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EVALUATING THE GENERAL V(λ) MISMATCH SPECTRAL QUALITY FACTOR INDEX $f_1^{'}$ AND THE UNCERTAINTY OF PHOTOMETERS

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ABSTRACT

The general term photometry refers to the measurement of light and its perceived brightness; it can be applied to various purposes, including lighting design, display calibration, and the setting of safety standards. A device used for measuring light is called a light meter or photometer. Ideally, such devices should have a spectral responsivity-that is, they should respond to light in a way which mimics the human eye's sensitivity to different wavelengths. The sensitivity of the human eye is described by the Commission Internationale de l'Éclairage, CIE, luminous efficiency function, V(λ), a plot of the sensitivity of the eye versus wavelength over the visible region, from violet, approximately 380 nm, through red, approximately 780 nm. In practical applications, it is usually preferable to detect light with silicon or selenium photodetectors and measure the electrical current generated. These photodetectors are sensitive to a wide range of wavelengths, including those outside of the visible spectrum: ultraviolet (UV) and infrared (IR). However, due to its nature, the spectral responsivity of silicon and selenium photodetectors is also different from that of the human eye. For example, silicon photodetectors are much more sensitive to infrared radiation, which is imperceptible to human vision. This in turn leads to erroneous light measurements when using the direct raw response of the detector. The spectral quality factor $f_1^{'}$ and $f_1^{''}$, indicating the mismatch between the spectral responsivity and the CIE luminous efficiency function V(λ), is the most crucial characteristic of photometers. The general mismatch index $f_1^{'}$, denoted as V(λ), delineates the disparity between a photometer's relative spectral responsivity and the spectral luminous efficiency function for photopic vision, V(λ). It's highly probable that photometers will adopt white light-emitting diode (LED) sources as calibration references going forward. This transition may necessitate refining the general V(λ) mismatch index's definition, possibly through alternative normalization methods for $f_1^{'}$ or by introducing a different assessment function for evaluating mismatches $f_1^{''}$. In this research, spectral quality factor $f_1^{'}$ for the photometer NIS-2 has been determined with value 3.8%. This percentage value is classified the photometer NIS-2 as medium quality. The uncertainty was determined through a calculation performed using my Microsoft Excel program, and the final value obtained is 0.010.

Keywords: spectral quality factor $f_1^{'}$, spectral quality factor $f_1^{''}$, total luminous flux, photopic response, photometers, spectroradiometers, spectral responsivity of sphere, uncertainty.

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1. INTRODUCTION

The general spectral quality or the spectral quality factor index $f_1^{'}$ for V(λ) mismatch measures the differences between the relative spectral responsivity of a photometer and the V(λ) spectral luminous efficiency function for photopic vision. The evaluation is required in order to ensure that light is adequately measured according to its appearance to the human eye under ample light conditions. Calibration of all future photometers will probably be carried out with a white LED light source as it will represent the new reference standard. The change will enhance the accuracy and reproducibility of the measurement of luminous flux when applied in many fields. This may require redefining the general spectral quality factor index $f_1^{'}$ for V(λ) mismatch, either by altering the normalization of the photometer's relative spectral responsivity or by introducing a new method for evaluating the mismatch spectral quality factor index $f_1^{''}$. Additionally, measuring colored LEDs is becoming increasingly significant. The general spectral quality factor index $f_1^{'}$ for V(λ) mismatch quantifies the discrepancy between the photometer's relative spectral responsivity, $S_{rel}(\lambda)$, and the V(λ) function for photopic vision. Initially, the CIE in 1982 introduced it as a framework that ought to be followed in the assessment of photometric performance within diverse lighting conditions. This was important in ensuring that measurements of light were consistent and accurate. A value close to zero is indicative of the fact that the photometer can perform with few adjustments when exposed to light sources whose spectral distribution is different from the known reference ones used during photometry. The latter feature enables the correct rendition in real-life applications, when the light conditions can considerably differ. In this respect, photometers reduce their needs for extensive recalibration so as to retain their accuracy and efficiency, which allows for better comparisons and assessments among various lighting systems. The photometer response is a function of

