Broadband Radiometric LED Measurements

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ABSTRACT

At present, broadband radiometric measurements of LEDs with uniform and low-uncertainty results are not available. Currently, either spectral radiometric measurements or broadband photometric LED measurements are used. The broadband photometric measurements are based on the CIE standardized V(λ) function, which cannot be used in the UV range and leads to large errors when blue or red LEDs are measured in its wings, where the realization is always poor. Reference irradiance meters with spectrally constant response and high-intensity LED irradiance sources were developed here to implement the previously suggested broadband radiometric LED measurement procedure [1, 2]. Using a detector with spectrally constant response, the broadband radiometric quantities of any LEDs or LED groups can be simply measured with low uncertainty without using any source standard. The spectral flatness of filtered-Si detectors and low-noise pyroelectric radiometers are compared. Examples are given for integrated irradiance measurement of UV and blue LED sources using the here introduced reference (standard) pyroelectric irradiance meters. For validation, the broadband measured integrated irradiance of several LED-365 sources were compared with the spectrally determined integrated irradiance derived from an FEL spectral irradiance lamp-standard. Integrated responsivity transfer from the reference irradiance meter to transfer standard and field UV irradiance meters is discussed.

Keywords: LED, LED radiometric measurement, broadband measurement, integrated radiometric quantities, LED integrated irradiance, UV-LED measurement, blue LED measurement, red LED measurements, flat-response LED meter, pyroelectric LED meter, filtered-Si LED meter

1. INTRODUCTION

At present, broadband UV measurements that produce uniform measurement results are not available. The International Committee on Illumination (CIE) recommends broadband UV measurements in the CIE TC2-47 Technical Report. This report is being published by the CIE Central Bureau. The report focuses on characterization of UV radiometers designed for various actinic spectra and different wavelength ranges between 200 nm and 400 nm. It also discusses calibration and measurement conditions of UV radiometers using both source- and detector-based calibration methods. Three reference-spectrum sources (Illuminant-A, blackbody, and deuterium) are proposed in the report for comparison of radiometers and also spectral mismatch corrections are applied to obtain the effective (also called broadband or integrated) responsivity. The UV radiometers discussed in the CIE report are always matched to a spectral response function, called action spectrum. The action spectrum is dimensionless (of unit 1), normalized to its maximum, and can describe an actinic effect of radiation on a radiant sensitive surface (like skin, eye, retina etc). The report also accepts action spectra like the CIE standardized UV-A, UV-B, and UV-C functions. These are all rectangular shape responsivity functions versus wavelength. Since all practical function realizations use optical filters, these rectangular-shape functions (for the UV radiometers) are usually poorly realized. The spectral mismatch errors (between the standard and realized functions) are large, resulting in significant measurement errors when the measured sources are changed (have different spectral distributions). Applying the spectral mismatch correction factors makes the measurement procedure and evaluation complicated.

Similarly, to the poor realization of the CIE standardized rectangular-shape UV responsivity-functions, the spectral mismatch errors between the realized and the CIE-standard V(λ) functions are large in the blue and red regions. In an earlier publication [3], instead of V(λ) based photometric measurements, a rectangular shape actinic function was realized

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for the photometric wavelength range using filtered Si photodiode. The goal was to perform accurate broadband radiometric LED measurements including the blue and red intervals. Since the realized function was several percent different from the constant between the 380 nm and 780 nm wavelength limits, where the function was blocked, spectral mismatch correction was applied to decrease the measurement errors. The spectral mismatch correction factor included the spectral distribution of a standard source and the measured spectral distribution of the test-LED of a particular application. As a result of the spectral mismatch correction for the realized actinic function, the broadband radiometric LED measurements could be performed with low uncertainty for the photometric wavelength range. However, this kind of broadband measurement requires the spectral distribution measurement of the test-LED, the spectral distribution of the source used for calibration, and the relative spectral responsivity measurement of the radiometer head.

Instead of using the traditional CIE recommended source-based or detector-based calibration methods, the broadband UV measurement procedure itself can be standardized to perform simple uniform measurements with low uncertainty. The standardization of the UV measurement procedure is discussed below for broadband UV sources. In the discussed example, UV-365 sources are measured. These “black lights” are applied for fluorescent crack-recognition using liquid penetrant inspection. At present, these nondestructive tests are performed with UV-meters based on the CIE standardized UV-A function. The different spectral responsivities of the commercially available UV-meters cause large measurement errors even if the same UV-365 source is measured.

In this work, because of environmental safety reasons, the originally used Hg source (the 365 nm emission line) is substituted by a high-power LED irradiance source that peaks at around 365 nm.

In order to achieve the 1 mW/cm^2 minimum irradiance required on the test-surfaces by the American Society for Testing and Materials, ASTM-E1417 [4], high-power UV LED sources are used in the here developed irradiance sources. They produce a 7.5 cm diameter spot at a distance of 40 cm from the source. In Fig. 1, the normalized spectral power distribution (SPD) of the UV-365 LED source is compared to a monochromator measured and normalized SPD of a Hg-lamp. The Hg-lamp has a continuum radiation and the 334 nm neighboring line can be seen well in the measurement. Another advantage of the LED source is that it does not have the continuum radiation. Figure 1 also shows the spectral response curves of a few UV meters. The response curves have different peak wavelengths and different spectral widths. It can be seen that only the meters with the wider response curves around the source-peak can produce uniform (similar) measurement results. (The output signal is equal to the spectral product of the LED distribution and the spectral response of the meter). The normalized signal readings of meter (3) and meter (2) were divided by the normalized reading of meter (1) when the shown UV-365 Hg-lamp was measured. The measurement error related to meter (1) was 42 % using meter (3) and 12 % for meter (2). Standardization of the spectral response function of LED measuring radiometers cannot solve this measurement non-uniformity problem. The goal of the new standard procedure is to obtain measurement results with small errors when different meters measure LEDs (or Hg sources) with reasonable (such as +/- 5 nm) peak wavelength differences relative to the 365 nm nominal wavelength.

