Research Note

Domestic Comparison of Relative Spectral Responsivity Measurements for Illuminance Meters

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ABSTRACT

A comparison of relative spectral responsivity measurements of illuminance meters was carried out among five companies – TOPCON Corp., HIOKI E.E. Corp., Minolta Co., Ltd., Yokogawa M&C Corp., and Matsushita Electric Industrial Co., Ltd.

The spectral responsivitys of the illuminance meters were measured by each company's spectral responsivity measurement system calibrated to each company's standard. As a result, the measured values of f_s (f_s is defined as the relative spectral responsivity error in Japanese Industrial Standard JIS-C-1609) differed within 1.7. The f_s is identical with the f_1' recommended by the CIE.

KEYWORDS: illuminance meter, spectral responsivity, Japanese Industrial Standard

1. Introduction

The illuminance meter is an important piece of equipment because it is one of the basic illumination measuring tools, and its spectral responsivity has been specified by the JIS[1]. However, there has been no ruling on how to measure the spectral responsivity, nor for the traceability of the spectral responsivity standard, so measuring the spectral responsivity is currently done independently by each manufacturer. Therefore, when different illuminance values are shown by the illuminance meters of different manufacturers, their mutual relationship is unknown, which has made users of the illuminance meters feel uncertain. In order to make a survey of this situation, the "Study and Research Committee Regarding the Measuring Method for Photodetector Spectral Responsivity"[2] of the Illuminating Engineering Institute of Japan has carried out a comparison test of the relative spectral responsivitys of the illuminance meters of five participants, including four domestic manufacturers of illuminance meters. Two reference sets consisting of one silicon photodiode (manufactured by Hamamatsu Photonics, S1337BQ) as a measuring material, of which the spectral responsivity had already been given, and two transfer illuminance meters (manufactured by TOPCON, IM-3) were prepared. Then, the relative spectral responsivity of each was measured using the spectral responsivity standard of each participant and the measuring equipment of each participant. The results were compared with each other. This paper reports these results.

2. Participants and Measuring Equipment

There were five participants in the comparison test:: four illuminance meter manufacturers – HIOKI E. E. Corp., Yokogawa M&C Corp., Minolta Co. Ltd., and TOPCON Corp. – and Matsushita Electric Industrial Co., Ltd. Matsushita Electric Industrial Co., Ltd. participated as the central laboratory for the mutual comparison, since their maintained standard showed deviations of 0.4% on an average and 1.1% at a maximum (standard deviation σ in wavelengths of 400 ~ 800nm) in comparison to the spectral responsivity measurements of a silicon photodiode by the Electrotechnical Laboratory (ETL) of the Industrial Technology Institute, Saitama University and Hamamatsu Photonics, which was done in 1992 under the program for the domestic comparison of the spectral responsivitys of photodetectors[3] by the "Special Study and Research Committee Regarding Irradiation Measuring Method for Ultraviolet Radiation" of the Illuminating Engineering Institute of Japan, in which they participated. The measuring equipment and the measuring conditions for each participant are shown in Table 1. Also the optical system of the spectral responsivity measuring equipment for each participant is shown in Fig.1~Fig.4. Each participant measures using a proprietary and different optical systems and different spectral responsivity standards, as seen in these figures.

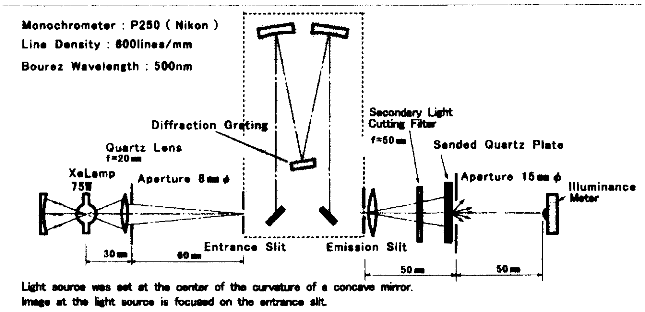

Fig.1 Configuration of the center lab' spectral responsivity measurement system.

