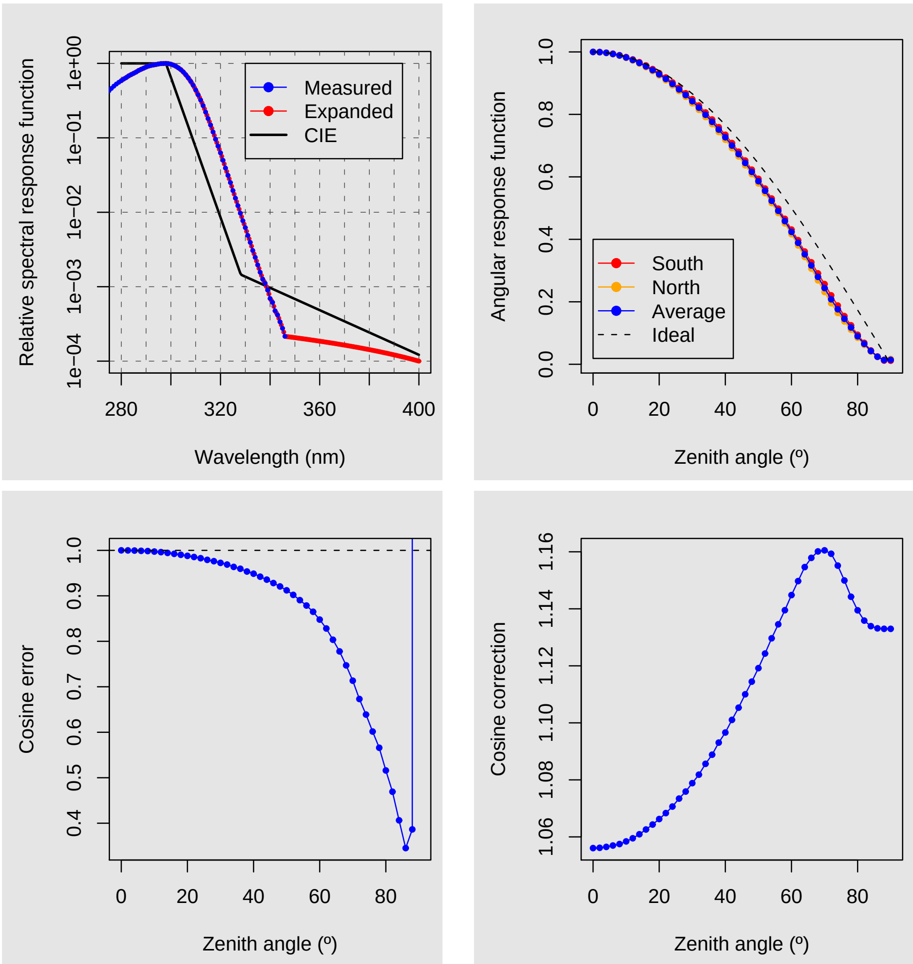

Figure 25: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB109) YES UVB-1 #010908

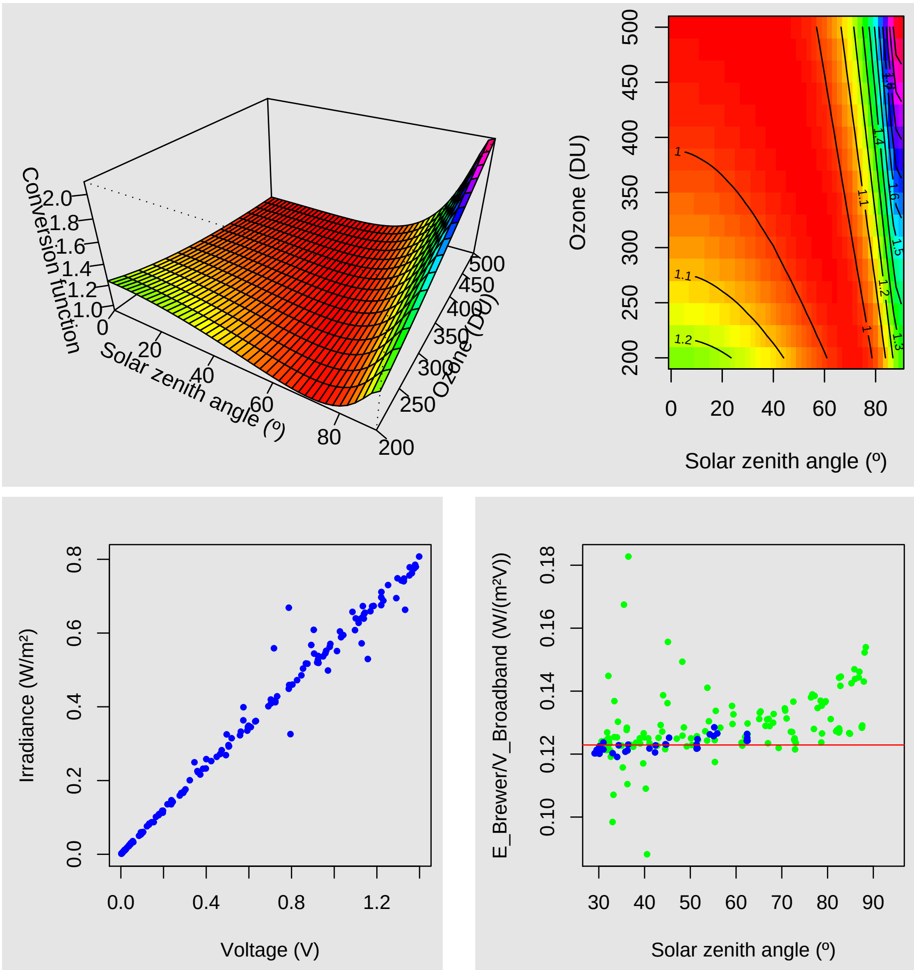

Figure 26: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB111) YES UVB-1 #970829

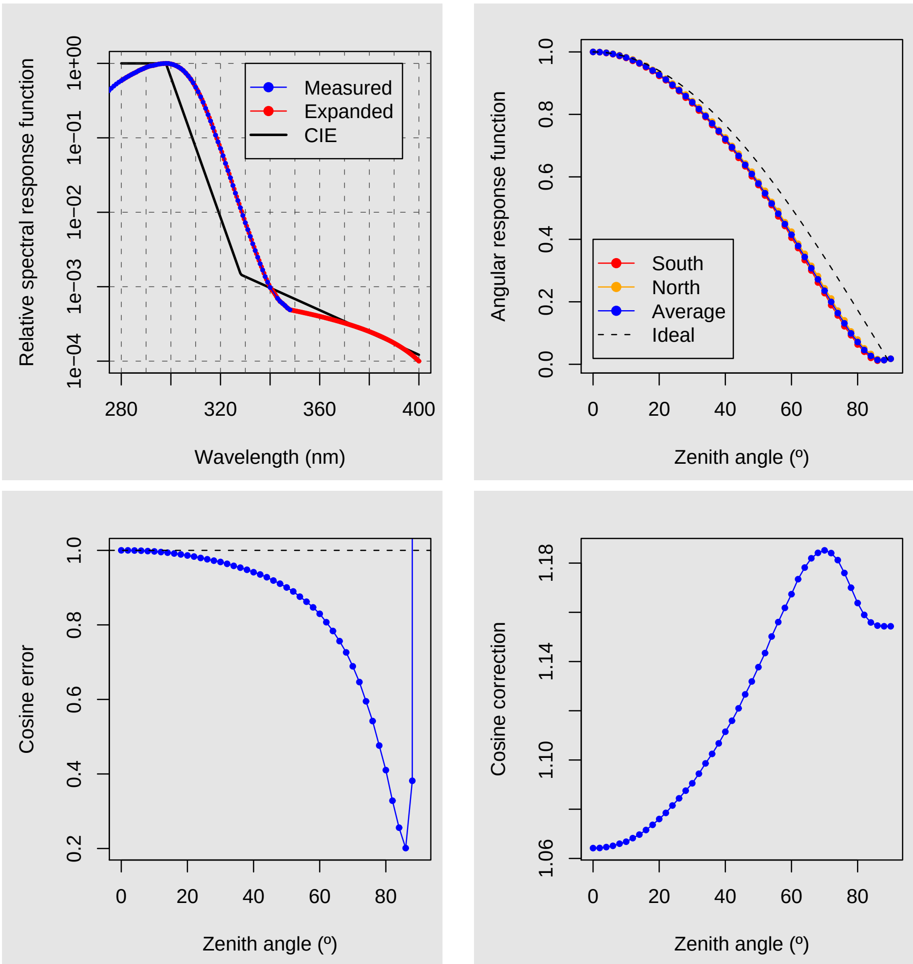

Figure 27: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB111) YES UVB-1 #970829

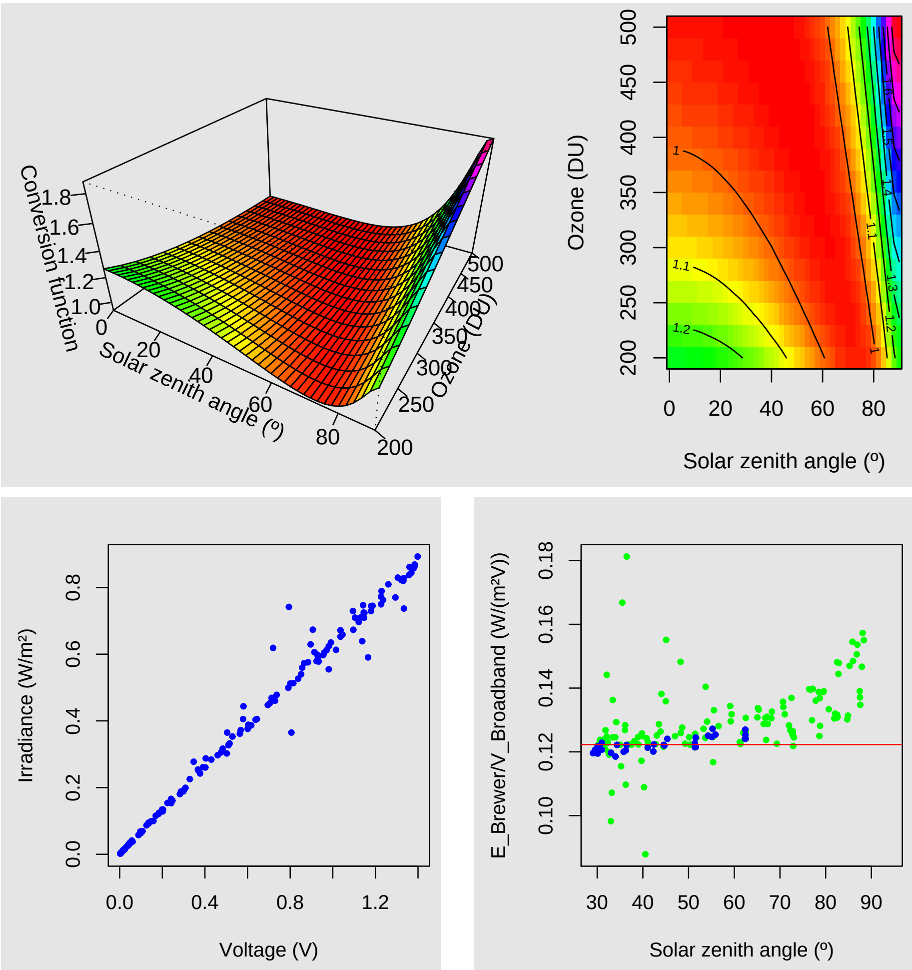

Figure 28: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB113) YES UVB-1 #990608

