Simple method of characterizing the spatial luminance distribution at the user position for autostereoscopic 3-D display

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Abstract — The image quality of autostereoscopic 3-D displays strongly depends on the user position. So, characterization of the spatial luminance distribution at the user position is important. For the measurement of the spatial luminance distribution, a method that places a diffuser screen at the user position and is illuminated by a 3-D display has been investigated. By placing the diffuser screen and 3-D display non-parallel, the luminance distribution at the various distances can be determined. Though the accuracy of this measurement method is somewhat limited, the measuring procedure is fast and simple, compared with other time-consuming methods.

Keywords — *Three-dimensional display, metrology, diffuser screen, 3-D cross-talk.*

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1 Introduction

The principle and various technologies related to 3-D displays has been known for a while.[1–5] Nowadays, 3-D technologies using special glasses are popular in 3-D movie theaters and 3-D television.[6] And research on autostereoscopic 3-D displays is going on as well. The principle of autostereoscopic 3-D display is control of the spatial luminance distribution at the user position such that each eye of the user can see a different image. Hence, this spatial luminance distribution is quite complex, and the spatial luminance distribution should be characterized in a spatial interval, which is much smaller than the inter-pupillary distance (IPD).

Various characterizing methods for 3-D display have been reported.[7–11] One method is the luminance measurement where the luminance measurement device (LMD) is located in the user position.[7,8] Another method is the construction of the spatial luminance distribution from the angular luminance distribution which is measured at multiple spots of an autostereoscopic 3-D display.[9] These methods focus on the light coming from the 3-D display. The former method is quite time-consuming, though it provides a reliable result. While the latter method can be performed in a short time, measuring equipment of extremely high angular resolution of less than 0.03° is reportedly required.[9]

In this paper, a measuring method focusing on how the incoming light converges on the user position is investigated. A diffuser screen is placed at the user position, and the spatial luminance on the screen illuminated by the light from the 3-D display is measured by a digital camera. The diffuser screen is tilted with respected to the 3-D display to obtain the luminance distribution at different distances.

2 Experimental setup

The measurement setup to characterize the spatial luminance distribution at the user position is illustrated in Fig. 1. The diffuser screen is illuminated by the 3-D display and the spatial luminance on the diffuser screen is captured by a digital camera. The horizontal and vertical directions of the sample 3-D display are selected as the x axis and z axis. The distance from the 3-D display is selected as y axis. And the center of the display is defined as (0, 0, 0) while the center of the diffuser screen is defined as (0, y_0, 0), where y_0 is the distance between the centers of the tilted diffuser screen and the 3-D display. The diffuser screen is tilted 45° along the rotational axis that is parallel to the x axis. In autostereoscopic 3-D displays, the luminance distribution along the vertical direction is known to vary less compared with those along the the x and y axis. Therefore, measurement of the spatial luminance distribution along the x and y axis is more important than along the z axis. By tilting the diffuser screen, the y position on the diffuser screen is not a fixed value and the luminance at the various y positions can be obtained. Luminance on the diffuser screen is captured by a digital camera (Canon EOS 500D), which is located at a distance of 80 cm, perpendicular to the diffuser screen. A commercial smart phone (LG Optimus 3-D) with a screen size of 94 × 56 mm and a resolution of 800 × 480, supporting a two-view autostereoscopic display by a switchable parallax barrier, is used as the 3-D sample. The luminance of the 3-D sample is set at the maximum. Because a smart phone is generally designed to be seen at arm's length, the distance between the center of the tilted diffuser screen and the 3-D display, y_0, is selected as 300 mm. The measurement condition of y_0 = 200 mm is also used. The value of y_0 is changed by moving the 3-D sample.

