Comparison Reproducibility of Measured and Calculated Color Speckle Distributions in CIE xyY Color Space

Junichi Kinoshita[1], Kazuhisa Yamamoto[1], Kazuo Kuroda[1]

jun1-istd@ile.osaka-u.ac.jp

Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita City, Osaka, 565-0871, Japan

Keywords: speckle, color speckle, laser display, laser lighting, speckle grain

ABSTRACT

Measured and calculated color speckle distributions were compared in the xyY_{norm} color space for two different RGB laser sources. The three different datasets were extracted for ensuring reproducibility of the comparisons. The triangular-shape trend of the measured distributions affected by the scale factors of RGB speckle grains was confirmed.

1 Introduction

Color speckle is optical noise caused by RGB laser outputs. Colorful speckle grains are observed in the uniform white, or any other color patterns projected on a diffusive screen. The color speckle grains are recognized as irregular interference patterns on retina generated via color-addition of the R, G, B monochromatic speckles. The color speckle noise should be reduced for laser display and lighting applications. Therefore. the color speckle has been discussed and analyzed aggressively [1-7]. The measurement method of color speckle was already published as the international standard, IEC 62906-5-4 [8]. The authors demonstrated that the color speckle distribution behaviors can be well visualized by plotting in the xyY_{norm} color space at the previous IDW conference [6]. We can analyze the CIE 1931 chromaticity (x, y) and the normalized illuminance Y_{norm} simultaneously in this 3D color space.

Very recently, it was found that the measured color speckle distribution was noticeably different from the calculated distribution in the xyY_{norm} color space [7]. The measured distribution took a more triangular shape than the calculated distributions particularly in the plane view corresponding to CIE 1931 chromaticity diagram. That is, the triangle vertices toward the RGB directions from the white point were stressed more acutely. This trend is caused by the different scale factors of the RGB speckle grains which has not been considered in the conventional color speckle calculation [7].

In this work, we ensured the above trend of the measured color speckle distributions by plotting three color speckle datasets in the xyY_{norm} color space using two different RGB light sources, one has relatively high RGB speckle contrasts, and the other has lower contrasts.

2 CONVENTIONAL CALCULATION METHOD

This section describes the method of the conventional color speckle calculation.

Each R, G, B laser source emits a laser light with a very narrow spectral linewidth. Therefore, the tristimulus values X, Y, Z can be approximately calculated using the single wavelength values of the R, G, B lasers and the single values of CIE colour matching functions corresponding to the wavelengths, $\bar{x}(\lambda_Q)$, $\bar{y}(\lambda_Q)$, $\bar{z}(\lambda_Q)$, (Q = R, G, B). The tristimulus values can be calculated as follows.

$$\begin{aligned} X &= \bar{x}(\lambda_R)E_{e-R} + \bar{x}(\lambda_G)E_{e-G} + \bar{x}(\lambda_B)E_{e-B} \\ Y &= \bar{y}(\lambda_R)E_{e-R} + \bar{y}(\lambda_G)E_{e-G} + \bar{y}(\lambda_B)E_{e-B} \\ Z &= \bar{z}(\lambda_R)E_{e-R} + \bar{z}(\lambda_G)E_{e-G} + \bar{z}(\lambda_B)E_{e-B} \end{aligned} \quad (1)$$

where, $E_{\mathrm{e\text{-}Q}}$ is the irradiance of each color. (The spectral power ratios are included.)

CIE 1931 chromaticity (x, y) are given as follows.

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z} \quad (2)$$

Illuminance E_{v} is obtained by,

$$E_v = 683 \times Y \quad (3)$$

Monochromatic speckle contrast for each color, $C_{\mathrm{s\text{-}Q}}$ is calculated by the following equation.

$$C_{s-Q} = \frac{\sigma_{e-Q}}{\bar{E}_{e-Q}} \quad (4)$$

where, $\bar{E}_{e\text{-}Q}$ is the average of the distribution of $E_{\mathrm{e\text{-}Q}}$, and the $\sigma_{\mathrm{e\text{-}Q}}$ is the standard deviation.