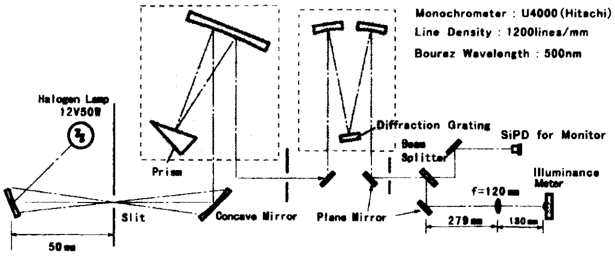

Fig.2 Configuration of the participant A and D' spectral responsivity measurement.

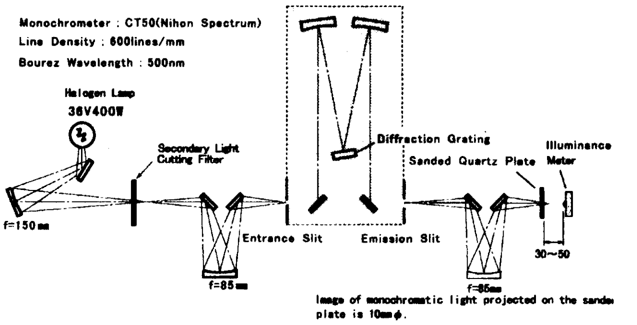

Fig.3 Configuration of the participant B' spectral responsivity measurement system.

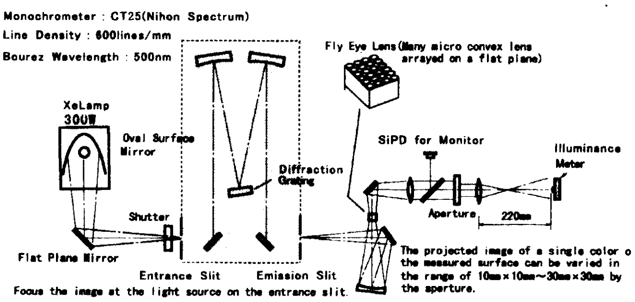

Fig.4 Configuration of the participant C' spectral responsivity measurement system.

There has been no established specification regarding the equipment to measure the spectral responsivity of a illuminance meter, and there are many cases in which the stipulations regarding the spectral measurement, as described in JIS Z 8724 "Measuring Method of Luminous Perceived Color," are followed. The measuring equipment of participant A and participant D in this current comparison are modifications of the U4000 spectrophotometer manufactured by Hitachi. They are based on measuring the spectral transmittance and absorptance, and they have diffraction grating ruling up of 1200 grooves per millimeter, which enables them to obtain a high wavelength resolution. However, the intensity obtained for a monochromatic light is poor, since its dispersing element consists of a prism and a diffraction grating. On the other hand, participant B and participant C use equipment that were originally designed for this purpose by the Japan Spectrum Co., Ltd.(Jasco), but the image focusing optical system for the radiated monochromatic light has not been unified and traces of trial and error attempts to modify it by the manufacturer, as well as by each participant, were observed.

The results of the actual comparison of the intensity of a monochromatic light of each manufacturer's measuring equipment by the transfer illuminance meter used for this comparison are shown in Figure 5.

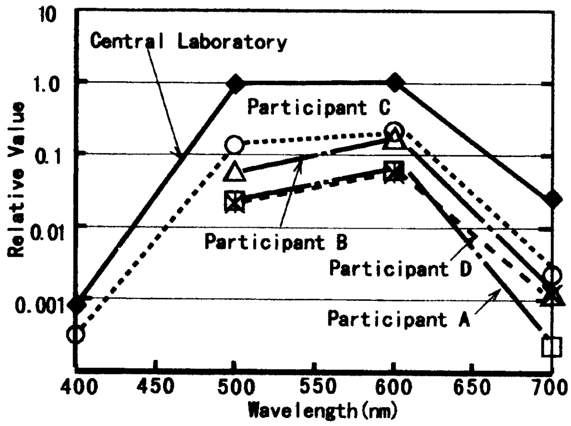

Fig.5 Output of participants' spectral responsivity measurement systems for transfer illminance meter.