White A4-sized paper with a width of 297 mm and a height of 210 mm is used as the diffuser screen. A rectangle

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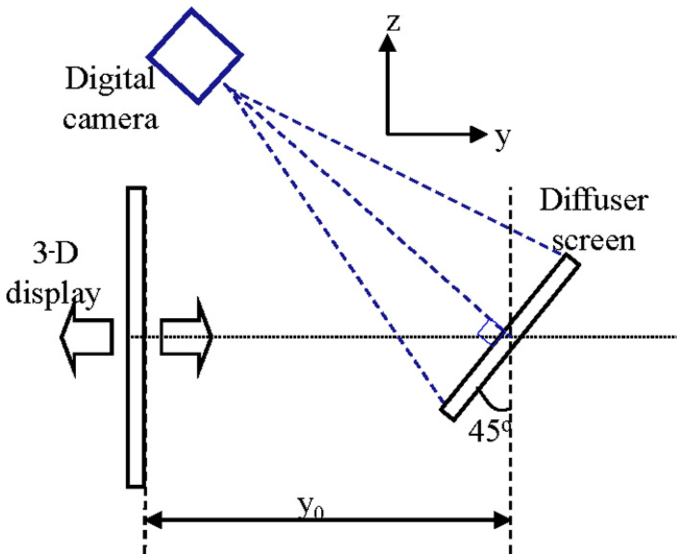

FIGURE 1 — Side view of the measurement setup where the diffuser screen is located in the user's position and the digital camera is used to capture the luminance distribution on the diffuser screen illuminated by the autostereoscopic 3-D display. Distance from the center of the 3-D distance to the center of the diffuser screen is defined as y_0. Horizontal and vertical directions are defined as the *x* direction and *z* direction.

pattern with a width of 275 mm and a height of 187 mm is drawn on the diffuser screen. The width of this pattern is slightly larger than four times the IPD, which is generally known to be 60–65 mm.[12] Hence, this width is expected to be wide enough to observe the periodic nature of the luminance profile at the viewing zones.

Generally, 3-D performance is characterized by 3-D cross-talk.[13] To measure the 3-D cross-talk, the test image data shown in Fig. 2 are used for the measurement. W and B represent the test image data of the white and the black. WB, BW, and BB represent the test image data for two eyes where the first and the second are for the left and the right

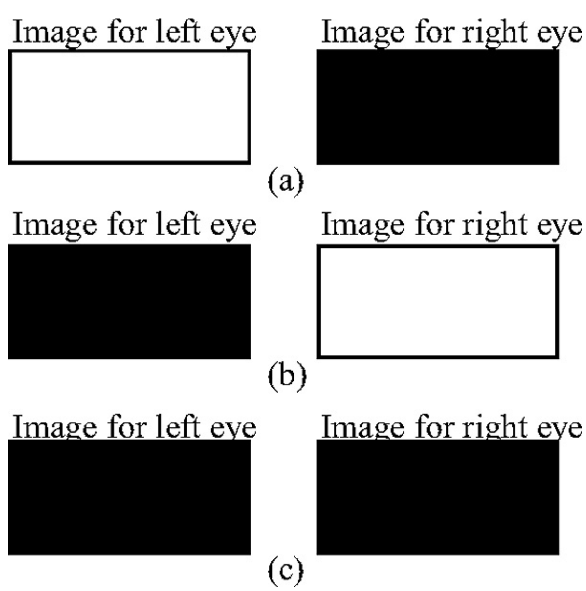

FIGURE 2 — Test image data for (a) WB, (b) BW, and (c) BB. The first and second letters represent the image for the left eye and the right eye. B and W represent the black and the white.

eyes. These left and the right images are combined as one side-by-side image file in jps format with an image size of 1600×480 pixels. This image file is used at the 3-D sample.

In this paper, 3-D cross-talk is defined as Eq. (1)[13]:

$$\text{3-D cross-talk for left eye} = \frac{\text{Lum(BW)} - \text{Lum(BB)}}{\text{Lum(WB)} - \text{Lum(BB)}}, \quad (1)$$

$$\text{3-D cross-talk for right eye} = \frac{\text{Lum(WB)} - \text{Lum(BB)}}{\text{Lum(BW)} - \text{Lum(BB)}}, \quad (2)$$

where Lum(BW), Lum(WB), and Lum(BB) represent the luminance when test image data BW, WB, and BB are used. The 3-D cross-talk for the right eye is equal to the inversion of 3-D cross-talk for the left eye. So, only 3-D cross-talk for the left eye is considered.

To measure the 3-D cross-talk, the diffuser screen and the 3-D sample are aligned as illustrated in Fig. 1 and the test image data of Fig. 2 are, respectively, used at the 3-D display. At each test image data and the conditions of y_0 200 and 300 mm, photos of the diffuser screen are captured. A measurement was performed in a dark room where the illumination at the position of the diffuser screen was below 1 lx.