The probability density function for the monochromatic speckle can be stochastically expressed as the following gamma distribution function using the monochromatic speckle contrast, $C_{\mathrm{s\text{-}Q}}$.

$$p(E_{e(norm)-Q}) = \frac{E_{e(norm)-Q}^{C_{s-Q}^{-2}-1}}{\Gamma(C_{s-Q}^{-2})} \exp(E_{e(norm)-Q}) \quad (5)$$

where, Γ is the gamma function, and $E_{e(norm)\text{-}Q}$ is the irradiance values normalized by the average.

The speckle irradiance values can be stochastically calculated by generating random numbers in the inverse function of Equation (5). (GAMMA.INV function in Microsoft Excel, for example.)

3 MEASUREMENTS

The measured values were obtained using the two RGB laser light sources, one is a laser module with a SMF (single mode fiber) end for the combined outputs of the single transverse / longitudinal mode RGB laser diodes (Shimadzu Corporation) [4], and the other is a raster-scanning mobile RGB laser projector (Celluon PicoBit) [3,5].

The measured data were obtained by the speckle measurement device, SM01VS11 provided by OXIDE Corporation [9]. The 2D image sensor (EMCCD: electron multiplying charge-coupled device) with a pixel size of 16×16 μm^2 was used for capturing the speckle data. A pinhole (iris) with a diameter of 1.2 mm was equipped in front of an imaging lens to realize optics with MTF equivalent to that of human eye. The monochromatic speckle data for each R, G, B wavelength were captured separately from the white projected data using R, G, B bandpass filters.

For the laser module, the R, G, B speckle irradiance data were captured together with the background laser transverse mode pattern. Therefore, the data were calibrated to be on the uniform background [4]. For the raster-scanning mobile laser projector, we could easily use a large uniform projected pattern.

The values of wavelengths, speckle contrasts, and white chromaticity (CIE 1931) for the laser module and the laser projector are summarized in Table 1 and Table 2, respectively.

Table 1 Wavelengths, speckle contrasts, and white chromaticity (CIE 1931) for the laser module

	R	G	B
Wavelength (nm)	639.9	520.3	455.7
Speckle contrast, $C_{s\text{-}Q}$	0.232	0.224	0.249
	x		y
White chromaticity	0.3006		0.2740

Table 2 Wavelengths, speckle contrasts, and white chromaticity (CIE 1931) for the laser projector

	R	G	B
Wavelength (nm)	643.6	518.9	446.4
Speckle contrast, $C_{s\text{-}Q}$	0.069	0.041	0.105
	x		y
White chromaticity	0.3059		0.2964

The R, G, B speckle contrasts are relatively high as 0.224-0,249 for the laser module, and relatively low as 0.041-0.105 for the laser projector.

4 Comparison of measured and calculated color speckle data

This section describes the comparisons of the measured and calculated data for the two RGB laser sources in Table 1 and Table 2.

The original measured data (2D: 300 rows × 300 columns) were chosen around the center area. The three datasets of color speckle distribution,300 rows × 15 columns = 4,500, Region 1 (10th-24th columns), Region 2 (140th-159th), and Region 3 (175th-189th), were picked up from the original measured data.

The three calculated datasets for comparison were obtained by repeating the conventional calculation three times, generating random numbers in the inverse function of Equation (5). The three calculated datasets of color speckle distribution are considered as different sequences of randomness.

4.1 Laser module

Figure 1 shows the measured and calculated 3D color speckle distributions in the xyY_{norm} color space for the laser module.

