Measure Uncertainty in Ultraviolet Index Standard

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Abstract This paper follows International Standards Organization (ISO) by “Guide to the Expression of Uncertainty in Measurement, GUM”. In order to measure Ultraviolet Index (UVI) standard, it is necessary in calibration or test laboratory field norm on the authentication. By distance Inverse-Square Law of the Optical Radiation, We constructed measurement equation, to consider the error source when you are measuring, to evaluate the uncertainty of system. Evaluate the uncertainty of this system:

The measurement distance is 75mm, ultraviolet index of the standard source is \( y = 11.7 \) UVI, effective degrees of freedom is \( V_{\text{eff}} = 67 \), coverage factor is \( k = 2.0 \), confidence level is 95%, the standard uncertainty is \( u_c = 0.13 \) UVI, expanded uncertainty is \( U = 0.3 \) UVI, the result is \( Y = y \pm U = 11.7 \pm 0.3 \) UVI.

Keywords Ultraviolet Index, Uncertainty, Calibration

1. Introduction

Measurement of light is an ancient science. Generally, it can be divided into optical radiation measurement [1], photometric measurement, and color measurement. Colorimetry[2] is clearly part of optical measurement related to color. Optical radiation and photometric measurements are measurements of optical parameters, and the main difference is that the latter includes the human visual response. The main purpose of this research is to construct a laboratory for testing standard. It refers to the spirit of ISO/IEC 17025 Standard, and follows “Guide to the Expression of Uncertainty in Measurement” (ISO GUM) made by ISO organization. The content includes UV test system construction, UVI transmittance measurement uncertainty, and the plan of measurement quality assurance that assures the stable operation of the laboratory system. Construct the equations of measurement uncertainty by the system methods that apply to the UVI transmittance measurement by UV spectroradiometer. The standard uncertainty is \( u_c = 0.13 \) UVI, expanded uncertainty is \( U = 0.3 \) UVI, the result is \( Y = y \pm U = 11.7 \pm 0.3 \) UVI.

2. Objectives

2.1. Definition of Measurement Uncertainty

Measurement uncertainty is an estimate of the interval[3] used to represent the degree of dispersion of the measured values, so it is an evaluation of measurement quality. The more concentrated the measurement results are, the higher the measurement quality is, that is, the measurement uncertainty is smaller. On the contrary, the more dispersed the measurement results are, the lower the measurement quality is, and the measurement uncertainty is larger relatively.

2.2. Process to Measure Uncertainty

- Confirm the measured value \( Y \)
- Construct the measurement equation
- List the error sources \( X_i \)
- Decide \( x_i \) the estimate value of \( X_i \)
- Calculate the standard uncertainty of the estimate values of \( X_i \) \( \mu(X_i) \) (Type A or B)
- Evaluate the covariance among the estimate values
- Calculate the estimate value \( y \) of the measured value \( Y \)
- Calculate the sensitivity coefficient
- Calculate the effective degree of freedom \( V_{\text{eff}} \)
- Calculate the combined standard uncertainty \( \mu_c \)
- Calculate the coverage factor \( k \)
- The expanded uncertainty is \( U = k \mu_c \)
- Express the measurement uncertainty

Figure 1. Flow Chart of Process to Measure Uncertainty
According to “Guide to the Expression of Uncertainty in Measurement, GUM”[4] published by International Standards Organization (ISO) in 2008, the eight steps of the process to measure uncertainty are illustrated in Fig. 1.[5]-[10]

3. Methods

3.1. Calibration Based on the Light Source

There are two methods for calibration; one is based on the light source, and the other is based on the instrument. The method based on the light source is shown in Fig. 2.[11]

The intensity of the light source is \( I \), and the illuminance[12] at \( r \) can be derived by inverse square law \( E = \frac{I}{r^2} \). Then, compare the derived illuminance with that measured by the calibrated instrument. It can be calibrated with different illuminance values by changing the distance between the light source and the calibrated instrument. The following items should be considered in this method: 1) distance accuracy, 2) stability of the light source, 3) uniformity of the light source, 4) cosine correction of the instrument.

3.2. Calibration Based on the Instrument

The other calibration method is based on the instrument. The instrument is calibrated by exchanging the position of the standard instrument with the calibrated one. The system structure is shown in Fig. 3.

