Color Speckle Analysis of RGB Laser Display using CIE xyY Color Space

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ABSTRACT

Color speckle of Rec.2020 RGB laser display is analyzed using CIE xyY color space. The Y-axis is normalized by the illuminance at the reference white. The relation between the chromaticity and the normalized illuminance is clarified along the three lines through each of the primary colors and the reference white.

1 INTRODUCTION

The color speckle theory was proposed for the first time by Kuroda et.al. [1]. Since then, many works on the color speckle have been published [2-5]. The international standard of the measurement method of the color speckle was also published in 2018 [6]. The color speckle is colorimetric optical noise consisting of random small color grains on human retina, which is caused by the interference of partially coherent red (R), green (G), blue (B) primary color laser lights. The color speckle is observed even if a uniform white pattern is projected on a screen.

The color speckle had been separately represented by the 2D chromaticity distribution on a chromaticity diagram and the illuminance distribution such as histograms. However, the relation between the chromaticity and the illuminance is not clearly analyzed by the separate representations. The authors have also tried to represent the color speckle three-dimensionally using the CIELAB color space [3]. However, the CIELAB color space is not appropriate for analyzing the color speckle behavior because the half of the color speckle data statistically exceed the maximum value of L*=100. The authors recently found that the xyY_{norm}, or the $u'v'Y_{\text{norm}}$ color space was more convenient for expressing color speckle data.

The color speckle behavior strongly depends on the R, G, B monochromatic speckle contrasts. In other words, the complicated color speckle behavior in the color space is generated as the combined effect of each behavior of the R, G, B colors [6] .

In this work, the color speckle behavior of RGB laser display compliant with ITU-R Recommendation BT.2020 (Rec.2020) is analyzed color by color in the xyY_{norm} color space. It is demonstrated that the color speckle data for one of the primary colors (R, G, B) was found to be plotted exactly on a line through the primary color and the reference white (W) in the color space. Therefore, the color speckle should be analyzed along the three lines, R-W, G-W, and B-W.

2 FORMULATION

The R, G, B laser diodes emit partially coherent light with a very narrow spectral linewidth. Therefore. the tristimulus values can be calculated using a single wavelength value and the corresponding single value of CIE colour matching functions, $\bar{x}(\lambda_Q)$, $\bar{y}(\lambda_Q)$, $\bar{z}(\lambda_Q)$, (Q=R, G, B). The tristimulus values X, Y, Z can be calculated by the following equations.

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

where, $E_{\text{e-Q}}$ is the irradiance of each color including spectral power ratio.

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

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

Illuminance E_{v} is obtained by,

$$E_v = 683 \times Y \tag{3}$$

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

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

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

The probability density function for the monochromatic speckle can be statistically expressed as a function of the monochromatic speckle contrast, $C_{\text{s-Q}}$.

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

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

Photometric speckle contrast, C_{ps}, for white color is expressed as follows, using equations (1)-(3).

$$C_{ps} = \frac{\sigma_v}{\overline{E}_v} \quad (6)$$

where, $\overline{E}_v$ is the average of the illuminance distribution of E_v, and σ_v is the standard deviation.

The illuminance values normalized by the value at the white point (W) is equal to the normalized values of Y_{norm}. The color speckle chromaticity coordinates, (x, y), spreads around W, depending on the R, G, B speckle contrasts, $C_{s\text{-}R}$, $C_{s\text{-}G}$, $C_{s\text{-}B}$.

3 CALCULATIONS AND COLOR SPACE PLOTS

3.1 Calculation parameter

The color speckle calculations were carried out using the equations in the previous section, assuming a Rec.2020 RGB laser display. The parameters involving the R, G, B colors and the reference white (W) of Rec.2020 are shown in Table 1.

Table 1 RGB parameters of Rec.2020

	R	G	B	W
CIE1931 chromaticity	x=0.708 y=0.292	x=0.170 y=0.797	x=0.131 y=0.046	x=0.3127 y=0.3290
wavelength	630nm	532nm	467nm	-
power ratio	0.397	0.307	0.296	-

3.2 Cases speckled for a single color

To analyze pure color speckle behavior of one of the R, G, B primary colors, the speckle contrast of this color was assumed to be 0.3 and the rest were 0.0. The speckle contrast values for the three cases are listed in Table 2.