The standard broadband radiometric procedure discussed here as an example can be extended to LEDs or LED groups for the UV, VIS, and near-IR wavelength ranges.

2. THE UV BROADBAND MEASUREMENT PROCEDURE

In the broadband UV measurement procedure, LED source(s) is measured with a broadband meter. In the discussed example, an LED-365 irradiance source is measured by a UV irradiance meter. The measured output signal of the meter is produced by the spectral product of the source distribution and the meter response function. The requirement from the broadband measurement procedure is to obtain invariance in the measured signal (at the output of the meter) for changes in both the LED source (peak and spectral-width) and the spectral-shape of the meter-response. In order to perform uniform broadband measurements, the spectral response of the meter must be broader than the distribution of the measured source(s) and the source distribution(s) must be inside of the spectral response function of the meter for all the expected source(s) and meter changes.

The broadband measurement procedure can be applied not only for UV-365 source(s) (used in the here discussed example) but also for any other UV sources if the here described procedure-requirement(s) is achieved. In the discussed example, to obtain the invariance in the measured (output) signal, the spectral response of the meter was selected to be close to constant in a spectral range equal to or wider than the widest source-distribution of the 365-nm source to be measured. This way, the spectral product of the source-distribution(s) and meter-responsivity-function produces signals with differences (errors) less than the required measurement uncertainty when different 365-nm sources (with different peak wavelengths and spectral widths) are measured.

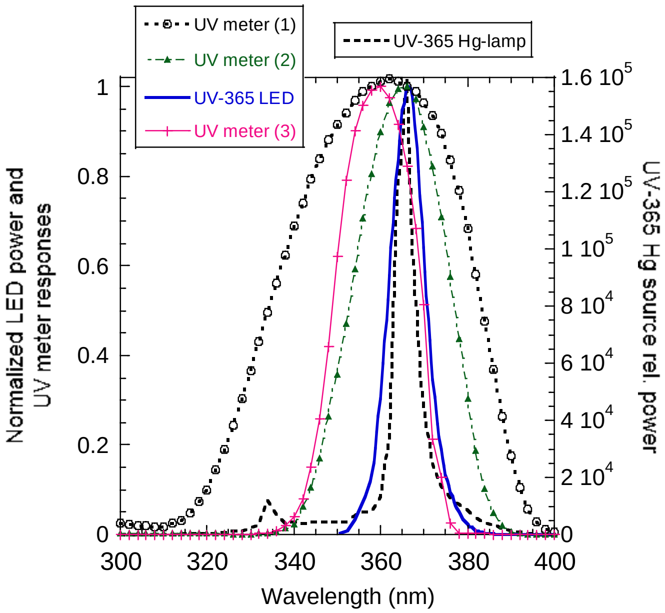

Fig. 1. Normalized distributions of Hg and LED-365 sources and UV meter responses.

Based on the here discussed procedure-requirements, existing UV meter models can be selected to obtain uniform broadband 365-nm measurements. Other UV meters, where the procedure-requirements (for spectral-responses) are not achieved, are non-ideal for uniform broadband UV measurements.

The broadband procedure can be applied for measurement of different kinds of sources, such as different single LEDs and/or a group of different LEDs, if the constant spectral response of the meter is extended to the wavelength range(s) where the measured sources emit radiation. The response deviation from constant, within the spectral range where the measured sources emit radiation, depends on the allowed uncertainty of the broadband measurement. Recently developed low-NEP pyroelectric detectors [5] are excellent candidates to measure not only UV but also other kinds of LEDs in the spectral range where the pyroelectric detector has close to constant spectral response. Based on this type of reference pyroelectric meter, the broadband scale-transfer procedure can be simplified, source standards will not be needed, and selection of the field test meters may not be needed.

3. INTEGRATED IRRADIANCE OF UV LEDS

LED-365 irradiance sources and spectrally "flat" UV irradiance meters have been developed to implement the UV broadband measurement procedure for non-destructive testing of metal parts [6]. In this application example, the excitation irradiance source peaks at a nominal wavelength of 365 nm. Typically, the purchased/applied high power LEDs have a few nm shift in their peak wavelength. In the discussed example, the peak of the purchased LED sources was at about 368 nm. Some UV irradiance meters, even if they were planned to have a constant response for the overall spectral range of the radiation produced by the LED-365 source, are spectrally "non-flat" in that range. The spectral irradiance $E(\lambda)$ of the LED-365 irradiance source and the spectral irradiance responsivity $s_{\mathrm{ref}}(\lambda)$ of the reference UV irradiance meter (used in the discussed example), that produce the measured output signal, are shown in Fig. 2. The goal of the suggested broadband measurement procedure is to determine a responsivity for the meter that can be used to measure the integrated irradiance from a test LED source [7].

Two different versions of the calibration steps were developed depending primarily on the spectral flatness of the meter.

3.1. Non-flat response method and use of an LED-365 standard

In this first version of the broadband calibration procedure, the UV meter has a poorly realized spectrally "non-flat" response. In order to keep the procedure user-friendly and accurate, in addition to the suggested broadband calibration procedure, a standard LED-365 irradiance source was developed. The integrated irradiance from the source is measured by a reference UV irradiance meter when the separation (according to the ASTM standard) is 40 cm between source and meter. The spectral irradiance $E(\lambda)$ of the standard source is needed to determine the integrated responsivity $\bar{s}_{ref}$ of the non-flat reference UV irradiance meter. Then, the integrated irradiance responsivity can be utilized for either direct measurement of an LED-365 source(s), or it could propagate the reference-level meter-calibration to field-level calibrations or measurements.