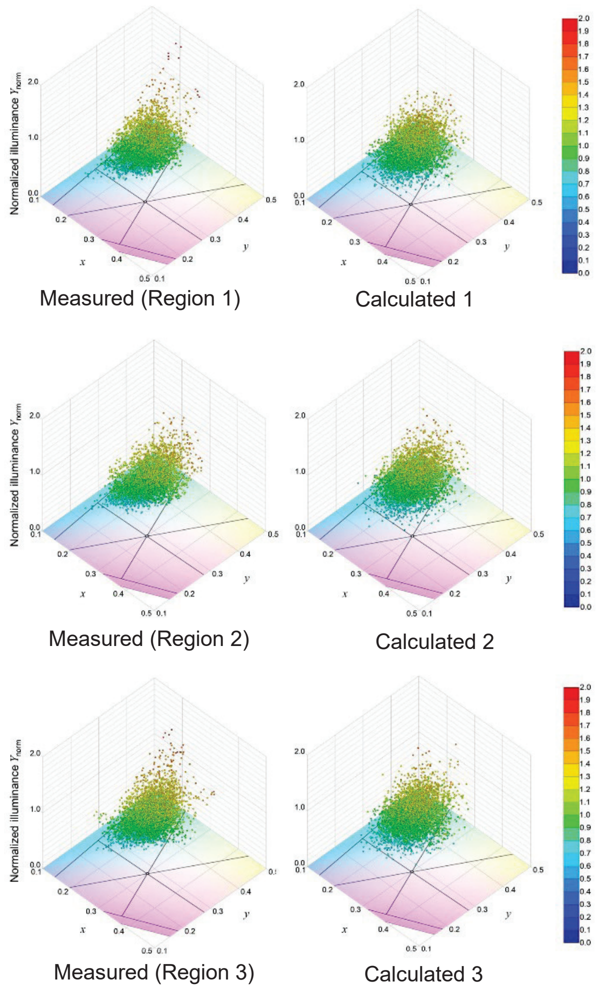

Fig. 1 Measured and calculated 3D color speckle distributions in xyY_{norm} space for laser module

The normalized illuminance, Y_{norm} was normalized by the average value. The Y_{norm} values can be distinguished by colors in the inserted legend, redder and bluer data points are higher and lower, respectively.

The plane views of the 3D color speckle distributions in Fig.1 are shown in Fig.2. The plane view is based on the CIE 1931 chromaticity diagram, but the Y_{norm} values can be observable by the color of the data points. The trend of the measured distributions taking a more triangular shape than the calculated distributions is clearly noticeable in the plane view. The triangle vertices for the measurement are extending towards the R, G, B directions. Particularly along the G direction, Y_{norm} points are enhanced.

The above trend is quite reproducible between the measured and calculated distributions through the three datasets.

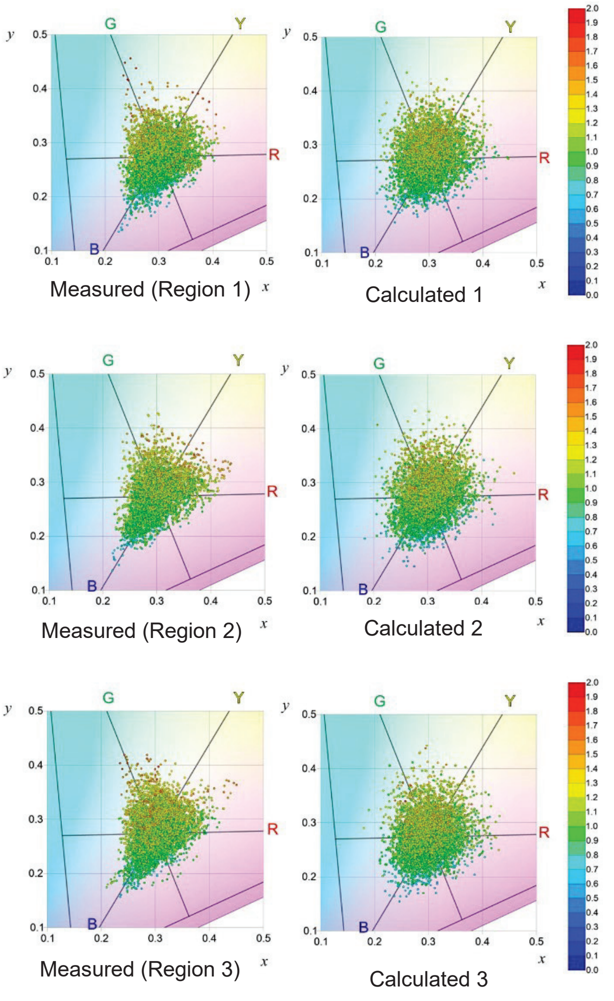

Fig. 2 Measured and calculated 2D color speckle distributions (CIE 1931 plane view) for laser module

4.2 Laser projector

The 3D color speckle distributions in the xyY_{norm} color space for the laser projector are shown in Fig.3. The plane views of the 3D color speckle distributions in Fig.3 are shown in Fig.4.