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its relative spectral responsivity $S_{rel}(\lambda)$ and the spectral distribution of the light source. Since, for a long time, lighting took the form of incandescent lighting predominantly, the responsivity of the photometer was standardized based on the relative spectral distribution of the CIE standard illuminant A, $S_A(\lambda)$ [1]. The initial reference to $f_1^{'}$ appears as an informative note in [2]. The measure most in use at that time for assessing spectral mismatch was the maximum value of the required spectral mismatch correction factor, for five light sources, referred to as $f_1^{'}$,CIE. This provided immediately a means of standardizing the quantification of differences in the performance of light sources. Subsequently, the general mismatch spectral quality factor index $f_1^{'}$ was recommended by the CIE in [2]. The procedure and justification for spectral responsivity normalization are thoroughly treated in references [3, 4]. A comprehensive summary of earlier literature is available in [5]. Updated background information on $f_1^{'}$ can be found in [1,6,7]. The general V(λ) mismatch spectral quality factor index $f_1^{'}$ relies on CIE illuminant A for its fundamental definition. Figure-1 shows that from 1990 up until the early 2000s, the number installed continuously increased, presumably due to urbanization and economic development. From the year 2005, however, an acceleration is visible, which can be explained by the beginning of the diffusion of energy-efficient lighting technologies like CFLs and LEDs. This transition was rightly guided by various regulatory efforts within the EU, such as the Ecodesign Directive, which has been phasing out inefficient incandescent bulbs to adopt energy-efficient lighting systems across households and industries. It is a challenge, since the incandescent sources used for calibration of photometers and similar to the CIE illuminant A have been phased out of the market. Probably, sources can still be found but their price will increase while their quality decreases. Hence, CIE technical committee TC 2-90 works on the use of an LED-based illuminant for calibration, supported by the EMPIR project 15SIB07 Photo LED. In Figure 2, a proposed L41 spectral distribution is given [8].

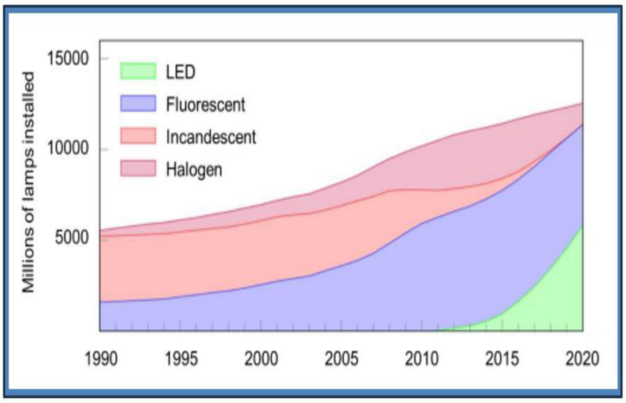

Figure-1. Total installed lamps in the EU from 1990 to 2020 [9].

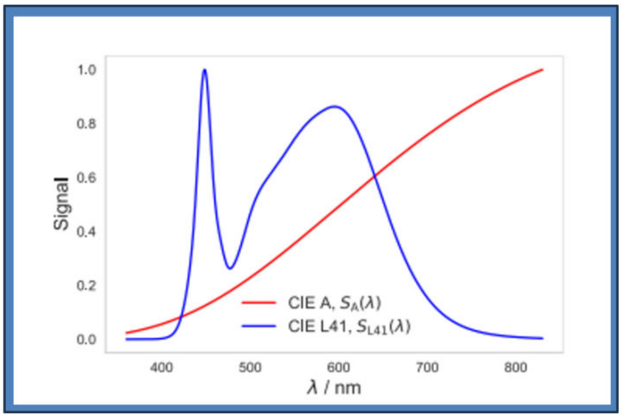

Figure-2. Illustrate the proposed L41, SL41(λ) spectral distribution [8].