In this version of the broadband calibration procedure [6], the following calibration steps can be used:

1) Satisfy the requirements for the spectral power distribution (SPD) of the standard source(s): Use LEDs with 365 nm ± 5 nm peaks and a maximum spectrum-half-width (FWHM) of less than 15 nm.
2) Calibrate the UV-LED excitation source for spectral irradiance (e.g. against an FEL standard lamp).
3) Select a reference irradiance meter with close to constant spectral response in the spectral interval where the measured LED emits radiation.
4) Calibrate the reference meter for spectral irradiance responsivity in the wavelength interval where the UV-LED emits radiation. Test the signal-leakage in the overall wavelength range where the detector of the meter can produce signal.
5) Calculate the output signal of the meter for the spectrally calibrated (standard) UV-LED source and a spectrally calibrated meter (using a spread-sheet).
6) Calculate the output signal of the meter by shifting the source peak ± 5 nm (to 360 nm and 370 nm) or less (depending on the uncertainty requirement for this reference scale) using the same relative spectral irradiance of the calibrated UV-LED source. The changes in the spectral product (for source and meter) are calculated to obtain the uncertainty of this reference-scale.
7) The reference UV meter can be accepted for scale transfer if the calculated output signals at the 360 nm and 370 nm wavelengths agree within the expected signal measurement uncertainty.

The above calibration steps are usually made at a national measurement institute (NMI). Utilizing steps 2 and 4, the measurement equation that describes the output signal of the reference meter for irradiance measurement mode can be written as

$$i_{ref} = \int_{\lambda} E(\lambda) s_{ref}(\lambda) \mathrm{d}\lambda \tag{1}$$

where $E(\lambda)$ is the spectral irradiance of the calibrated (standard) UV-LED source, $s_{ref}(\lambda)$ is the spectral irradiance responsivity of the reference meter, and λ is the wavelength.

Using the ASTM standardized requirement, the integrated irradiance can be determined in the reference plane of the meter, 40 cm away from the source:

$$\bar{E} = \frac{i_{ref}}{\bar{s}_{ref}} \tag{2}$$

where the integrated irradiance responsivity of the reference meter is:

$$\bar{s}_{ref} = \frac{i_{ref}}{\int E(\lambda)\mathrm{d}\lambda} \tag{3}$$

In the discussed example, i_{ref} was both calculated (using the above mentioned spreadsheet) and measured for the LED-365 (NIST #1251) standard and the reference UV irradiance meter (NIST #130301). The calculated value of 3.13 x 10^{-5} A, was 2.2 % different from the measured value of 3.198 x 10^{-5} A. The spread-sheet calculated integrated irradiance responsivity of the reference meter was $\bar{s}_{ref}$ = 2.93 A mm^2/W. Using the measured current value, the integrated irradiance from the used LED-365 standard (NIST #1251) was 1.09 $\mathrm{mW/cm}^2$, 9 % higher than the minimum irradiance level required by the ASTM standard.

After these reference-level calibration steps, the reference meter (with the known integrated responsivity) can be taken to a field laboratory where the field-level calibration steps can continue the above steps:

8) Substitute the field (test) UV meter for the reference (calibrated) UV meter in the same irradiance at the ASTM standardized 40 cm distance from the source of the standard LED-365 irradiance source and use the ratio of the meter's output signals as the calibration factor for the test UV meter. The test meter also should have close to flat spectral response in the wavelength range where the standard LED emits radiation. Otherwise, significant errors can be introduced in the measurement of the field-source during the scale transfer.

Note: Using the here discussed broadband measurement procedure, spectral response measurement of test (field) UV meters is not needed.

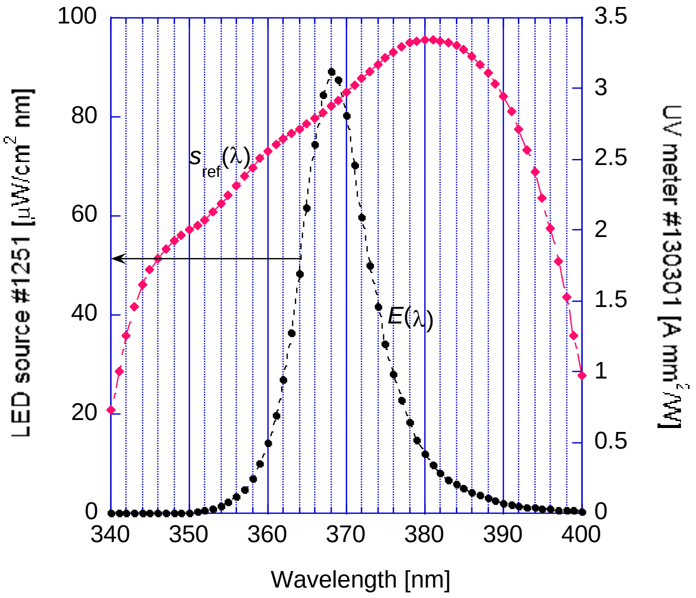

Fig 2. Spectral irradiance E(λ) of an LED-365 standard irradiance source (#1251) and spectral irradiance responsivity $s_{ref}(\lambda)$ of a reference UV irradiance meter (#130301).

3.2. UV meter-based calibrations without using a source standard

A source standard will not be needed if the reference meter has a known constant spectral responsivity for the wavelength range where the measured LED(s) emits optical radiation. Similarly, when the response of the reference meter is not constant but an average responsivity can be determined for (most of the) measured radiation, the source standard will not be needed.

3.2.1. Spectrally "flat" responsivity standard

The procedure for broadband UV calibrations and measurements can be simplified when UV meters with spectrally constant response are used. Calibration of the reference meter for constant irradiance responsivity is enough to measure the integrated irradiance (or any other output radiometric quantity) of a test LED source(s). When using these spectrally "flat" standard meters, use of a standard source is not needed. In this detector-based calibration, the only standard is the meter with the known constant spectral responsivity. When the spectral flatness (the curve shape) is known, one absolute tie point can be enough to convert the relative response function into absolute (e.g. to obtain the constant spectral irradiance responsivity).

