Intercomparison of monochromatic source facilities for the determination of the relative spectral response of erythemal broadband filter radiometers

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The relative spectral responses of erythemally weighted broadband radiometers determined at three different laboratories are compared, and the systems are described. The results of measurements of four different broadband radiometers are discussed. Although the common dynamic range of the measured relative spectral responses is approximately 10^4, the differences in the relative spectral response functions are lower than 20%. These differences are related mostly to measurement uncertainties and differences in the spectral response facilities.

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High-quality calibration of broadband detectors is based on the determination of the radiometer's relative spectral response $r(\lambda)$, which is normalized to the response at the wavelength of the maximal response, by use of a tunable monochromatic light source. The radiometer's absolute calibration factor c is derived by a comparison of its signal readout S during outdoor operation with simultaneous global spectral irradiance measurements $I(\lambda)$ (Refs. 1–4):

$$cS = \int I(\lambda)r(\lambda)\mathrm{d}\lambda.$$

This method of separation between relative measurements in the laboratory and absolute calibration outdoors has the advantages of taking into account the angular distribution of UV radiation from the sky and of being independent of the geometry of the detector.

To detect changes in the spectral characterization of erythemally weighted broadband filter radiometers, each individual relative spectral response $r(\lambda)$ must be investigated by a laboratory calibration with a monochromatic light source adjustable from at least 280 to 400 nm.[5–8]

In this study the relative spectral responses from four erythemally weighted broadband filter radiometers from different manufacturers are measured at two different laboratories. Two of these radiometers are measured by a third laboratory. All measurements are performed within a 3-week period to minimize changes in the radiometers.

The spectral response facility SRF-J1001 in the laboratory at the Institute for Medical Physics, developed by Calibration Measurement Software Solutions (CMS) for characterizing the radiometers of the Austrian monitoring network,[3,9] consists of a 1000-W xenon light source that is attached to a Bentham DM150 double monochromator. A water filter between the light source and the entrance slit is used to absorb infrared radiation and thus prevent heating from the double monochromator. The DM150 is equipped with gratings of 2400 lines/mm and has a focal length of 150 mm. The tunable entrance and exit slits are adjusted to an approximately triangular slit function of 4 nm (alternatively 1.9 nm) FWHM. To obtain maximal radiation output of the monochromatic source, routine measurements are carried out with the 4-nm slit. The wavelength uncertainty of the DM150 is based on measurements of spectral discharge lamps and is less than 0.2 nm.

The double monochromator's stray-light suppression has been determined to be better than 10^{-5} (10^{-6} at 1.9-nm slit) at 8 nm from the nominal wavelength. Especially for the spectral response characterization of erythemally weighted detectors, high stray-light rejection is important because the radiometer's relative spectral response differs by a factor of approximately 10^4 between the UVB and the UVA range. An optimized output optic transmits the monochromatic light from the DM150 to the broadband detector and to a reference diode. The diode is used to correct for instabilities in the light output of the xenon light source.

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The spectral throughput of the spectral response facility is characterized from 255 to 455 nm is steps of 2 nm. The total power at each wavelength setting of the monochromatic source is obtained from the wavelength integration of the exit spectrum measured with a calibrated double monochromator.

The output from the broadband detector and the diode is recorded automatically while the DM150's wavelength is changed from 265 to 400 nm in steps of 1 nm. A 3-s delay before starting the measurement at each wavelength minimizes the effect of the settling time of the radiometer. After offset correction, the relative spectral response $r(\lambda)$ of the detector is determined from the relation between the detector output and the absolute spectral intensity data.

The monochromatic source B3388 at the European Reference Centre for Ultraviolet Radiation Measurements uses a Bentham double monochromator with a focal length of 150 mm and a grating of 2400 lines/mm. A 300-W xenon lamp is used as a radiation source. It is coupled into the monochromator with an optical fiber, and the whole setup is optimized to maximize the transmission through the system. The entrance and exit slits are 1.57 mm wide and produce a nearly triangular slit function with a FWHM of 1.9 nm.