The output value of the participants A and D is lower than that of the central laboratory by more than one significant digit. This seems to be attributable to the fact that participants A and D use a 50W halogen lamp for the light source, which has a radiation intensity that is small compared to the light source of the central laboratory, which is 75W Xe lamp with a single diffraction grating monochrometor.

The participant C uses a single diffraction grating monochrometor, as is the case with the central laboratory, but it is considered that the loss of monochromatic light in the light emission optical system is large.

With participant B, it is considered that the radiant flux out of the exit slit is lowered due to a long focal distance in the entrance optical system. By the way, the central laboratory and the participant B use a light diffuser in the emission optical system, and it was observed that the radiant flux out of the exit slit was not reduced remarkably compared to the others. When the light diffuser is not used in the emission optical system, there is the possibility that the symmetry of the emitted

Table 1. Specification of participants' spectral responsivity Measurement systems.

Participant	Central Laboratory	Participant A	Participant B	Participant C	Participant D
Monochrometor	Single Diffraction Grating P250 (Nikon)	Prism Diffraction Grating U4000 (Hitachi)	Single Diffraction Grating CT50 (Jasco)	Single Diffraction Grating CT25 (Jasco)	Prism Diffraction Grating U4000 (Hitachi)
Diffraction Grating (λ_b :Bourez Wavelength)	600 grooves/mm λ_b =500nm	1200 grooves/mm λ_b =500nm	600 grooves/mm λ_b =500nm	600 grooves/mm λ_b =500nm	1200 grooves/mm λ_b =500nm
Focal Length	258mm	398mm	500mm	250mm	398mm
F Number	4.6	10	5.3	4.3	10
Light Source Used	Xe Lamp 75W	Halogen Lamp 12V50W	Halogen Lamp 36V400W	Xe Lamp 300W	Halogen Lamp 12V50W
Light Diffuser on the Emission Side	Sandblasted Quartz Plate	Nil	Sandblasted Quartz Plate	Nil	Nil
Spectral Responsivity Standard	SiPD S1337 for mutual comparison	SiPD S1337 ETL revision '94.3	SiPD S1337 ETL revision '92.5	SiPD S1337 ETL revision '94.4	SiPD S1337 ETL revision '84.2
Range of Measured Wavelength	340～830nm	360～830nm	360～830nm	380～780nm	380～780nm
Wavelength Width of Slit	5nm	5nm	5nm	5nm	5nm
Interval of Measured Wavelength	5nm	5nm	5nm	5nm	5nm

(ETL revision:Date of revision by the Electrotechnical Laboratory(ETL) of Industrial Technology Institute) monochromatic light (image) is reduced due to unevenness in the light illuminating the diffraction grating after passing through the slit. On the contrary, it is anticipated that the evenness of the emission of a monochromatic light (image) will be improved by the use of the light diffuser in the emission optical system.

3. Comparison of Measurements

The mutual comparison was made in the following two steps: (1) a comparison was made with the silicon photodiode that was prepared by the central laboratory and the spectral responsivity standard being used by each participant, and (2) a comparison was made of the spectral responsivity of a transfer illuminance meter, which was prepared by the central laboratory, measured by each participant using its own spectral responsivity standard and spectral measurement equipment.

Regarding the procedure for the comparison measurement, Matsushita Electric Industrial, which is not a illuminance meter manufacturer but which had joined the previous domestic comparison of spectral responsivity measurements[3], was assigned to be the central laboratory, and the silicon photodiode, of which the spectral responsivity had been determined by Saitama University based upon the standard of the Electrotechnical Laboratory (ETL), was used. Then the spectral responsivity of the photodetector to be used for comparison and the transfer illuminance meter to be used as a test subject were measured at the central laboratory. For the spectral responsivity standard and for a photodetector for comparison, silicon photodiode S1337-1010BQ (manufactured by Hamamatsu Photonics) was used.