1.1 The General V(λ) Mismatch Spectral Quality Factor Index ($f_1^{'}$)

Since either of these lamp-monochromator or laser-based systems cannot measure the spectral responsivity and spectral quality factor of photometers with adequate accuracy, the calculation of uncertainties becomes very important. The spectral quality factor $f_1^{'}$ is an integrated value over the visible wavelength range, and thus it is very important to check the contribution of each factor in the measurement of spectral responsivity. The uncertainty of the spectral quality factor $f_1^{'}$ can change substantially depending on how the uncertainty components are treated. Once the relative spectral responsivity of the photometer $S_{rel}(\lambda)$ and its associated uncertainties have been determined, the GUM method permits the calculation of a value and uncertainty for the spectral quality factor $f_1^{'}$ as recommended by CIE [10-14]. The spectral quality factor $f_1^{'}$ is calculated from the relative spectral responsivity $S_{rel}(\lambda)$ of the sphere-photometer system according to Yoshi Ohno [15,16]. The spectral matching of a photometer is high quality if $f_1^{'}$

value lower than three percent, medium quality if $f_1^{'}$ value higher than three percent and lower than eight percent, and poor quality if $f_1^{'}$ value higher than eight percent. In ISO/CIE 19476:2014 [17]. It is defined as

$$f_1^{'} = \frac{\int_{\lambda=380nm}^{780nm} \left| S_{rel}^{*}(\lambda) - V(\lambda) \right| .d\lambda}{\int_{\lambda=380nm}^{780nm} \left| V(\lambda).d\lambda \right.} \times 100\% \qquad (1)$$

λ , $V(\lambda)$, $s(\lambda)$, $S_{rel}^{*}(\lambda)$, are respectively defined as the wavelength, the spectral luminous efficiency function for Photopic vision, the CIE Illuminant A standard distribution , and the normalized spectral responsivity which is calculated by weighting the absolute spectral responsivity of the detector given by [18]:

$$S_{rel}^{*}(\lambda) = \frac{\int_{\lambda=380nm}^{780nm} S_A(\lambda).\, V(\lambda).\, d\lambda}{\int_{\lambda=380nm}^{780nm} S_A(\lambda).\, s(\lambda).\, d\lambda} \times s(\lambda) \qquad (2)$$

$S_A(\lambda)$, $s(\lambda)$ Spectral mismatch is typically a systematic measurement error.

1.2 The General V(λ) Mismatch Spectral Quality Factor Index ($f_1^{''}$)

For spectral mismatch, the cause can typically be determined and the effect can be calculated from the spectral mismatch correction factor (SMCF), $F(S_C(\lambda), S_Z(\lambda))$, applied to the luminous responsivity, $S_{v,Z}$, defined by:

$$S_{v,Z} = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} S_Z(\lambda).s(\lambda)\, d\lambda}{K_m \int_{360}^{830} S_Z(\lambda).V(\lambda)\, d\lambda} \qquad (3)$$

Where $S_Z(\lambda)$ is the spectral distribution of the measured radiation, Z, and $K_m \cong 683\, lm.W^{-1}$ (in air), and given by

$$F(S_C(\lambda), S_Z(\lambda)) = \frac{1}{a_C} = \frac{\int_{\lambda=\lambda_{T,\min}}^{\lambda_{T,\max}} S_Z(\lambda).s_T(\lambda).d\lambda}{\int_{\lambda=\lambda_{\min}}^{\lambda_{\max}} S_Z(\lambda).s_{rel}(\lambda).d\lambda} = \frac{\int_{\lambda_{T,\min}}^{\lambda_{T,\max}} S_Z(\lambda).s_T(\lambda).d\lambda}{\int_{\lambda=\lambda_{\min}}^{\lambda_{\max}} S_Z(\lambda).s_{rel,T,C}(\lambda).d\lambda} \qquad (4)$$

where

$S_C(\lambda)$ is the spectral distribution of the calibration source, C,

$S_Z(\lambda)$ is the spectral distribution of the measured radiation,

$s(\lambda)$ is the relative spectral responsivity of the detector.

When the test and calibration sources differ considerably from the CIE Illuminant A, this kind of spectral mismatch, if not corrected, can give rise to large relative errors. A number of authors have examined this function $f_1^{'}$ in terms of the spectral mismatch correction factor (SMCF) of LED sources. [19-21]. The spectral mismatch correction factor F (SC(λ), Sj(λ)) allows the spectral mismatches that occur when one light source of a particular spectral distribution is measured using a device that was calibrated against another light source of a different spectral distribution.

