Stray light correction of array spectroradiometer measurement in ultraviolet

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Abstract. For most of the array spectroradiometer, stray light is significant in UV band. Stray light correction of a UV array spectroradiometer is investigated using optical filters. If a group of filters with continuous bandpass are chosen, stray light contribution due to all the bands can be obtained using a numerical algorithm. The array spectroradiometer with the stray light corrected is used to measure the spectral irradiance of several UV lamps. The measurement results are compared to a double monochromator spectroradiometer. When xenon lamp is the array spectroradiometer calibration lamp, after stray light correction, the difference can be improved from nearly 10% to 2.0% in UVC band. When tungsten lamp is the calibration lamp, the difference can be improved from around 90% to less than 20%.

1. Introduction

UV radiometers are used to measure the UV light sources. According to the CIE concept, UV can be divided into UVC (200-280) nm, UVB (280-315) nm and UVA (315-400) nm. However, there is not a one-to-one match between UV radiometers and CIE UV conception. Various radiometers are needed in order to meet the demands of different application fields. For example, narrow band UVC is popular in UV disinfection; the spectral irradiance at 310 nm and 340 nm are needed in aging applications; narrow band UVB is needed in psoriasis treatment; UVA is usable in the crack detection. It’s hard to cover all the potential fields just using radiometers, especially with new growth in UV demand. On the other hand, UV radiometers are often used to measure UV light sources different from those used by the manufacturer. The spectral mismatch can bring big problem for the measurement.

It’s obvious that traditional scanning spectroradiometer can solve the problem. However, it is large and not convenient to take along. In addition, the scanning speed also limits its use. Since compact array spectroradiometer has a fast acquisition speed and is portable, it is widely used in photometric and radiometric measurement in recent years. The characteristic of the array spectroradiometer was investigated during the past ten years, such as the bandwidth, the stability and the stray light [1-9]. However, report on the UV spectroradiometer application in direct use is not much due to the significant stray light in UV band. Zong has proposed a stray light correction method using tunable lasers [1]. Feldman has implemented a digital micromirror device in array spectroradiometer to reduce the stray light [6]. Shaw has investigated the stray light of array spectrometers using a series of cut-on filters [7]. Compared to the tunable laser method, the filter method is much cheaper and can save a lot of time. Shindo has investigated the stray light of array-based spectrometers in UV band using cut-on filter correction method [8]. Kenji analysed the heterochromatic stray light and proposed a practical
method to correct the stray light [9]. In this paper, optical filters method is also used to analyze the stray light effect in UV region.

2. Experiment and results

2.1. Array spectroradiometer

The optical setup of array spectroradiometer is shown in Figure 1. Through the entrance slit, the light is collimated by the collimating mirror and illuminates the grating. The grating diffracts the light spectrum and makes different wavelengths received by different parts of the CCD detector. Each pixel of the CCD detector and the corresponding wavelength has a one-to-one relationship, which can be defined by the atomic lines of spectral calibration lamps, such as Hg-Ar lamp. UV array spectroradiometer covering 200 nm to 460 nm is investigated, with 2048 pixels and 1800 lines/mm grating. Since array spectroradiometer has 2048 pixels, the wavelength interval between each pixel is about 0.127 nm. The wavelength accuracy is found to be less than 0.1 nm.

![Figure 1. Optical setup of array spectroradiometer.](image1)

2.2. Stray light test of array spectroradiometer using optical filter

If a single wavelength laser is used to irradiate the array spectroradiometer, the response of the array spectroradiometer at other wavelength is due to stray light. Similarly, if a lamp with bandpass optical filter is used, the response of the array spectroradiometer out of filter bandpass region should be due to stray light.

A Schott GG450 filter is mounted in front of the array spectroradiometer. Figure 2 shows the stray light ratio in UV band. The blue and green lines are the ratios with and without filter using xenon lamp and tungsten lamp, while the red line is the transmittance of the optical filter. It can be seen that the optical filter has a transmittance less than 0.1% in 200 nm – 400 nm. However, the ratios are much larger than the filter transmittance, especially when tungsten lamp is used. The difference between the ratios and the transmittance is the stray light, which is due to the visible and infrared spectra of the lamps. The stray light dominates when tungsten lamp is used, while the stray light accounts for less than 6.0% for the xenon lamp.

