UV scale calibration transfer from an improved pyroelectric detector standard to field UV-A meters and 365 nm excitation sources

G. P. Eppeldauer[1], V. B. Podobedov, and C. C. Cooksey,

National Institute of Standards and Technology
100 Bureau Drive, Gaithersburg, MD, USA 20899

ABSTRACT

Calibration of the emitted radiation from UV sources peaking at 365 nm, is necessary to perform the ASTM required 1 mW/cm^2 minimum irradiance in certain military material (ships, airplanes etc) tests. These UV "black lights" are applied for crack-recognition using fluorescent liquid penetrant inspection. At present, these nondestructive tests are performed using Hg-lamps. Lack of a proper standard and the different spectral responsivities of the available UV meters cause significant measurement errors even if the same UV-365 source is measured. A pyroelectric radiometer standard with spectrally flat (constant) response in the UV-VIS range has been developed to solve the problem. The response curve of this standard determined from spectral reflectance measurement, is converted into spectral irradiance responsivity with <0.5% (k=2) uncertainty as a result of using an absolute tie point from a Si-trap detector traceable to the primary standard cryogenic radiometer. The flat pyroelectric radiometer standard can be used to perform uniform integrated irradiance measurements from all kinds of UV sources (with different peaks and distributions) without using any source standard. Using this broadband calibration method, yearly spectral calibrations for the reference UV (LED) sources and irradiance meters is not needed. Field UV sources and meters can be calibrated against the pyroelectric radiometer standard for broadband (integrated) irradiance and integrated responsivity. Using the broadband measurement procedure, the UV measurements give uniform results with significantly decreased uncertainties.

Keywords: UV responsivity scale, LED-365 irradiance, broadband UV measurement, integrated radiometric quantities, LED integrated irradiance, UV-LED measurement, flat-response UV meter, pyroelectric UV standard

1. INTRODUCTION

The International Committee on Illumination (CIE) recommended UV-A action spectrum has a rectangular shape that can be realized only with large spectral mismatch errors. Significant measurement errors are obtained when the measured sources are changed (have different spectral distributions). Applying spectral mismatch correction factors in different applications, makes the measurement procedure and evaluation complicated.

Instead of using the traditional CIE recommended source-based or detector-based calibration methods, a broadband UV measurement procedure is suggested here for standardization to perform simple uniform measurements with low uncertainty. The broadband UV measurement procedure has been discussed earlier [1, 2].

It is necessary to perform the ASTM required 1 mW/cm^2 minimum irradiance [3] from UV sources peaking at 365 nm when ship and airplane components are examined in non-destructive military material tests. UV "black lights" are applied for the crack-recognition using fluorescent liquid penetrant inspection. At present, these nondestructive tests are performed using the 365 nm excitation line of Hg-lamps. In order to phase out mercury, LED-365 irradiance sources have been developed within this work to substitute the traditionally used UV lamps. In the UV meters used for this inspection, the CIE standardized UV-A function is realized using optical filters and Si photodiodes. The realized spectral responsivities of the available UV-meter models are different producing significant measurement errors even if the same UV-365 source is measured.

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[1] george.eppeldauer@nist.gov; phone 1 301 975-2338; fax 1 301 869-5700

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A pyroelectric radiometer standard with spectrally flat (constant) response in the UV-VIS range has been developed at NIST to perform uniform UV irradiance measurements with low uncertainty. The relative response of this organic-black coated radiometer was determined from spectral reflectance measurements. The relative curve was converted into a spectral irradiance responsivity function using an absolute tie point from a Si-trap detector traceable to the primary standard cryogenic radiometer.

The flat pyroelectric radiometer standard can be used to perform uniform integrated irradiance measurements from all kinds of UV sources (with different peaks and distributions) without using any source standard. Using this broadband calibration method, yearly spectral calibrations for the reference UV (LED) sources and irradiance meters [2] is not needed. Field UV meters (including existing commercial meters) may be calibrated against the pyroelectric radiometer standard for broadband (integrated) irradiance responsivity when both measure the same UV source. In this case, spectrally flat response for the field meter is not required. Using the broadband procedure, the UV measurement uncertainties can be significantly decreased.