A new approach for the definition of an adjusted V(λ) mismatch index $f_1^{''}$ was introduced by Ferrero et al. [21-25] which provides a better correlation to the average absolute spectral mismatch error than $f_1^{'}$, when this error is evaluated for broadband sources (phosphor-based LEDs and blackbody sources). Young et al. [23] introduced a new mismatch index called f-LED, specifically for colored LEDs. This index is defined as the average spectral mismatch error over a wavelength region relative to the central wavelength of that region. They employed a model-based specific SMCF, as shown in Equation (5).

$$\varepsilon_{\lambda_C,\lambda_m,\Delta\lambda_C} = 1 - \frac{\int_{\lambda=\lambda_{\min}}^{\lambda_{\max}} S_{mLED}(\lambda,\lambda_p=\lambda_C,\Delta\lambda_C).s_{rel}(\lambda).d\lambda \int_{\lambda=\lambda_{T,\min}}^{\lambda_{T,\max}} S_{mLED}(\lambda,\lambda_p=\lambda_m,\Delta\lambda_C).s_T(\lambda).d\lambda}{\int_{\lambda=\lambda_{\min}}^{\lambda_{\max}} S_{mLED}(\lambda,\lambda_p=\lambda_C).s_T(\lambda).d\lambda \int_{\lambda=\lambda_{\min}}^{\lambda_{\max}} S_{mLED}(\lambda,\lambda_p=\lambda_m,\Delta\lambda_C).s_{rel}(\lambda).d\lambda} \qquad (5)$$

where $S_{mLED}(\lambda, \lambda_p = \lambda_C, \Delta\lambda_C)$ represents a model function for the SD of an LED with peak wavelength λ_p and a full-width at half maximum (FWHM).

Since $f_1^{'}$ was defined only for general lighting, it might be necessary to provide a new index to evaluate the mismatch of photometers for lighting conditions under colored LED sources. Nowadays, almost all sources to be measured in photometry are light-emitting diode (LED)-based. Furthermore, the present general mismatch index might not predict the expected range of spectral mismatch errors when measuring colored LED-based light sources. $f_1^{''}$ is defined in Equation (6) [1].

$$f_1^{''} = \sqrt{2 \int_{\nu_\lambda=0}^{\nu_{\lambda,C}} \left| \hat{\delta}_S \right| d\nu_\lambda} \qquad (6)$$

$f_1^{''}$ equals the standard deviation of δs when the cut-off frequency $\nu_{\lambda,C}$ is infinite, but it is lower for a finite $\nu_{\lambda,C}$. A standardized value of $\nu_{\lambda,C}$ could be used for general lighting applications due to consistency and reliability purposes in conventional lighting. In more specific situations, say involving only phosphor-based LED light sources, other values may be recommended to account for the peculiar spectral features of such light sources. The spectral distributions of the phosphor-based LEDs can be quite different from those of traditional light sources, which might affect proper measurement and performance of the lighting itself.

In the present study, a measuring arrangement was developed using the NIS spectroradiometer together with an integrating sphere system for the purpose of assessing the spectral responsivity and spectral quality factor of the NIS sphere-photometer. The setup shall afford high-accuracy measurements of the sphere-photometer performance in respect to various wavelengths. The spectroradiometer integrated with the sphere system enables the setup to generate a uniform distribution of light. It can accurately characterize the response of the photometer as a result of variable spectral inputs. It becomes highly relevant to the improvement of measurement precision, especially in those applications where such factors play a key role in spectral responsivity and spectral quality factor for performance and reliability.

