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Calibration and characterization of UV sensors for water disinfection

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Abstract
The National Institute of Standards and Technology (NIST), USA is participating in a project with the American Water Works Association Research Foundation (AwwaRF) to develop new guidelines for ultraviolet (UV) sensor characteristics to monitor the performance of UV water disinfection plants. The current UV water disinfection standards, ÖNORM M5873-1 and M5873-2 (Austria) and DVGW W294 3 (Germany), on the requirements for UV sensors for low-pressure mercury (LPM) and medium-pressure mercury (MPM) lamp systems have been studied. Additionally, the characteristics of various types of UV sensors from several different commercial vendors have been measured and analysed. This information will aid in the development of new guidelines to address issues such as sensor requirements, calibration methods, uncertainty and traceability. Practical problems were found in the calibration methods and evaluation of spectral responsivity requirements for sensors designed for MPM lamp systems. To solve the problems, NIST is proposing an alternative sensor calibration method for MPM lamp systems. A future calibration service is described for UV sensors intended for low- and medium-pressure mercury lamp systems used in water disinfection applications.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

UV radiation effectively inactivates common pathogens found in ground and surface waters such as *Cryptosporidium*, *Giardia*, and most bacterial pathogens (e.g. *Escherichia coli*). Water treatment facilities recently started using UV radiation for disinfection of drinking water, replacing standard chemical treatment. Typically, low-pressure mercury (LPM) and medium-pressure mercury (MPM) lamps are used in the UV reactors at the facilities. In these reactors, water flowing at a given rate should receive an appropriate UV dose. UV sensors mounted on the wall of the UV reactor or inserted into the water flow monitor the dose level by measuring the irradiance from the lamps. The UV sensors currently in use have a variety of designs and performance characteristics. Austria and Germany have developed or are developing standards for the sensor design and performance to be used to validate new facilities and for their maintenance. These two standards differ significantly in their requirements and do not address some of the problems associated with the UV monitors. There are already many water plants employing UV sensor systems consistent with one or the other standard.

To resolve this confusion, the American Water Works Association Research Foundation (AwwaRF) decided to develop new guidelines for UV monitors. The National Institute of Standards and Technology (NIST) is participating in this project in collaboration with Carollo Engineers (Boise, ID), Camp Dresser & McKee Inc. (Denver, CO), and the University of Veterinary Medicine (Vienna, Austria). The current UV water disinfection standards, ÖNORM M5873-1 and M5873-2 [1], and DVGW W294 3 [2], on the requirements for UV sensors for LPM and MPM lamp systems were studied. Additionally, the characteristics of various types of UV sensors from several different commercial vendors were measured and analysed at NIST. This information will aid in the development of new guidelines addressing sensor requirements, calibration methods, uncertainty and traceability. Through these studies, a practical problem

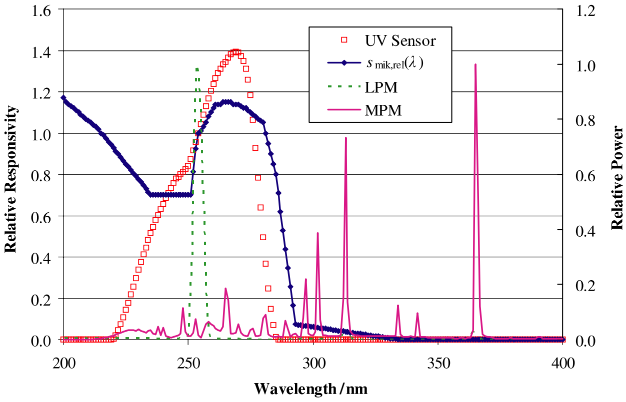

Figure 1. The microbicidal action spectrum, $s_{\mathrm{mik,rel}}(\lambda)$; the spectrum of an LPM lamp and an MPM lamp; and an example of the spectral responsivity of a UV sensor.

was identified in the calibration methods and evaluation of spectral responsivity requirements for sensors designed for MPM lamp systems. A solution for this problem is discussed.