Spectrally "flat" UV meters can be made with either filtered quantum detector (like silicon detector and glass input-filters) or pyroelectric detectors. For these "flat" meters, Eq. 1 can be applied. Since $s_{\mathrm{ref}}(\lambda) = s$ = constant, the output signal of the reference meter will be

$$i_{ref} = i = s\int_{\lambda} E(\lambda)d\lambda \tag{4}$$

and the integrated irradiance will be

$$\overline{E} = \frac{i}{s} \tag{5}$$

where the unit of i is A, the unit of s is A cm^2/W, and the obtained unit for $\overline{E}$ is W/cm^2.

Using a pyroelectric detector, the deviation from a spectrally constant response can be an order of magnitude smaller than using a filtered Si photodiode. Also, the wavelength coverage of a pyroelectric detector with the flat response will be much wider.

3.2.2. Average-responsivity standard

Equation 5 can also be used when the reference meter has a "non-flat" response around the peak of the measured LED. This situation is shown in Fig. 2. In this case, instead of using a spectrally constant ("flat") responsivity, the average responsivity around the LED peak can be used. In our example, the NIST #130301 reference meter was used which has a significant slope at the 368 nm peak of the measured NIST #1251 LED. Since the response-slope is symmetrical around the peak-wavelength of the measured LED within a wide enough (about +/- 8 nm) range, it was simple to determine the average responsivity for the measured LED. As can be seen in Fig. 2, the average responsivity of the meter for most of the LED radiation is 2.875 A mm^2/W, equal to the responsivity at the LED peak-wavelength. The integrated irradiance of the LED source using this "average responsivity" method will be:

$$\overline{E} = \frac{i}{s} = \frac{3125 * 10^{-8}}{2.875} = 1.087 \text{ mW/cm}^2 \tag{6}$$

where 3125 x 10^{-8} is the sum of the measured current values between 300 nm and 400 nm calculated using a spread-sheet. The spread-sheet was made to calculate the output signal, the integrated irradiance, and the integrated responsivity for a few UV-365 sources and UV irradiance meters.

The integrated irradiance value in Eq. 6 agrees with the 1.09 mW/cm^2 obtained using $E(\lambda)$ for $\overline{s}_{ref}$ determination. This means that the two methods where the “flat” or average responsivities are used as standards, will produce equal integrated irradiance to the integrated irradiance produced by the “non-flat” meter-response method where a standard source was used (as discussed above in Section 3.1). In summary, a standard source was used for the determination of $\overline{E}$ in the non-flat response method, and no standard source is needed when the “flat” or average responsivity standards are used.

3.2.3. Use of spectrally-flat filtered-Si meters

Spectrally “flat” irradiance meters built with multilayer thin-film and glass filters were discussed earlier [6]. These meters utilized UV damage resistant nitrided Si photodiodes. These filtered meters have good stability but the curve shapes are different. The different curve-shapes are acceptable when the procedure described in Section 3.1 is used. The filtered-Si UV meters are operated in DC measurement mode. Figure 3 shows the spectral irradiance responsivity of several of these UV-365 meters. The graph also shows a monochromator measured Hg line distribution and several LED-365 source-distributions. The peak wavelengths are 3 nm or 4 nm different than the nominal 365 nm peak value. The blocking of the meters outside of the bandpass interval to about 1000 nm is at the 0.1 % level. The relative response function of six new-generation UV-365 meters is shown in Fig. 4. The maximum-to-minimum response deviation from the constant is about 3% to 10 %. Similar “flatness” is illustrated in Fig.5, where a nitrided Si photodiode was filtered to obtain a meter with close to constant response for the 345 nm to 440 nm range to measure UV and blue LEDs. The response deviation from constant is +/- 7.5 % for the realized C and +/- 7.2 % for the realized D functions.

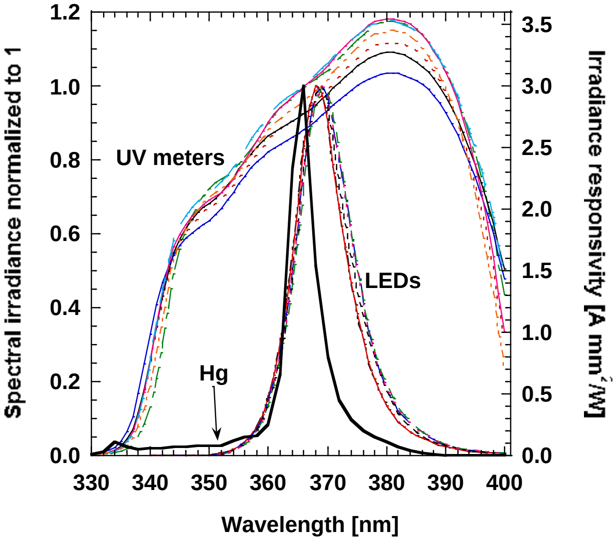

Fig. 3. Spectral irradiance of LEDs with 365 nm nominal peak, monochromator measured Hg-line distribution, and irradiance responsivity of UV-365 meters.

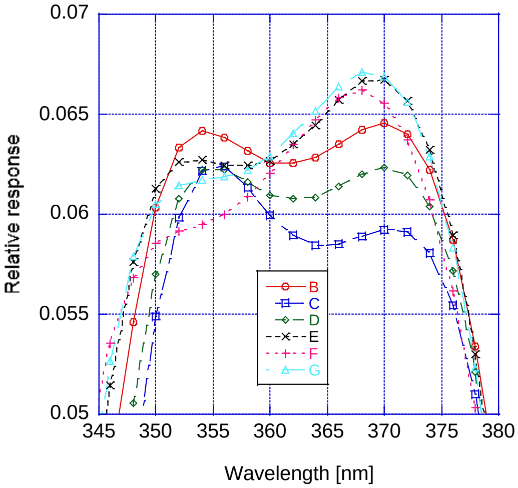

Fig. 4. Relative spectral responses of six new generation UV-365 meters (B to G).