![Figure 2. The UV stray light ratios using xenon lamp and tungsten lamp.](image2)
Figure 3 shows the relative spectral power distribution of xenon lamp and tungsten lamp at the same distance. The ratio of spectral irradiance at 310 nm and 253.7 nm to the integral spectral irradiance (500-1100) nm is about $2.5 \times 10^5$ and $2.3 \times 10^6$ for tungsten lamp, while the ratio is $5.6 \times 10^4$ and $2.4 \times 10^4$ for xenon lamp. It's obviously that xenon lamp has a much large UV spectral proportion and the stray light ratio is much smaller.

2.3. Stray light correction method

Since Schott GG450 filter has a high transmittance in visible and infrared, the stray light ratio due to visible and infrared can be measured. If UVA, UVB and UVC bandpass filters are used, the stray light ratio due to UVA, UVB and UVC band can be obtained. Equation (1) and (2) describe the relationship between the real spectral irradiance and the measured spectral irradiance when an optical filter is used. $E_{\text{lamp}}(\lambda_0)$ is the spectral irradiance of the lamp at wavelength $\lambda_0$, while $E_{\text{measur}}(\lambda_0)$ is the spectral irradiance measured by the array spectroradiometer. $E_{\text{lamp}}(\lambda)$ is the spectral irradiance of the lamp at wavelength $\lambda$, $T(\lambda)$ is the transmittance of the filter at wavelength $\lambda$, $R(\lambda \rightarrow \lambda_0)$ denotes the stray light contribution at wavelength $\lambda_0$ due to wavelength $\lambda$. $S_{\text{with}}(\lambda_0)$ is the spectroradiometer signal obtained with the filter, $S_{\text{without}}(\lambda_0)$ is the signal obtained without the filter, $\lambda_l$ and $\lambda_f$ are the lower and upper wavelengths in summation. If no filter is used, $T(\lambda) = 1$. Then the right term of equation (1) will be $S_{\text{without}}$. It’s easy to see that the measured spectral irradiance is bigger than the real spectral irradiance of the lamp due to the stray light. As an approximation, $R(\lambda \rightarrow \lambda_0)$ in equation (2) is moved out of the summation, $T(\bar{\lambda})$ is average transmittance between $\lambda_l$ and $\lambda_f$.

$$E_{\text{lamp}}(\lambda_0)T(\lambda_0) + \sum_{\lambda_l=200}^{\lambda_f=280} E_{\text{lamp}}(\lambda)T(\lambda)R(\lambda \rightarrow \lambda_0) + \sum_{\lambda_l=200}^{\lambda_f=280} E_{\text{lamp}}(\lambda)T(\lambda)R(\lambda \rightarrow \lambda_0) + \sum_{\lambda_l=400}^{\lambda_f=1100} E_{\text{lamp}}(\lambda)T(\lambda)R(\lambda \rightarrow \lambda_0) = E_{\text{measur}}(\lambda_0)$$

$$R(\lambda \rightarrow \lambda_0) \sum_{\lambda=\lambda_l}^{\lambda=\lambda_f} E_{\text{lamp}}(\lambda) = \frac{S_{\text{with}}(\lambda_0)}{S_{\text{without}}(\lambda_0)} / T(\bar{\lambda})$$

A group of filters consisting of UVC, UVB, UVA and Schott GG400 filter can cover all the wavelengths from 200 nm to 1100 nm. The transmittance of the UVA, UVB and UVC filters are listed in figure 4. With the four filters, the $R$ parameter of a certain lamp can be obtained. According to
equation (1), the relationship of the real spectral irradiance of the lamp and the measured spectral irradiance can be described using equation (3).

\[
\begin{bmatrix}
1 & R_{uvb \rightarrow uvc} & R_{uva \rightarrow uvc} & R_{uvo \rightarrow uvc} \\
R_{uvc \rightarrow uvb} & 1 & R_{uva \rightarrow uvb} & R_{uvo \rightarrow uvb} \\
R_{uvc \rightarrow uva} & R_{uvb \rightarrow uva} & 1 & R_{uvo \rightarrow uva} \\
R_{uvc \rightarrow nonuv} & R_{uvb \rightarrow nonuv} & R_{uva \rightarrow nonuv} & 1
\end{bmatrix}
\begin{bmatrix}
E_{uvc} \\
E_{uvb} \\
E_{uva} \\
E_{non-uv}
\end{bmatrix}
= 
\begin{bmatrix}
E_{uvc}' \\
E_{uvb}' \\
E_{uva}' \\
E_{non-uv}'
\end{bmatrix}
\] (3)