Table 2 Monochromatic speckle contrasts in the cases speckled for a single color

	$C_{s\text{-}R}$	$C_{s\text{-}G}$	$C_{s\text{-}B}$	C_{ps} (W)
Case 1	0.3	0	0	0.074
Case 2	0	0.3	0	0.198
Case 3	0	0	0.3	0.017

The calculations of the monochromatic speckle of Q=R, G, B were carried out using equation (5), Then the color speckle distribution in the color space was calculated using equations (1)-(3).

The calculated results were plotted in the xyY_{norm} color space. The 3D view for the cases 1, 2, and 3 was shown in Fig.1. The plotted data are indicated as colored points classified by the Y_{norm} levels (as the 20 steps in the graph legend). The 2D views for the cases 1, 2, and 3 were shown in Fig.2. The view of the x-y plane is shown as the conventional CIE 1931 chromaticity diagram. The data are plotted as colored points classified by the Y_{norm} levelsl. The cases 1, 2, 3 are independent phenomena. However, they were plotted in the same color space intentionally for convenience of comparison and the paper-space-saving. As in Fig.2, the data are aligned exactly on a line through the primary color point Q (Q=R, G, B) and the W point. Considering this result, the side views are chosen as the planes with the vertical axis as Y_{norm} and the horizontal axis as the Q-W line. The plotted data on the QWY_{norm} side views were calculated by the coordinate conversion of the x-y plane. The conversion step 1 was to shift the origin to W, and the step 2 was to rotate the Q-W line in the direction of the original y-axis.

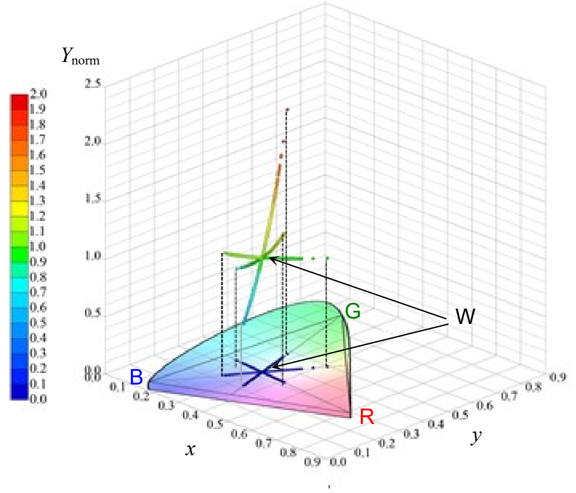

Fig. 1 Data plot in the xyY_{norm} color space (3D view) for cases 1, 2, and 3

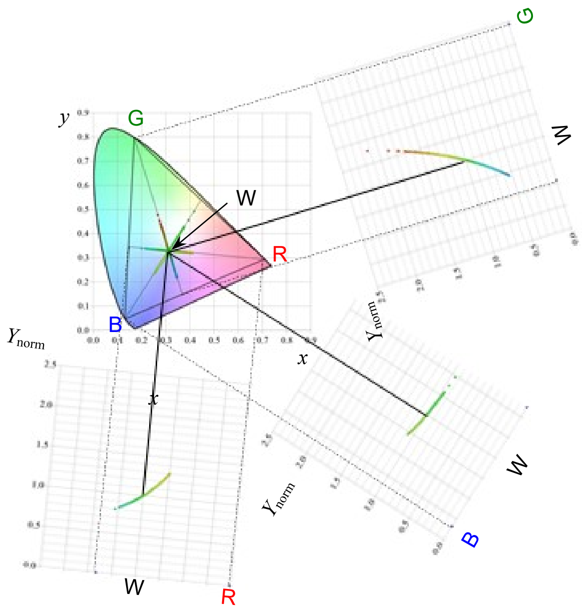

Fig. 2 Data plot in the xyY_{norm} color space (2D views) for cases 1, 2, and 3

The variance values along the Q-W lines (//), along their cross lines (⊥), and along the Y_{norm} axis were calculated. The covariance values are also calculated. The variance and covariance values are summarized in Table 3. Only the variance values along the Q-W line (//) represent the color speckle behavior of the cases with speckle only for a single color. The variance along the cross lines (⊥) and the covariance (//-⊥) are null. The results are reasonable because the color speckle behavior of the cases with speckle only for a single color is just on a line through the Q-W points. The covariance (//-Y_{norm}) implies the correlation between the Y_{norm} (illuminance) and the converted chromaticity values along the Q-W line. The curve in the GWY_{norm} side view of Fig.2 showed a strong positive correlation. High photopic luminous efficiency at the G point affects the positive correlation. The covariance (//-Y_{norm}) value for the GWY_{norm} side view (the case 2) is the largest, which well agreed with the above fact. The other covariance (//-Y_{norm}) values also well agreed with the trends of the curves in the side views of Fig,2.