The monochromatic source is characterized over the wavelength range 260–400 nm by use of a second spectroradiometer placed behind the exit slit of the monochromatic source. On the basis of measurements of the spectral throughput at various wavelengths, the stray-light rejection of B3388 could be estimated: At 5 nm from the nominal wavelength the measured rejection is higher than 10^{-4}, and no transmitted radiation could be measured at more-distant wavelengths due to the low radiation intensity. On the basis of the shape of the spectral transmission function, the stray-light rejection at 10 nm from the nominal wavelength is estimated to be greater than 10^{-6}. The spectral throughput of the monochromatic source is determined every 2–5 nm on two different occasions and agrees to better than 2% for wavelengths greater than 290 nm. The wavelength uncertainty of the monochromatic source is based on measurements of spectral discharge lamps and is less than 0.1 nm.

In the Joint Research Centre (JRC) laboratory the spectral response functions of the four filter radiometers discussed in this Letter are obtained by several successive wavelength scans from 400 to 280 nm every 2 nm. Initiating measurements at low signal levels minimizes the influence of the settling time of the radiometer on the measured spectral response. This effect is investigated by successive spectral response measurements from 280 to 400 nm (up) and from 400 to 280 nm (down). The largest effect is observed in the wavelength region 300–340 nm in which the spectral response function changed by 2–3 orders of magnitude depending on the radiometer type. Differences between the up and down scans are of the order of 10%.

For the measurement of the spectral response function the broadband radiometer is scanned with monochromatic radiation between 280 and 400 nm. The spectral radiation is generated by a 3000-W xenon short-arc high-pressure lamp and a single monochromator (Oriel MS257) mounted on a linear optical bench. The monochromator has focal length of 257.4 mm and uses a grating with 1200 lines/mm optimized for 350 nm. A roughly triangular spectral transmission function of 1.9 nm FWHM is obtained with an exit slit width of 0.62 mm. The full width of the spectral transmission function increases to 4 and 8 nm at a relative intensity level of 10^{-3} and 10^{-4}, respectively. The spectral scans are carried out with an incremental step width of 1 nm and a wavelength uncertainty less than 0.3 nm. The nominal radiative energy flux provided by the monochromator output is approximately 45 μW at 300 nm and 150 μW at 400 nm with a roughly linear relationship between the points.

The spectral responses of the two erythemally weighted filter radiometers, YES930807 from Yankee Environmental Systems and SC1349 from Scintec Atmosphärenmesstechnik, were measured by the CMS and JRC laboratories. The radiometers KIP599 from Kipp & Zonen (KIP) and SL4406 from Solar Light were measured by all three laboratories, CMS, JRC, and KIP.

To control the stability of the broadband detectors, the SCI349 and SL4406 radiometers were measured at CMS 5 days before and 2 days after the laboratory measurements at JRC. Differences between the two sets of measurements were of the order of 2% for the SCI349 and 6% for the SL4406 over the wavelength range 280–380 nm. Similar results are expected from the other detectors.

As can be seen in Fig. 1, the relative spectral responses from all four radiometers have a maximum response between 290 and 294 nm followed by a decreasing sensitivity toward longer wavelengths. The relative responses of all four investigated radiometers at 340 nm are from 4×10^{-3} for the SCI349 radiometer to 4×10^{-4} for the SL4406 radiometer. At wavelengths longer than 340 nm most radiometers show a region of more or less stable responsivity followed by a further decrease in the sensitivity after approximately 370 nm.

The dynamic range of the measured spectral responses depends first on the radiation output of the monochromatic sources used for these measurements and second on the stray-light rejection capabilities of the monochromatic source used for the spectral response determination. As can be seen in Table 1, which summarizes the salient measurement features of each radiometer as it was used at each laboratory, the differences in intensity are nearly a factor of 10 between the CMS and the JRC and KIP setups. This can be partly explained by the larger throughput of the CMS system due to the wide slit (factor of 4) and by the lower intensity of the primary radiation source of the JRC setup.