3 Result and analysis

Figure 3 shows photographs of the diffuser screen at different distances, y_0, when the test image data of WB and BW are used for the 3-D display. Figure 4 illustrates the relationship between the *XY* coordinate of the photos shown in Fig. 3 and the *xyz* coordinate defined in Fig. 1. For the horizontal direction, the *X* axis of the photo is equal to the *x* axis of the measurement system. The *Y* axis of the photo is on the *yz* plane and is 45° to the *y* axis. Hence, the (*X*, *Y*) position of the photo corresponds to (*x*, *y*, *z*) as follows:

$$(x, y, z) = (X, y_0 + Y/\sqrt{2}, Y/\sqrt{2}). \quad (3)$$

In Fig. 3, the luminance change along the *Y* axis can be related to the dependence of the spatial luminance on the *y* and *z* positions as the *Y* position is related to the *y* and *z* position. As the height *H* of the diffuser screen is 187 mm, the *y* coordinate of the upper boundary of the screen is $(H/2) \sin 45° = 66.1$ mm apart from the center of the screen. Hence, the data measured at $y_0 = 200$ mm cover the *y* range of 133.9–266.1 mm, while the data measured at $y_0 = 300$ mm cover the *y* range of 233.9–366.1 mm. In Fig. 3, the periodic luminance change is observed along the horizontal direction. Dark and bright regions are interchanged for the test image data of WB and BW. Bright regions in Figs. 3(a) and 3(c) corresponds to the region where the left image can be well observed. On the other hand, bright regions in Figs. 3(b) and 3(d) corresponds to the region where the right image can be well observed. If the distance between these dark and bright regions is about equal to the IPD, two eyes can see the different images as required for an autostereoscopic two-view displays.

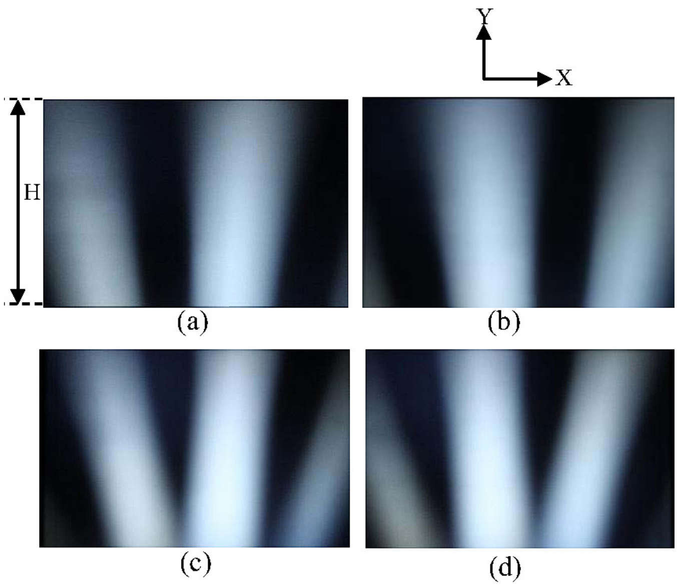

FIGURE 3 — Photos of the diffuser screen illuminated by a 3-D display when the image data and distance from the 3-D display are (a) WB, 300 mm, (b) BW, 300 mm, (c) WB, 200 mm, and (d) BW, 200 mm. *X* and *Y* represent the horizontal and the vertical position of the photo of the tilted screen.

From the gray data of each photo, a $\gamma = 2.2$ is used to convert the gray level to the luminance such that the luminance is equal to (gray level/255)$^{\gamma}$. From this luminance data of arbitrary units (A.U.), Eq. (1) is used to calculate the spatial distribution of 3-D cross-talk for the left eye. The results are shown in Fig. 5 which shows a contour map of base 10 of the logarithm of 3-D cross-talk. Equi-lines in Fig. 5 represent the 3-D cross-talk values of 0.01, 0.1, 1, 10, and 100, respectively. The lower side of each figure is close to the 3-D display, compared with the upper side of each figure. The 3-D cross-talk shows the periodic trends along the *X* direction while the periods of 3-D cross-talk increase as the *Y* value increases.

