INVITED PAPER *Special Section on Electronic Displays*

Spectrophotometer Calibration by a Double Integrating Sphere Reference Light Source and Display Panel Measurement Using Dark Sphere

Tatsuhiko MATSUMOTO[†,††a)], ***Member***, **Shigeo KUBOTA**[††], **Tsutomu SHIMURA**[††], **Shuichi HAGA**[†], **Takehiro NAKATSUE**[†], ***and*** **Junichi OHSAKO**[††], ***Nonmembers***

SUMMARY We succeeded to develop a reference light source in the range of very low luminance using a double integrating sphere system, and calibrated a commercial spectrophotometer below 1×10^{-5} cd/m^2 levels, which is 1/100 lower than the specified limit for measurement. And we improved measurements in the ultra low luminance range of displays using the calibrated commercial spectrophotometer and a dark sphere to suppress the influence of the surround.

key words: *display contrast measurement, spectrophotometer calibration*

1. Introduction

Today, various types of flat-panel displays such as LCD, OLED and others are improving their performance toward higher contrast. As a result, the dynamic contrast of the LCD TV of more than 1M:1 has been achieved by LED backlight local dimming control technology. It is realized by the improvement of the black level of the panels.

Figure 1 shows the necessary black level to realize the 1M:1 contrast ratio. If the white level is 400 cd/m^2, the black level should be less than 4×10^{-4} cd/m^2. However, this is in the luminance range lower than the specified limit of measurement of commercial spectrophotometers.

Moreover, the measurement of the black level of a panel is influenced by the stray light in the surround such as the lights emitted by peripheral equipment in a darkroom (Fig. 2(a)), and even in a completely dark room, the light from the display panel outside the measuring point may be reflected and influence the measurement (Fig. 2(b)).

Therefore, we examined the limitations of the accuracy of a commercial spectrophotometer in the ultra low luminance region and also examined the influence of the stray light in the darkroom on the measurement of the display panel using a dark sphere.

2. Calibration of the Spectrophotometer

2.1 Principle of Luminance Reduction in a Double Integrating Sphere System

Luminance is generally a complex photometric quantity, because it is defined as the second derivative of the luminous flux with respect to the area of source aperture dA_S and the projected solid angle $\cos\theta_S d\omega_S$ into which the luminous flux is emitted: $L = d^2\Phi/\cos\theta_S dA_S d\omega_S$ [3].

Within an integrating sphere, however, since the sphere wall surface is an approximately Lambertian surface, the luminance on the sphere wall is constant. Given Φ_{in} as the input flux, taking the total flux after multiple diffuse reflections as $\Phi = (1+\rho+\rho^2+\ldots)\Phi_{in} = \rho/(1-\rho)\Phi_{in}$, where ρ is the average reflectivity of the diffuse wall, the definition of luminance on the sphere wall is much simplified (proportional to luminous flux Φ) as described by

$$L = \rho_w/(1-(1-f)\rho)\Phi_{in}/\pi S \tag{1}$$

where ρ_w is the diffuse wall reflectivity, f is the ratio of the port areas to the total sphere wall area $S = 4\pi r^2$ and r is the radius of the sphere.

From this point, an integrating sphere is much advantageous to describe the luminance of a standard light source.

Equation (1) is the so-called integrating sphere equation, which furthermore reveals an important relationship between the luminances of two spheres connected by a circular aperture. Given the luminance of the first sphere wall L_1, surrounded by the Lambertian sphere wall, the luminance over the circular aperture (radius a) is also L_1 and it behaves as a Lambertrian source, which emits flux $\Phi_{in} = \pi L_1 A_S$ into the second sphere, where $A_S = \pi a^2$. Substituting these into Eq. (1), the luminance of the second sphere wall L_2 is given by

$$\begin{aligned} L_2 &= \rho_w/(1-(1-f)\rho)L_1 A_S/S \\ &= \rho_w/(1-(1-f)\rho)(a/2r)^2 L_1 \end{aligned} \tag{2}$$

showing that the luminance reduction ratio between the two sphere walls is proportional to the squared ratio of a to $2r$:$(a/2r)^2$.

This double integrating sphere system has advantages

Manuscript received March 4, 2010.
Manuscript revised June 11, 2010.

