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Ultraviolet spectral irradiance measurements: an intercomparison of spectroradiometers in laboratory combined with a workplace field test

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Abstract

Ultraviolet (UV) irradiance measurements are usually associated with large inaccuracies and uncertainties complicating the comparability of corresponding measurement equipment and its data. For supervisors or safety experts, though, it is mandatory to measure reliable UV irradiances with regard to occupational safety regulations. The following work aims at an intercomparison of five different types of spectroradiometers regarding their wavelength alignment and irradiance accuracy in the UV spectral region that provides the reader with information on how to determine and compare the measurement accuracies of their own devices. In a first step, measurements of two UV irradiance standards, a deuterium and a halogen lamp, were carried out. The percentage deviations of the measured total UV irradiances from their calibrated ones are smaller than $\pm 10\%$ for all spectro-radiometers. The quality of wavelength accuracy as well as of the spectral bandwidth, both investigated by means of a low pressure mercury argon lamp are consistent with those stated by the manufacturers. In a second step, UV radiation from a metal active gas welding arc was examined at three distances in combination with a variation of welding current and arc length to check the behaviour of UV irradiance accuracy in field. The overall averaged standard deviation of these field measurements for all CCD array detectors is given by $\pm 8\%$. For high welding currents this accuracy decreases to $\pm 21\%$.

1. Introduction

It is well known that ultraviolet (UV) radiation emitted by welding arcs is highly hazardous for welders with adverse health effects [1, 2] even for new techniques [3]. Whereas the welder himself has to wear personal protective equipment people working nearby or passing the welding place are usually not considered to be at risk although welding arcs emit long-range UV radiation. From an occupational safety point of view the UV exposure for these large number of such passers-by and adjacent workplaces must be taken into account. Therefore, in the beginning of 2015 the realization of a European PEROSH (Partnership for European Research in Occupational Safety and Health)

research project focusing on the 'Exposure of Workers to Indirect IR and UV Radiation Emitted by Arcs, Flames and Thermal Radiators' (indIR-UV) started. Scientists from Austria (leadership), France, Germany, Italy, Poland and Spain participate in this partnership finally aiming at an improvement of working conditions.

The first measurements showed, though, that each institute has a different laboratory equipment with either UV specialized devices, instruments with a large accessible wavelength range or (spectro-) radiometers designed for fast and easy use. Among the PEROSH partners, questions of measuring accuracy[10] and comparability of irradiance values came up immediately.

Consulting literature reveals that some work already has been done with respect to the accuracy of optical devices. For example, Leszczynski *et al* described the results of their international intercomparison of erythemally weighted radiometers [5]. A similar work was published ten years later by Huelsen *et al* [6]. Most articles can be found regarding the comparability of optical devices for measuring solar radiation [7–10]. The Thematic Network for UV Measurements regularly treats the topic of measuring uncertainty and accuracy in their UVNEWS since 1998 [11]. In addition, there are also detailed analyses of measurement uncertainties such as temporal and temperature instabilities, nonlinearities in the signal, cosine error and so on [12–15]. These are just a few contributions and the listing is far from being complete. But all of the mentioned intercomparisons focus on solar UV irradiance measurements which lack UVC radiation and start with well-defined initial situations i.e. recently calibrated optical devices with knowledge about their calibration uncertainties.

For this work, we choose a more practical approach. The aim was to check the comparability of spectroradiometers (and radiometers) within the European occupational safety community in their actual state to account for every day usage with UV radiation sources like lamps or welding arcs [16, 17] and to allow the reader to decide on his own which device to use for what purpose (laboratory or field measurements). Consequently, the present article does not deal with the topic of measuring uncertainty but with an intercomparison of five different types of spectroradiometers regarding their measuring accuracies of absolute UV irradiance and their wavelength misalignments. The outcome of this intercomparison will give the reader an idea of the reliability of UV irradiances measured in laboratory or at workplaces, especially with regard to UV exposure limit values.

For this purpose, standard deuterium and halogen lamps (test of irradiance accuracy) as well as a low pressure mercury argon lamp (test of wavelength alignment) were used for laboratory measurements. To grant access to a wide dynamic range and to verify in real life situations the UV radiation from a MAG welding arc was investigated as a function of welding current and arc length at three distances. Results for radiometers and their usability in laboratory or at workplaces will be presented in a second article currently in preparation [18].

Finally, it is important to emphasize that this work's findings cannot be generalized entirely for all spectroradiometers of each type or for all configurations of one CCD array detector. Even more, it might appear that the measurement accuracies of identical spectroradiometers with exactly the same configuration do not match with each other. Associated reasons can be manifold, for example, after delivery of a new device its ability to perform accurate UV measurements can get lost just during transport or due to an improper subsequent in-house calibration.

2. Technical details

2.1. Spectroradiometers

Besides well known CCD array detectors that are common within the PEROSH group like e.g. the Instrument Systems CAS140CT-152 recently launched devices are also in use, see table 1. Most of these spectroradiometers are equipped with cooled back-thinned CCD chips except for the ULS2048XL and the Spectis 5.0 Touch, the latter being internally temperature corrected. Both devices also have special stray light correction procedures: Spectis 5.0 Touch uses the 'Optical Straylight Reduction' method whereas the spectral data of the ULS2048XL get post-processed [19]. The BTS2048-UV-S utilizes edge filters and the other spectroradiometers reduce the amount of stray light by their individual design of the Crossed Czerny Turner spectrograph.