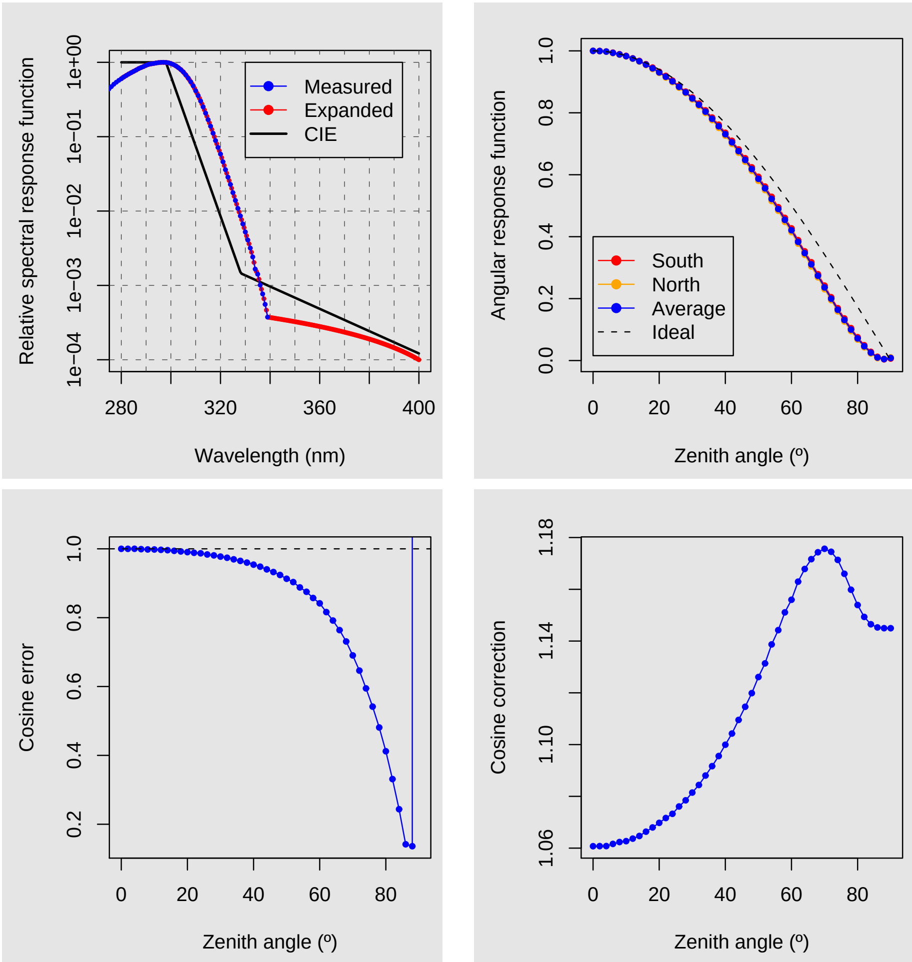

Figure 29: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB113) YES UVB-1 #990608

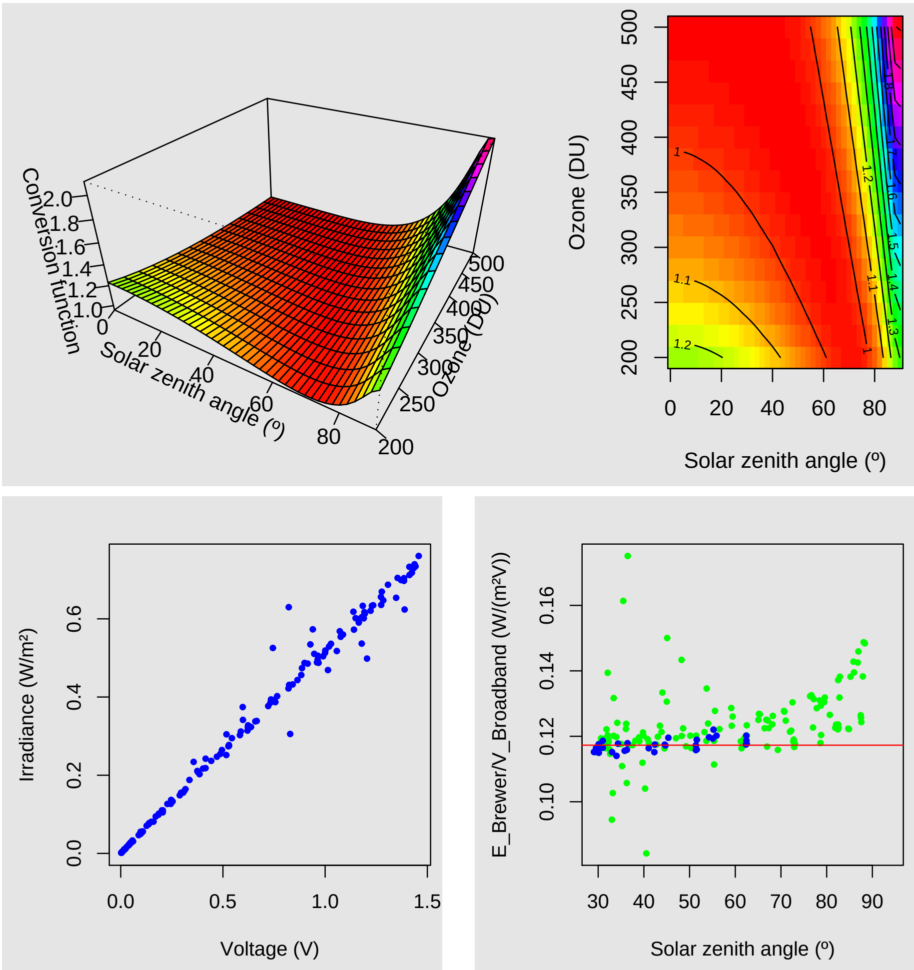

Figure 30: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB115) YES UVB-1 #030521

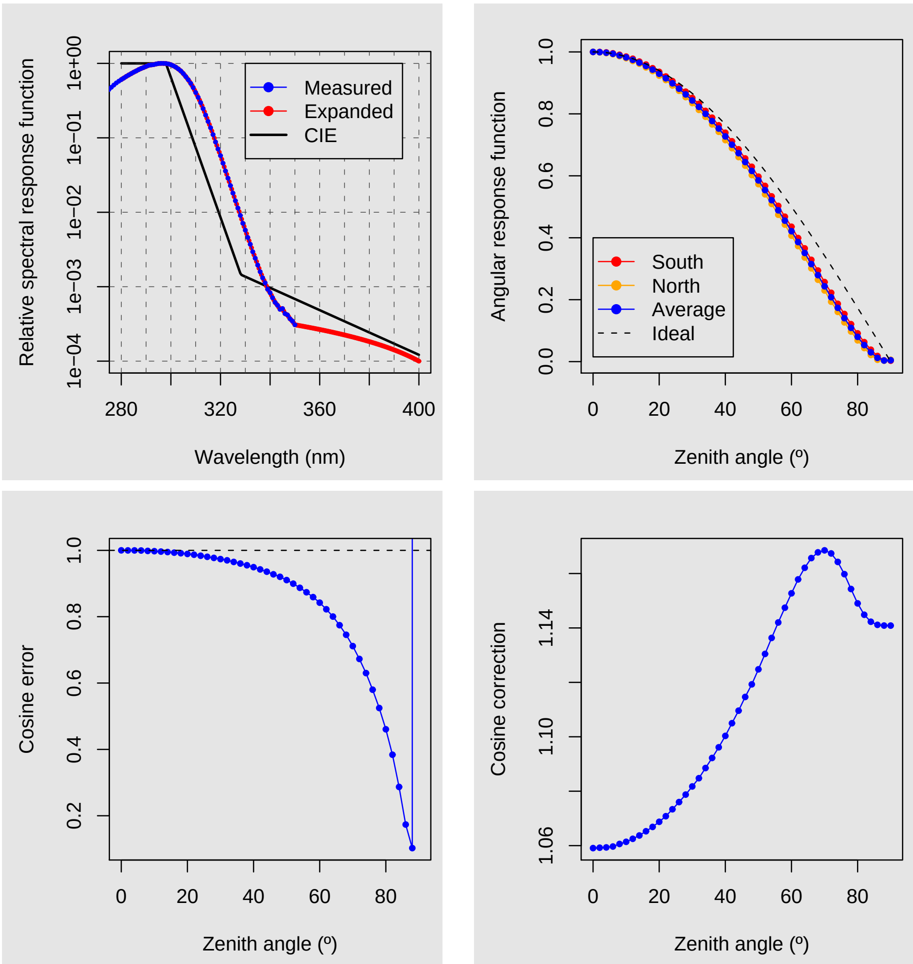

Figure 31: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB115) YES UVB-1 #030521

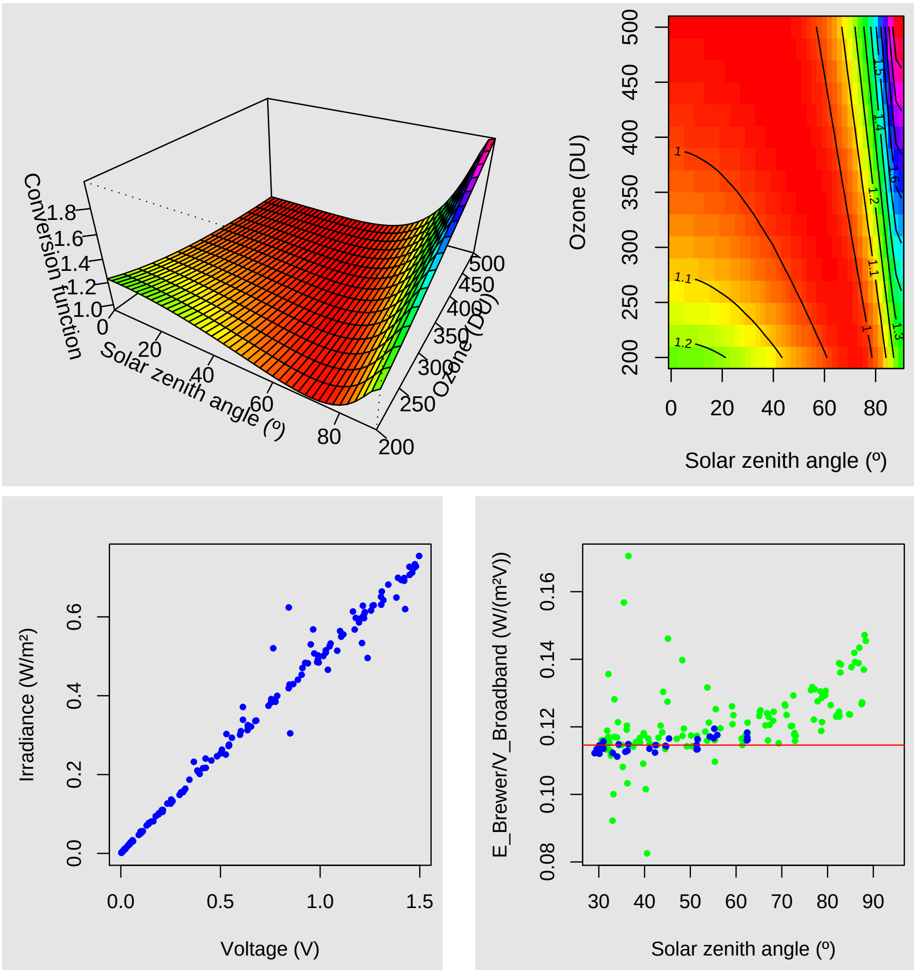

Figure 32: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB117) YES UVB-1 #970839