Although the silicon photodiode was used as a spectral responsivity transfer photodetector, the transfer photodetector for the spectral responsivity comparison was attached to a case as shown in Figure 6 in consideration of its transportation and also to prevent the influence of errors due to uneven responsivity in the vicinity of the photo-receiving surface. The IM-3 transfer illuminance meter (manufactured by TOPCON) was used for comparison of the spectral responsivity measurements of the illuminance meters.

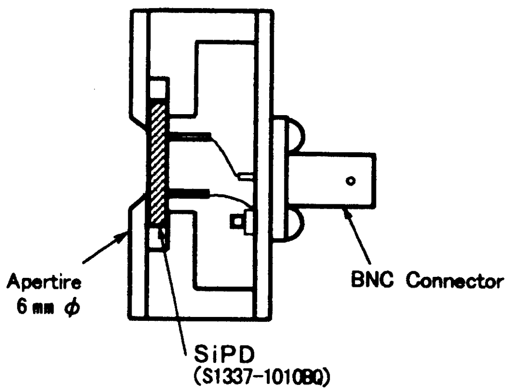

Fig.6 Construction of spectral responsivity transfer photodetector compared with participants' standard.

3.1 Steps for Mutual Comparison

The transfer photodetector and transfer illuminance meters for comparison were transferred by the following routes after dividing the four participants into two groups, each consisting of two participants.

a) Central Laboratory → Participant A → Participant B →Central Laboratory

b) Central Laboratory → Participant D → Participant C →Central Laboratory

(1) The spectral responsivity of the transfer photodetector and the transfer illuminance meter for comparison were measured by the central laboratory using its spectrum measuring equipment, based on the aforementioned spectral responsivity standard.

(2) The transfer photodetector for comparison that was provided by the central laboratory was measured by each participant based on the standard adhered to by the participant in order to check the participant's spectral responsivity standard. Furthermore, the IM-3 transfer illuminance meter (manufactured by TOPCON), which was provided by the central laboratory, was measured using the participant's standard, in order to compare the spectral responsivity measurements of the transfer illuminance meter of each participant. Then, the test subjects were returned to the central laboratory.

(3) The central laboratory again measured the test subjects returned from the participants under the same conditions as those that were applied before their transfer and obtained the differences of measurements by themselves before and after the transfer. Then they compared the spectral responsivity standard and spectral responsivity measurements of the participants' transfer illuminance meters versus theirs.

3.2 Steps for Comparison of Measurements

3.2.1 Normalization (Formalization) of Data and Evaluation of Deviation

In regard to the mutual comparison of the measured values in this test, the following two methods were standardized in order to evaluate the mutual differences.

(a)Comparison by wavelength of spectral responsivity measurements.

(b)Comparison based upon the maximum value of the spectral responsivity.

In method (a) the procedure was to normalize by the average of all the measured zones and then to compare the deviations by each wavelength as a percentage of each value, which was then applied to the "comparison of spectral responsivity standard of each participant" as described later. In method (b) the procedure was to normalize by the maximum value (peak value) of the spectral responsivity and to express the deviations by wavelength as a percentage after dividing them by the maximum value, which was then applied to the "comparison of the spectral responsivity measurements of each participant's transfer illuminance meter."

It was a requirement of the measurement procedure to measure three times at every 5nm in the range of wavelengths from 380nm to 780nm. Each test subject was installed and removed at each time of measurement, thus incorporating an evaluation of repeatability.