The accessible wavelength region $\delta\lambda$ clearly indicates that all spectroradiometers are able to measure in the lower UVC regime. However, the BTS2048-UV-S is optimized for UV measurements, the CAS140CT-152 can also detect visible light and the other devices even reach the near infrared spectral region. It is obvious that there is a strong correlation between the physical resolution of the CCD chip, the maximum $\delta\lambda$ and the resulting λ_{FWHM} (FWHM: **F**ull **W**idth at **H**alf **M**aximum). For example, the BTS2048-UV-S covers the smallest wavelength range with 2048 pixels and, consequently, shows the best spectral bandwidth. Those devices with the

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[10] We refer to ISO/IEC Guide 98-3:2008(E) that defines accuracy as 'closeness of the agreement between the result of a measurement and a true value of the measurand' [4]. The term uncertainty expresses e.g. the standard deviation.

Table 1. Technical data of the tested CCD array spectroradiometers according to the manufacturers. Due to simplicity, an internal number (no.) is assigned to every device. All spectroradiometers are equipped with a back-thinned CCD chip. The corresponding number of pixels, spectral ($\delta\lambda$) and dynamic ranges (δE) as well as the spectral bandwidth λ_{FWHM} are given in the tabular. To allow comparing of portability, dimensions $L \times W \times H$ and weight m of the devices are listed, too. Regarding the input optics, the **F**ield **O**f **V**iew or the cosine error f_2 are presented (if available). The lower part of the table shows spectroradiometer settings with regard to integration time and spectra averaging number. Automatic or manual integration time setting as well as the measurement repetition number (if available) are given in parentheses. Devices no. 5a and 6 were set to 70%–90% and 50%–70% CCD saturation accompanied by the listed ranges of integration times.

No.	1	2	3	4	5a, 5b, 6
Device	BTS2048-UV-S	QE65000	Spectis 5.0 Touch	ULS2048XL	CAS140CT-152
Company	Gigahertz-Optik	Ocean Optics	GL Optics	Avantes	Instrument Systems
# pixel	2048	1044×64	2048	2048	1024×128
$\delta\lambda$ (nm)	200–430	220–980	200–1050	200–1000	200–800
λ_{FWHM} (nm)	0.8	1.6	2.5	2.5	2.7
δE	10^9	$<10^{10}$	10^7	$<10^{10}$	10^{10}
$L \times W \times H$ (cm)	$10.3 \times 10.7 \times 5.2$	$18.2 \times 11.0 \times 4.7$	$11.1 \times 21.0 \times 5.8$	$17.5 \times 11.0 \times 4.4$	$19.2 \times 33.0 \times 34.8$
m (kg)	0.5	0.45	1.5	0.855	~10
FOV/f_2	$-/ \leqslant 3\%$	$180°/-$	$-/ < 1.5\%$	$180°/-$	5a, 5b: $-/90\%$ 6: $-/61\%$
calibration	manufacturer	in-house	manufacturer	in-house	5a: in-house 5b, 6: manufacturer
int. time	0.1–2 s (auto)	100 ms (man)	1–10 s (man)	0.18–1.2 s (auto)	5a: 0.04–1 s (auto) 5b: 20–500 ms (man) 6: 10–60 ms (man)
# av. spectra	1–5	8	8 (3–16)	2–30	5a: 1–10 (3) 5b: 10 6: 16–100 (7–56)

same number of pixels but broader $\delta\lambda$ have larger λ_{FWHM}. Spatial dimensions as well as the weight of the optical devices are also listed in table 1 to allow the reader to compare portability and field of use, respectively.

Notice that the input optics of the Instrument Systems CCD array detectors have two different cosine errors f_2, EOP-140 (**E**ntrance **OP**tics, devices 5a and 5b, $f_2 = 90\%$) and EOP-120 (device 6, $f_2 = 61\%$), and their cosine correction is weak. In contrast, devices 1–4 are cosine corrected very well. All input optics are equipped with polymer diffusors suitable for UV wavelengths. Regarding the welding arc as a point source and assuming that the flickering of the welding arc is the dominant reason of measurement uncertainty thus neglecting influences of UV reflections or ambient light contributions, the kind of input optic will play a minor role.

Spectral irradiance and wavelength calibrations were performed either by the manufacturer or in-house by each operator itself. For the in-house irradiance calibration, standard deuterium and halogen lamps, all traceable to national or NIST (National Institute of Standards and Technology) standards, have been used in combination.

In general, the main parameters to get a good signal-to-noise (S/N-) ratio are integration time and spectra averaging number that were set up individually for each spectroradiometer and for every single weld labelled with a running number n. An overload of the CCD array as well as signal levels below 20% are counterproductive with regard to the S/N-ratio and have been avoided. Some of the spectroradiometer's operators performed several measurements during one single weld. The corresponding repetition numbers are also listed in table 1.

2.2. Standard radiation sources
Standard deuterium and halogen radiation sources with low burning periods (intended for annual spectroradiometer calibration, only) were used for the intercomparison of spectroradiometers. The Bentham CL3 UV spectral irradiance standard containing a 30 W deuterium lamp was calibrated at the end of 2014, the 150 W CL6 quartz halogen lamp (also made by Bentham) in mid of 2012. The CL3 lamp primarily emits in the spectral range below ~285 nm, see figure 1. Consequently, for purposes of calibration, it is recommended to use a radiation source with higher UVA irradiance output in addition, e.g. the CL6 lamp. Here, $E(\lambda)$ increases for $\lambda > 250$ nm with a maximum close to 800 nm (not shown in figure 1) that generates a lot of stray light, unfortunately.