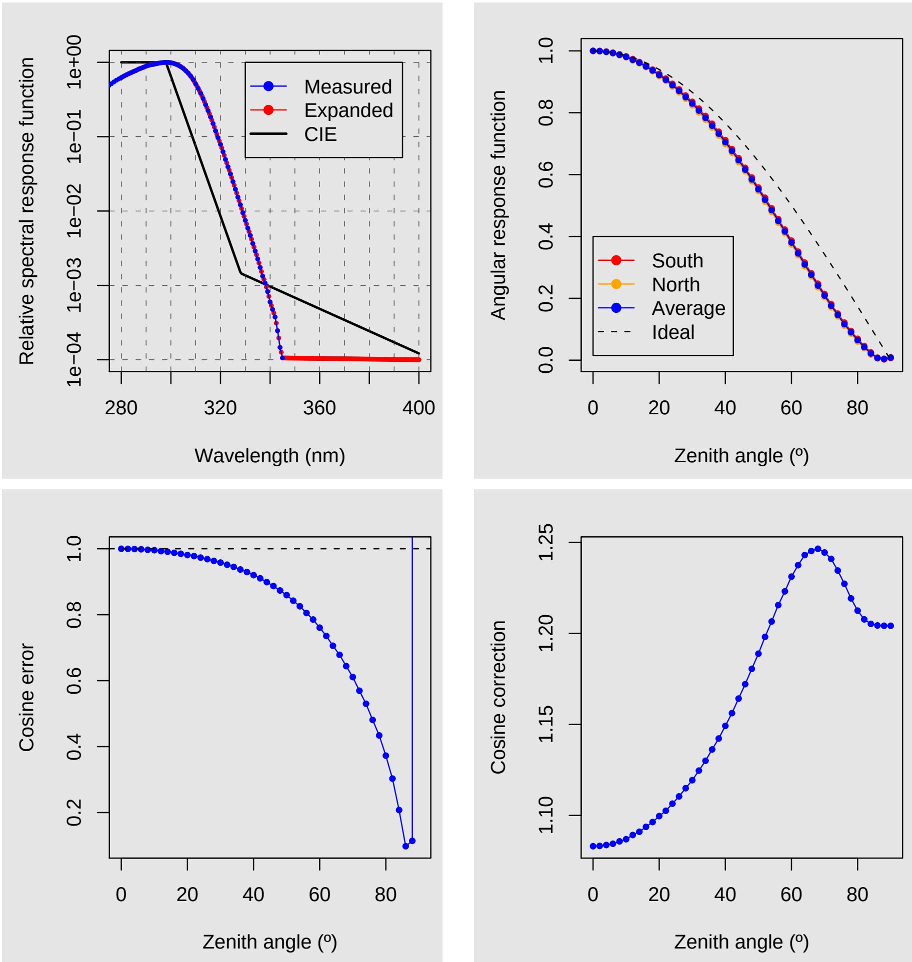

Figure 33: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB117) YES UVB-1 #970839

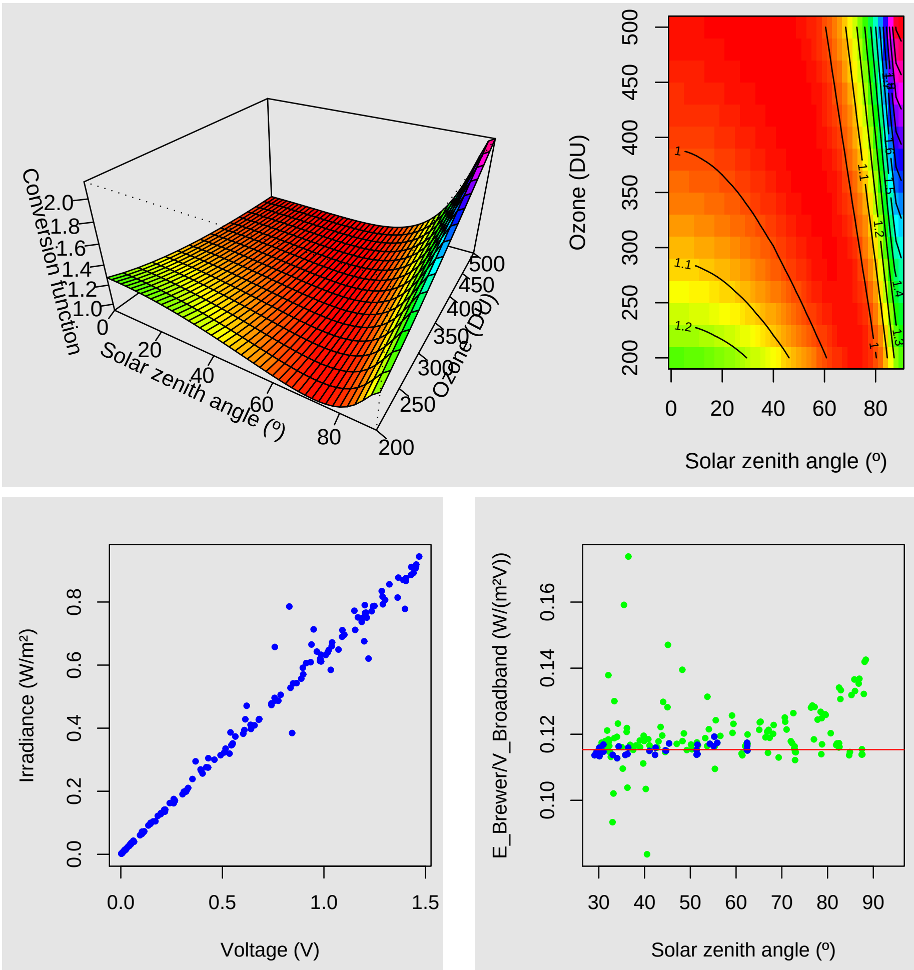

Figure 34: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

8.2.2 Kipp & Zonen broadband radiometers

(BB201) Kipp & Zonen UVS-E-T #010540

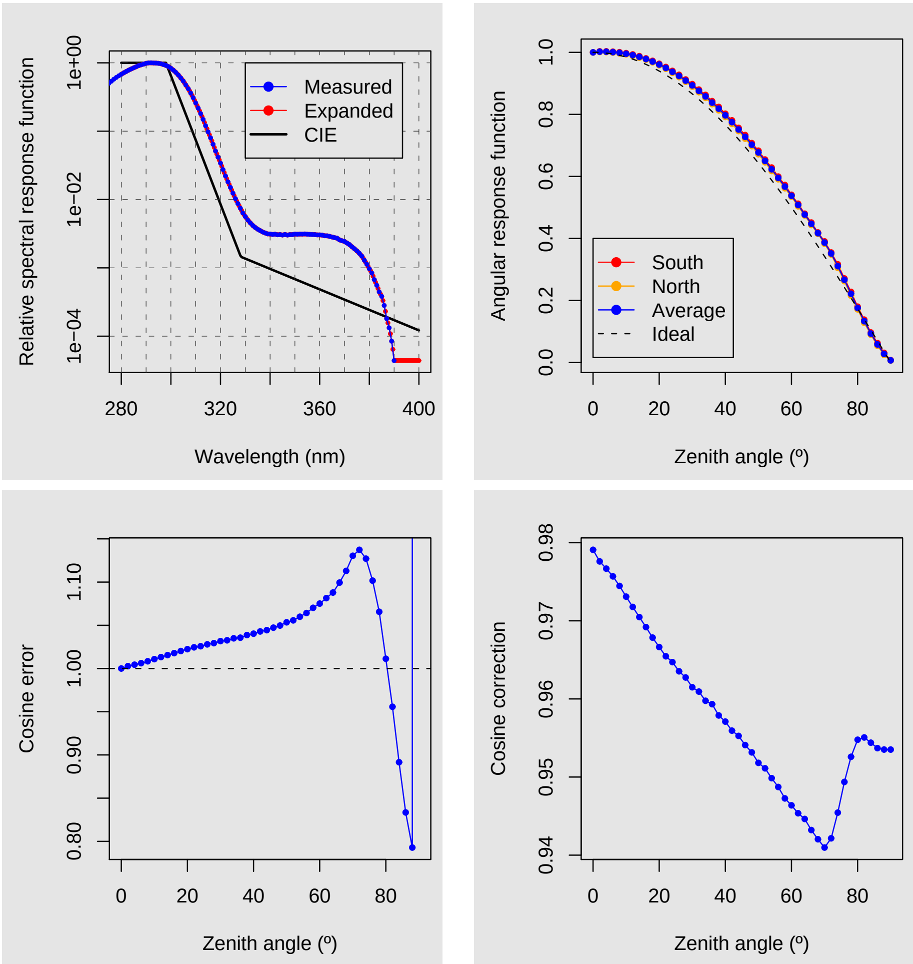

Figure 35: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB201) Kipp & Zonen UVS-E-T #010540

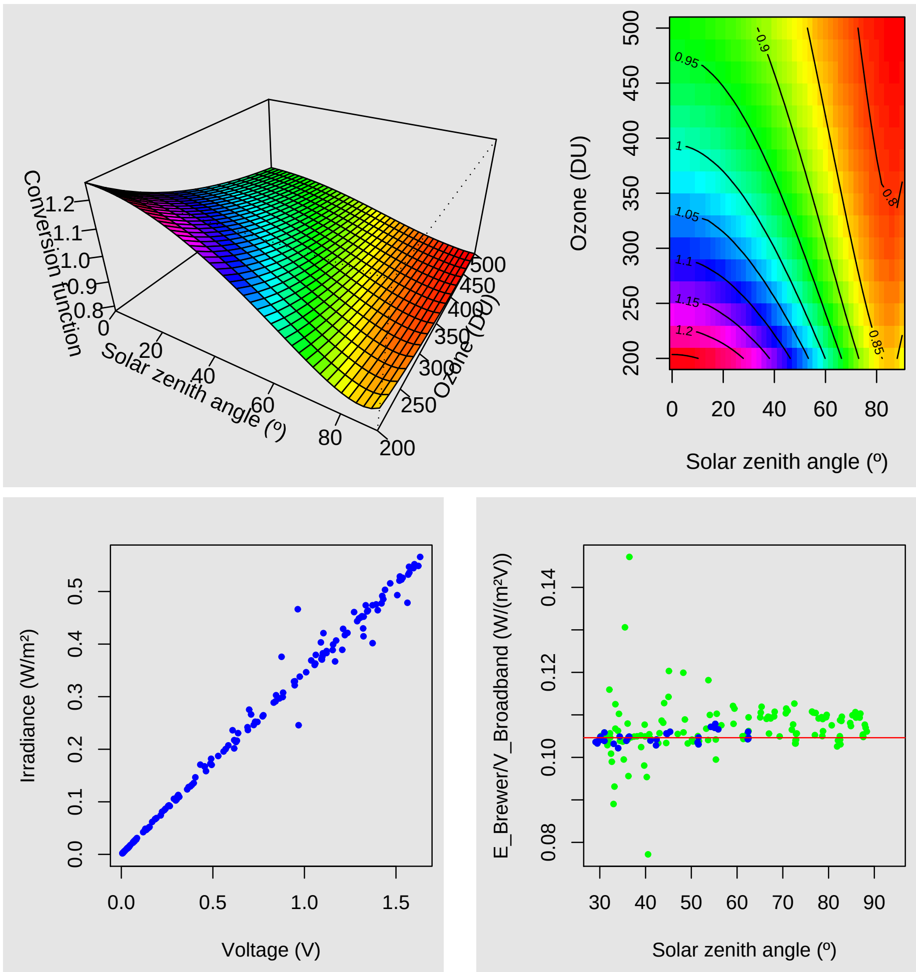

Figure 36: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB203) Kipp & Zonen UVS-E-T #000532