First, adjust the distance between the standard instrument and the light source to measure the standard ultraviolet index \( UVI_{std} \). Then, use the same distance to measure the ultraviolet index of the calibrated instrument \( UVI_{test} \). The UVI instrument can be calibrated by comparing the standard value with the test one. The following items also need to be considered in the method based on the instrument: 1) consistency of the reference surface, 2) uniformity of the light source, 3) cosine correction of the instrument or the distance between the instrument and the light source. The data in this paper are measured by UVI instrument, but are calculated with the unit of irradiance \( W/m^2 \). The measured values should be transferred by \( 1 UVI = 0.025 W/m^2 \)[13] before being calculated.

4. Results

4.1. Structure of Measurement System

According to the calibration methods mentioned in 3.2, the structure of the system in this thesis is shown in Fig. 4.

4.2. Experiment Procedures

Measurement procedures of the experiment: Set up the equipments as Fig. 5.

Align the end surface of the instrument and the standard light source with the platforms respectively, and consider them as the starting and the end points for distance...
calculation.

Procedures:
Use TES-1367 thermo-hygrometer to record the humidity and temperature of the environment before measurement, and record them again after measurement. Check the level and the collimation of the instrument and the standard light source: Confirm if the emitting light of the light source and the instrument are at the same level, and if the light has a collimated incident. The method of confirmation: First, take the instrument to the position that the light source emits from, and observe if the detector of the instrument collimates with that position. If not, adjust the level of the supporting bar and the direction of the platform, shown as Fig. 6. Turn on the power of the instrument and the light source for 40 minutes before measurement [14][15]. When the system is steady, the measured values without the light source should be recorded.

The displacement platform should be aligned with the slide scale to reduce the error. Every time after measurement, the light source should be changed to Solar Light PMA2100. Then, measure and record the data at the starting, middle and end point with erythemal spectral detector to ensure the stability of the standard light source.

4.3. Error Sources and Calculate Uncertainty

Actually, the error sources include the measurement methods, the equipments, the people, the environment, and the measured objects. Because of the time issue, only the measurement equipments and the environment are discussed in the thesis. Other factors are ignored. The error sources in our research are shown in Fig. 7. The four main impact factors are lamp current, UV radiation intensity, range, and meter reading.

- **Distance**: Due to the inverse square law of irradiance, the error of distance is necessary to be considered.
- **Temperature and Humidity**: Find the correlation coefficient $r$ by the measured values of ultraviolet index. “Using (1), temperature and humidity. The correlation $r$ between temperature and UVI is -0.228, and that between humidity and UVI is $0.215$. The correlations are both below 0.3. Temperature and humidity are low correlation, and aren’t included in error factors.
- **Angle**: The angle is always set to zero about light source before measurement every time, so the error of angle is not considered.
- **Other Errors**: Other errors are interferences of other light sources, the calibration differences of thermo-hygrometer, thermal expansion coefficient of other measurement equipments, etc. These can be extended for advanced research direction.

![Figure 6. Align the Instrument and the Standard Light Source with the Platform](image)

The measurement equation of this research is shown below:

$$E = \frac{I \times i}{L^2}$$  \hspace{1cm} (2)

Which:
- $I$: Radiation Intensity Unit: Watt/Steradian (W/Sr)
- $E$: Irradiance Unit: Watt/meter$^2$ (W/m$^2$)
- $L$: Measurement Distance Unit: meter (M)
- $i$: Lamp Current Unit: Ampere (A)

Definitions:
- $e$: UVI Reading
- $e_1$: Resolution of UVI instrument
- $e_2$: Repeatability UVI instrument
- $I$: Radiation Intensity of Standard Lamp
- $i$: Current of Standard Lamp
- $L$: Distance

The measurement equation is represented by a function:

$$\Delta E = e - E = e - \frac{I \times i}{L^2} = f(e, I, i, L)$$  \hspace{1cm} (3)

Combined Standard Uncertainty:

$$U_{(\Delta E)} = \sqrt{\left(\frac{\partial f}{\partial e} u^2(e) + \frac{\partial f}{\partial I} u^2(I) + \frac{\partial f}{\partial i} u^2(i) + \frac{\partial f}{\partial L} u^2(L)\right)^2}$$  \hspace{1cm} (4)

Each sensitivity coefficient $\frac{\partial f}{\partial X_i}$ can be calculated below:

$$\frac{\partial f}{\partial e} = 1$$  \hspace{1cm} (5)
### Table 1. The Uncertainty Analysis of UVI Detector Calibration