The R, G, B speckle contrasts are much smaller than those for the laser module (see Table 1 and Table 2). As a result, the color speckle distributions for the laser projector are also much smaller than those for the laser module. However, the smaller range of the x, y, Y_{norm} axes should be noted when comparing Fig.1, 2 and Fig.3, 4.

The trend of triangular shape for the measured color speckle distribution in Fig.4 is distinctive as well as in the laser module. However, the distributions are shorter (thinner) in the G-W and R-W directions, and longer (broader) in the B-W-Y direction because the B speckle contrast is much larger than G and R. Therefore, particularly for the Y (Yellow) direction, higher Y_{norm} points are outstanding. The above trend is common to all the three datasets.

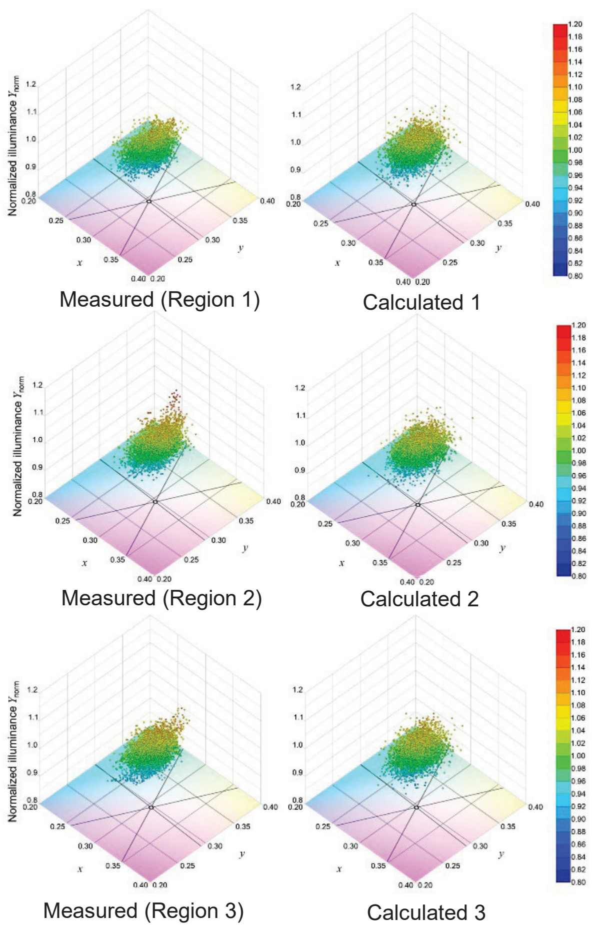

Fig. 3 Measured and calculated 3D color speckle distributions in the xyY_{norm} space for laser projector