Furthermore, the wavelength alignment of the CCD array detectors were checked. Therefore, a 10 W low pressure mercury argon lamp (HgAr-lamp) was used and emission lines with high (253.65 nm, labelled as emission line I) and low (334.15 nm, II) irradiance as well as a double line (maximum at 404.66 nm, III) were chosen.
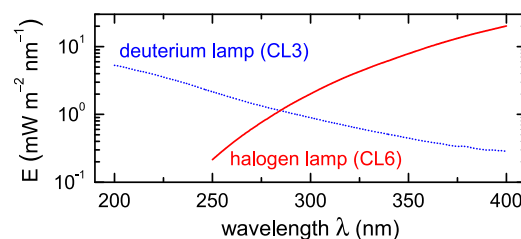
Figure 1. Semi logarithmic spectral irradiances $E(\lambda)$ of the CL3 UV spectral irradiance standard ($\cdots\cdots$) and of the halogen CL6 lamp (——). Both radiation sources cover approximately two orders of calibrated irradiance, with higher output of the CL3 lamp below about 285 nm.
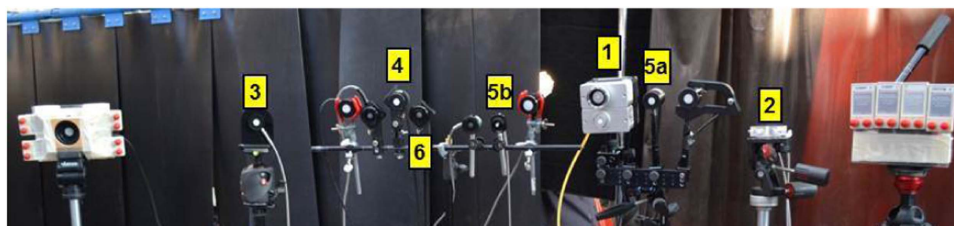

Figure 2. Arrangement of spectroradiometers during the measurements in the Institute of Welding together with their internal numbers given in table 1 or 2. Radiometers that will be discussed elsewhere [18] are depicted, too.

2.3. Experimental setup

Measurements of spectral irradiances emitted by the standard radiation sources were performed at distances of 14 mm (CL6) and 200 mm (CL3), both distances were determined with metal spacers of appropriate length, and less than 5 cm (HgAr-lamp). Assuming that the length accuracy of the spacers as well as their positioning between the lamps and the spectroradiometers result in a distance uncertainty of 0.5 mm, the CL6 irradiances are accompanied by an error of $\pm7\%$ that has to be taken into account for an evaluation of measurement accuracy. The $\pm0.5\%$ irradiance error for the CL3 lamp, though, will be neglected. Furthermore, the exit windows of the lamp housings and the input optics of the spectroradiometers were aligned using a laser beam. Due to the low irradiance emissions of all lamps and to avoid ambient light contributions the air-conditioned laboratory was darkened.

The Instytut Spawalnictwa (Institute of Welding) in Gliwice, Poland was selected as location for the field measurements. At that institute, a metal active gas (MAG) welding arc was examined within the current range of 120–350 A with corresponding voltages ranging from 15 to 35 V. The arc length was adjusted automatically according to the parameters of the welding machine: 10 mm for 120 A, 15 mm for 160, 180, 220 and 250 A, and 20 mm for 300 and 350 A. The welding additive was a G3Si1 electrode wire according to EN ISO 14341. The shielding gas was a mixture of 82% Ar with 18% CO_2. All welding runs were performed on a rotating steel tube so that the arc was stationary. Background measurements (bg) were performed regularly ($n = 0, 15, 25, 47$) and subtracted subsequently from the spectral irradiances. With device no. 4, an individual bg was measured for every weld.

The input optics of the optical devices (including radiometers [18]) were positioned at an average height of (1.45 ± 0.03) m, see figure 2, with the welding spot being located 1.07 m above the floor, to account at least to some extent for the polar angle dependence of the welding arc [20]. All input optics were focused on the welding spot by a modified laser pointer. In order to have access to a larger dynamic range δE three detection distances were selected: (2.59 ± 0.03) m, (3.47 ± 0.03) m and (4.12 ± 0.03) m, these values being averaged over all device positions with corresponding standard deviations.

3. Interlaboratory test

In this section, experimental results of the measurements performed in laboratory will be presented beginning with a check of wavelength calibration quality. Afterwards, the accuracy of absolute irradiance measurements will be analysed.

Table 2. Absolute deviations of measured emission line positions with regard to the target wavelengths (I) 253.65 nm, (II) 334.15 nm, and (III) 404.66 nm. The spectral bandwidth λ_{FWHM} of the high intensity line (I) is also shown. All values are given in nm.

No.	Device	I	II	III	λ_{FWHM}
1	BTS2048-UV-S	0.02	0.01	0.03	0.69
2	QE65000	−2.34	−2.41	−2.53	1.09
3	Spectis 5.0 Touch	−0.11	0.29	0.62	2.40
4	ULS2048XL	0.06	0.09	0.11	2.19
5a	CAS140CT (EOP-140)	0.35	−0.15	0.34	2.97
5b	CAS140CT (EOP-140)	−0.25	−0.25	−0.26	2.92
6	CAS140CT (EOP-120)	−0.32	0.17	−0.34	2.67

3.1. Wavelength misalignment of spectroradiometers

For a quantification of wavelength misalignment the absolute deviations of the actual emission line positions were calculated with regard to the target wavelengths given in section 2.2. Moreover, based on the high intensity line at 253.65 nm, the spectral bandwidth λ_{FWHM} was determined, too. Corresponding data are presented in table 2. Best results were achieved with the BTS2048-UV-S: measured emission line positions deviate by just a few tens of picometers and the spectral bandwidth is even better than stated by the manufacturer. The ULS2048XL shows similar results but with a larger λ_{FWHM}. A comparison of the CAS140CT-152 spectroradiometers equipped with two different input optics does not reveal any particular differences: the absolute line position deviations are comparable and the bandwidth is close to the stated value of 2.7 nm, see table 1. The wavelength misalignment of the GL Optics spectroradiometer (device no. 3) is comparable to those of the Instrument Systems devices.