2. EXPERIMENTS AND MEASUREMENTS

The photometers shall be designed to possess spectral responsivity that closely approximates the V(λ)-function laid down by International Commission on Illumination, CIE. This function is related to the definition of luminous sensitivity of the human eye under photopic conditions, essential for correct measurement of light intensity as perceived by the human eye. In the normal measurement of illuminance with a photometer, spectral mismatch errors originate from the deviations of the V(λ)-function from the actual spectral responsivity of the photometer. Fortunately, this mismatch can be corrected if the spectral responsivity of the photometer and the spectral power distributions of the light sources being measured are known. CIE quality factors, normally expressed in percentage, are usually applied for the quality of the performances of photometers in standard lighting conditions. These quality factors cannot be applied directly for correcting the measured values; however, these factors contribute significantly to indicating the reliability of a photometer-a device with superior quality characteristics normally possesses lower measurement uncertainties since smaller correction factors are required. This is as shown in Figures 3 and 4, where the developed measurement system for this study comprises an integrating sphere of 2.5 meters and an LMT U1000 photometer. It should also comprise a very stable and accurate power source, as well as standard reference luminous flux sources, so that the obtained measurement is both correct and reliable. The comprehensive setup latterly allows precise assessments of spectral responsivity and quality factors that contribute to an improved understanding and evaluation of lighting performance [26].

Figure-3. The luminous flux measurements facilities at NIS.

Figure-4. LMT U1000 photometer at the National Institute of Standards.

The NIS integrating sphere, coupled with the highly accurate Ocean Optics 2000 array spectroradiometer, forms an effective and versatile solution for spectral power distribution measurements within the wavelength range from 200 nm up to 1100 nm. More importantly, such an assembly enables the derivation of radiometric, photometric, and colorimetric parameters with high accuracy in conformance with the CIE standards within the critical visible light range from 380 nm to 780 nm. The optical fiber of the Ocean Optics 2000 spectroradiometer channels light from the test source to the main unit of the spectroradiometer. The entering light, on a high-quality grating, is dispersed onto a CCD array that converts it into electrical signals for further processing. This is interfaced to a computer equipped with specific software, which controls the measuring process and carries out several complicated analyses of data, delivering very accurate and reliable results. The NIS spectral responsivity system, incorporating a double monochromator and a reference detector, was used for measuring the relative spectral irradiance responsivity of the LMT photometer. Care was taken to align the monochromatic light beam so that its divergence of about 1 degree would completely fill the aperture in front of the photometer head and provide a uniform illumination over the sensor area. The LMT photometer spectral responsivity was measured as a function of the wavelength in steps of 1 nm over the range from 380 nm to 780 nm.

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The bandwidth was set at 4 nm for the monochromator in order to allow precision as high as possible for the desired wavelengths. The spectral responsivity data resulting from that was gathered by recording the photocurrent generated by the photometer through the use of an I 1000 photocurrent meter; it allows very good monitoring of the response of the photometer against different wavelengths. This is done to ensure the system provides spectral responsivity measurements that are both reliable and accurate, since these are critical in defining and hence improving the performance of photometric devices under various light sources [26].

3. RESULTS AND DISCUSSIONS

In Figure 5 the spectral responsivity of the human eye is compared with that of two photometers, NIS-1 and NIS-2. This plot shows graphically the closeness with which the two photometers simulate the response of the human eye to light at different wavelengths. This is expressed with spectral responsivity of the human eye by the CIE V(λ) function, which has a peak in the green region around 555 nm, reflecting the heightening of sensitivity to green light under photopic conditions by the eye. On the other hand, while the responsivity of the photometers is designed to follow the curve as closely as possible, the response of the photometers may vary from this alignment, especially at the extremes of the visible spectrum, like violet and red. NIS-1 and NIS -2 photometers are permitted small departures from the V(λ) curve. Unless these are accounted for, spectral mismatch errors can lead to photometric measurements. For example, if these are below 400 nm or above 700 nm, the photometer may overestimate or underestimate the light's intensity with respect to human perception. The comparison in Figure 5 is critical since it shows how close such instruments can approximate to human vision, an important pre-condition for the accuracy of the measurements in practical light applications. The understanding of such differences allows correction factors or adjustments in calibration procedures so as to increase the reliability of the measurements made under both standard and special lighting conditions. This analysis confirms, eventually, that the selection of photometers with spectral responsivities similar to the human eye's sensitivity will minimize uncertainty in measurement and maximize the accuracy of a general photometric evaluation.