Table 3 Variance, covariance for cases 1, 2, and 3

	Case 1 RWY_{norm}	Case 2 GWY_{norm}	Case 3 BWY_{norm}
Variance (//)	0.00122	0.00170	0.00168
Variance (⊥)	0.00000	0.00000	0.00000
Variance (Y_{norm})	0.00651	0.00651	0.00651
Covariance (//-⊥)	0.00000	0.00000	0,00000
Covariance (//-Y_{norm})	0.00280	0.00870	-0.00069

3.3 Cases with speckled for all the R, G, B colors

The color speckle behaviors when speckled for all the R, G, B colors were calculated (Cases 4 and 5). The monochromatic R, G, B speckle contrast values used in the calculations are listed in Table 4.

Table 4 Monochromatic speckle contrasts in the cases speckled for all the R, G, B colors

	$C_{s\text{-}R}$	$C_{s\text{-}G}$	$C_{s\text{-}B}$	C_{ps} (W)
Case 4	0.3	0.3	0.30	0.214
Case 5	0.15	0.15	0.15	0.106

The 3D view representation of the plotted data in the xyY_{norm} color space for the case 4 is shown in Fig.3. The 2D view representations of the data for the case 4 is shown in Fig.4. The variance and covariance data are listed in Table 5.

Figures 3 and 4 show a usual scattering color speckle distribution. The distribution of case 4 looks strongly affected by the line distribution in Figs.1 and 2. The spaces among the line distributions are filled up with data points created by the interaction with the monochromatic speckles of the rest of colors. However, some details slightly differ between them, which will be discussed in the next section.

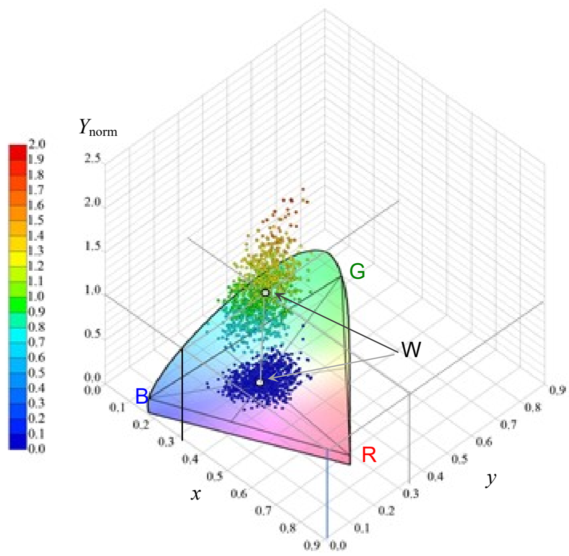

Fig. 3 Data plot in the xyY_{norm} color space (3D view) for case 4

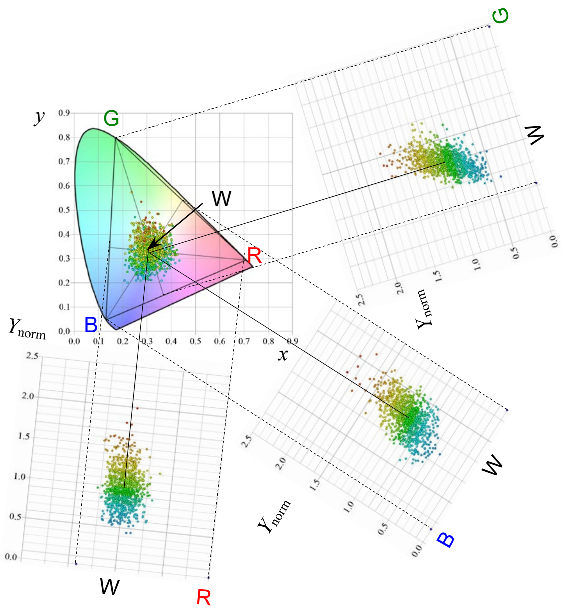

Fig. 4 Data plot in the xyY_{norm} color space (2D views) for case 4

Table 5 Variance, covariance for case 4

	RWY_{norm}	GWY_{norm}	BWY_{norm}
Variance (//)	0.00282	0.00200	0.00183
Variance (⊥)	0.00173	0.00255	0.00272
Variance (Y_{norm})	0.04593	0.04593	0.04593
Covariance (// ⊥)	-0.00016	0.00046	-0.00035
Covariance (// Y_{norm})	0.00058	0.00649	0.00575

The 3D view in the xyY_{norm} color space for the case 5 is shown in Fig.5. The 2D views for the case 5 are shown in Fig.6. The variance and covariance data are listed in

Table 6.