2. Problems with irradiance calibration of sensors

The physical quantity to be measured is the microbicidal irradiance, defined as the total irradiance ($\mathrm{W\,m^{-2}}$) weighted by the microbicidal action spectrum $s_{\mathrm{mik,rel}}(\lambda)$ as shown in figure 1. According to ÖNORM M5873-1, M5873-2 and DVGW W294-3, UV sensors for both LPM and MPM lamp systems are calibrated for irradiance responsivity against an LPM lamp (254 nm line emission). Since the value of $s_{\mathrm{mik,rel}}(\lambda)$ is unity at 254 nm, and LPM lamps only have microbicidally significant flux at 254 nm, the measured irradiance from an LPM lamp is equal to the microbicidal irradiance. Instruments can be calibrated for microbicidal irradiance responsivity using an LPM lamp, regardless of the sensor's spectral responsivity. This method works well for LPM lamp systems. However, there is a problem for MPM lamp systems. The spectral output from MPM lamps differs significantly from LPM lamps. In addition, real UV sensors never have spectral responsivities perfectly matched to $s_{\mathrm{mik,rel}}(\lambda)$. In fact, many of the sensors used for MPM lamp systems have fairly large deviations from $s_{\mathrm{mik,rel}}(\lambda)$. As a consequence of the differences between the LPM and MPM spectral distributions and the differences between the sensor spectral responsivities and $s_{\mathrm{mik,rel}}(\lambda)$, measurement errors in the microbicidal irradiance occur. This source of measurement error, called a spectral mismatch error, is well known in other applications, e.g. photometry, where a detector's responsivity is tuned to match the spectral luminous efficiency function, $V(\lambda)$. Note that if a UV sensor had a spectral responsivity perfectly matched to $s_{\mathrm{mik,rel}}(\lambda)$, there would be no problem, that is, the irradiance value measured by the sensor would be equal to the microbicidal irradiance.

To ensure that such errors will not be significant, the ÖNORM and DVGW standards specify requirements for the relative spectral responsivity of sensors used for MPM lamp systems. DVGW W294-3 requires that a term $f_{1,z}$ be calculated from the relative spectral responsivity of the sensor, and the sensors must meet $f_{1,z} \leqslant 0.25$ (reference sensors) or $f_{1,z} \leqslant 0.40$ (duty sensors). $f_{1,z}$ is defined as

$$f_{1,z} = \frac{\int_{220}^{340} |s_{\mathrm{rel}}(\lambda) - s_{\mathrm{mik,rel}}(\lambda)|\, S_{\lambda,\mathrm{Z}}(\lambda)\,\mathrm{d}\lambda}{\int_{220}^{340} s_{\mathrm{mik,rel}}(\lambda)\, S_{\lambda,\mathrm{Z}}(\lambda)\,\mathrm{d}\lambda}, \qquad (1)$$

where $s_{\mathrm{rel}}(\lambda)$ is the relative spectral responsivity of the sensor and $S_{\lambda,\mathrm{Z}}(\lambda)$ is the spectral distribution of the defined MPM lamp spectrum. ÖNORM M5873-2 does not require the measurement of relative spectral responsivity of the sensors, but it requires measurement with two specified cutoff filters and a MPM lamp calibrated using a spectroradiometer. The D value is calculated from these results as

$$D = \frac{E_{\mathrm{mik,Sens}} - E_{\mathrm{mik,Rad}}}{E_{\mathrm{mik,Rad}}}, \qquad (2)$$

where $E_{\mathrm{mik,Sens}}$ is the sensor reading with one of the specified filters and $E_{\mathrm{mik,Rad}}$ is the spectroradiometer reading with the same filter. The sensors must meet $|D| < 0.2$ for both filters. The evaluation of the relative spectral responsivity is critical but not easy in either standard. In addition, NIST found that many of the currently used commercial sensors do not meet these requirements. Reference sensors that meet the requirements can still have errors as high as 20%. Based on the results of evaluating real sensors, a new calibration scheme is proposed.

3. Characterization of the UV sensors

Ten different UV sensors from six different manufacturers designed for water disinfection monitoring have been characterized at NIST for several parameters. The relative spectral responsivity measurements were taken at two NIST facilities. The first is a monochromator-based spectral responsivity measurement facility referred to as the Spectral Comparator Facility (SCF) [3]. This system was designed for spectral power responsivity measurements (the beam underfills the detector). The facility also has the capability to measure a detector's irradiance responsivity. The absolute irradiance responsivity in $\mathrm{V\,(W\,m^{-2})^{-1}}$ or $\mathrm{A\,(W\,m^{-2})^{-1}}$ is measured by spatially scanning the beam across the detector entrance aperture in very small distance intervals using an X–Y stage [4]. In this manner, NIST was able to measure the spectral irradiance responsivity of ten sensors though measurements of some of the sensors had very large uncertainties due to extremely low signals. The incident flux in this facility is fairly low, of the order of 1 μW, while these sensors are designed for very high irradiance levels (up to $2000\ \mathrm{W\,m^{-2}}$).