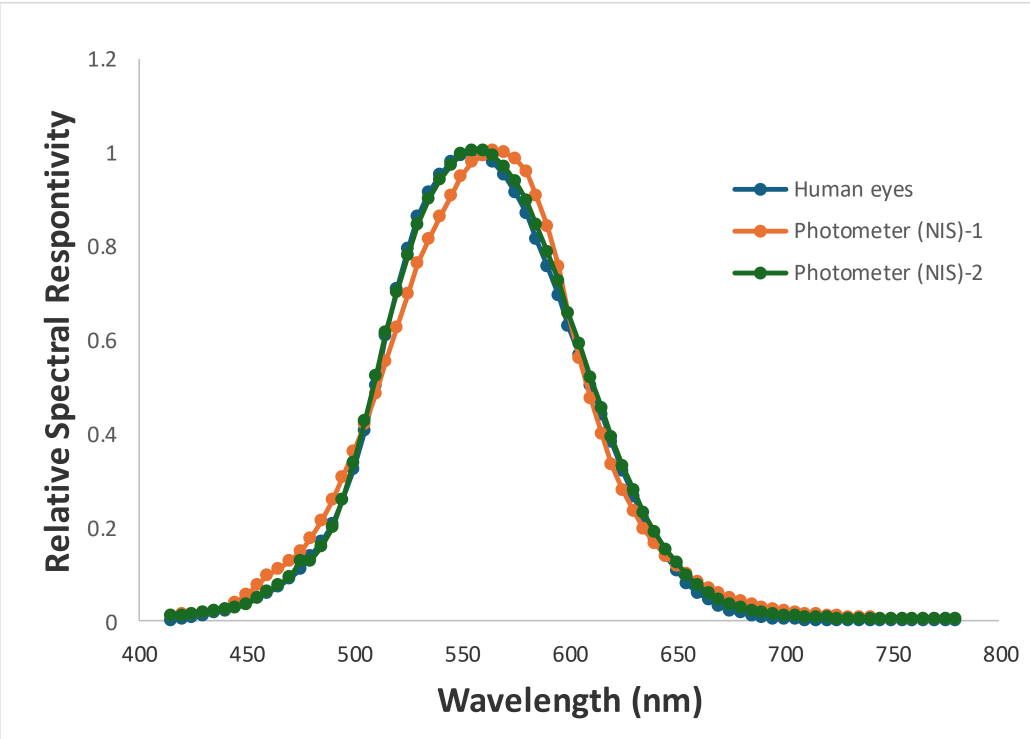

Figure-5. Illustrates the comparative spectral responsivity of human eyes alongside the relative spectral responsivity of Photometer NIS-1 and Photometer NIS-2.

Figure 6 presents a comprehensive analysis of the spectral responsivity of the human eye in relation to the spectral responsivity of two sphere photometers, NIS-1 and NIS-2, offering valuable insights into how these instruments compare to the human visual system across different wavelengths of light. The human eye's spectral responsivity, defined by the CIE V(λ) function, serves as the reference standard, especially under photopic (daylight) conditions where peak sensitivity occurs around 555 nm. By contrasting this with the spectral responses of NIS-1 and NIS-2, the figure reveals areas where the photometers align closely with human vision, as well as

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regions where discrepancies may arise, particularly at the extremities of the visible spectrum, such as in the blue (shorter wavelengths) and red (longer wavelengths) regions. These differences are critical because they can lead to spectral mismatch errors during measurements if not corrected, particularly when measuring light sources with distinct spectral distributions like LEDs or fluorescent lamps. This comprehensive figure highlights the degree to which the sensitivity of these sphere photometers matches or diverges from the human eye's response across a range of wavelengths, providing valuable insights into their performance and potential applications. Figure 7 illustrates the relative spectral responsivity of both the NIS-1 and NIS-2 photometers, in addition to the NIS-1 and NIS-2 sphere photometers. This figure emphasizes how each device's responsivity diverges from the standard V(λ) curve, providing a clear visual representation of the variations and potential discrepancies in their spectral response characteristics.