Device no. 2, the Ocean Optics QE65000, could resolve emission line I with a bandwidth of only 1.09 nm, however, it seems that the whole wavelength calibration is shifted by ∼2.4 nm to shorter wavelengths. It is important to note that such a wavelength misalignment can lead to large errors of unweighted as well as of actinic irradiances, for example, in the case of the solar spectrum. For this work, though, an assessment of a typical MAG welding spectrum measured by the QE65000 revealed a ∼2% underestimation of the effective irradiance. Similar conclusions can be drawn for the total irradiances of the CL3 (∼4%) and CL6 lamp (<1%). Consequently, the QE65000 spectra were not shifted by +2.4 nm but analysed in their original state.

3.2. Analysis of spectral irradiance accuracy

Subsequent to the wavelength alignment check, the test of irradiance accuracy started with the CL3 UV spectral irradiance standard, figures 3(a) and (b). Spectral irradiances $E(\lambda)$ measured by the BTS2048-UV-S (no. 1) and the QE65000 (no. 2) are close to the calibrated irradiance $E^{\mathrm{CL3}}(\lambda)$ of the deuterium lamp. Spectral differences, though, are hard to recognize. Therefore, it makes sense to define the percentage deviation with regard to the calibration data according to

$$\Delta E^{\mathrm{CL3,CL6}}(\lambda) = \frac{E(\lambda) - E^{\mathrm{CL3,CL6}}(\lambda)}{E^{\mathrm{CL3,CL6}}(\lambda)} \times 100. \tag{1}$$

The corresponding results for the CL3 lamp are depicted in figure 3(c). $\Delta E^{\mathrm{CL3}}(\lambda)$ for the BTS2048-UV-S is close to zero percentage deviation and lies within a ±10% regime. The fluctuations above ∼350 nm are caused by a small denominator $E^{\mathrm{CL3}}(\lambda)$. Percentage deviation for the QE65000 (no. 2) is also small with regard to the CL3 irradiance standard although wavelengths shorter than 220 nm are lacking and no conclusions can be drawn for the deep UVC region. Interestingly, Spectis 5.0 Touch (no. 3) and ULS2048XL (no. 4), those devices with the largest accessible wavelength ranges, show a virtually linear dependency in $\Delta E^{\mathrm{CL3}}(\lambda)$ with values ranging from −20% up to +10%, reflecting to some extent the accuracy of prior irradiance calibration and especially for $\lambda < 250$ nm the UVC detector sensitivity.

In general, similar results are obtained for the CAS140CT-152 spectroradiometers, see figures 3(b) and (d). Even more, small $\Delta E^{\mathrm{CL3}}(\lambda)$ values are achieved for $\lambda > 350$ nm. However, two of the devices show deviations reaching −20% below about 230 nm. As the measurement conditions were always the same, this finding originates from an inadequate prior calibration in the UVC spectral region. Note that device 5a has been calibrated in laboratory whereas both other spectroradiometers were sent to the manufacturer. An influence of equipped input optics is not recognizable.

Figures 3(e) and (f) present the calibrated spectral irradiance of the CL6 radiation source, $E^{\mathrm{CL6}}(\lambda)$, as well as the CL6 spectra measured by several optical devices. Correction of stray light works well for the BTS2048-UV-S (no. 1), the Spectis 5.0 Touch (no. 3), and the ULS2048XL (no. 4) spectroradiometers, see figure 3(g): their
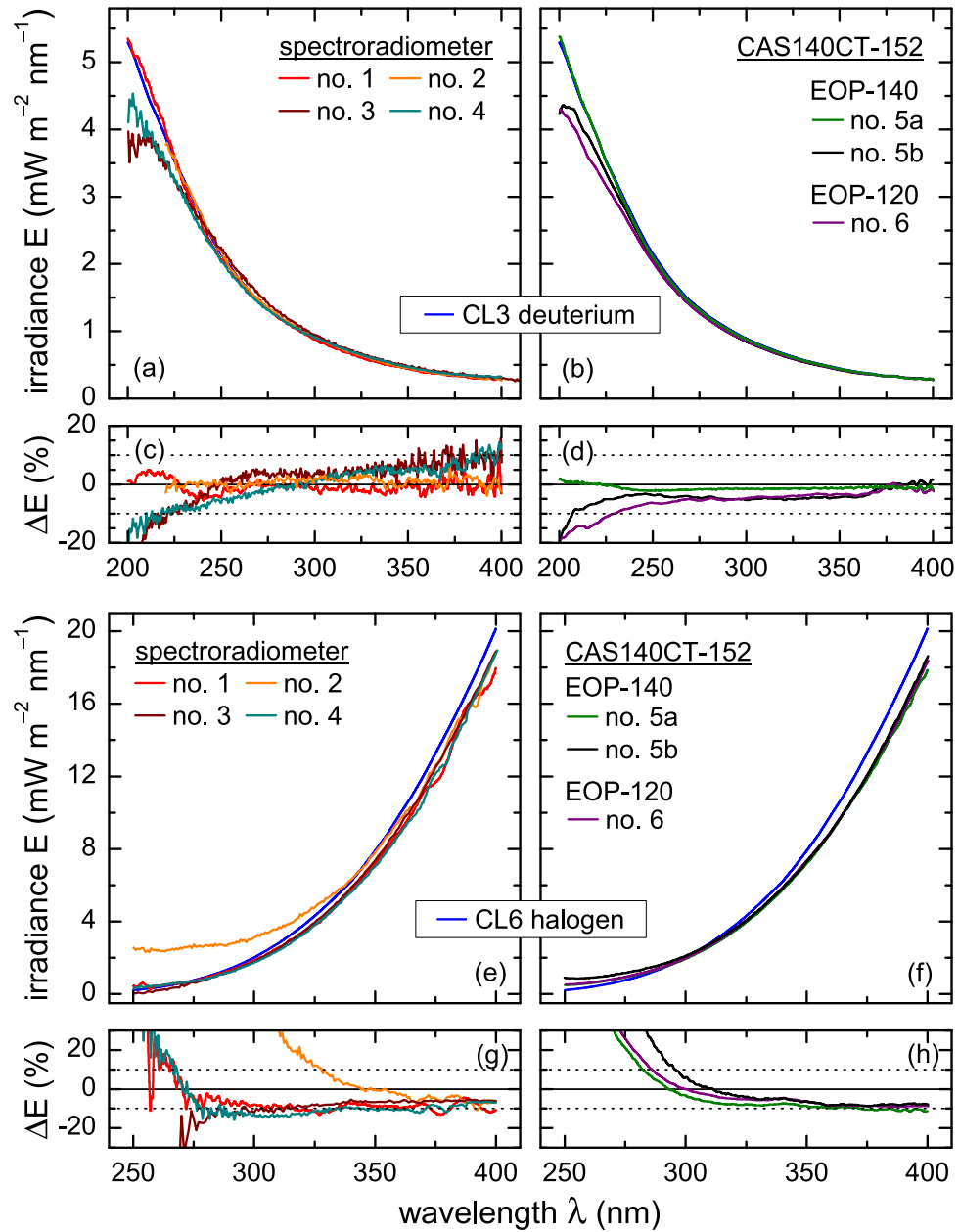
Figure 3. Comparison of the spectral irradiances $E(\lambda)$ of (a), (b) a CL3 deuterium and (e), (f) a CL6 halogen radiation source measured by the spectroradiometers listed in table 1. According to (1), the spectral percentage deviations with regard to the calibration data are given in frames (c), (d) and (g), (h). Solid black lines represent zero deviation whereas dotted lines are drawn to visualize a $\Delta E = \pm 10\,\%$ regime. Note the different scaling of the spectral irradiance and percentage deviation ordinates in (a), (b) and (e), (f) and (c), (d) and (g), (h), respectively.