3.2.2 Comparison of Spectral Responsivity Standard of Each Participant

The measured values of each participant and ETL (the measured value by Saitama University) were normalized as follows to yield $S_f(\lambda)$ and $S_c(\lambda)$. The values of $S_{tm}(\lambda)$ and $S_{cm}(\lambda)$ were the averages of three measurements.

$$S_f(\lambda)=\frac{S_{tm}(\lambda)}{\sum_{\lambda=380}^{780} S_{tm}(\lambda)} \quad \cdots\cdots (1)$$

$$S_{CR}(\lambda)=\frac{S_{cm}(\lambda)}{\sum_{\lambda=380}^{780} S_{cm}(\lambda)} \quad \cdots\cdots (2)$$

The deviations of the measured values by wavelength for each participant from the values of ETL were obtained, which was set as the deviation of the spectral responsivity standard $R_s(\lambda)$.

$$R_s(\lambda)=\frac{S_f(\lambda)-S_c(\lambda)}{S_c(\lambda)}\times 100\ (\%) \quad \cdots\cdots (3)$$

Evaluation by this method becomes more severe when the value of $S(\lambda)$ gets smaller.

3.2.3 Comparison of Each Participant's the Spectral Responsivity Measurements of Transfer Illuminance Meter

The measured values for each participant and the central laboratory were normalized as follows to yield $S_{ti}(\lambda)$ and $S_{ci}(\lambda)$. The values of $S_{tim}(\lambda)$ and $S_{cim}(\lambda)$ were the averages of three measurements.

$$S_{ti}(\lambda)=\frac{S_{tim}(\lambda)}{\sum_{\lambda=380}^{780} S_{tim}(\lambda)} \quad \cdots\cdots (4)$$

$$S_{ci}(\lambda)=\frac{S_{cim}(\lambda)}{\sum_{\lambda=380}^{780} S_{cim}(\lambda)} \quad \cdots\cdots (5)$$

The differences by wavelength between the measured values of each participant and those of the central laboratory were divided by the peak value (555nm) of the central laboratory in order to obtain the deviation of the spectral responsivity measurements of the transfer illuminance meter $R(\lambda)$.

$$R(\lambda)=\frac{S_{ti}(\lambda)-S_{ci}(\lambda)}{S_{ci}(\lambda)(555\mathrm{nm})}\times 100\ (\%) \quad \cdots\cdots (6)$$

Since the maximum value (peak value) of the spectral responsivity is the basis for evaluation, the deviation (%) is compressed in proportion to the value of $S(\lambda)$ versus the maximum value. For example, if the value of $S(\lambda)$ is one tenth of the maximum value, the deviation will be one tenth of the original value.

3.2.4 Comparison of Relative Spectral Responsivity Based upon New and Old JIS (From the Results of the Spectral Responsivity Measurements of Each Participant's Illuminance Meter)

Although it is reasonable to evaluate the spectral responsivity of a illuminance meter based upon the current JIS (published in 1993), evaluation was also made based upon the old JIS (published in 1983) since it enables evaluation of the inclination by wavelength of the deviation of the spectral responsivity from the standard spectral luminous efficacy.

(1) For comparison of the relative spectral responsivity, the Color Correction Factors, based upon the old JIS(JIS C1609-1983) were calculated using the following equation.

$$\mathrm{C.C.F.}=\frac{\sum_{\lambda=\lambda 1}^{\lambda 2} V(\lambda)\sum_{\lambda=400}^{760} M(\lambda)S(\lambda)}{\sum_{\lambda=400}^{760} M(\lambda)V(\lambda)\sum_{\lambda=\lambda 1}^{\lambda 2} S(\lambda)} \quad \cdots\cdots (7)$$

Here, λ_1 and λ_2 are the minimum and maximum wavelengths (nm) in each wavelength range in the following table, $V(\lambda)$ is the standard spectral luminous efficacy (standard relative luminous efficiency), and $M(\lambda)$ is the relative value of the spectral radiant exitance of a black body at the distribution temperature 2856K.