For the condition of y_0 = 300 mm, the interval of 3-D cross-talk along the horizontal direction is measured to be

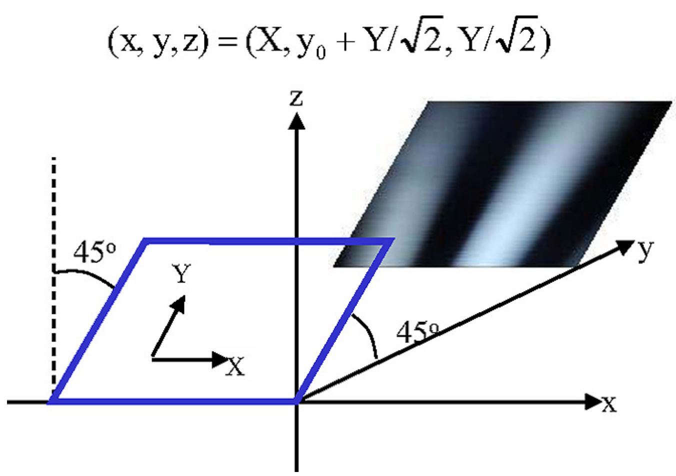

FIGURE 4 — Relationship between the *xyz* coordinate of the measurement setup defined in Fig. 1 and the *XY* coordinate of the photo defined in Fig. 3.

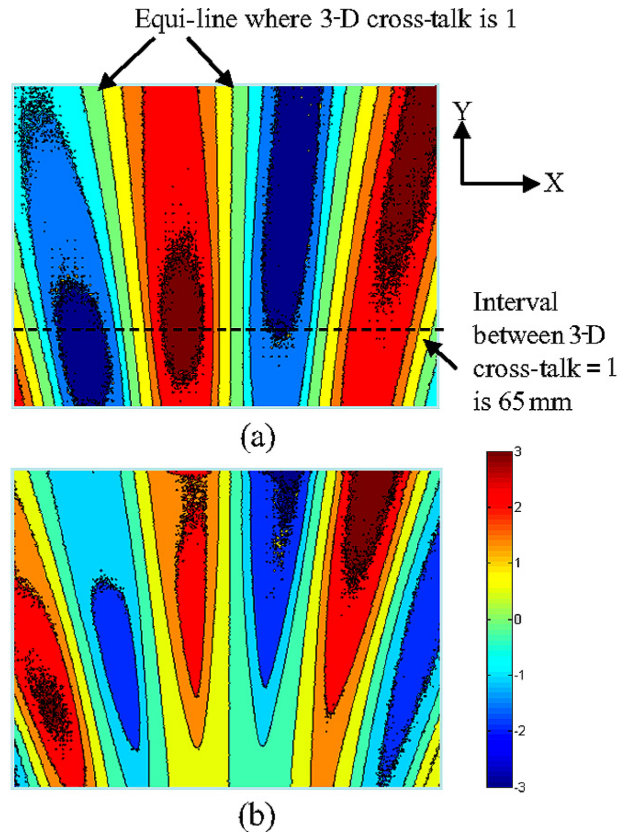

FIGURE 5 — Contour map of the base 10 logarithm of 3-D cross-talk, which is calculated from the luminance distribution on the diffuser screen for the test image data of WB, BW, and BB. The distance from the 3-D display, y_0, is (a) 300 mm and (b) 200 mm. Along the dotted line, intervals between 3-D cross-talk = 1 are 65 mm.

equal to an IPD of 65 mm at the downward vertical position of $Y = -49$ mm from the center of the diffuser screen. This position corresponds to the position that $y = y_0 - 34.6$ mm = 265.4 mm and $z = -34.6$ mm in *xyz* coordinate defined in Fig. 1. Figure 6 illustrates the luminance profile along the *x* axis for the *y* position of 265.4 mm and the *z* position of –34.6 mm. At the positions of the first and the third peaks, the luminance of the image for the left eye is strong while the image for the right eye is almost zero. So these are the positions for the left eye to observe the 3-D display. Similarly, the positions of the second and the fourth peaks are positions for the right eye.