spectra show percentage deviations $\Delta E^{CL6}(\lambda)$ close to -10%, discrepancies below ~ 275 nm result from small $E(\lambda)$ values and an $E^{CL6}(\lambda) \approx 0$. The percentage deviation $\Delta E^{CL6}(\lambda)$ below ~ 330 nm rises to values of 1000% (not shown) for the QE65000 (no. 2). In particular for this tested device, stray light correction does not work properly. The accuracy of irradiance measurements within deviation limits of 0 to -10% does not differ particularly above ~ 300 nm for the Instrument Systems devices, see figure 3(h). Again, $\Delta E^{CL6}(\lambda < 300$ nm$)$ increases up to $\sim 250\%$ as a result of the small denominator $E^{CL6}(\lambda)$ in combination with stray light.

Note that all of these results do not solely reflect the quality of stray light correction but the consequences of inaccuracies in prior irradiance calibrations, too. Moreover, there seems to be an almost constant -10% shift of ΔE^{CL6} above ~ 300 nm that either originates from a systematic positioning error or from an irradiance loss of the CL6 lamp, see section 5.1.

3.3. Total irradiance comparison

For a thorough analysis of the spectral deviations presented in section 3.2 it is useful to integrate the irradiances $E(\lambda)$ of the measured spectra as well as of the standard radiation sources,

Table 3. Deviations ΔI_{ij} in % according to (3) for UVA, UVB, UVC and the whole UV spectral region. Columns 3 to 6 represent values calculated with regard to the CL3 calibration standard, those from column 7 to 10 refer to the CL6 lamp. For the latter radiation source, the UVC spectral region is limited to 250–280 nm. The spectroradiometer QE65000 can detect spectral irradiance above 220 nm, only.

		CL3 (deuterium)				CL6 (halogen)			
No.	Device	ΔI_{UVA}	ΔI_{UVB}	ΔI_{UVC}	ΔI_{UV}	ΔI_{UVA}	ΔI_{UVB}	ΔI_{UVC}	ΔI_{UV}
1	BTS2048-UV-S	2.64	0.88	1.60	1.65	−9.20	−8.11	8.96	−8.83
2	QE65000	1.53	2.29	−0.30	0.44	−3.13	60.89	385.65	7.81
3	Spectis 5.0 Touch	7.89	6.19	−8.02	−4.49	−6.34	−10.88	−33.32	−7.10
4	ULS2048XL	5.90	1.26	−9.16	−6.15	−9.46	−13.57	9.07	−9.46
5a	CAS140CT-152 (EOP-140)	−1.26	−1.52	−1.40	−1.39	−9.70	−2.37	39.66	−8.37
5b	CAS140CT-152 (EOP-140)	−9.42	−4.90	−6.80	−6.18	−7.97	6.53	95.07	−5.25
6	CAS140CT-152 (EOP-120)	−2.70	−4.35	−10.56	−8.90	−8.36	0.05	44.78	−6.89

$$I_{ij} = \int_{\lambda_i}^{\lambda_j} E(\lambda)\,\mathrm{d}\lambda. \tag{2}$$

Here, the symbol I was chosen not to get confused with spectral irradiances $E(\lambda)$ although the denomination E_{ij} typically is assigned to total irradiances. The wavelengths λ_{ij} are given by $\lambda_1 = 200$ nm, $\lambda_2 = 280$ nm, $\lambda_3 = 315$ nm and $\lambda_4 = 400$ nm dividing the whole UV spectrum ($I_{\mathrm{UV}} \coloneqq I_{14}$) into UVC ($I_{\mathrm{UVC}} \coloneqq I_{12}$), UVB ($I_{\mathrm{UVB}} \coloneqq I_{23}$) and UVA ($I_{\mathrm{UVA}} \coloneqq I_{34}$) as it is used throughout the literature. Consequently, in analogy to (1), the percentage deviations of the total irradiance values follow as

$$\Delta I_{ij}^{\mathrm{CL3,CL6}} = \frac{I_{ij} - I_{ij}^{\mathrm{CL3,CL6}}}{I_{ij}^{\mathrm{CL3,CL6}}} \times 100. \tag{3}$$

This is a comfortable quantity to analyse the accuracy of UV irradiance measurements. The calculated percentage deviations are listed in table 3.