U_{offset} is subtracted from the measured spectral responses of each radiometer. The CMS and JRC laboratories define U_{offset} as the value given by a radiometer when no light impinges on it. On the other hand, KIP uses the mean of the measured spectral response values at 398, 399, and 400 nm for

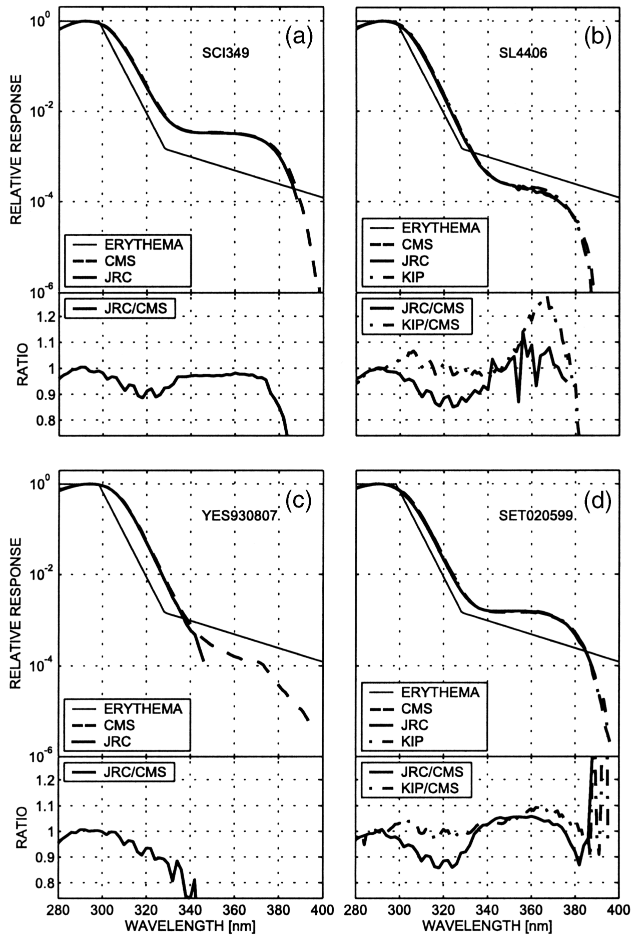

Fig. 1. Relative spectral response measurements.

Table 1. Measurement Features

Radiometer	Feature	JRC	CMS	KIP
SCI349	U_{offset} (mV)	8.72	8.67	–
	U_{max} (mV)	193	1365	–
	wl_{max} (nm)	388	390	–
SL4406	U_{offset} (mV)	0.031	0.031	0.630
	U_{max} (mV)	188	1814	922
	wl_{max} (nm)	376	390	389
YES930807	U_{offset} (mV)	−0.168	−0.182	–
	U_{max} (mV)	173	1337	–
	wl_{max} (nm)	346	389	–
SET020599	U_{offset} (mV)	0.114	0.124	0.240
	U_{max} (mV)	172	1682	160
	wl_{max} (nm)	388	397	395

U_{offset} to maximize the dynamic range of the measured spectral response. As can be seen in Table 1, U_{offset} as determined by KIP is much higher than the ones determined by CMS and JRC. This is probably due to a substantial stray-light contribution from the single monochromator used in the KIP laboratory.

U_{max} is the voltage at the maximal response of the detector (at 292 or 293 nm) and wl_{max} is the longest wavelength reliably measured by each laboratory (see Table 1). The consequence of the higher output intensity of the CMS relative to the JRC system is clearly seen in the longer wavelength range of the measured spectral responses, particularly with the SL4406 (390 versus 376 nm) and YES930807 (389 versus 346 nm) radiometers.

Except for the YES930807 radiometer, for which the common wavelength range is only from 280 to 346 nm, the relative spectral responses measured by the three laboratories differ by less than 15% over the wavelength range 280–380 nm, even though the responses change by 3–4 orders of magnitude. The largest differences are seen in the wavelength region 300–340 nm, in which there is also the largest change in the spectral response of the radiometers. Measurements of the SL4406 with the 4- and 1.9-nm slit of CMS explain approximately 5% of the discrepancies between JRC and CMS in this wavelength region.

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