The luminance data can be measured at the positions where the tilted screen occupies, but this does not provide data at the different y positions with the fixed *z* position such as $z = 0$. To check the dependence of the spatial luminance on the *z* direction, data measured at the conditions of y_0 = 200 and 300 mm are compared. Figure 7 illustrates the relative positions of the diffuser screens at the conditions of y_0 = 200 mm and 300 mm. The two ranges overlap at the *y* range of 233.9–266.1 mm, where $z - z' = 100$ mm. For example, in case for a *y* position of 265.4 mm, a *z* position of –34.6 mm at the condition of y_0 = 300 mm corresponds to a *z* position of 65.4 mm at the conditions of y_0 = 200 mm. Figure 8(a) illustrates the luminance profile along the *x* axis for the *y* position of 265.4 mm, *z* position of 65.4 mm, determined

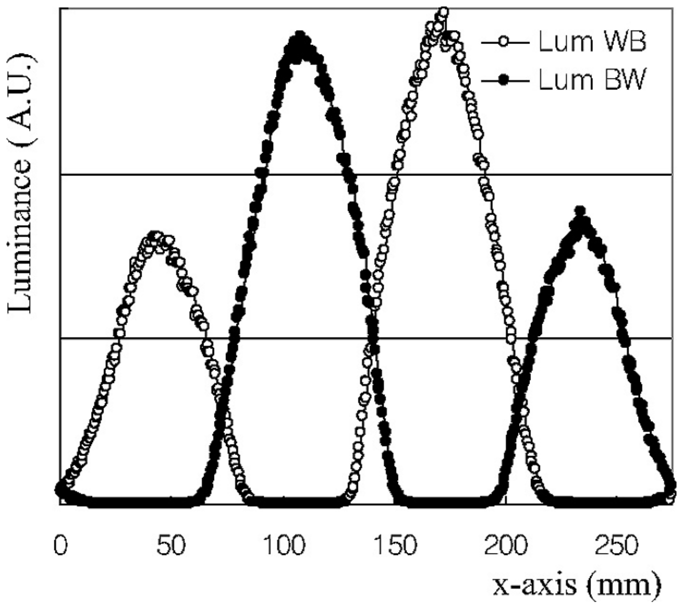

FIGURE 6 — Luminance profile along the x axis derived from the condition of y_0 = 300 mm, where the y position is 265.4 mm and the z position is –34.6 mm. WB and BW represent the test image data. Horizontal and vertical axes represent the horizontal position on the diffuser screen and the relative luminance of the arbitrary unit (A.U.).

from the measurement conditions of y_0 = 200 mm. Figure 8(b) illustrates 3-D cross-talk at y = 265.4 mm for two conditions of y_0.

The y positions of the lower side of Fig. 5(a) and the upper side of Fig. 5(b) overlap. The contour maps of Figs. 5(a) and 5(b) at the overlapped regions and two curves of 3-D cross-talk of Fig. 8(b) show that the profiles of 3-D cross-talk are somewhat similar, though the results at y_0 = 200 mm were derived from the upper side and the results at y_0 = 300 mm were from the upper side of the diffuser screen. This similarity can be attributed to the fact that the optical element in front of the autostereoscopic 3-D display, such as lenticular lens and the parallax barrier, is uniform along the vertical direction and the spatial luminance varies slightly along the vertical direction, compared with x or y direction. Therefore, for the diffuser screen of height H and tilted angle θ, the z position in the range of $-(H/2)$ and $+(H/2)$ sin θ has relatively little effect on the spatial luminance distribution. Hence, it is expected that the spatial luminance along the y axis at z = 0 can be derived for the distance range of $y_0 - (H/2)\sin\theta$ and $y_0 + (H/2)\sin\theta$ using the tilted diffuser screen.

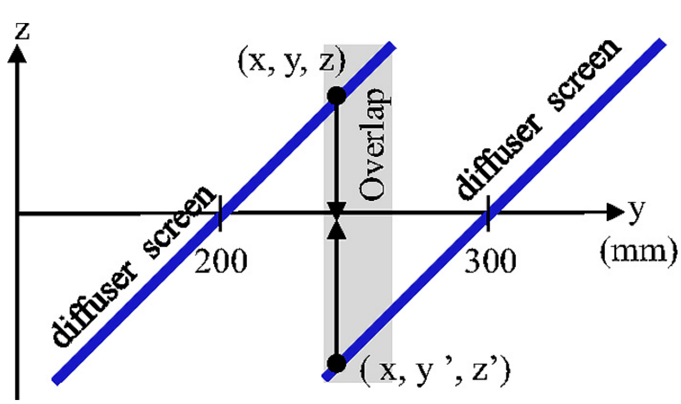

FIGURE 7 — Relationship of positions between the diffuser screen condition of y_0 = 200 and 300 mm. Position y of the diffuser screens at two y_0 conditions overlaps when $z - z'$ = 10 and $z > 0$ and $z' < 0$.