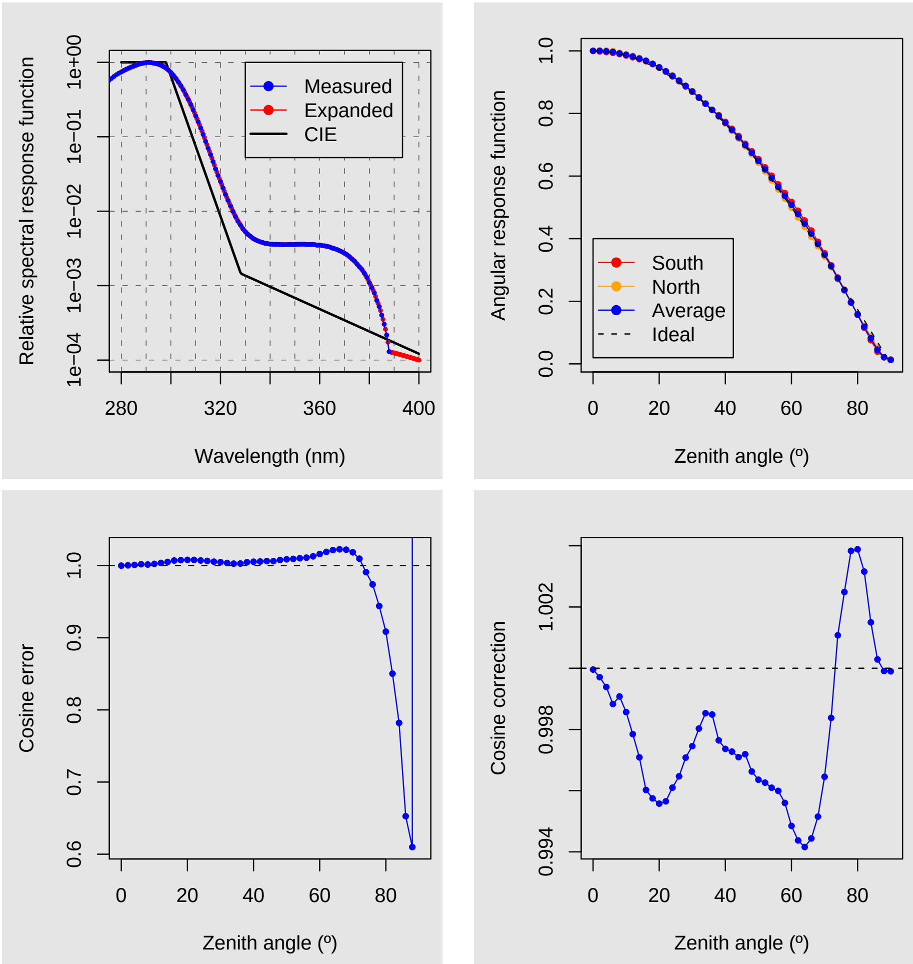

Figure 37: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB203) Kipp & Zonen UVS-E-T #000532

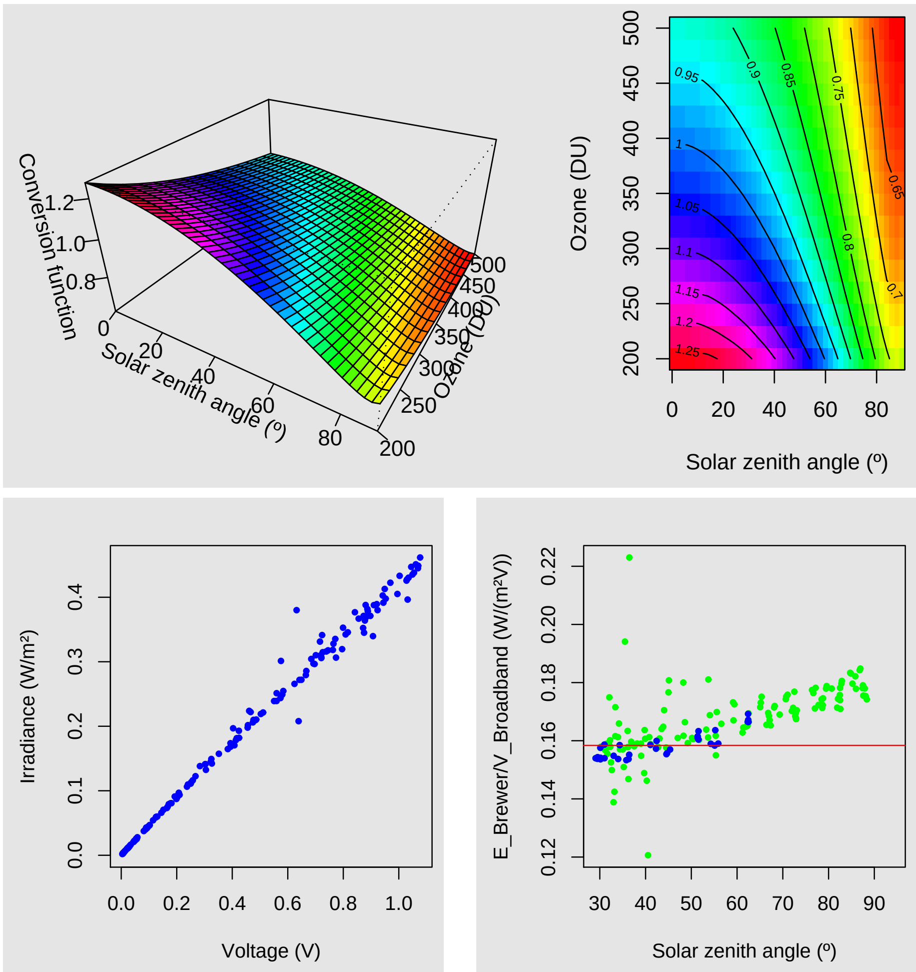

Figure 38: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB205) Kipp & Zonen UVS-E-T #020599

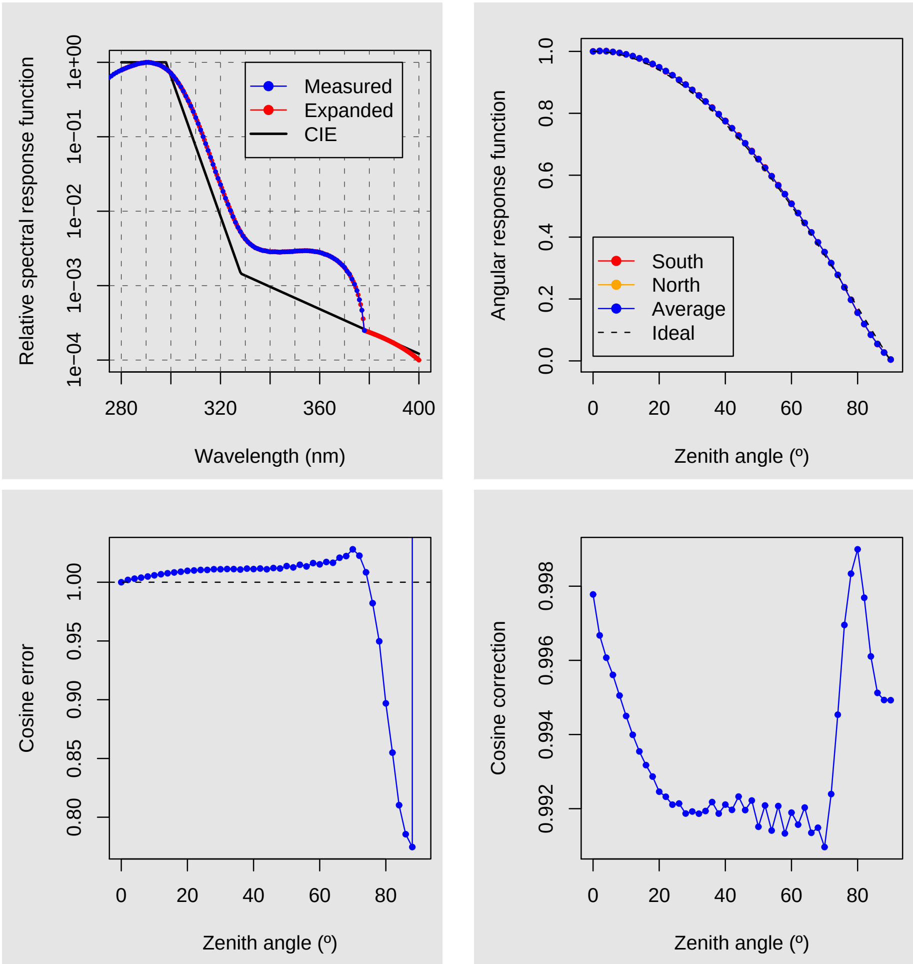

Figure 39: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB205) Kipp & Zonen UVS-E-T #020599

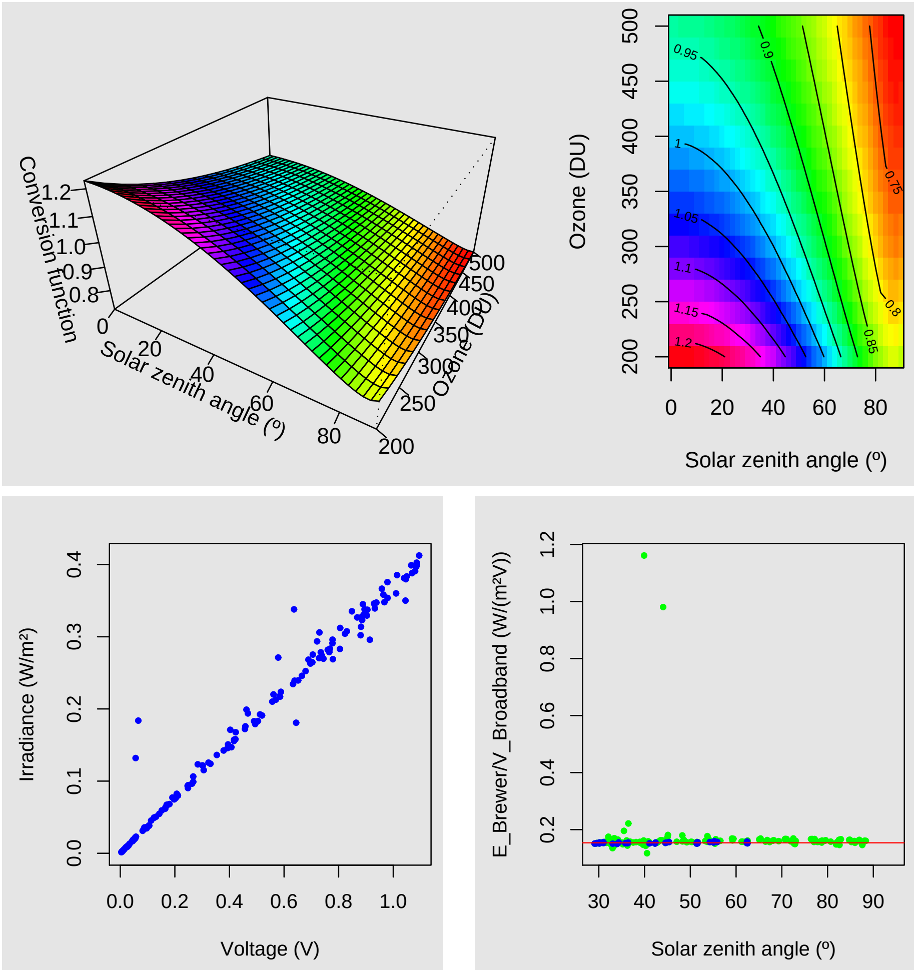

Figure 40: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB207) Kipp & Zonen UVS-E-T #000392