(2) For comparison of the relative spectral responsivity (comparison of the evaluation coefficient (f_s) for deviations from the standard relative luminous efficiency) based upon JIS (JIS C1609-1993), the relative spectral responsivity ($S(\lambda)_{rel}$) was obtained by measuring 81 wavelengths at each 5nm in the range of wavelengths from 380nm to 780nm, and the deviation f_s from the standard spectral luminous efficacy (standard relative luminous efficiency $V(\lambda)$) was calculated based on the following equation. By the way, JIS classifies an f_s level below 4% as minute class and that exceeding 4% and below 8% as general AA class.

$$f_s=\frac{\sum_{\lambda=380}^{780} |S'(\lambda)_{rel}-V(\lambda)|\,\Delta\lambda}{\sum_{\lambda=380}^{780} V(\lambda)\,\Delta(\lambda)}\times 100\ (\%) \quad \cdots\cdots (8)$$

$S'(\lambda)_{rel}$ is expressed by the following equation:

$$S'(\lambda)_{rel}=\frac{\sum_{\lambda=380}^{780} M(\lambda)\,V(\lambda)\,\Delta\lambda}{\sum_{\lambda=380}^{780} M(\lambda)\,S(\lambda)_{rel}\,\Delta(\lambda)}\times S(\lambda)_{rel} \quad \cdots\cdots (9)$$

Here, $M(\lambda)$ is the relative value of the spectral radiant exitance of a black body at the distribution temperature 2856K, $V(\lambda)$ is the standard spectral luminous efficacy (standard relative luminous efficiency) ,and $\Delta\lambda$ is the interval of measuring wavelength (5nm). By the way, f_s is equivalent to f_1 as stipulated by CIE[4].

4. Results and Their Evaluation

The above measurements were made during the period from May 1995 through January 1996. The results are as follows.

4.1 Comparison of Measurements of Spectral Responsivity Standard

Figure 7 shows the deviations of the spectral responsivity standard $R_s(\lambda)$, which are the deviations of the measurements by each participant from the ETL value (measurements by Saitama University) obtained from the measurement results of the spectral responsivity of the comparison photodetector based upon each participant's spectral responsivity standard. It was observed that the deviations of each participant tended to increase compared to the ETL values in the shorter wavelengths and that the degree of this tendency was similar among them, except for participant D. Since the spectral responsivity standard used by the participant D is SiPD530UV, to which a revision was made by ETL more than 10 years ago as shown in Table 1, it is considered that there naturally would be changes generated after long time.

Also, it is considered that the differences among participants, except participant D, were generated because ETL modified the scales after supplying the materials to each participant (1994).

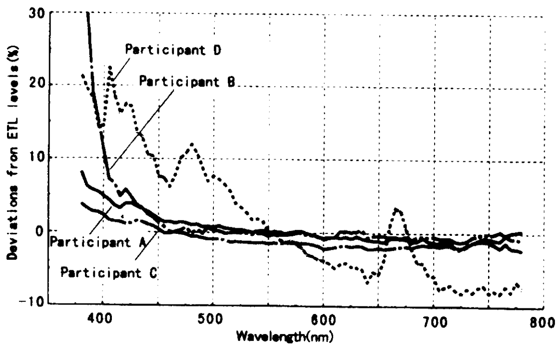

Fig. 7 Percent differences from ETL of all participants' spectral responsivity standards.

4.2 Comparison of the Spectral Responsivity Measurements of the Transfer Illuminance Meters

The deviations of the spectral responsivity measurements of the transfer illuminance meters from the measurements by the central laboratory are shown in Figure 8. Participants B, C and D showed a difference of about ±1.5% at most versus the measurements by the central laboratory.

Meanwhile, participant A showed the difference of about ±3% at most versus the measurements by the central laboratory.

By the way, although the sign of the deviation was reversed from minus to plus at the border of wavelength 555nm, which is the maximum value of spectral responsivity of the transfer illuminance meter, as seen in A, B and D, this was because the profile of the spectral responsivity shifted positively or negatively in the direction of wavelength axis. It is considered that this is attributable to an aberration of the wavelength scale on the measuring equipment.