The relative spectral responsivity for eight of the sensors was also measured in another NIST facility capable of generating higher levels of monochromatic UV flux. This facility, the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources facility (SIRCUS) [5], can generate monochromatic beams with up to ≈100 mW of power in the 200 nm to 400 nm region using the frequency doubled, tripled and quadrupled output from a pulsed Ti–sapphire laser, which has a quasi-CW emission (pulses at a very high frequency, 76 MHz). To measure the irradiance responsivity of the sensors, a frosted quartz diffuser plate was placed in front of the detectors to generate a quasi-uniform irradiance field at the detector reference plane. The sensors were placed at about 8 cm from the diffuser. The diffuser plate was a temporary set-up to produce a spatially uniform irradiance field over the entrance aperture of these UV sensors at a sufficient irradiance level. The responsivity of the sensors under test was compared with a reference irradiance standard detector (silicon trap detector with a calibrated aperture). The irradiance levels ranged from approximately 2 W m^{-2} to 20 W m^{-2} at 254 nm.

The relative spectral responsivity of one sensor from each manufacturer is shown in figure 2. The data are normalized at 254 nm. The relative uncertainty of these results varies depending on the wavelength and sensor and was preliminarily estimated to be less than 10% ($k = 2$) (except in the region where the responsivity tapers off) based on a comparison between the results of SCF and SIRCUS and other analyses. The uncertainty should be improved in the future.

The measurement results indicate a large variation in the spectral responsivities of the commercial sensors. The spectral mismatch of these sensors (deviation of the relative spectral responsivity curve from the microbicidal action spectrum $s_{\mathrm{mik,rel}}(\lambda)$) causes errors in the measured microbicidal irradiance as large as 170% (excluding sensor #7—designed for LPM lamp systems). Table 1 shows the results of the calculation for these sensors on the requirements

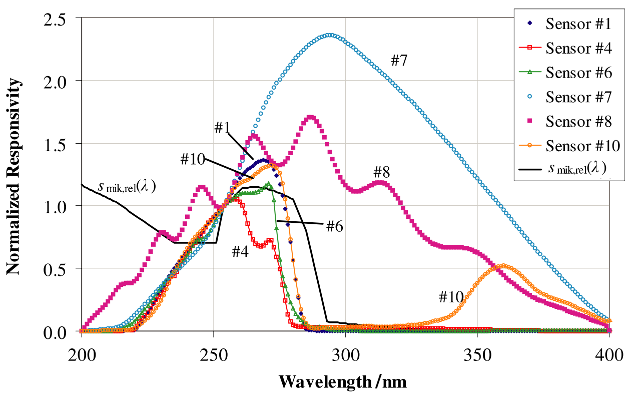

Figure 2. Relative spectral irradiance responsivity data of six of the sensors measured by SCF and SIRCUS.

of the relative spectral responsivity in the DVGW and ÖNORM standards. Most of the sensors did not meet the requirements.

The linearity of eight sensors at 254 nm over a limited range was measured at the SIRCUS facility. The sensor under test was irradiated by 254 nm radiation in the same measurement configuration as for the spectral responsivity measurements. The laser power was changed, and signals from the reference detector and the sensor under test were recorded. The maximum irradiance levels were limited to ≈25 W m^{-2} due to the limitation of the laser power and optical system setting of the SIRCUS facility. This upper limit did not reach even 10% of the full scale for many of the sensors. Some significant non-linearity at low irradiance levels was observed as shown in figure 3 for some of the sensors.

The temperature dependence of the 254 nm responsivity of the sensors was also measured as shown in figure 4. One sensor from each manufacturer (six sensors in total) was tested. The measurements were made using a variable temperature chamber. A twin tube 35 W LPM lamp was operated outside the chamber, whose intensity drift was monitored and corrected. The irradiance level at the sensor front surface was ≈3 W m^{-2}. The temperature of the chamber was varied from 10 °C to 35 °C for each sensor, and the output signal was recorded. The results indicate that the temperature dependence was generally not significant. The changes are mostly less than 1% in this temperature range and are insignificant.