[†] The authors are with Sony, Tokyo, 141-0001 Japan.
[††] The authors are with The Univ. of Tokyo, Tokyo, 153-8505 Japan.
a) E-mail: Tatsuhiko.Matsumoto@jp.sony.com

DOI: 10.1587/transele.E93.C.1590

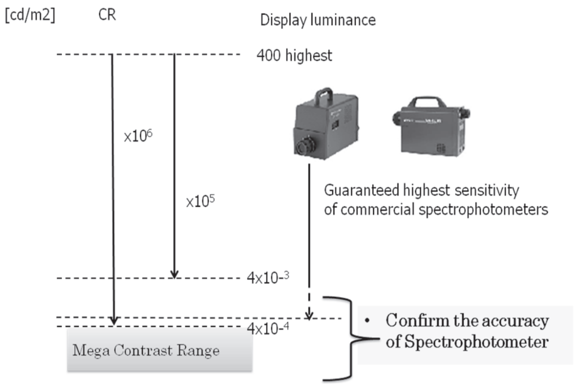
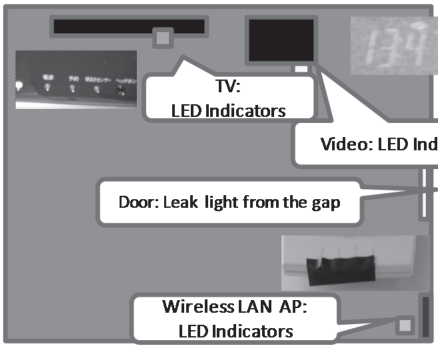
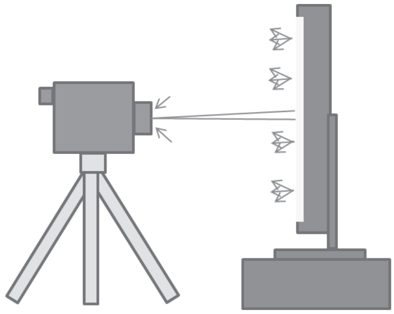


Fig. 1 Necessary black level for mega contrast range.



(a) Stray light in the surround



(b)The diffused light from outside the measuring point

Fig. 2 Examples of stray light which influence the measurement at very low luminance.

for luminance reduction compared to methods using the inverse square law of distance on an optical bench, which requires critical alignment. Figure 3 shows an example of the conventional luminance calibration method using a standard incandescent lamp for luminous intensity and a white reflectance standard [5].

The luminance of the white reflectance standard L_s is described by

$$L_s = \rho_s I/\pi D^2 \tag{3}$$

where I is the luminous intensity of the standard incandescent lamp for luminous intensity, D is the distance between the lamp and the reflectance standard, and ρ_s is the reflectivity of the white reflectance standard.

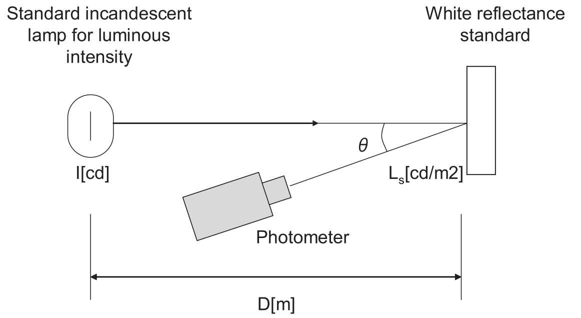


Fig. 3 Luminance calibration using the inverse square law of distance.

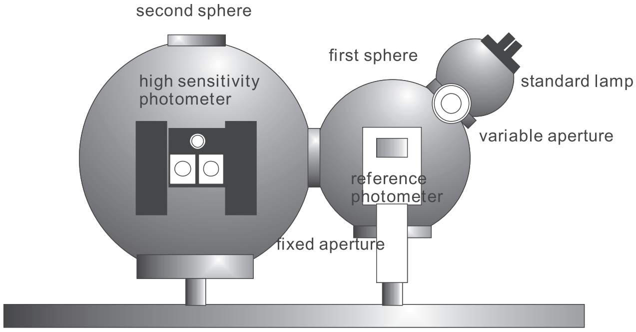


Fig. 4 Sphere configuration for very low luminance light source.

The specified minimum luminous intensity of the standard lamp is 10 cd, and the maximum distance of the optical bench for calibration is 5 m [6]. By applying Eq. (3) with I =10.0 [cd], D =5.0 [m], and ρ_s =1.0, the luminance of the white reflectance L_s is calculated to be 0.127 cd/m^2. So, this method cannot realize accurate calibrated luminance in the range below 10^{-2} cd/m^2.

Figure 4 shows the actual configuration of the double integrating sphere system for a very low luminance light source.

The diameters of the first and second spheres are 8”(~200 mm) and 12”(~300 mm), respectively. We chose the value of the ratio of the luminances of the first and second spheres to be about 300:1 by selecting the diameter of the aperture. Therefore, when the luminance of the first sphere is in the range of 10^{-3} cd/m^2, in which the accuracy of the photometer is guaranteed, the achievable luminance of the second sphere is in the 10^{-5} cd/m^2 range. In this way, we can examine the limitation of the commercial spectrophotometer by measuring the deviation of the ratio of the luminances of the first and second spheres in the very low luminance range.