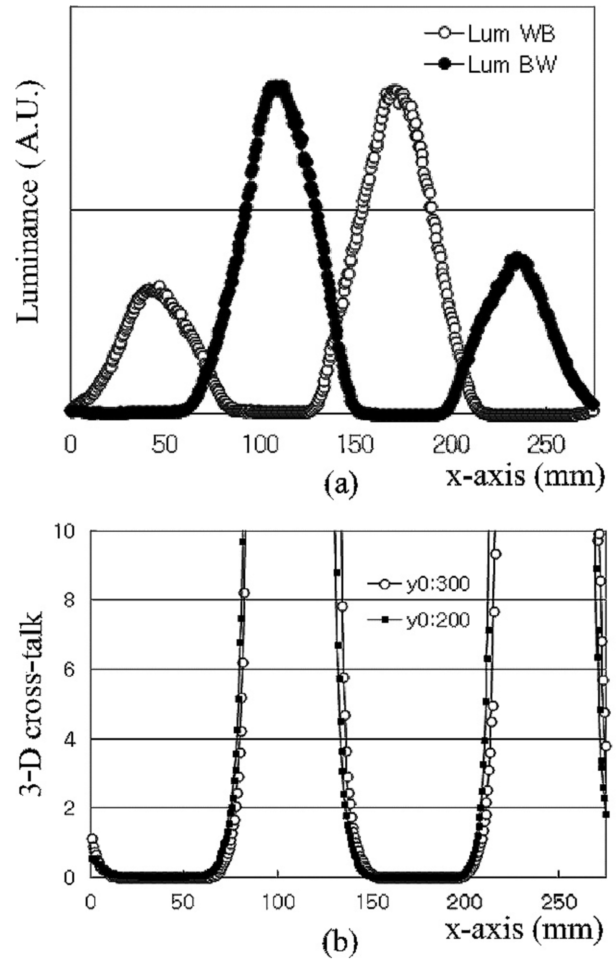

FIGURE 8 — (a) Luminance profile along the x axis derived from the condition of y_0 = 200 mm, where the y position is 265.4 mm and the z position is +65.4 mm. WB and BW represent the test image data. Horizontal and vertical axes represent the horizontal position on the diffuser screen and the relative luminance of the arbitrary unit (A.U.). (b) 3-D cross-talk at the y position of 265.4 mm, determined from the y_0 conditions of 200 and 300 mm. The horizontal and vertical axis represent the horizontal position on the diffuser screen and 3-D cross-talk.

The digital photo consists of the image data of 256 gray levels. If one gray level is assumed as the error range of digital photo, the error of one gray level roughly corresponds to the change of 0.4% in 256 gray levels. When γ = 2.2 is used to convert the gray level to the luminance, this change of 0.4% results in a luminance change of 0.9%, and the accuracy of luminance can be treated as about 0.9%. In the case of 3-D cross-talks, 3-D cross-talk of a few percent is reported to be noticeable.[14] In Eq. (1), subtraction between two luminance values can cause an error of 1.8%. The 3-D cross-talk obtained by this method is expected to be useful in determining whether 3-D cross-talk is noticeable or not at the various user positions.

4 Conclusion

Measurement of the spatial luminance distribution for an autostereoscopic 3-D display is quite time-consuming work. Generally, an autostereoscopic 3-D display has a relatively small positional dependence along the vertical direction. By tilting the diffuser screen, the luminance distribution at different distances from the 3-D display can be quickly measured fast.

This method is expected to provide a fast and simple method to characterize the spatial luminance distribution at user positions. However, because the luminance distribution is derived from the two-dimensional luminance at the diffuser screen, the accuracy of the proposed method is somewhat limited. But, it is expected to be combined with other accurate but time-consuming measuring method to shorten the overall measuring time. For example, this method can be used to obtain the overall luminance profile and determine the possible positions for further measurement. Then, at these positions, the LMD can be placed to obtain reliable and accurate data.

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