2. UV MEASUREMENT PROBLEM

The realizations of the rectangular shape action spectrum for two commercial UV-A meters are illustrated in Fig. 1 [4].

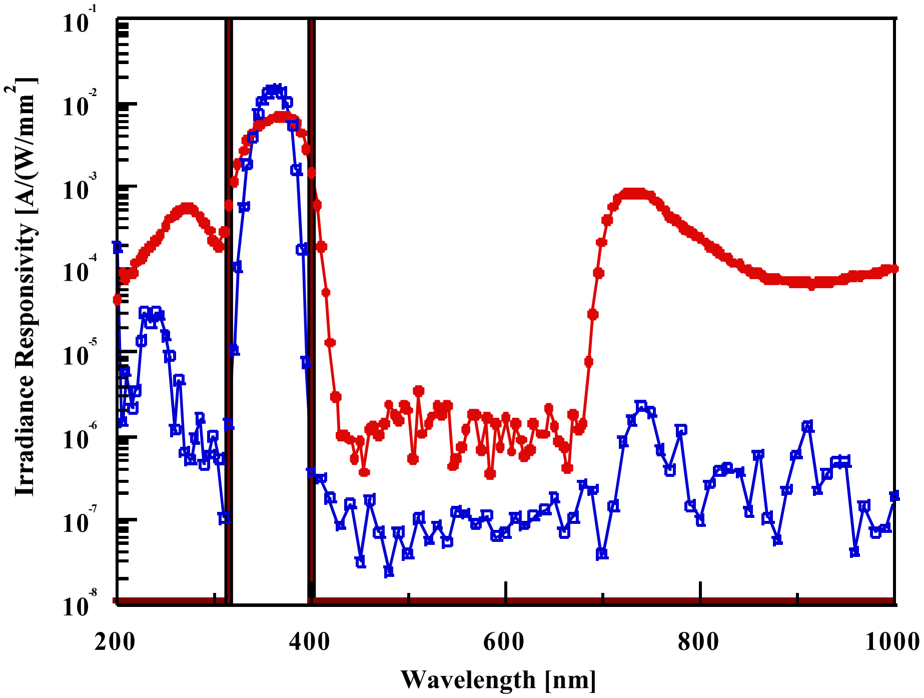

Fig. 1. The CIE standardized UV-A (rectangular-shape) function with two realized spectral responsivity functions.

The full-dots show an average realization and the open-squares represent a better realization. It can be seen that both realizations have large spectral mismatch errors relative to the CIE (rectangular-shape) standard function. The measurement errors may increase to several times ten percent when the standard lamp type (e.g. an FEL lamp) is different than the test lamps e.g. mercury, deuterium, or xenon.

A reasonable calibration (correction) factor for broad-band UV measurements cannot be assigned based on the CIE UV-A standard responsivity function. Also, the spectral power distribution of the excitation 365-nm sources has not been standardized which is a must if the realized spectral responsivity function of the UV meter is different from the standard function. The wavelength range of the presently used CIE standard function is too broad for the required tests where 365-nm excitation sources are used.

The goal of the present work is to make the broadband UV measurements uniform and to lower the broad-band UV (with a typical emissivity peak of 365 nm) irradiance measurement uncertainties. To achieve this goal, first a new procedure for standardized measurements was developed using reference UV excitation sources and meters [ref] and then spectrally flat reference meters were developed to simplify the procedure and using only a broadband pyroelectric detector based calibration without the need for a reference (standard) source.

3. SOLUTION OF PROBLEM USING FLAT METER

In the previously suggested measurement procedure [1, 2], the UV LED source(s) is measured with a broadband meter. In the discussed example, an LED-365 irradiance source was measured with a UV irradiance meter. The measured output signal of the meter was equal to 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. 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 within the spectral response function of the meter for all the expected source(s) and meter changes.

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. Using the broadband procedure, output signals can be measured with differences (errors) less than the required measurement uncertainty when different 365-nm sources (with different peak wavelengths and spectral widths) are measured.

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. Using the flat-response reference pyroelectric meter, the calibration procedure can be simplified, spectral calibrations for the standards are not required, source standards will not be needed, and selection of the field test meters is not necessary.