With $-8.90\% \leqslant \Delta I_{\mathrm{UV}}^{\mathrm{CL3}} \leqslant 1.65\%$, good agreement prevails for the entire UV spectral region of the CL3 lamp. Positive percentage deviations appear for the BTS2048-UV-S and the QE65000 whereas all other spectroradiometers detect too little UVC irradiance with regard to the CL3 deuterium lamp resulting in negative $\Delta I_{\mathrm{UV}}^{\mathrm{CL3}}$ values. An overall tendency in $\Delta I_{ij}^{\mathrm{CL3}}$ for the UVA and UVB spectral regions is not recognizable. Focusing on the Instrument Systems devices, the effect of prior irradiance calibration becomes observable: while device no. 5a agrees well with the CL3 UV irradiance, $\Delta I_{\mathrm{UV}}^{\mathrm{CL3}}$ increases for spectroradiometer 5b and reaches the largest deviation for CAS140CT-152 (EOP-120), device no. 6. All Instrument Systems spectroradiometers show negative $\Delta I_{ij}^{\mathrm{CL3}}$.

Despite the high amount of visible radiation thus of stray light from the CL6 lamp, the total UV irradiances $\Delta I_{\mathrm{UV}}^{\mathrm{CL6}}$ range from -9.46% to -5.25%. Here, the QE65000 (no. 2) has not been considered due to its bad stray light correction and the resulting huge errors of 61% and 386% in the UVB and UVC regions, respectively, that lead to a positive $\Delta I_{\mathrm{UV}}^{\mathrm{CL6}}$. However, the QE65000 shows the smallest $\Delta I_{\mathrm{UVA}}^{\mathrm{CL6}}$. The presence of stray light is depicted by the high $\Delta I_{\mathrm{UVC}}^{\mathrm{CL6}}$ values of several other devices, too. Lowest deviations are achieved by BTS2048-UV-S and ULS2048XL. Except for the Spectis 5.0 Touch and the ULS2048XL, those devices with the largest accessible wavelength ranges all spectroradiometers show an increase in ΔI_{ij} from UVA to UVC, in contrast to the finding for the CL3 lamp. Several reasons could explain this outcome, e.g. the prior irradiance calibration, the detector sensitivity, the quality of stray light correction, the constant -10% CL6 irradiance loss, the decreasing denominator I^{CL6}, or a combination of all or just part of this enumeration. The actual cause, though, must remain open without any further experiments.

4. UV irradiance field measurements

Requirements for spectroradiometers change with regard to field measurements. For example, there can be different measurement geometries (distances, viewing angles) or strongly flickering welding arcs accompanied by immense fluctuations in their UV radiation emission. Consequently, the spectroradiometers had to be able to gather irradiance values under such conditions even when ambient light is present. With the outcome of the interlaboratory test in the previous chapter in mind the question of measurement accuracy under field conditions arises.

Usually, the detection of UV radiation in field, for example at workplaces, aims at the determination of biologically effective (actinic) irradiance with regard to risk analysis. This is carried out by multiplying $E(\lambda)$ with the so-called actinic action spectrum $S(\lambda)$ that weights UVB and UVC much stronger than compared to UVA radiation [21]. The resulting effective irradiance E_{eff} is calculated according to
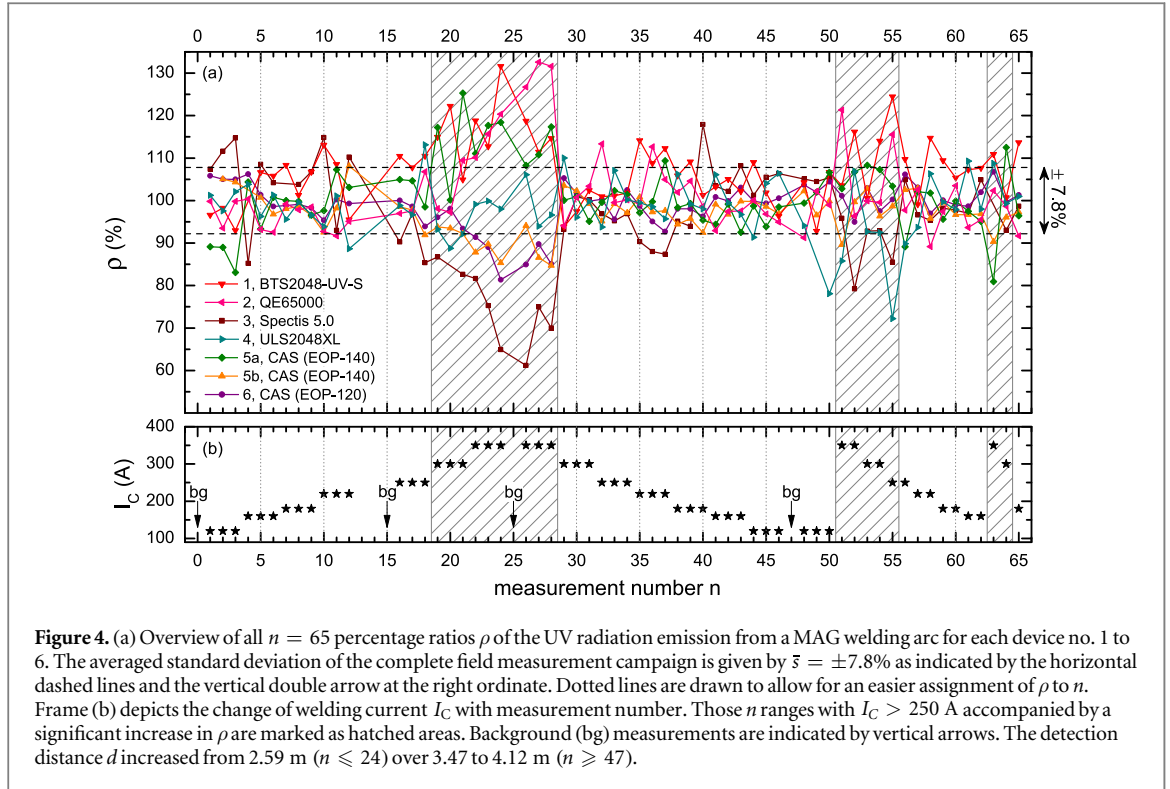
Figure 4. (a) Overview of all $n = 65$ percentage ratios ρ of the UV radiation emission from a MAG welding arc for each device no. 1 to 6. The averaged standard deviation of the complete field measurement campaign is given by $\bar{s} = \pm 7.8\%$ as indicated by the horizontal dashed lines and the vertical double arrow at the right ordinate. Dotted lines are drawn to allow for an easier assignment of ρ to n. Frame (b) depicts the change of welding current I_C with measurement number. Those n ranges with $I_C > 250$ A accompanied by a significant increase in ρ are marked as hatched areas. Background (bg) measurements are indicated by vertical arrows. The detection distance d increased from 2.59 m ($n \leqslant 24$) over 3.47 to 4.12 m ($n \geqslant 47$).