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>Variation Range of Uncertainty Source</th>
<th>Probability Distribution</th>
<th>Standard Uncertainty $u(x_i)$</th>
<th>Sensitivity Coefficient $\frac{\partial f}{\partial x_i}$</th>
<th>Component of Uncertainty $u(x_i)$</th>
<th>Degree of Freedom $v(x_i)$</th>
<th>Evaluation Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>--</td>
<td>--</td>
<td>0.044 UVI</td>
<td>1</td>
<td>0.045 UVI</td>
<td>69</td>
<td>-</td>
</tr>
<tr>
<td>$e_1$</td>
<td>0.1</td>
<td>t</td>
<td>0.033 UVI</td>
<td>1</td>
<td>0.033 UVI</td>
<td>30</td>
<td>A</td>
</tr>
<tr>
<td>$e_2$</td>
<td>0.188</td>
<td>Rectangular</td>
<td>0.029 UVI</td>
<td>1</td>
<td>0.029 UVI</td>
<td>50</td>
<td>B</td>
</tr>
<tr>
<td>I</td>
<td>0.01</td>
<td>-</td>
<td>5.4x10^{-4} W/Sr</td>
<td>177.8 m$^2$</td>
<td>0.00096 W/m$^2$ = 0.038 UVI</td>
<td>50</td>
<td>B</td>
</tr>
<tr>
<td>i</td>
<td>1.5x10^{-4}</td>
<td>Rectangular</td>
<td>1.4x10^{-7} W/Sr</td>
<td>177.8 m$^2$</td>
<td>2.6x10^{-10} W/m$^2$ = 0.001 UVI</td>
<td>$\infty$</td>
<td>B</td>
</tr>
<tr>
<td>L</td>
<td>1</td>
<td>Normal Distribution</td>
<td>0.00033 m</td>
<td>14.2 W/m$^3$</td>
<td>0.0032 W/m$^2$ = 0.12 UVI</td>
<td>50</td>
<td>B</td>
</tr>
</tbody>
</table>

1) Measurement Distance: 75mm; 2) $U_c(\Delta E) = 0.13$ UVI; 3) $\nu_{eff} = 67$; 4) $U(\Delta E)_s = 0.3$ UVI (Coverage Factor $k = 2.00$)

#### Calculation of each standard uncertainty:

- **UVI Reading ($e$):**
  \[
  U_c(e) = \sqrt{U_c^2(e_1) + U_c^2(e_2)} = \sqrt{0.12^2 + 0.038^2} = 0.13 \text{ UVI}
  \]
- **Resolution ($e_1$):**
  The resolution of the instrument is: 0.1 UVI. It belongs to type B uncertainty evaluation. According to the references, the shape of the probability distribution is rectangular. The degree of freedom is $\nu_1 = 50$.
- **Repeatability ($e_2$):**
  It belongs to type A uncertainty evaluation. The degree of freedom is $\nu_2 = 31 - 1 = 30$.
- **Radiation Intensity of Standard Lamp (I):**
  Radiation intensity of the light source is 0.00165 W/Sr. The measurement distance is 75 mm => 0.075 M. The standard uncertainty is $U_s(I) = 0.038$ (UVI).
- **Current of Standard Lamp ($i$):**
  0.001 UVI
- **Distance (L):**
  Distance variation is less than $\pm 1$ mm. The data have more probability of appearing in the center than at both ends. The data of distances are estimated to form a normal distribution, and the degree of freedom $\nu_L = 50$.
- **Standard uncertainty of distance ($L$):**
  $U_s(L) = 0.12$ UVI

### 5. Discussion and Conclusions

This paper refers to “Guide to the Expression of Uncertainty in Measurement” of ISO GUM to complete the uncertainty evaluation of UVI measurement. It is expected to get the ISO 17025 certification from international laboratory. It is calibrated by the UVI instrument and the UVB biologic lamp sold in the market. The error values can be known, and the reliability of the product is got by the users. Besides, the standard light source used in this thesis hasn’t been calibrated by the advanced laboratory. If the light source is calibrated in the future, this paper will become more credible. Finally, in our laboratory we built this measurement distance is 75 mm, ultraviolet index of the standard source is $y = 11.7$ UVI, effective degrees of freedom is $\nu_{eff} = 67$, coverage factor is $k = 2.0$, confidence level is 95%, the standard uncertainty is $u = 0.13$ UVI, expanded uncertainty is $U = 0.3$ UVI, the result is $Y = y \pm U = 11.7 \pm 0.3$ UVI.

### REFERENCES