The color speckle distribution in the case 5 is shrunk compared with case 4 due to smaller speckle contrasts.

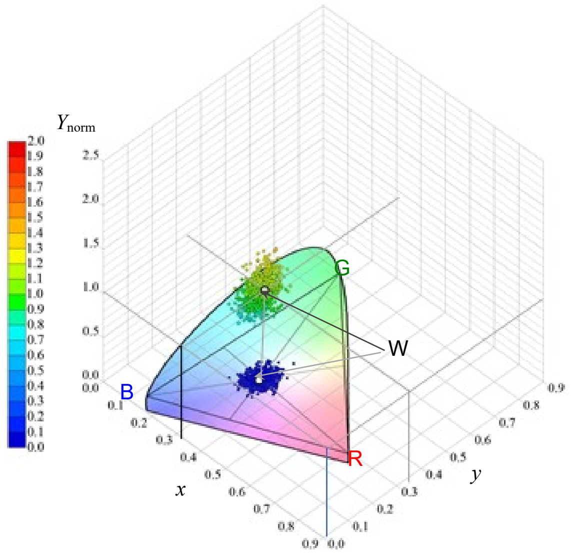

Fig. 5 Data plot in the xyY_{norm} color space (3D view) for case 5

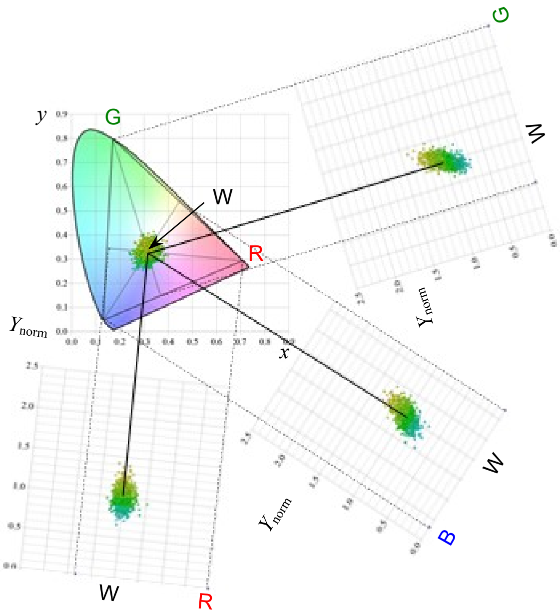

Fig. 6 Data plot in the xyY_{norm} color space (2D views) for case 5

Table 6 Variance, covariance for case 5

	RWY_{norm}	GWY_{norm}	BWY_{norm}
Variance (//)	0.00069	0.00054	0.00049
Variance (⊥)	0.00048	0.00064	0.00068
Variance (Y_{norm})	0.01125	0.01125	0.01125
Covariance (//⊥)	-0.00004	0.00010	-0.00007
Covariance (// Y_{norm})	-0.00017	0.00167	-0.00147

4 DISCUSSION

The "line" distribution in the xyY_{norm} color space in the cases with speckled only for a single color (in cases 1, 2, 3) is a fundamental behavior of color speckle. When the rest of the colors have no speckle, their optical powers are kept constant at the same values as the white point (W). That is, the constant powers of the rest of colors limit the shape of the distribution only to the "line". On the other hand, the speckles of all the colors interact each other and create the scattered distributions in cases 4 and 5. In case 4, the covariance (//-Y_{norm}) of the BWY_{norm} side view becomes larger and that of the RWY_{norm} side view becomes smaller than the single-color speckled cases. The larger speckle values tend to move toward more saturated color affected by the lower-half speckle values of the other colors. For this reason, the color speckle in the case of R, G, B fully developed speckles can spread all over the gamut area.

5 CONCLUSION

The color speckle of Rec.2020 RGB laser display was analyzed using the xyY_{norm} color space. The relation between the chromaticity and the normalized illuminance Y_{norm} was clearly visualized. The variance and covariance in the QWY_{norm} plane (Q =R, G, B) well agreed with the visualized data trends. The data in the single-color speckled cases were plotted exactly on the line through the Q and the W points. The data in the all R, G, B speckled cases were scattered by the interactive effect.

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