4. INTEGRATED IRRADIANCE MEASUREMENT

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 [3]. 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 suggested broadband measurement procedure, the integrated irradiance from a test UV LED source can be measured [6, 8]. Two different versions of the calibration steps (depending primarily on the spectral flatness of the meter) were also discussed earlier [7].

The measurement equation that describes the output signal of the reference meter for irradiance measurement mode can be written as

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

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:

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

where the integrated irradiance responsivity of the reference meter is:

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

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 reference calibration steps [7].

When using the above discussed broadband measurement procedure, spectral response measurement of test (field) UV meters is not needed. Also, 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 [7].

4.1. Pyroelectric UV irradiance 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 another 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 relative 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).

A spectrally “flat” UV meter can be made with either filtered quantum detector (like silicon detector and input optical filters) or pyroelectric detector. 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 [7]. Also, the wavelength coverage of a pyroelectric detector with the flat response will be much wider.

Reference-level integrated irradiance calibrations are discussed below when using a pyroelectric “flat” irradiance meter standard. 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 front-surface of the pyroelectric detector. The picture of the recently developed pyroelectric UV standard meter is shown in Fig. 2.

Fig. 2. Picture of a temperature controlled hybrid pyroelectric UV detector standard of low NEP.
The $LiTaO_3$ crystal is covered with organic-black coating.

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 needs a shorter calibration time and it is less expensive than the presently applied spectral calibration techniques. 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 the absolute tie point 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 [7].

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. The irradiance responsivity from the near-IR was extended to the UV range based on the close to constant spectral absorptance (relative response) curve derived from spectral reflectance measurements of the black coating. For this scale extension, the output of the pyroelectric detector was compared to the output of a silicon trap-detector transfer-standard for which the irradiance responsivity was known in the visible range. The detector substitution was made in the collimated radiation from a LED irradiance source peaking at 660 nm. In Fig. 3, the absorptance curve of the organic black coating is shown in the range of 0.25 μm to 0.8 μm together with the absolute tie point at 660 nm. The absorptance, which is proportional to the response, is equal to 1–R if the transmittance is negligibly small (where the reflectance is R). The tie point converts this relative response curve into absolute spectral irradiance responsivity. Based on the small changes in this relative curve, the irradiance responsivity of the pyroelectric detector was taken as a constant 910 $VW^{-1}cm^2$ between 0.25 μm and 0.75 μm. The uncertainty budget of the spectral irradiance responsivity is shown in Table 1. The expanded (k=2) irradiance responsivity uncertainty between 0.25 μm and 0.75 μm is 0.5 %. The max-to-min response change was +/- 0.12 % between 300 nm and 660 nm and +/- 0.18 % between 0.25 μm and 0.75 μm.

A second tie point is also shown at 365 nm where the LED-365 excitation sources were calibrated against an FEL lamp standard [7]. The uncertainty of the FEL source-based spectral irradiance calibrations was 1.6 % (k=2).

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 [9] as well.

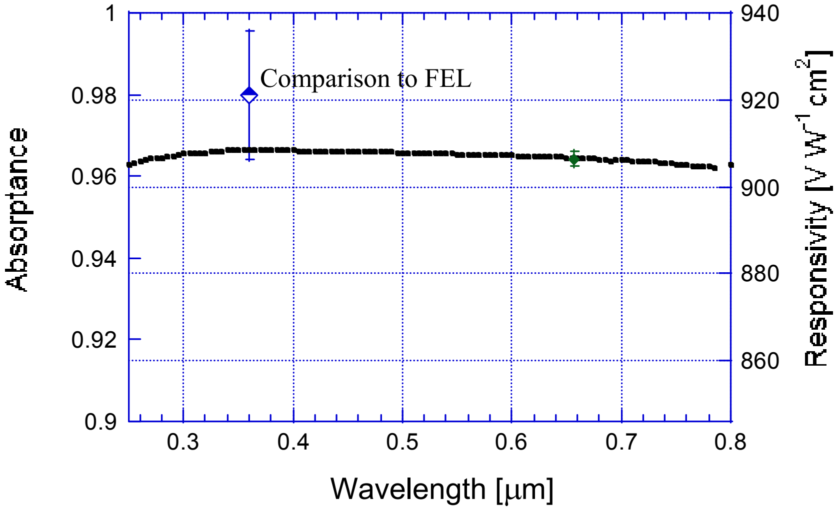

Fig. 3. Spectral absorption (1-reflectance) curve of the organic black coated pyroelectric detector standard. The irradiance responsivity tie (absolute) point against a Si-trap detector is shown at the 660 nm peak of the transfer LED.