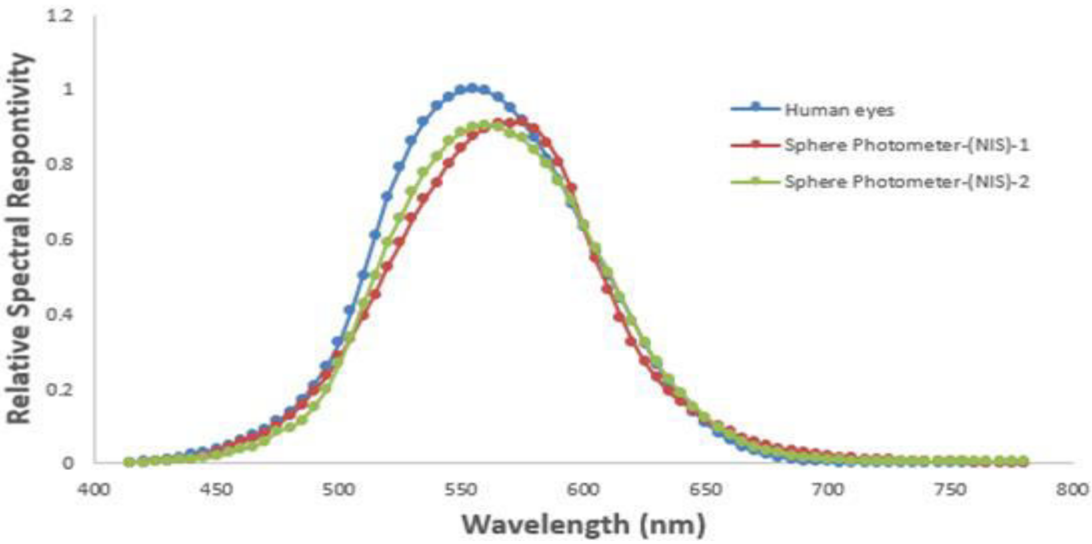

Figure-6. Illustrates the comparative spectral responsivity of human eyes alongside the relative spectral responsivity of Sphere Photometer NIS-1 and Sphere Photometer NIS-2.

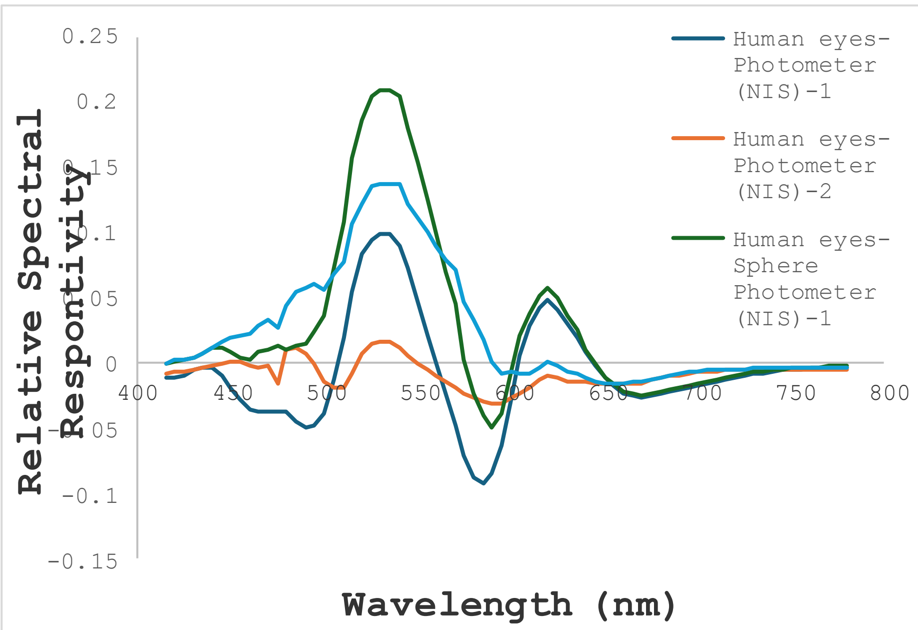

Figure-7. Illustrate the relative spectral responsivity of the NIS-1 and NIS-2 photometers, as well as the NIS-1 and NIS-2 sphere photometers, highlighting their deviation from the V(λ) curve.