The angular responsivity of six sensors was also measured for radiation at 254 nm. The results are shown in figure 5. A twin tube 35 W LPM lamp with an aperture screen was used as the source. The irradiance level at the sensor front surface was ≈3 W m^{-2}. The drift of the lamp intensity was monitored using a monitor detector and corrected. The relative uncertainty of these measurements was ≈1% ($k = 2$) with an angle setting repeatability of less than 1°.

4. Proposed calibration scheme

To solve the practical problems found in the calibration methods and evaluation of the spectral responsivity requirements for sensors designed for MPM lamp systems, NIST is proposing an alternative sensor calibration method for MPM lamp systems. The root of the problem is that the MPM lamp has a very different (multi-line) spectrum than the LPM calibration lamp (a single emission line at 254 nm). The proposed

Table 1. Calculation results of spectral mismatch errors.

	DVGW requirement			ÖNORM requirement (MPM: ÖNORM M5873-2)			
Sensor	DVGW $f_{1,z}$	$f_{1,z} < 0.25$	$f_{1,z} < 0.4$	ÖNORM D_{A}	ÖNORM D_{B}	$\lvert D_{\mathrm{A,B}}\rvert < 0.2$	Error for MPM
		Ref. sensor	Duty sensor				
1	0.30	NO	YES	0.19	1.00	NO	−19%
4	0.40	NO	NO	0.47	0.07	NO	−39%
6	0.31	NO	YES	0.36	0.75	NO	−30%
7	2.70	NO	NO	6.92	76.20	NO	321%
8	1.45	NO	NO	3.53	37.71	NO	172%
10	0.27	NO	YES	0.68	13.11	NO	20%

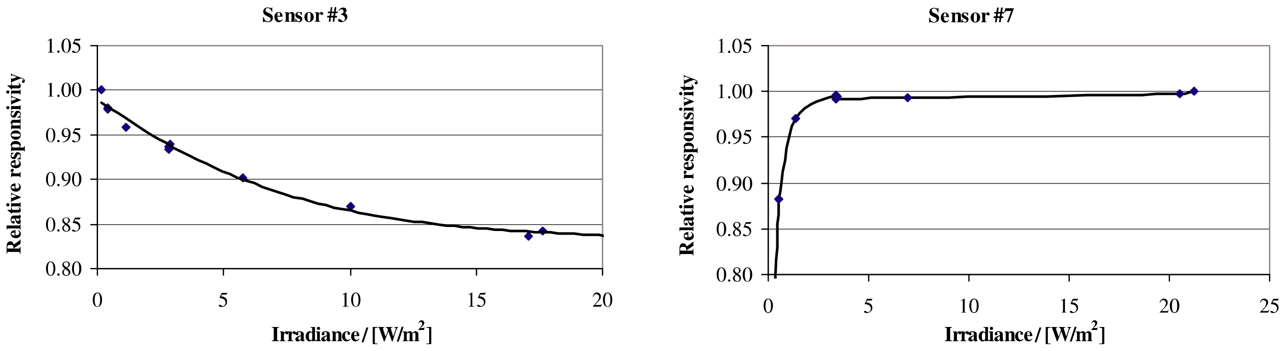

Figure 3. Two examples of the linearity data measured using the SIRCUS facility.

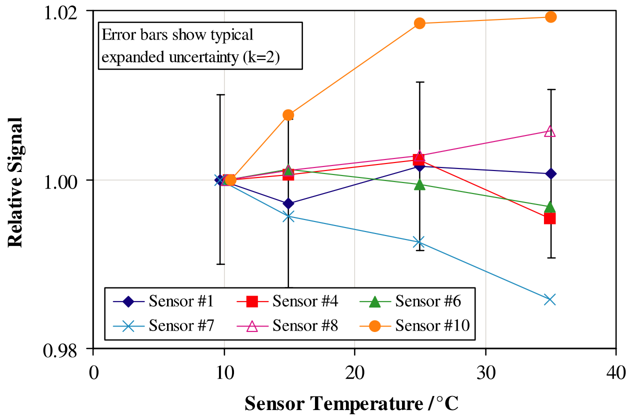

Figure 4. Temperature dependence for six UV sensors, one from each manufacturer. Error bars show typical expanded uncertainty ($k = 2$).