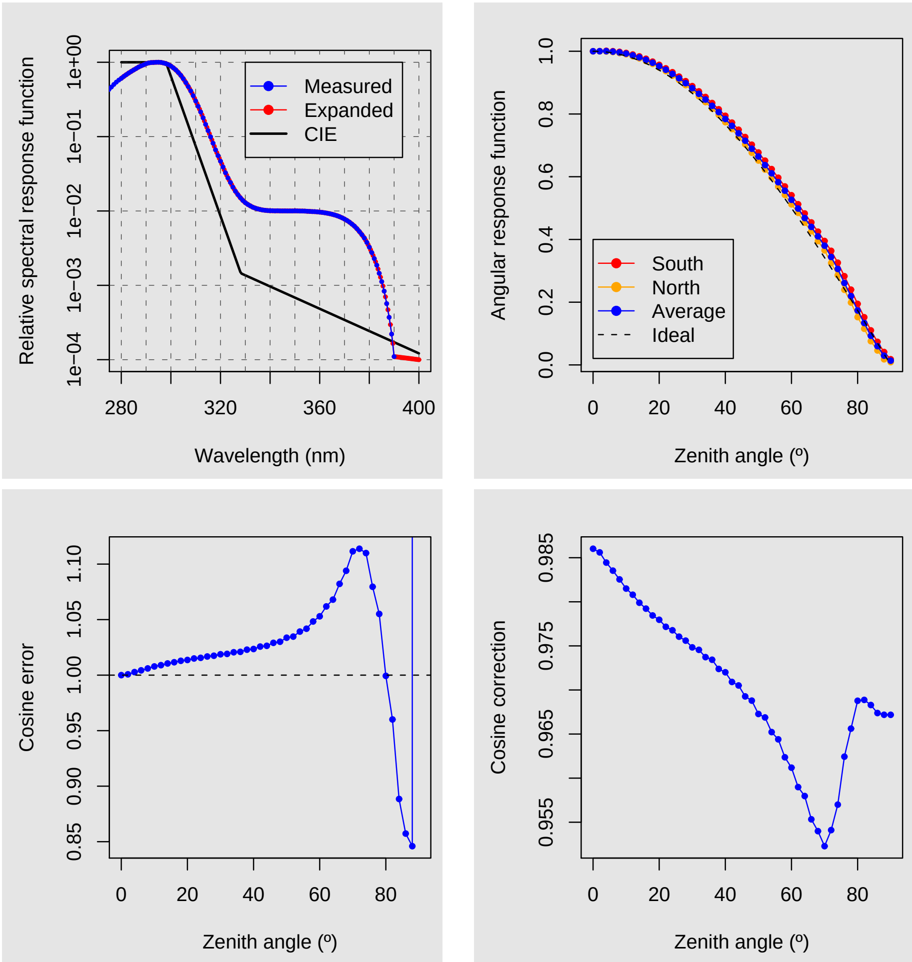

Figure 41: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB207) Kipp & Zonen UVS-E-T #000392

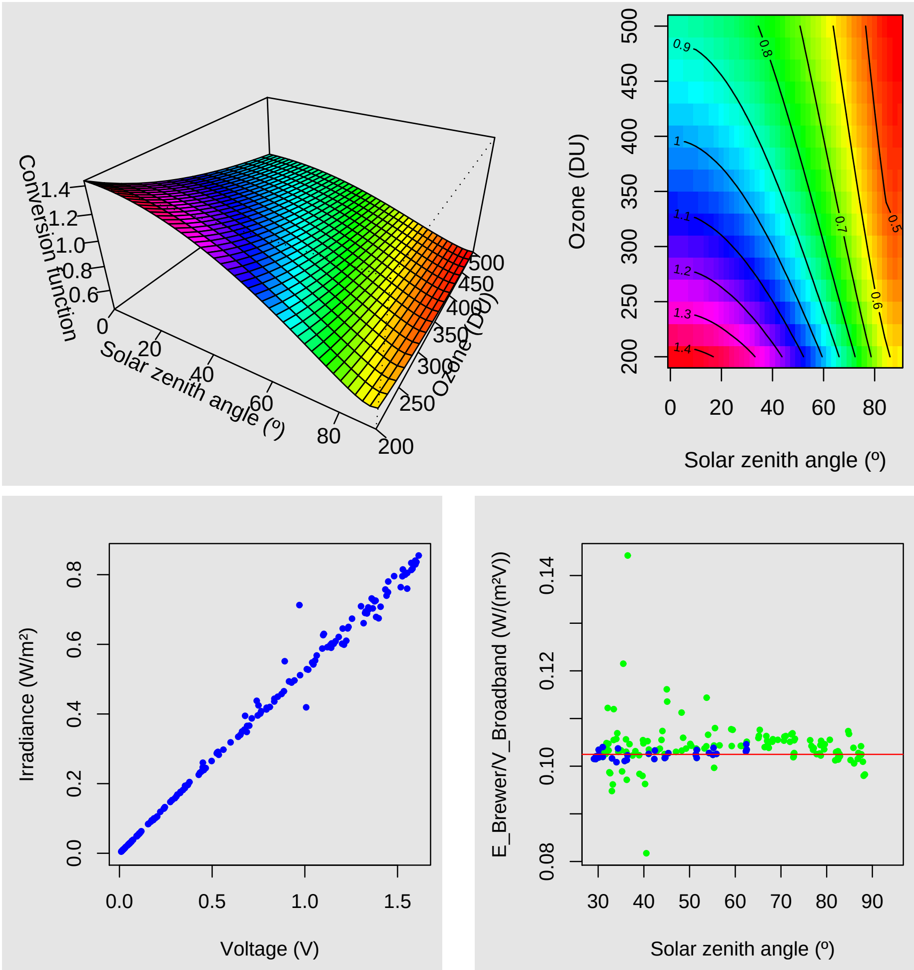

Figure 42: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB209) Kipp & Zonen UVS-E-T #000518

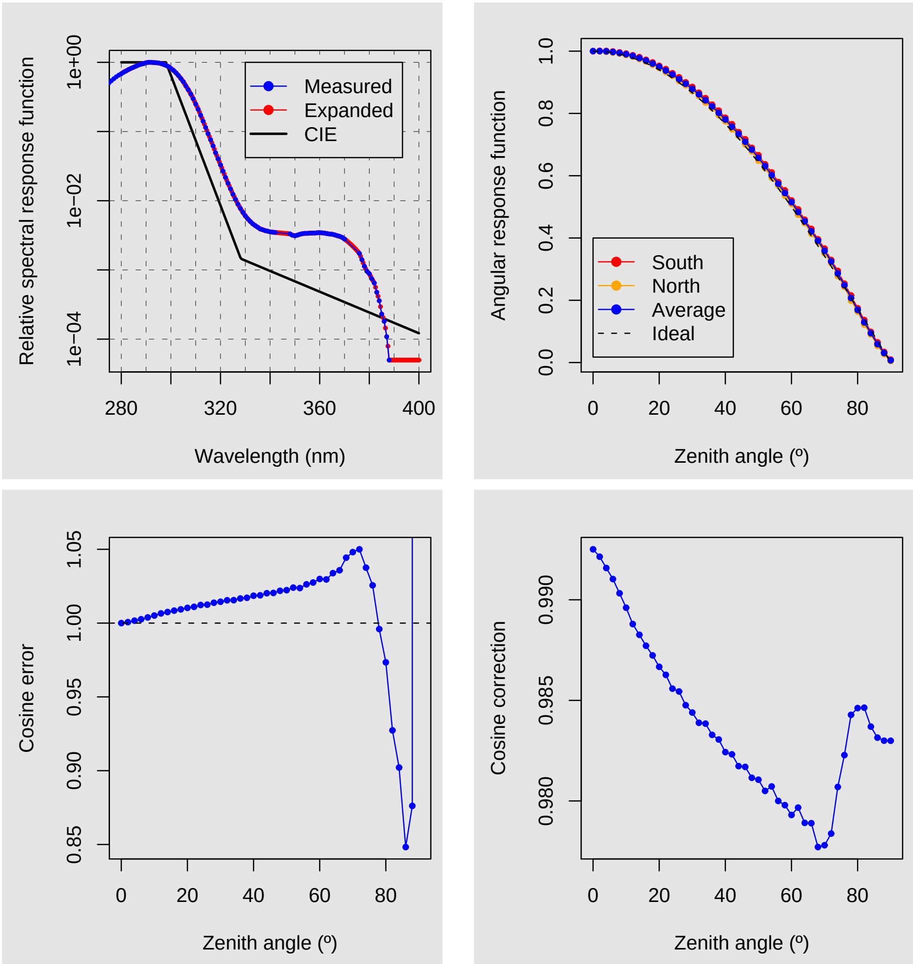

Figure 43: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB209) Kipp & Zonen UVS-E-T #000518

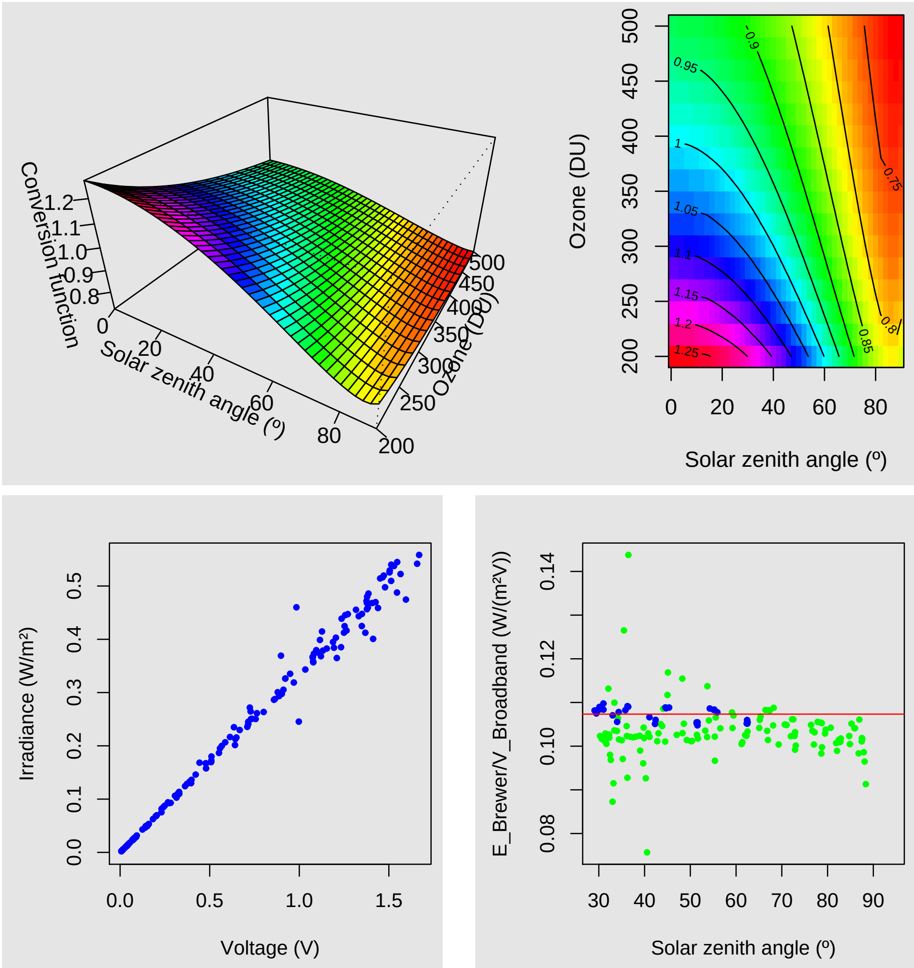

Figure 44: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB211) Kipp & Zonen UVS-E-T #060625