In equation (3), the first column is a matrix. Subscript uvc, uvb, uva and uvo correspond to UVC band, UVB band, UVA band and out of UV band. The second column and third column correspond to the real and measured spectral irradiance of the light source in UVC, UVB, UVA and out of UV band. For example, if $\lambda_0 \in UVC$ and UVB filter is used, the right term of equation (2) is $R_{uvc \rightarrow uvb}$, which is stray light contribution in UVC band due to UVB band. As a simplification, $R_{uvc \rightarrow uvc(\lambda \neq \lambda_0)}$ is omitted. Since the $R$ parameters in the first column can be obtained with the help of the four filters, the stray light can be easily corrected. After transformation, the real spectral irradiance of the lamp in the ultraviolet band can be obtained.

2.4. Stray light correction results

In order to test the capability of the stray light correction method, comparison was carried out in contrast with a double monochromator spectroradiometer. The comparison is done according to the following procedure. First, xenon lamp with known spectral irradiance is used to calibrate the array spectroradiometer and the double monochromator spectroradiometer. Second, the stray light ratio is test using four filters and the xenon lamp. Third, the stray light of the array spectroradiometer is corrected. Finally, the array spectroradiometer and the double monochromator spectroradiometer are used to measure the same UV lamps, and the measurement results are compared.
The spectra of the UV lamps are shown in figure 5. Black light high-pressure Hg lamp and low-pressure Hg lamp are both narrow band lamps, while UVB fluorescence is a broad band lamp. Table 1 shows the comparison results using xenon lamp. For the UVA, UVB, and UVC lamp, integral spectral irradiance of (360-370) nm, (280-320) nm, and (250-260) nm are compared. The result in the second column using double monochromator spectroradiometer is set to 1.000. The third and fourth columns show the ratio using array spectroradiometer before and after stray light correction. It can be seen that after stray light correction, the difference in UVC band can be improved from 9.4% to 2.0%. In addition, the difference in UVB and UVA can be improved to less than 0.5%. Table 2 shows the comparison results using tungsten lamp calibration. For the UVA and UVB lamp, the difference can be improved to less than 5.0%, which implies the feasibility using filter correction method. However, the stray light level is too high in UVC band, where the parameters $R$ in equation (2) are much greater than 1, while the parameters $R$ are less than 0.1 when using the xenon lamp. Before correction, the difference in UVC band is greater than 90%. The stray light is nearly 10 times bigger than the actual signal. After stray light correction, the difference is less than 20%. In figure 2, oscillation can be seen which means the signal-to-noise is not good. Considering the bad signal-to-noise and approximation of the method, the UVC correction result is acceptable.

**Table 1.** Comparison using xenon lamp calibration.

| Lamp                   | Double monochromator | Array spectroradiometer | After stray light correction |
|------------------------|-----------------------|-------------------------|----------------------------|
| Low-pressure Hg         | 1.000                 | 0.906                   | 0.980                      |
| UVB fluorescence        | 1.000                 | 0.982                   | 0.997                      |
| Black light high-pressure Hg | 1.000               | 0.992                   | 1.001                      |

**Table 2.** Comparison using tungsten lamp calibration.

| Lamp                   | Double monochromator | Array spectroradiometer | After stray light correction |
|------------------------|-----------------------|-------------------------|----------------------------|
| Low-pressure Hg         | 1.000                 | 0.093                   | 0.816                      |
| UVB fluorescence        | 1.000                 | 0.781                   | 1.049                      |
| Black light high-pressure Hg | 1.000               | 0.925                   | 0.983                      |

3. Conclusion
For most of ultraviolet array spectroradiometer, the quantum efficiency of CCD detector in visible and infrared band differs not too much from the ultraviolet band. Lamp with large spectral power distribution variation from UV to other wavelength will bring significant stray light in the UV band. With a group of optical filters, the stray light due to different wavelength range can be corrected. After stray light correction, consistency can be seen especially for the xenon lamp.

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