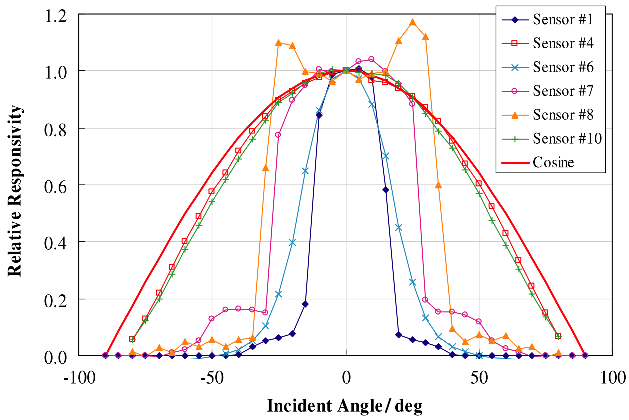

Figure 5. Angular response for six UV sensors, one from each manufacturer.

method is to use an MPM lamp as a calibration source to calibrate the sensors used for MPM lamp systems. This approach is based on the well-established principle that errors are minimized in any measurement system when the standard and test sample are of the same type (strict substitution). In strict substitution, many of the measurement error components are cancelled out. If the UV sensor is calibrated using an MPM lamp, and subsequently measures MPM lamps having the same spectral distributions, the error will be zero, theoretically, regardless of the spectral responsivity of the sensor. In real cases, there are variations in the spectra of MPM lamps, and so the errors will not be zero, but errors will be significantly reduced even with sensors having a large deviation from $s_{\text{mik,rel}}(\lambda)$. Figure 6 shows five MPM lamp spectra (provided by courtesy of Alexander Cabaj) that were used in analysing the effect of lamp spectra variation with the proposed calibration scheme. Data below 240 nm were not used, assuming water absorption. Lamp MPM3 was chosen as the calibration lamp and the errors were evaluated when measuring the other lamps with the sensors. The errors when using the new calibration method are reduced by an order of magnitude as shown in figure 7.

The actual calibration of sensors with this method can be performed simply. It only requires an MPM lamp and a reference standard sensor calibrated for MPM microbicidal irradiance responsivity. The reference standard sensor is

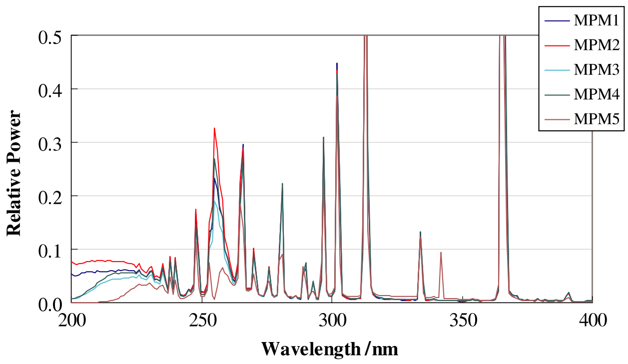

Figure 6. Five MPM lamp spectra used in the analysis of the effect of lamp spectra variation with the proposed calibration scheme with MPM lamps. MPM3 was used as the calibration lamp.

calibrated, e.g. by a national laboratory, as

$$s_{\text{microb}}(\text{MPM}) = s(254\,\text{nm}) \times \frac{\int_\lambda s_{\text{rel}}(\lambda) E_{\text{MPM}}(\lambda)\,\text{d}\lambda}{\int_\lambda s_{\text{mik,rel}}(\lambda) E_{\text{MPM}}(\lambda)\,\text{d}\lambda} \tag{3}$$

where $s_{\text{microb}}(\text{MPM})$ is the microbicidal responsivity of the reference sensor for MPM lamps, $s(254\,\text{nm})$ is the absolute irradiance responsivity of the reference sensor at 254 nm, $s_{\text{rel}}(\lambda)$ is the relative spectral responsivity of the reference sensor (and $s_{\text{rel}}(254\,\text{nm}) = 1$), $E_{\text{MPM}}(\lambda)$ is the spectral distribution of an MPM lamp, and $s_{\text{mik,rel}}(\lambda)$ is the microbicidal