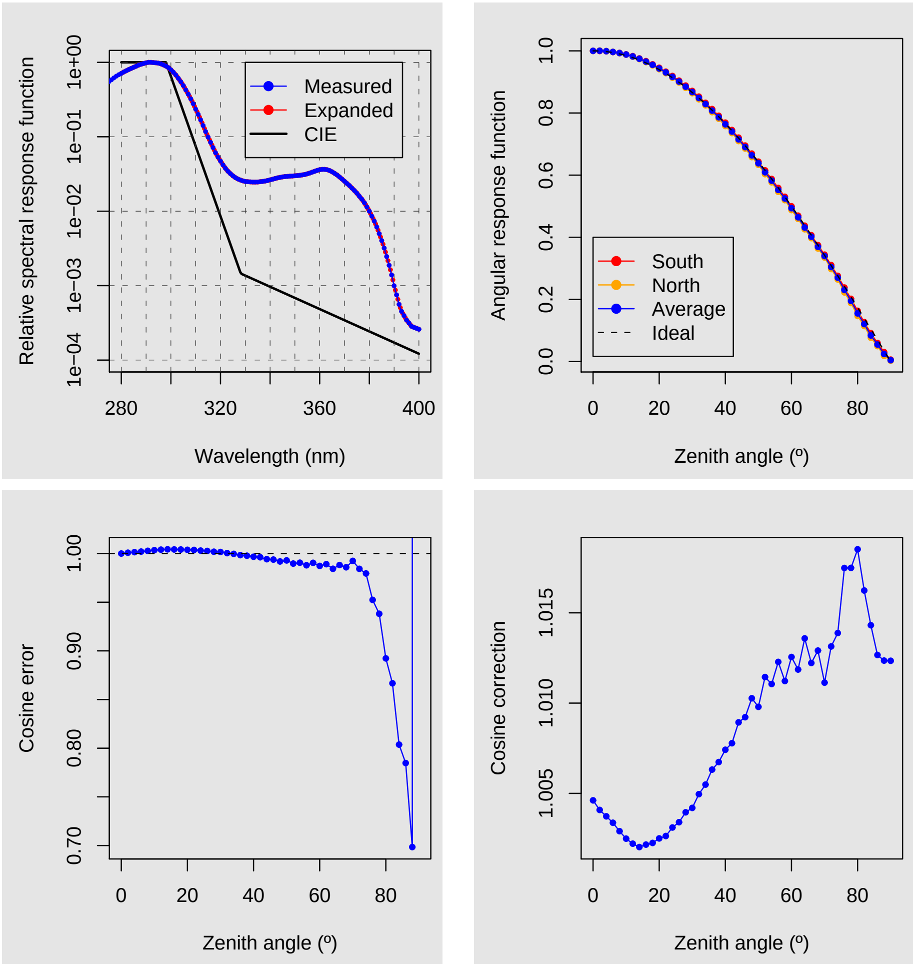

Figure 45: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB211) Kipp & Zonen UVS-E-T #060625

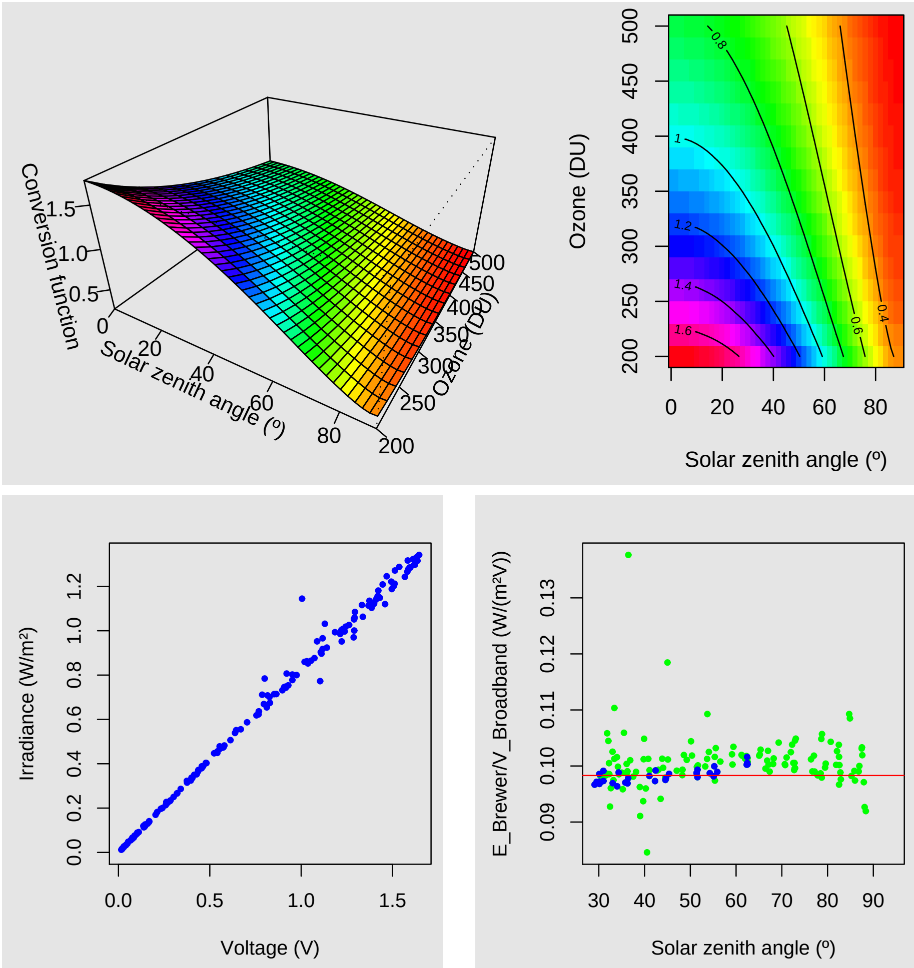

Figure 46: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB213) Kipp & Zonen UVS-E-T #060634

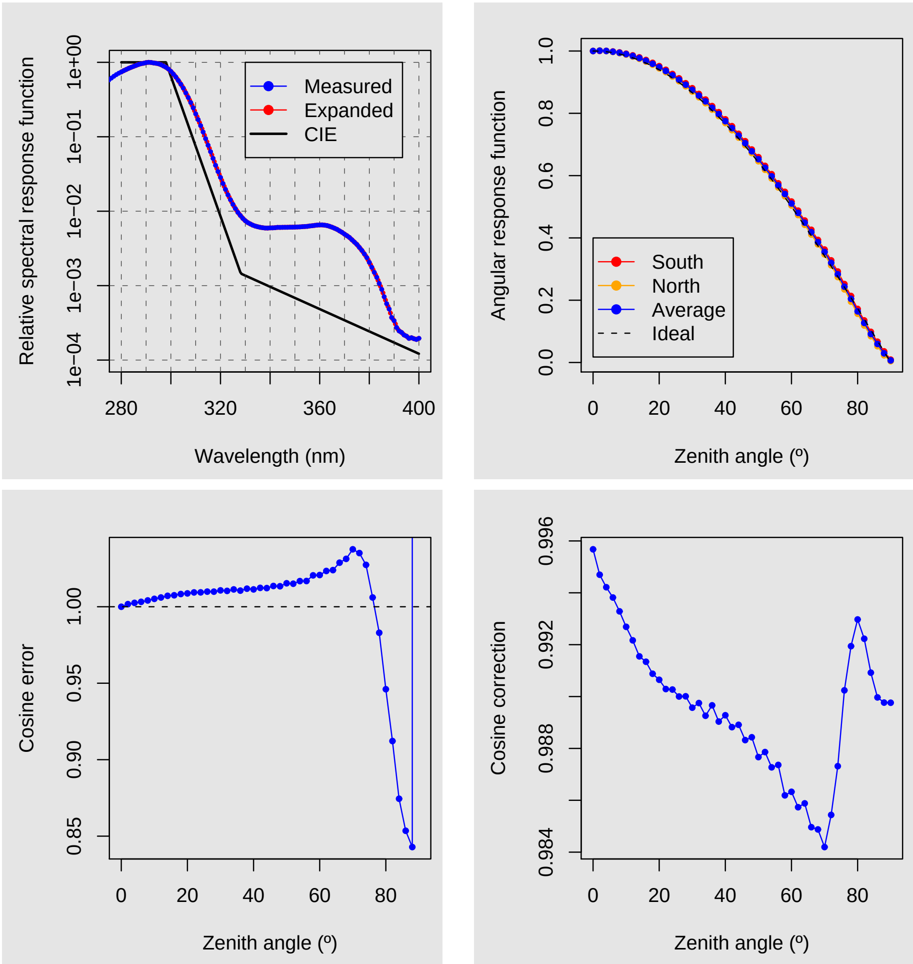

Figure 47: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB213) Kipp & Zonen UVS-E-T #060634

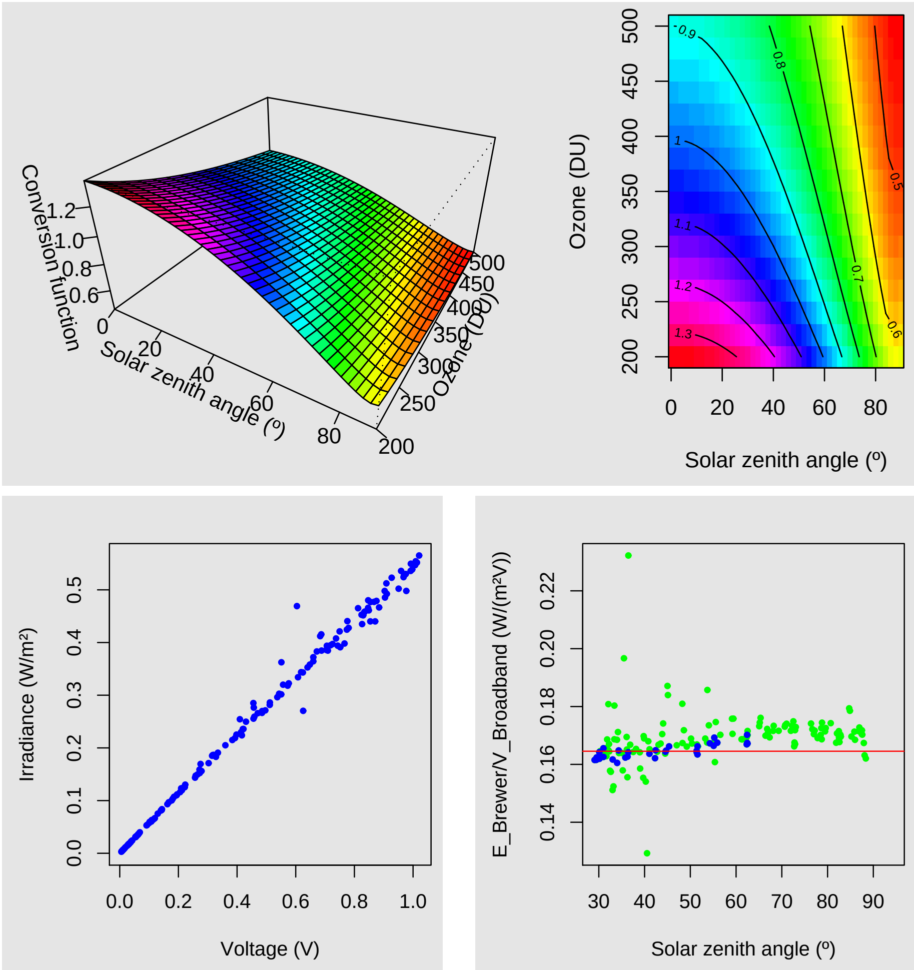

Figure 48: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB215) Kipp & Zonen UVS-E-T #070638