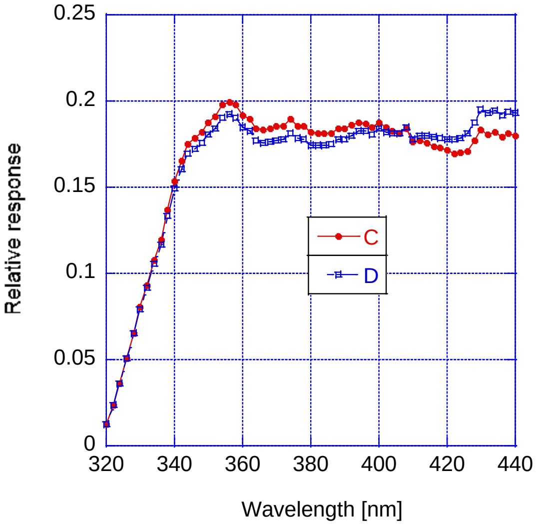

Fig. 5. Filtered Si “flat” meter for the 345 nm to 440 nm range to measure UV and blue LEDs.
Response deviation from constant is +/- 7.5 % for realization C and +/- 7.2 % for realization D.

4. ADVANCED INTEGRATED IRRADIANCE REFERENCE CALIBRATIONS

As discussed above, the integrated irradiance from LED sources can be easily measured using spectrally “flat” irradiance meters. Reference-level integrated irradiance calibrations are discussed below when using a pyroelectric “flat” irradiance meter standard.

As determined from spectral reflectance measurements, the spectral response of the reference pyroelectric detector can deviate +/- 0.1 % from constant between 330 nm and 400 nm. The deviation from constant can be a dominant uncertainty component of the integrated irradiance measured by the pyroelectric detector after its calibration. The here suggested broadband calibration will need shorter calibration time and it is less expensive than the presently applied spectral calibration techniques. Due to better spectral flatness of detector responsivity, the related measurement errors described in Section 3 can be reduced as well. As a result of the simplified broadband calibration and scale transfer, the expected combined uncertainty for the reference integrated irradiance measurement is about 0.5 % (k=2) which is significantly lower that the about 5 % (k=2) uncertainty achieved using the previously discussed methods.

The spectral irradiance responsivity calibration of a pyroelectric detector in the UV takes a few steps including the realization/transfer of absolute tie points in the visible or near-IR range, measurement of absorptance of the black coating on the top of the pyroelectric crystal, measurement of the integrated irradiance from a stable UV source and validation of this measured integrated irradiance from an independent irradiance measurement of the same UV source, in our case against an FEL lamp standard [6].

4.1. Use of spectrally flat low-NEP pyroelectric detectors

Low-NEP pyroelectric detectors available for improvement of the response deviation from constant are introduced here. Pyroelectric detectors work only in AC measurement mode therefore the output signal of the LED must be modulated. The modulation can be done either in the feeding current of the LED or with a light chopper. The modulated (AC) output signal from the meter can be measured using a simple and inexpensive lock-in amplifier.

As an example, a hybrid (detector and preamplifier are in the same metal can) pyroelectric detector that has an NEP of about 10 nW/Hz$^{1/2}$ is used here to measure five LED-365 irradiance sources. The picture of this temperature controlled detector is shown in Fig. 6. This detector can measure radiant power down to 1 μW with a signal-to-noise ratio (S/N) of 100. An organic black absorbing coating is applied on the pyroelectric detector.

Fig. 6. Picture of a temperature controlled hybrid pyroelectric radiometer.
The LiTaO$_3$ crystal is covered with organic-black coating.

The measurements, described below, are the first time calibration of the irradiance responsivity of a pyroelectric detector. The measurements of the low-NEP pyroelectric detector were performed in AC mode using a lock-in amplifier and a chopping frequency of 10.5 Hz. A beam geometry (without using any integrating sphere) at the output of a monochromator [8] was used in the near-IR range and the irradiance responsivity scale was extended to the UV range based on the close to constant spectral absorptance (relative response) curve. For this scale extension, the output of the pyroelectric detector was compared to the output of a sphere-input extended-InGaAs (EIGA) transfer-standard for which the irradiance responsivity was known between 0.6 μm and 2.6 μm. The EIGA standard is periodically evaluated together with other NIST reference detectors to ensure that the aging effect, if any, can be neglected. In Fig. 7, the absorptance curve of the organic black coating is shown in the range of 0.25 μm to 2 μm together with a few tie points around 1 μm. The absorptance versus wavelength curve was determined from spectral reflectance measurements of the black coating. The absorptance, which is proportional to the response, is equal to 1–reflectance if the transmittance is zero. The tie points convert this relative response curve into absolute spectral irradiance responsivity. Based on the small changes in the absorptance curve, the irradiance responsivity of the pyroelectric detector was taken as a constant 910 VW^{-1}cm^2 between 0.25 μm and 0.5 μm (in the range of the measured LED sources). However, certain variations, smaller than the measurement uncertainty, may be expected. The uncertainty of the absorptance data is a few times smaller than that of the irradiance responsivity tie points (2.6 % *k*=2), thus the uncertainty of the tie point(s) is the dominating component in the calibration uncertainty budget. It is also anticipated that the spectral irradiance responsivity follows the absorptance data obtained with the underfilled sensor area. The tie point shown at about 365 nm in Fig. 7 will be discussed in Section 4.3. The less than +/- 1 % deviations from constant up to 2 µm makes it possible to apply these broadband (integrated) irradiance LED measurements for the VIS-NIR range as well.