$$E_{\text{eff}} = \int_{200\,\text{nm}}^{400\,\text{nm}} E(\lambda) S(\lambda) \mathrm{d}\lambda. \qquad (4)$$

Instead of presenting these absolute effective irradiances, an analysis of the percentage ratio ρ of the device specific E_{eff} with regard to the mean value $\overline{E_{\text{eff}}}$ of all spectroradiometers, $\rho = E_{\text{eff}} / \overline{E_{\text{eff}}}$, provides a tool to evaluate over-or underestimations of measured irradiances.

In figure 4(a), the percentage ratio ρ of the MAG welding arc investigation is depicted as a function of measurement number n for each device. For 'moderate' welding currents $I_C \leqslant 250$ A in figure 4(b) the percentage ratios of the spectroradiometers are close to the mean value (100%) and range within an averaged standard deviation of $\bar{s}_\rho = \pm 7.8\%$. However, this accuracy changes for higher welding currents investigated in measurements number 19–28 and 51–55. Here, spectroradiometer no. 3 mainly underestimates the irradiance whereas others (no. 1 and 2) overestimate it. The ρ values of the ULS2048XL are either close to the mean ($n = 19$–28) or lie below the $\pm \bar{s}$ regime. These findings originate from the fact that the higher I_C the stronger the fluctuations of the radiation emission of the welding arc. Consequently, depending on integration time and spectra averaging number of each spectroradiometer, see table 1, as well as on starting time of data acquisition the calculated ρ values then reflect either an instant record or a time averaged 'mean' value of the flickering welding arc, see section 5.2.

Focusing on 'high' welding currents, i. e. $I_C \geqslant 300$ A, $n = 63$ and 64 also attract attention. Although their percentage ratios ρ are close to or even within the $\pm 7.8\%$ regime the absolute values of irradiance (not shown) did not fit to other welds with comparable parameters. This was also the case for $n = 52$. Examining the measurement conditions, there were no peculiarities like extraordinary welding parameters or intense sunlight incidence. It might be that some problem appeared with the rotating tube mechanism not having been recognized by the welder. Consequently, the welds $n = 52, 63$ and 64 were not taken into account for the following analysis.

Table 4 summarizes the results of figure 4(a). The average percentage ratios $\overline{\rho}$ with regard to all 62 measurements as well as their overall standard deviations s_ρ are listed for each spectroradiometer. As already mentioned above, $\overline{\rho}$ is an indicator whether the device over-or underestimates the irradiation whereas s_ρ reflects the 'stability' of the spectroradiometer. Interestingly, the BTS2048-UV-S that showed minor deviations with regard to the CL3 deuterium lamp, see table 3, now has the highest $\overline{\rho}$ value. Device no. 3 seems to be the less stable one with $s_\rho = \pm 12.0\%$. Concerning the ULS2048XL, continuous bg data acquisition did not result in improved $\overline{\rho}$ or s_ρ values. The Instrument Systems spectroradiometers are comparable among each other. Overall, the percentage ratios range from 95.8% up to 107.1% and the overall standard deviations are within $\pm 12.0\%$. Averaging s_ρ over all spectroradiometers provides the total field measurement accuracy given by $\bar{s}_\rho = \pm 7.8\%$. A different procedure of data averaging can be performed by taking all $7 \times 62 = 434$ irradiance values into account at once. The resulting standard deviation denoted as s_n is 8.1%.

Table 4. Summary of the $\rho(n)$ data presented in figure 4(a). The average percentage ratio $\overline{\rho}$ as well as the corresponding overall standard deviation s_ρ, both given in %, are listed.