The general V(λ) mismatch spectral quality factor index $f_1^{'}$ for sphere photometer NIS-1 was determined to be 6.25%, classifying it as medium quality. The uncertainty associated with this spectral quality factor was 0.014 [27,28.]. The general V(λ) mismatch spectral quality factor index $f_1^{'}$ for the sphere photometer NIS-2 was found to be 3.8%. This value reflects the precision and accuracy of the photometer's spectral measurements, placing it in the medium quality category. This classification sheds light on the photometer's performance capabilities and its suitability for various applications. Using Equation (8), the uncertainty of the spectral quality factor $f_1^{'}$ for the photometers was calculated with the Microsoft Excel program.

4. UNCERTAINTY

To evaluate the uncertainty of photometer general V(λ)

mismatch spectral quality factor index $f_1^{'}$:

$$\partial^2 f_1^{'} = \partial^2 S_A(\lambda)\left(\frac{\partial f_1^{'}}{\partial S_A(\lambda)}\right)^2 + \partial^2 S_{rel}^{*}(\lambda)\left(\frac{\partial f_1^{'}}{\partial S_{rel}^{*}(\lambda)}\right)^2 \quad (7)$$

So the uncertainty of the photometer quality factor $f_1^{'}$ which can be determined regarding to Equation (6) and according to reference [27-30]:

$$u(f_1^{'}) = \left[\begin{array}{l} \partial^2 S_A(\lambda)\left(\frac{\left(\sum S^{*}_{rel}(\lambda)\right)}{\left(\sum S_A(\lambda) S^{*}_{rel}(\lambda)\right)} - \frac{\left(\sum S_A(\lambda)V(\lambda)\right)\left(\sum S^{*}_{rel}(\lambda)\right)^2}{\left(\sum S_A(\lambda)S^{*}_{rel}(\lambda)\right)^2\left(\sum V(\lambda)\right)} + \frac{S^{*}_{rel}(\lambda)}{\left(\sum S_A(\lambda)S^{*}_{rel}(\lambda)\right)}\right)^2 + \\ \partial^2 S^{*}_{rel}(\lambda)\left(\frac{S_A(\lambda)}{\left(\sum S_A(\lambda)S^{*}_{rel}(\lambda)\right)} - \frac{\left(\sum S_A(\lambda)V(\lambda)\right)\left(\sum S^{*}_{rel}(\lambda)\right)S_A(\lambda)}{\left(\sum S_A(\lambda)S^{*}_{rel}(\lambda)\right)^2\left(\sum V(\lambda)\right)} + \frac{\left(\sum S_A(\lambda)V(\lambda)\right)}{\left(\sum S_A(\lambda)S^{*}_{rel}(\lambda)\right)\left(\sum V(\lambda)\right)}\right)^2 \end{array}\right]^{1/2} \quad (8)$$

By using Equation (8), the resulting uncertainty for the NIS-2 photometer was found to be 0.010. These calculations provide a more comprehensive understanding of the photometer's measurement reliability and potential areas for improvement.

5. CONCLUSIONS

The index of general V(λ) mismatch spectral quality factor is one of the most important metrics, which details and nuances performance analyses with regard to measurement accuracy and reliability. An analysis was made on two photometers: NIS-1 and NIS-2. I made some careful examination of the uncertainties of both photometers using Equation (8) with the use of appropriate computational tools such as Microsoft Excel. To begin with, the spectral quality factor percentage was calculated for NIS-1, and this is equal to 6.25%, hence this instrument is a middle-quality instrument. These classes give an approximate definition about its performance, though this device does have an uncertainty of 0.014. This uncertainty term means that the spectral measurements obtained using this device fall into a class that requires detailed evaluation and interpretation of the spectrum data obtained from the latter [27,28]. Regarding NIS-2, our study revealed a spectral quality factor of 3.8%. This figure is a comparable medium-grade classification and represents the accuracy and precision of the photometer in spectral measurements. It should be further mentioned that this was accompanied by an uncertainty calculation of 0.010, which better defined the reliability of the measurement by NIS-2. Such calculations give not only a holistic picture of their measurement capabilities but also present the arenas where potential improvement and refinement of calibration might be in order. The detail analysis therefore greatly enhances the general reliability and performance of the photometers in diverse applications. I hereby recommend the use of the NIS-2 photometer in place of NIS-1 photometer for Total luminous flux measurements.

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