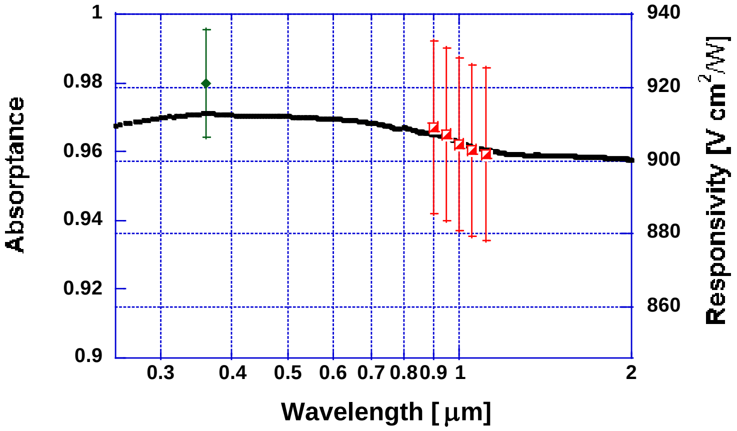

Fig. 7. Spectral absorption (1-reflectance) curve of organic black coating and irradiance responsivity tie (absolute) points derived from a sphere-input extended-InGaAs radiometer. See Section 4.3 for explanation of the tie point at 365 nm.

While the maximum deviation from the spectrally constant absorptance is +/- 0.2 % between 250 nm and 420 nm, the shown dominating 2.6 % (*k*=2) uncertainty component for the responsivity function is too high. Realizing tie points with much lower uncertainty will lead to significant improvement in the overall uncertainty of the spectral responsivity in the UV.

4.2. UV irradiance measurements using pyroelectric detector-standard and LED-365 source

The development of LED-365 irradiance source standards was discussed in our previous publications [6]. These sources were designed to satisfy the ASTM requirement to produce a target-spot irradiance of 1 mW/cm^2 or higher. This high irradiance requires 250 µW radiant power from a UV-365 source uniformly distributed on a ¼ cm^2 detector.

The irradiance from five UV sources was measured at a distance of 0.4 m. First, the irradiance non-uniformity was measured within a target-spot of 80 mm x 80 mm. The measurements were made in two orthogonal directions (along X and Y axes). The data presented in Fig. 8 indicate about 15 % irradiance non-uniformity at the distance of +/- 40 mm from the center of the output beam spot. However, in the center area of about 20 mm x 20 mm, the non-uniformity is estimated about 5 % (or about 1 % in the 5 mm x 5 mm area). It should be noted that the maximum radiation and its position with respect to the optical axis may not match and can vary from source to source. The legends (series numbers) in Fig. 9 are related to the serial numbers of the LED-365 sources. The data are normalized to the maximum radiation in the target-spot.

The irradiance produced by each LED-365 irradiance source was measured by the calibrated pyroelectric radiometer. The integrated irradiance is

$$\overline{E} = \frac{U \cdot c}{s} \qquad (7)$$

where *U* is the output voltage (in V) of the pyroelectric radiometer as measured by the lock-in amplifier, *s* is the constant spectral responsivity of the pyroelectric radiometer, equal to 910 VW^{-1}cm^2, and *c* is a conversion factor (constant) between the voltage measurements performed in AC and DC modes during the calibration. For an ideally chopped signal (with square wave shape), *c* is equal to 2.22. However, this conversion factor depends also on the actual shape of the chopped signal and it is affected by geometrical and frequency dependent factors as well. In the present measurement, *c*=2.33 was obtained using the actual geometry and calculating the ratio of the Si detector-based meter readings in DC and AC measurement modes. The summary for the integrated irradiance produced by each LED-365 source is presented in Table 1. The integrated irradiance was higher than the minimum 1 mW/cm^2 value required by the ASTM standard. The measurement uncertainty was dominated by the 2.6 % (*k*=2) uncertainty of the irradiance responsivity tie points.

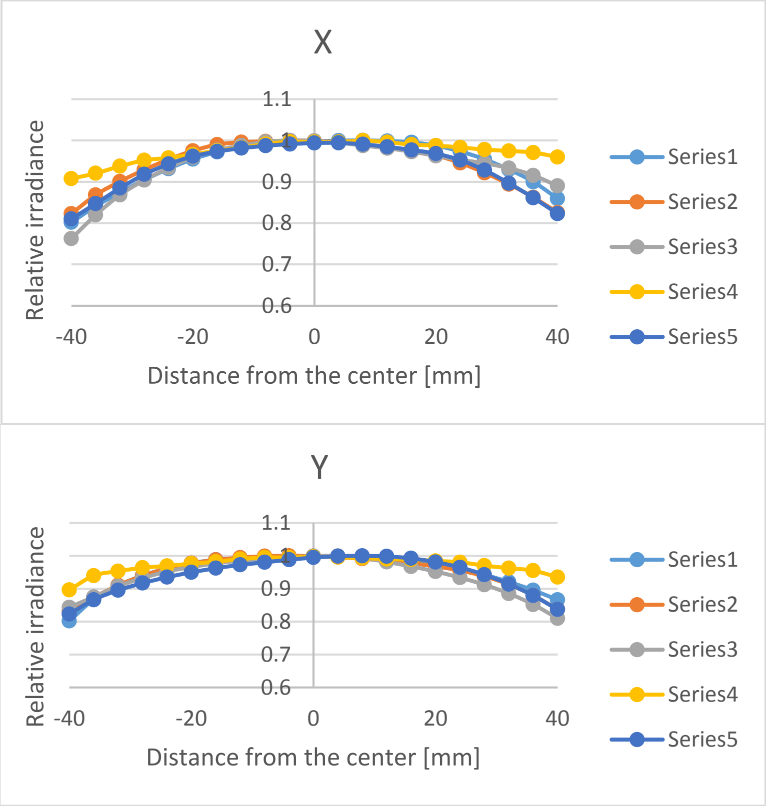

Fig. 8. Relative integrated irradiance produced by five UV irradiance sources in the 80 mm x 80 mm target-spot at a distance of 0.4 m.

Table 1. Pyroelectric radiometer output voltage and derived integrated irradiance for five LED-365 irradiance sources at a distance of 0.4 m.