No.	Device	$\overline{\rho}$	$\pm s_\rho$
1	BTS2048-UV-S	107.1	7.7
2	QE65000	101.8	9.5
3	Spectis 5.0 Touch	95.8	12.0
4	ULS2048XL	98.1	7.1
5a	CAS140CT-152 (EOP-140)	101.3	8.3
5b	CAS140CT-152 (EOP-140)	96.9	4.7
6	CAS140CT-152 (EOP-120)	98.7	5.2
	$\overline{s}_\rho$ (mean s_ρ)		7.8
	s_n (E_{eff} data)		8.1
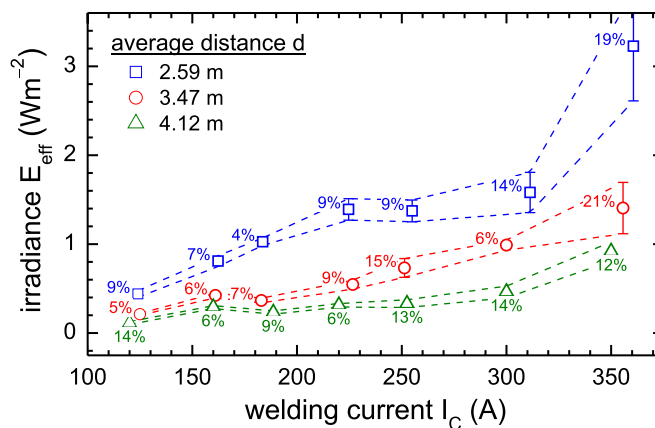
Figure 5. Effective irradiances E_{eff} as a function of welding current I_C and distance d. Standard deviations are given as numbers and visualized by dashed lines. Corresponding error bars are shown when they exceed the symbol size, only. Note that the depicted irradiance data are taken from figure 4.

Besides a variation of the welding current I_C, a change of the detection distance d not only is quite typical for field measurements but can test the dynamic range of the spectroradiometers, too, as irradiance typically is proportional to d^{-2}. Figure 5 visualizes the effective irradiances E_{eff} as a function of welding current at three distances. Irrespective of the true mathematical $E_{eff}(I_C)$ description that can be linear, square, exponential, or sigmoidal [22], here, the focus lies on measurement accuracy. Strong fluctuations of the arc due to the applied high currents that already have been present in figure 4 emerge in figure 5, once again. Despite of these effective irradiances no general trend can be found depending on I_C or d and error bars are small. Overall, the standard deviations range within ±21%.

5. Discussion

5.1. Interlaboratory test

One of the dominating effects on spectral UV measurement is given by quality and type of prior irradiance calibration. For example, the CCD array detectors from Instrument Systems are intended for measurements of UV as well as visible light. Consequently, it is necessary to perform the calibration procedure with a broadband radiation source like a halogen lamp taking into account higher UVC irradiance measurement errors. Device no. 5a, however, was calibrated with superimposed CL3 and CL6 irradiance data resulting in minor deviations with regard to the spectral irradiance of the deuterium lamp and in lower ΔI_{UVC}^{CL6} values for the halogen lamp when compared with devices no. 5b and 6. Of course, the choice of edge wavelength between both spectral irradiance standards plays a crucial role for the quality of this calibration procedure.

In contrast to the irradiance calibration that can be checked and corrected regularly, the amount of out-of-range (OoR) and in-range stray light and its consideration with regard to spectral irradiance is given by the device itself (or the data has to be post-processed). OoR stray light occurs when the measured UV irradiance is

comparatively small with regard to the visible or IR part of the spectrum and thus has to be taken into account mainly for the CL6 radiation source. The BTS2048-UV-S, the Spectis 5.0 Touch, and the ULS2048XL are equipped with working OoR stray light correction by using edge filters, see figure 3. For the CCD array detectors of Instrument Systems, stray light emerges in the measured spectra of the CL6 lamp. Stray light correction does not work properly for the QE65000 that is not suited for accurate UVC measurements in presence of high amounts of visible radiation (in contrast to radiation sources with dominating UV emission like the CL3 lamp).

Overall, it seems that all spectroradiometers detect less UVA irradiance than compared to the calibrated irradiance of the CL6 lamp, see figures 3(e) and (f). Unprecise distances or poor alignments can be excluded as systematic errors because the length of the CL6 spacer was determined accurately and the measurement place was set up again for every device, the latter producing a statistical and not a systematic error. One possible reason could be a loss of irradiance due to ageing [12] although the last calibration has been in 2012 and the CL6 lamp has not been used extensively.

5.2. Field measurements

There was a tendency to higher percentage ratios ρ with increasing welding currents. This is due to the fact that some spectroradiometers performed in 'auto mode' adapting the integration time before each single measurement while for some other devices it had to be set manually, see table 1. In both cases, high welding currents accompanied by high irradiance values led to shorter integration times. Consequently, the averaging effect across the flickering welding arc gets lost and each spectroradiometer measures another part of the flicker, thus, getting higher deviations among each other.

The operator of the spectroradiometer itself also plays a major role. The time of data acquisition start is a crucial factor because detection of the arc ignition can lead to $10\times$ enhanced E_{eff} values than compared to the rather stable arc phase after some seconds of welding. This 'overshoot' is even more pronounced for high welding currents I_C. Consequently, individual measurement uncertainties can rise up to 40%. Although the European standard EN 14255-1 [23] 'allows' a $\pm30\%$ maximum permissible uncertainty of UV measurements being compared to exposure limit values it is important to note that especially for strongly flickering welding arcs several measurement scenarios must be performed for a reliable risk assessment. Moreover, as the UV exposure limit values are given in terms of radiant exposure $H = E \cdot t$ [21], a typical exposition scenario has to be investigated to receive a representative irradiance value E.

Overall, the results of figure 4 clearly demonstrated that reliable irradiance data can be found for moderate welding currents within an averaged standard deviation of $\pm7.8\%$ and intercomparability is given for the tested spectroradiometers.

6. Concluding remarks

Irrespective of individual technical irradiance measurement problems the accuracy of tested spectroradiometers ranged in between $\pm10\%$ for lab conditions, in good agreement with other studies [8, 10]. Measurements in real life situations, e. g. with fluctuations of UV radiation emission from a welding arc provided an intercomparison of spectroradiometers with a standard deviation of $\pm8\%$. It is obvious that *one* high precision laboratory calibration is a much bigger challenge for the accuracy of spectroradiometers than several multiple-averaged field measurements. In case of high welding currents the measurement accuracy decreased to $\pm21\%$. This mainly depends on the welding scenario, the spectroradiometer settings, as well as on the operator itself.

Acknowledgments

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