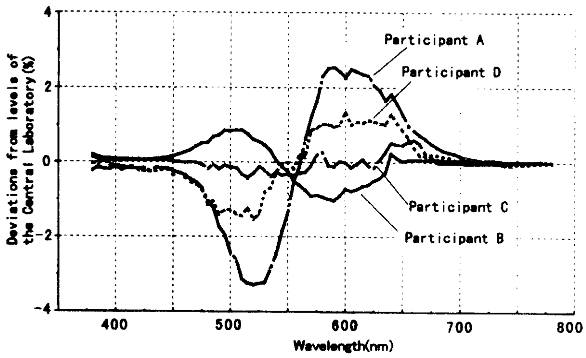

Fig. 8 Percent differences from center lab of all participants' spectral responsivity measurements for transfer illuminance meter.

4.3 Comparison of Color Correction Factor for Zone Light and f_s

A color correction factor corresponding to the entrance of the limited wavelength (band spectrum) and f_s were obtained from the spectral responsivity measurements of the transfer illuminance meters, and they were compared. The results are shown in Table 2.

With participant A, the color correction factors for band spectrum were larger than those of the central laboratory below 600nm, while they were smaller above 600nm. This is considered to have been caused by to the large aberration of the wavelength scale on participant A's measuring equipment.

The color correction factors of participants A and D significantly exceeded the measurements of the central laboratory in the wavelength from 450 to 500nm. Regarding participant D, this is considered to be attributable to the large deviation of spectral responsivity of the spectral responsivity standard that is currently used.

Furthermore, the spread of f_s (%) by the spectral responsivity property test of JIS based upon the measured data was obtained to find the maximum 1.7 points among the five participants. When the f_s value of a transfer illuminance meter being sold on the market is taken into consideration, the spread is required to be below 0.5 point at most.

5. Summary

Regarding the domestic comparison of the relative spectral responsivity measurements for the transfer photodetectors and the transfer illuminance meters, it was known that f_s (%) was currently within 1.7 points. Differences in the values of the spectral responsivity standards being used for measuring and

Table 2. Comparison of participant's Color Correction Factors And fd for transfer illuminance meter.

Wavelength Region	Central Laboratory		Participant A	Participant B	Participant C	Participant D
	C. C. F.	reproducibility				
400~760nm	1.01	<0.6%	1.02	1.01	1.01	1.02
450~500nm	1.11	<5.8%	1.18	1.03	1.12	1.20
500~550nm	1.02	<2.0%	1.07	1.00	1.02	1.04
550~600nm	0.99	<0.3%	1.00	1.00	0.99	0.99
600~650nm	1.04	<1.8%	0.99	1.05	1.04	1.01
650~700nm	0.73	<2.4%	0.65	0.70	0.70	0.70
f_s (%)	4.45±0.05		5.6±0.5	4.65±0.05	4.65±0.05	5.05±0.25

aberrations of the wavelength scales of the measuring equipment can be counted as the causes of the differences. However, it was found that the difference in f_s (%) was consistent within 0.2 point when two participants, which showed large differences due to these two causes, are excluded. Therefore, it is considered that consistency within 0.5 points can be achieved if these two participants calibrate their spectral responsivity standards and calibrate the wavelength scales of the measuring equipment in the future.

Currently, it is possible to request the test for the value analysis of spectral responsivity to the Electrotechnical Laboratory and other national research centers. However, in contrast to the cases of the luminous intensity and spectral irradiance standards, it is not included in a traceability system, and there is no guaranty of continuity and accuracy in these values. (The traceability system (JCSS:Japan Calibration Service System) for luminous intensity standard and spectral irradiance standard has been established. In this system, the nationally authorized monitoring companies periodically check against the national standard, based on the stipulated administrative standards.) It is considered that highly accurate measurement can be expected and also that the differences in spectral responsivity measurements among participants can be reduced, if a traceability system for the spectral responsivity standard is established and if calibration of the wavelength of the measuring equipment is appropriately performed in the future.

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