Measured units / source #	**1**	**2**	**3**	**4**	**5**
U [V]	0.622	0.617	0.608	0.613	0.622
$\overline{E}$ [mW cm^{-2}]	1.59	1.58	1.56	1.57	1.59

4.3. Validation of pyroelectric detector measured integrated irradiance and UV responsivity

The integrated irradiances from five LED-365 sources of the same model were determined using two different methods. The first method, as described above, utilized the constant spectral irradiance responsivity of a low-NEP pyroelectric radiometer. In the second method, used for validation, the spectral irradiance of each LED source was derived from a traditional FEL lamp standard [6]. This spectral calibration method and setup used to determine the spectral irradiance of the UV-LED sources has already been discussed [6]. The measured spectral irradiance functions of six newly developed LED-365 irradiance sources are shown in Fig. 9. The performed spectral irradiance uncertainty was 1.6 % (*k*=2).

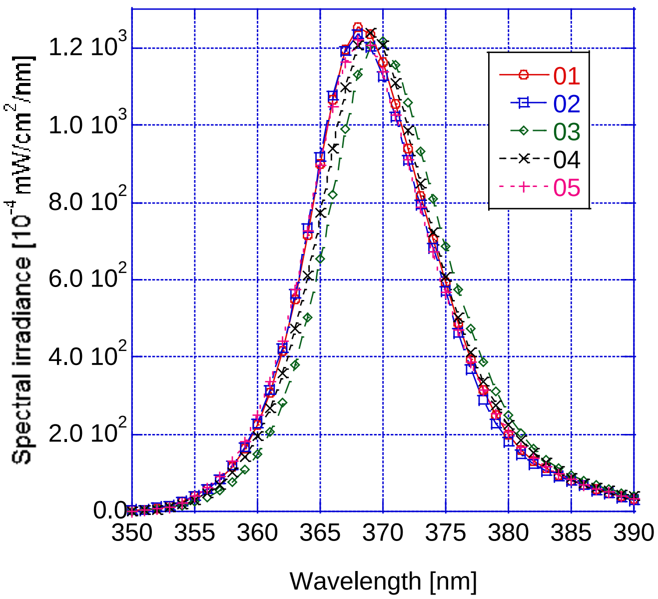

Fig. 9. Five LED-365 source standards (#01 to #05) calibrated against an FEL lamp standard.
The spectral irradiance uncertainty is 1.6 % (*k*=2).

The integrated irradiance ratios of the five LED-365 sources from the spectral and broadband measurements are shown in Table 2. The average disagreement between the integrated irradiances obtained from the two different methods is 1.2 %.

Table 2. Integrated irradiance ratios of five LED-365 sources determined from spectral and broadband calibrations.

LED#	**FEL S193 based mW/cm²**	**Pyro-based mW/cm²**	**FEL/Pyro**
1	1.624	1.59	**1.021**
2	1.596	1.58	**1.010**
3	1.569	1.56	**1.005**
4	1.591	1.57	**1.013**
5	1.611	1.59	**1.013**
		Average:	**1.012**

These data may be used to produce an indirect but additional tie point for calibration of irradiance responsivity of the pyroelectric detector. The tie point at 365 nm has a lower uncertainty of 1.6 % (*k*=2) versus the 2.6 % (*k*=2) found from the near-IR tie points. Thus the additional tie point presented in Fig. 7 supports the UV responsivity of the pyroelectric detector obtained from the near -IR data and absorptance in Section 4.1.

Since the maximum deviation from the spectrally constant absorptance is +/- 0.2 % between 250 nm and 420 nm, there is a possibility to significantly improve the UV responsivity scale. The future plan is to decrease the uncertainty of the irradiance responsivity tie points to the ~0.2 % (*k*=2) level using a Si-trap reference detector and also to use a high-power LED irradiance transfer source in the red. Using the high intensity LED source, the source-to-detector separation can be increased resulting in smaller distance measurement uncertainty. Applying these improvements, the planned uncertainty for the integrated irradiance measurements is less than 0.5 % (*k*=2).

The pyroelectric radiometer based broadband LED measurements can be applied for all kinds of LEDs or LED groups and also the measurements can be made in radiance or radiant-power modes as well.

5. INTEGRATED IRRADIANCE OF BLUE LEDS

As an example, the pyroelectric detector based broadband radiometric LED measurement was extended for deep-blue LEDs. The obtained results are presented here. LEDs with 400 nm and 405 nm peaks were selected where the responsivity deviation of the realized photopic curve is large (a few percent) compared to the CIE standard V(λ) function. One-channel surface-mount LED modules with integrated lens on a standard starboard configuration were selected. These commercially available packages were screwed to thermoelectrically controlled LED-mounts. A metal tube was attached to the LED-mount to hold a collimating convex-lens. The integrated LED-lens was located in the focus of the collimating lens of the tube. The spatial uniformity of the obtained irradiance field (as an example) is shown in Fig. 10. The separation between the source and the target was 400 mm. The diameter of the scanning aperture was 5 mm. The irradiance measurements were performed in the center-area of the target spot.

The spectral irradiance measurements, as performed with a spectrograph, for the two blue LEDs are shown in Fig. 11.

The integrated irradiance values obtained from the broadband pyroelectric-detector-based measurements are shown in Table 3. The estimated low-end limit for the pyroelectric detector measured irradiance is about 4 μW/cm^2 at a signal-to-noise ratio of 100. The 2.6 % (*k*=2) measurement uncertainty can be significantly improved by decreasing the uncertainty of the irradiance responsivity tie points as shown in Fig. 7.

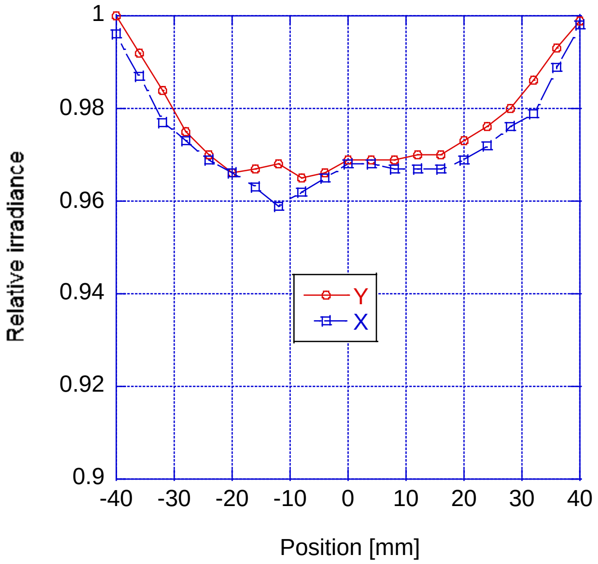

Fig. 10. Irradiance changes along the X and Y axes of the target spot from the blue (405 nm peak) LED.