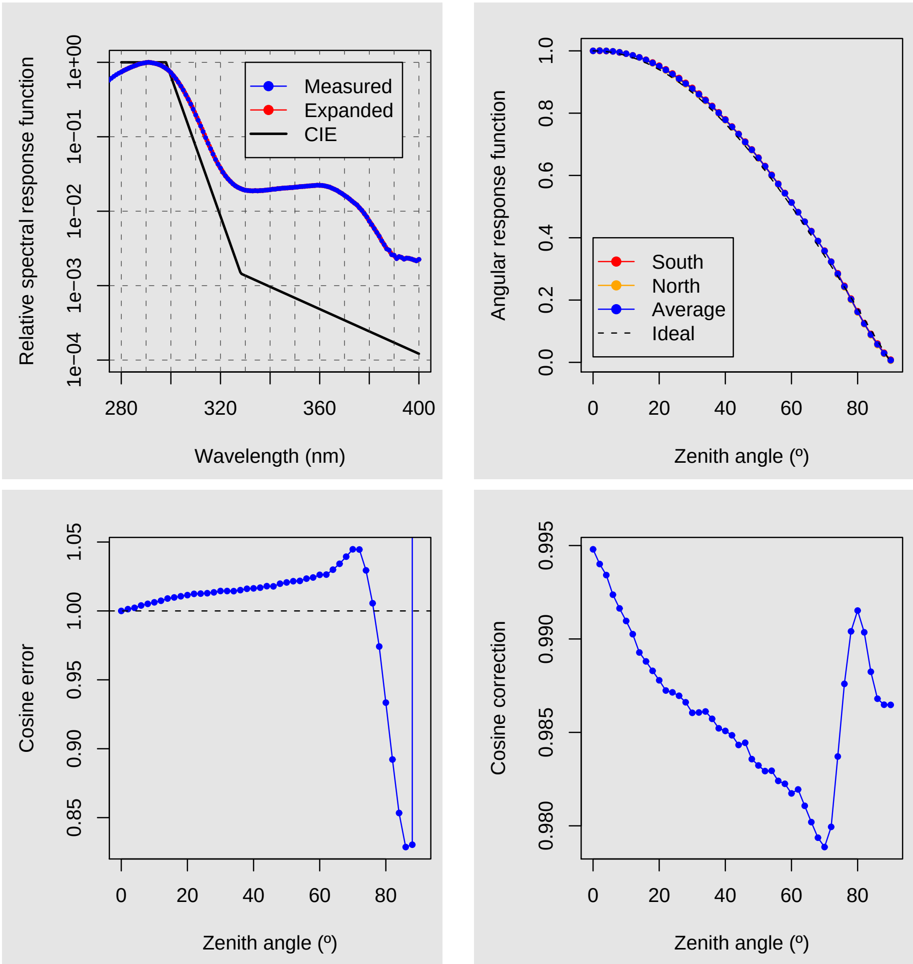

Figure 49: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB215) Kipp & Zonen UVS-E-T #070638

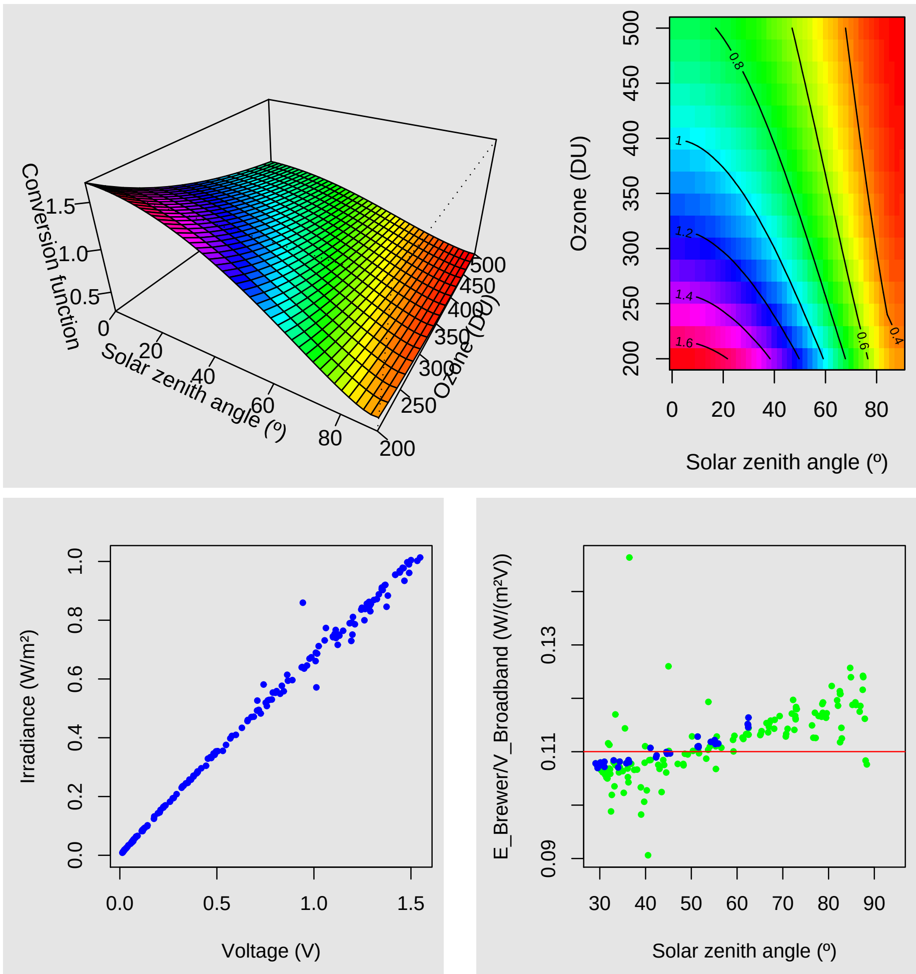

Figure 50: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB217) Kipp & Zonen UVS-E-T #000409

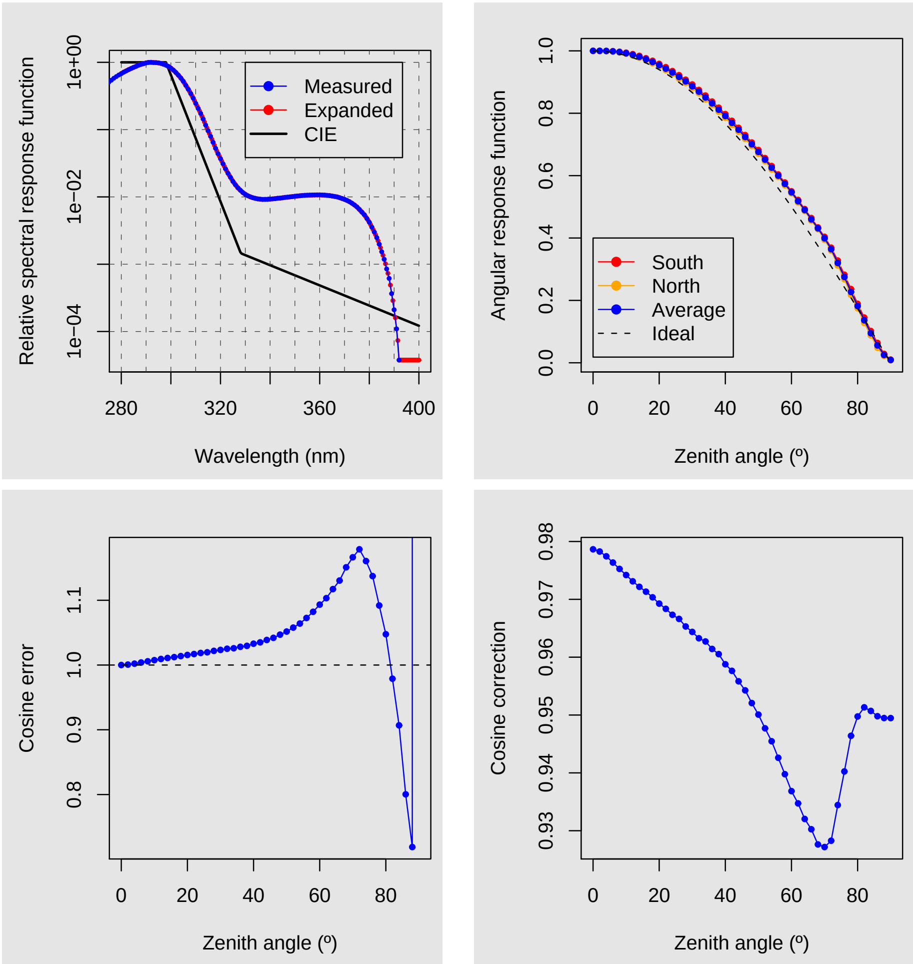

Figure 51: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB217) Kipp & Zonen UVS-E-T #000409