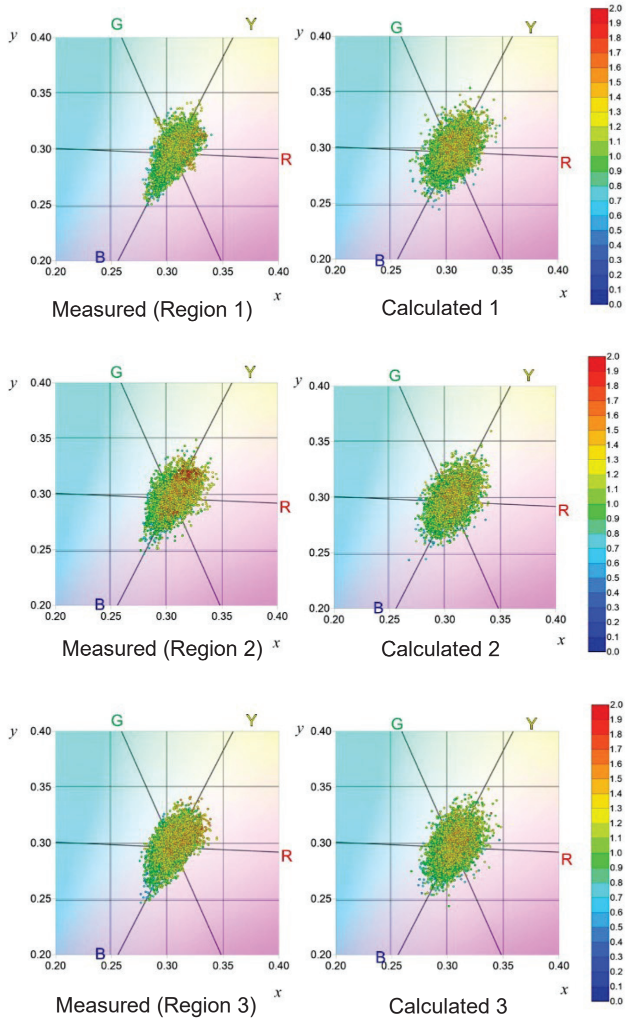

Fig. 4 Measured and calculated 2D color speckle distributions (CIE 1931 plane view) for laser projector

5 Discussion

The trend of the measured color speckle distributions (triangular shape) is caused by the different scale factors of the RGB speckle grains that has not been considered in the conventional color speckle calculation [7]. It is not so easy to analyze the speckle grain size because the speckle grain structure is generated in random and irregular manners. However, the grain size stochastically distributes depending on the wavelength. That is, stochastically largest grain size for the R-speckle and the smallest for the B-speckle will occur.

The following cases generate the triangular shape trend for the measured color speckle distributions.

(1) Higher-illuminance, larger R speckle grains possibly include more G, B speckle grains smaller in size and lower in illuminance,

(2) Lower-illuminance, larger R speckle grains possibly include more G, B speckle grains smaller in size and higher in illuminance.

6 Conclusions

The measured and the calculated color speckle distributions were compared in the xyY_{norm} color space for two different RGB laser light sources, one is a laser module with a SMF output (larger speckle contrasts), and the other is a raster-scanning mobile RGB laser projector (smaller speckle contrasts). Three different datasets of color speckle distribution were picked up from the measured data for ensuring reproducibility. Also, three different datasets of the conventional calculation were repeated three times. The trend of triangular-shape color speckle distributions for the measurement in the plane view was reproducibly confirmed both for the laser module and laser projector. The trend of the measured color speckle distributions is caused by the different scale factors of the RGB speckle grains which has not been considered in the conventional color speckle calculation method.

References

[1] K. Kuroda, T. Ishikawa, M. Ayama, S. Kubota, “Color speckle”, Opt. Rev. 21 (1), pp. 83-89 (2014).

[2] J. Kinoshita, K. Yamamoto, K. Kuroda, “Color speckle measurement errors using system with XYZ filters”, Opt. Rev. 25 (1), pp. 123-130 (2018).

[3] J. Kinoshita, K. Yamamoto, A. Takamori, K., Kuroda, K. Suzuki, “Visual resolution of raster-scan laser mobile projectors under effects of color speckle”, Opt. Rev. 26 (1), pp.187-200 (2019).

[4] J. Kinoshita, K. Ochi, A. Takamori, K. Yamamoto, K. Kuroda, K. Suzuki, K. Hieda, “Color speckle measurement of white laser beam emitted from fiber output of RGB laser modules”, Opt. Rev. 26 (6), pp.720-728 (2019).

[5] J. Kinoshita, A. Takamori, K. Yamamoto, K. Kuroda, K. Suzuki, K. Hieda, “Nonuniformity measurement of image resolution under effect of color speckle for raster-scan RGB laser mobile projector”, IEICE TRANS.ELECTRON., Vol.E105-C (2) (2022).

[6] J. Kinoshita, K. Yamamoto, K. Kuroda, “Color speckle analysis of RGB laser display using CIE xyY color space”, The 28th International Display Workshop. PRJ7-2 (2021).

[7] J. Kinoshita, K. Yamamoto, K. Kuroda, “Grain-size effect of RGB monochromatic speckles on color speckle distributions”, Proc. SPIE: The 11th Laser Display and Lighting Conference 2022, LDC-9-04, LDC 2022 abstract book, SPIE digital library, (To be published in July, 2022).

[8] IEC 62906-5-4:2018, Laser display devices - Part 5-4: Optical measuring methods of colour speckle. (2018).

[9] K. Suzuki, S. Kubota, “Understanding the exposure-time effect on speckle contrast measurements for laser displays”, Opt. Rev. 25 (1), pp.131-139, (2018).