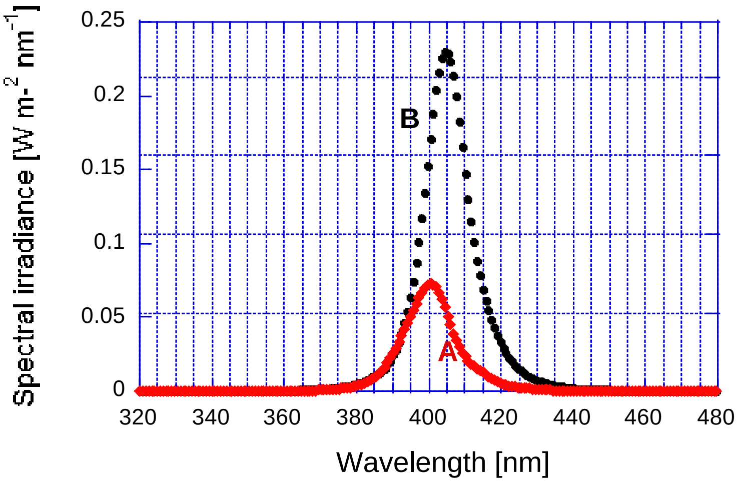

Fig. 11. Spectral irradiance measurements of two deep-blue LED sources.

Table 3. Integrated irradiance of LEDs A and B of Fig. 11.

$\overline{E}_A$ [mW/cm^2]	$\overline{E}_B$ [mW/cm^2]
0.14	0.42

6. DETERMINATION OF INTEGRATED IRRADIANCE RESPONSIVITY OF FIELD UV METERS

Utilization of the pyroelectric detector-based (standard) radiometer allows to simplify the calibration of the filtered Si transfer-standard and field UV (test) irradiance meters. The field UV meters should have a broad enough spectral response to measure the integrated irradiance from a UV source. Since these test meters are calibrated against the standard using detector-substitution when measuring the same source, the spectral flatness of these test meters is not an important issue. Before calibrating a test meter, the integrated irradiance responsivity of the pyroelectric radiometer is to be determined as described in Section 3.

In the following scale transfer, the test-meter can be substituted for the reference pyroelectric meter of known constant irradiance responsivity and the signal ratio, when they are measuring the same source, can be used to determine the “flat” irradiance responsivity of the test-meter. The integrated irradiance from the source will be equal to the ratio of the test-meter’s output signal divided by the ‘flat” irradiance responsivity of the test-meter. The “flat” irradiance responsivity of the test meter is

$$r_t = \mathrm{k}s \tag{8}$$

where k is a correction factor obtained as the ratio of the test-meter output-voltage to the output-voltage of the reference meter when both measure the same irradiance. The constant irradiance responsivity of the reference (standard) meter is *s*. This responsivity, as mentioned above, is usually determined in a primary level calibration laboratory. The following simple transfer-calibrations can be performed in field calibration places. The integrated irradiance measured by the test meter will be

$$\overline{E} = \frac{U_t}{ks} \tag{9}$$

where *U*t is the output voltage of the test irradiance meter.

Continuing our previous UV-365 source measurement examples, the integrated irradiance responsivity of any field radiometer (including existing commercial meters) may be calibrated against a calibrated filtered UV-365 (transfer standard) radiometer if the same source is used what was used earlier for the calibration of the filtered UV-365 transfer-standard irradiance meter. Also, in this case, spectral flatness for the field detector responsivity function is not required. However, if a different source is measured in the field, then the filtered UV-365 transfer-standard meter should be calibrated for that source first. If the difference between the different sources is not too high, as illustrated in the example of Fig. 9, the correction to the responsivity of the applied UV-365 transfer-standard meter could be performed using its known spectral responsivity curve (see examples of the functions in Figs. 3 to 5).

7. CONCLUSIONS

A broadband radiometric measurement procedure has been developed to perform uniform LED calibrations and measurements with low uncertainty. As an example, the procedure has been implemented here for UV and blue LEDs. For reference-level calibrations, LED-365 irradiance source standards and UV irradiance meters have been developed. Using a low-NEP pyroelectric radiometer, a UV response function with +/- 0.2 % maximum deviation from constant has been realized between 250 nm and 420 nm. Using the constant irradiance responsivity of a reference pyroelectric radiometer, the integrated irradiance from all kinds of LEDs can be measured without using a source standard. The 2.6 % (k=2) uncertainty, dominated by the irradiance responsivity reference (absolute tie) points for the pyroelectric radiometer, can be improved significantly. The developed LED-365 irradiance sources and UV irradiance meters can be used to calibrate field UV irradiance meters against the working standard meter when using the same LED-365 source. Using the pyroelectric standard based broadband procedure, yearly spectral calibrations for the working standards is not needed. Also, any field radiometer (including existing commercial meters) may be calibrated against a calibrated (filtered) UV-365 (transfer standard) radiometer if the same source is used what was used earlier for the calibration of the filtered UV-365 transfer-standard meter. In this case, spectral flatness for the field detector responsivity function is not required. When a different source is measured in the field, then the filtered UV-365 transfer-standard meter should be calibrated for that source first. If the difference between the different sources is not too high (as illustrated in the example of Fig. 9), the correction to the responsivity of the applied UV-365 transfer-standard meter could be performed using its known spectral responsivity curve. Using the discussed broadband calibration procedure, fast, inexpensive, and accurate LED measurements can be performed in irradiance, radiance, or radiant-power modes.

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