Table 1. Uncertainty budget of the spectral irradiance responsivity of the flat pyroelectric detector standard for the 250 nm to 750 nm wavelength range.

Relative uncertainty components	**[%]**
$\Delta\lambda$	0.03
Distance	0.04
Target spot non-uniformity	0.10
Spectral response change	0.18
Output signal ratio	0.10
Reference Si-trap	0.10
Combined (*k*=1)	**0.25**
Expanded (*k*=2)	**0.5**

5. INTEGRATED IRRADIANCE MEASUREMENTS WITH TEST UV METERS

Utilization of the pyroelectric detector-based (standard) radiometer allows to simplify the calibration of the filtered Si detector 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 meter 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 above.

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

$$r_\mathrm{t} = \mathrm{k}s \tag{6}$$

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

$$\overline{E} = \frac{U_t}{ks} \tag{7}$$

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.

5.1. Pyroelectric detector based broadband calibration of UV meters for non-destructive testing

The broadband calibration can substitute the expensive spectral calibrations of the previously developed LED-365 irradiance sources and the UV irradiance meters. Figure 4 illustrates a field calibration setup for broadband scale transfer from the flat pyroelectric detector standard to the previously developed UV-365 irradiance meters. The calibrated UV-365 irradiance meters are used for non-destructive material testing.

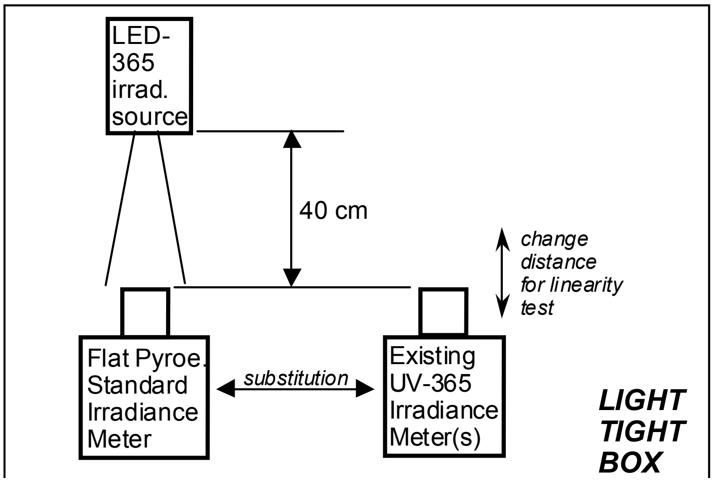

Fig. 4. Setup for broadband scale transfer from the flat pyroelectric standard to previously developed UV-365 irradiance meters.

6. CONCLUSIONS

A broadband UV measurement procedure has been developed at NIST to calibrate UV sources for integrated irradiance. An irradiance meter standard has been developed for the UV range using a spectrally flat-response pyroelectric detector of low-NEP. A spectrally constant UV absorptance function with an irradiance tie point has been realized for the 250 nm to 660 nm wavelength range. This new detector-based UV irradiance responsivity scale has a 0.25 % (*k*=1) uncertainty. The flat pyroelectric detector standard was used to calibrate existing filtered Si UV irradiance meters. The filtered Si meters measured the integrated irradiance of both the recently developed reference LED-365 excitation sources and field UV-365 sources. The broadband UV measurement procedure can be applied for all kinds of LEDs or groups of LEDs without using any source standard. The pyroelectric detector standard can be used to directly calibrate either UV irradiance meters and/or UV excitation (irradiance) sources. The broadband measurement procedure was successfully applied for fluorescent crack-recognition when using liquid penetrant inspection in non-destructive material testing.

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