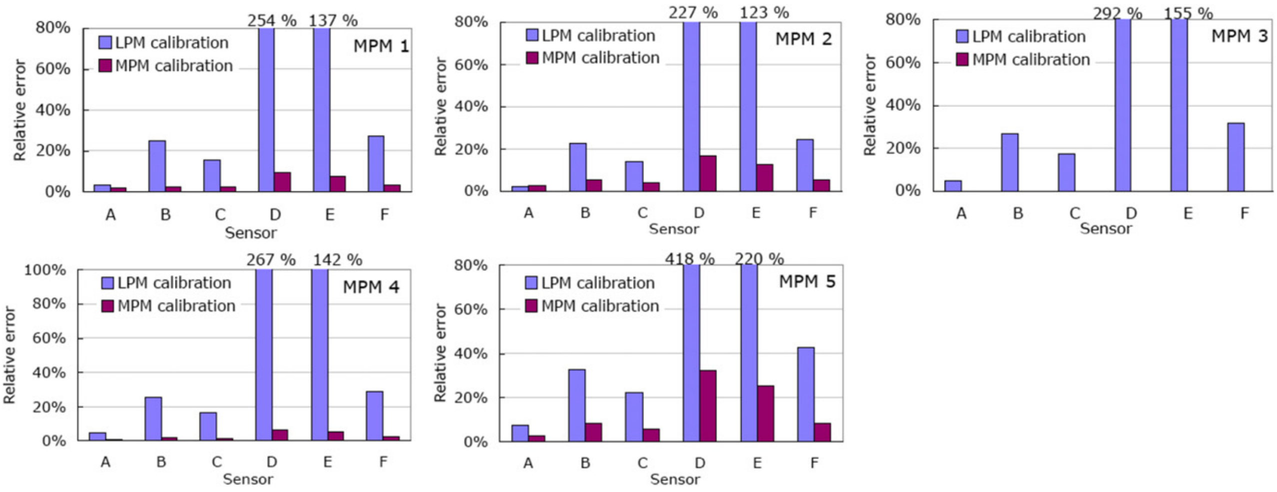

Figure 7. Results of variation in MPM lamp spectra analysis. Errors are reduced by an order of magnitude, even for sensors having a large deviation from $s_{\mathrm{mik,rel}}(\lambda)$. MPM3 was used as the calibration lamp.

action spectrum. The second term on the right-hand side of the equation is the correction factor for the MPM lamp. The same sensor also holds the calibration for LPM lamps as $s_{\mathrm{microb}}(\mathrm{LPM}) = s(254\,\mathrm{nm})$.

Then, the UV sensor under test can be calibrated simply by comparison to the reference standard sensor under illumination by an MPM lamp (or by an LPM lamp for LPM lamp systems). This calibration can be performed easily at calibration and testing laboratories, with no need for spectral measurements. To ensure consistency in the calibration approach, a reference MPM lamp spectrum may need to be defined; ÖNORM M5873-2 already lists a nominal MPM lamp spectrum. A similar example exists in photometry, where a representative spectral distribution of incandescent lamps is standardized as CIE Standard Illuminant A (blackbody radiation at 2856 K). Photometers are normally calibrated using a standard incandescent lamp approximating this spectrum. With this approach, photometric calibration results are universal [6].

5. Future work

The development of a facility at NIST dedicated to the calibration of UV water disinfection sensors is planned. The facility will consist of a set of reference standard UV sensors (and/or a reference spectroradiometer), a set of stable LPM and MPM lamps, a variable attenuator that allows decadal changes in the irradiance level at the reference plane, an automatic shutter to minimize exposure (and damage) of the sensors by high-level UV exposure, and a radiometric bench on which the distance between the test sensor and the lamp can be variably set, all of which will be enclosed in a light-tight housing. With such a facility, reference standard UV sensors can be calibrated traceable to the national scale for microbicidal irradiance responsivity for either or both the MPM lamp spectrum and the LPM lamp spectrum at the irradiance levels the sensors are used. The target calibration uncertainty using the proposed new method and facility is ≈5% ($k = 2$). This facility and calibration service will establish traceability of the UV sensors for the water treatment community.

Acknowledgments

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