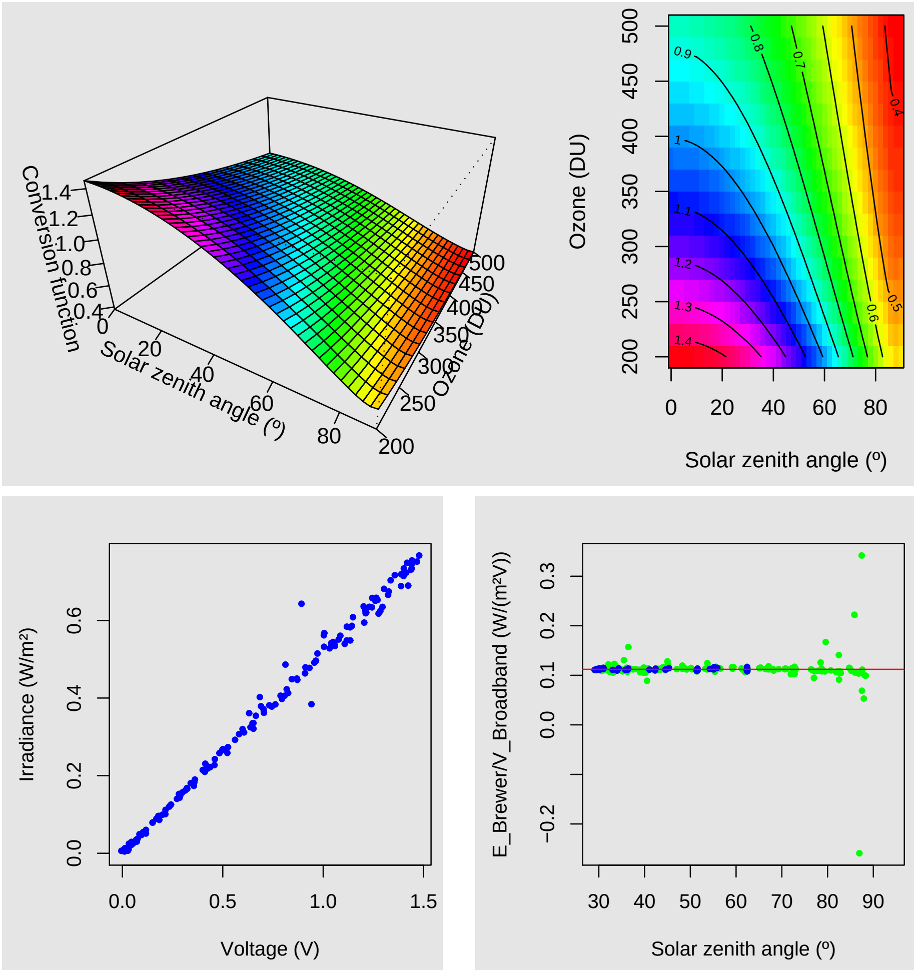

Figure 52: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

8.2.3 Solar Light broadband radiometers

(BB301) Solar Light SL-501 #5806

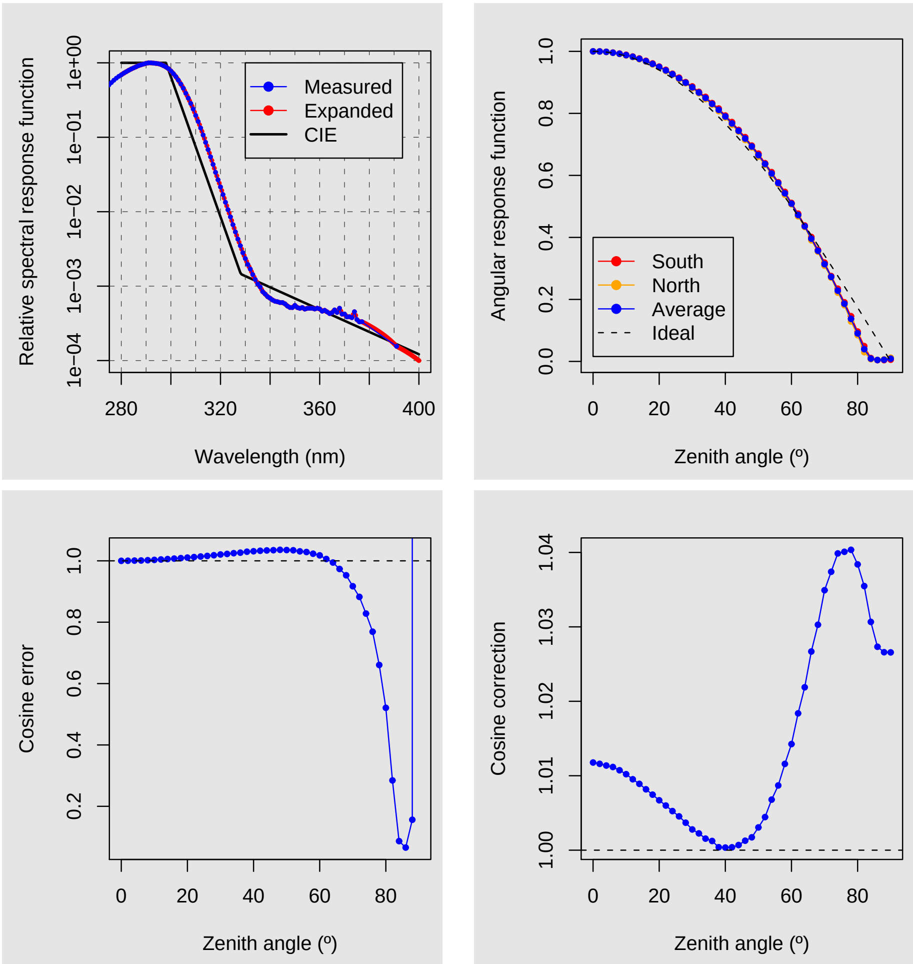

Figure 53: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB301) Solar Light SL-501 #5806

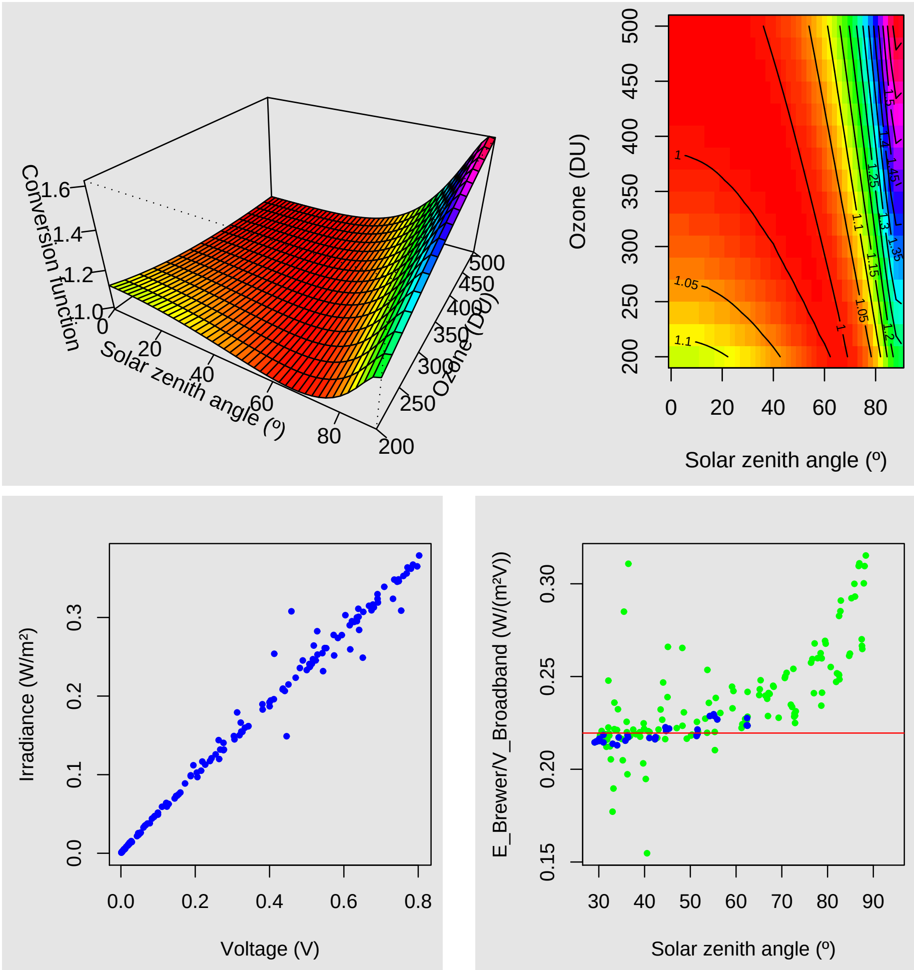

Figure 54: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

(BB303) Solar Light SL-501 #5775

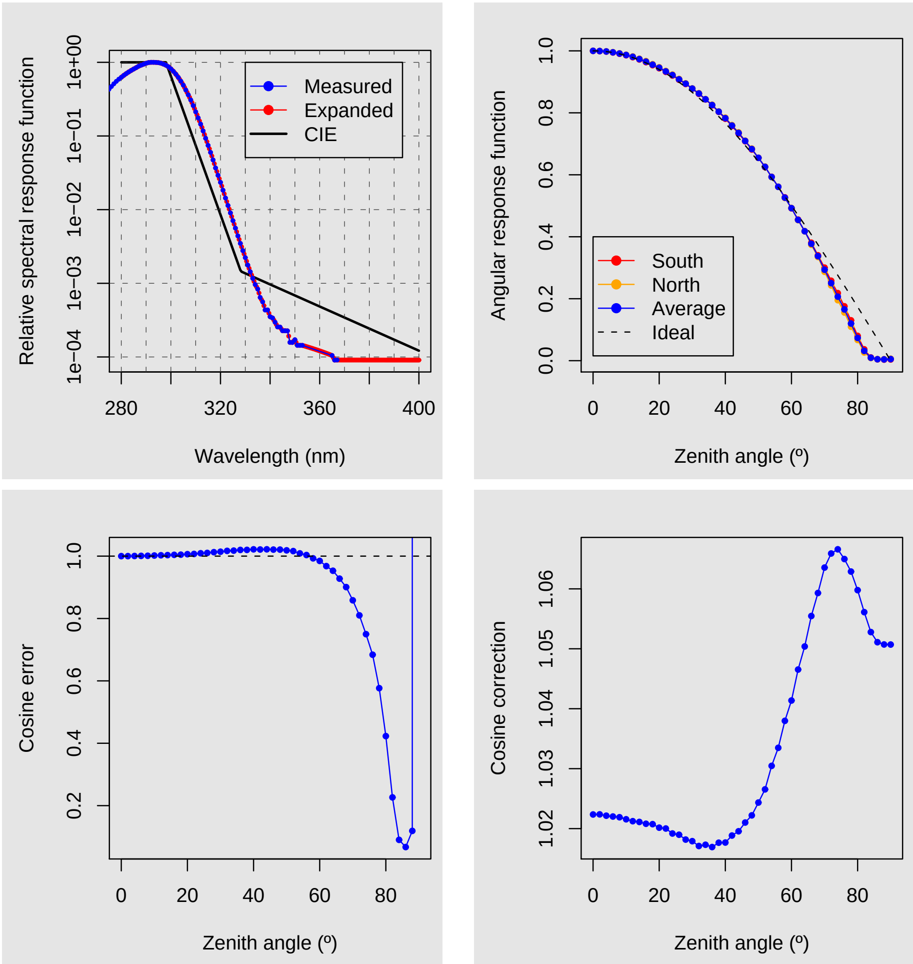

Figure 55: Top: Relative spectral and angular response functions. Bottom: Cosine error and correction.

(BB303) Solar Light SL-501 #5775

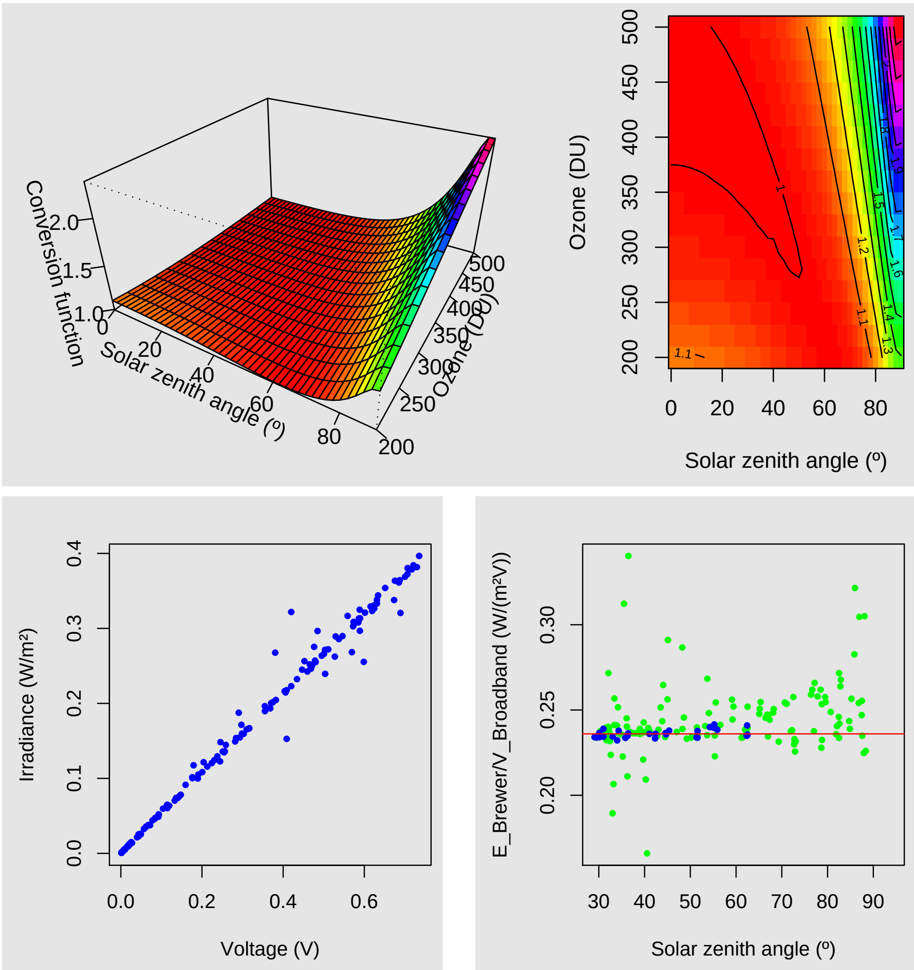

Figure 56: Top: Conversion function. Bottom: UVER irradiance as measured by Brewer #150 versus radiometer signal, and its sensitivity to the solar zenith angle.

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