A commercially available photometer is on the first sphere, and our original high sensitivity photometer is on the second sphere as a monitor to check the linearity between the luminances L1 and L2.

The detector of the high sensitivity photometer is a Si photo diode S9295 of Hamamatsu Photonics cooled to −20°C. We stored this detector and an operational amplifier integrating circuit board in a metal case attached to a heat

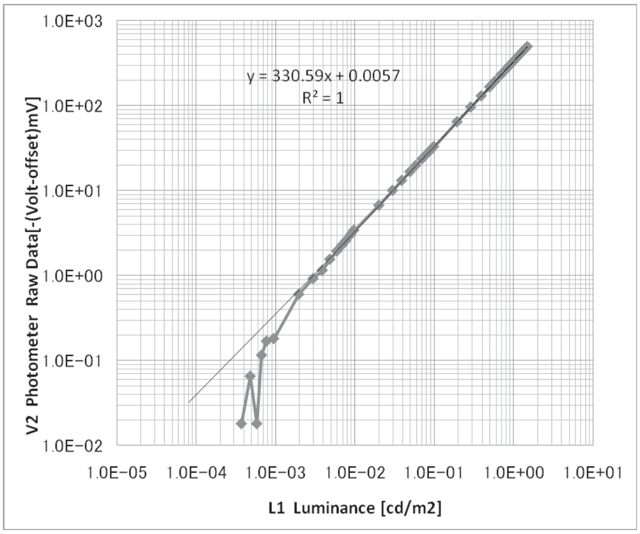


Fig. 5 Relationship between luminance of first sphere (L1) and values of the original photometer of second sphere (V2).

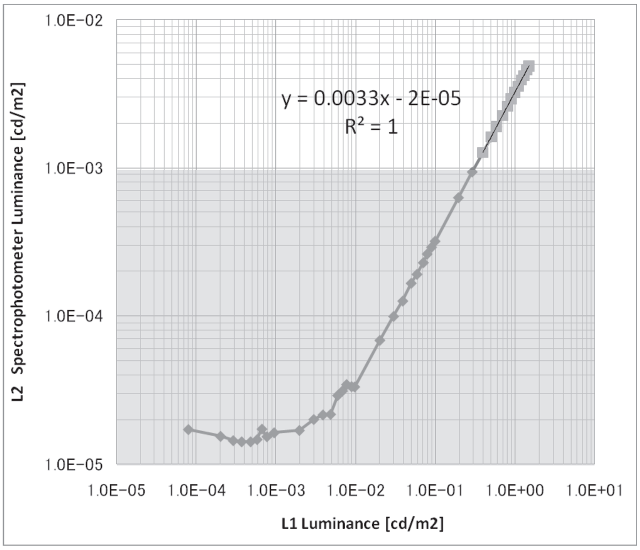


Fig. 6 Relationship between the luminance of the first and second spheres (L2 luminance was measured by a commercial spectrophotometer which is guaranteed in the luminance range higher than 10^{-3} cd/m^2).

sink unit for heat dissipation.

2.2 Experiment to Verify Luminance Reduction Constancy

Figure 5 shows the relationship between the luminance (L1) of the first sphere and the values (V2) measured by the original photometer which represents the luminance (L2) of the second sphere. The linearity of the relationship between L1 and V2 is maintained down to 2×10^{-3} cd/m^2 of L1 luminance, where L2 is at the level of 6.6×10^{-6} cd/m^2 and V2 continues to decrease to 1.0×10^{-1} mV as L1 decreases down to around 1×10^{-3} cd/m^2.

Figure 6 shows the results of luminance measurements

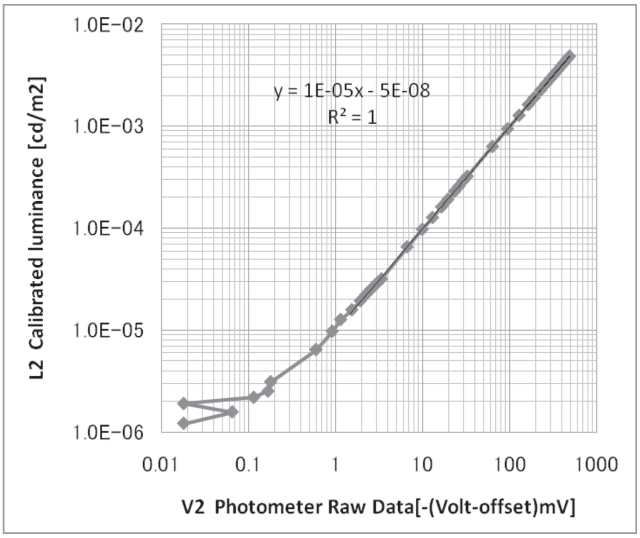


Fig. 7 Luminance determination (Relationship between V2 and L2).

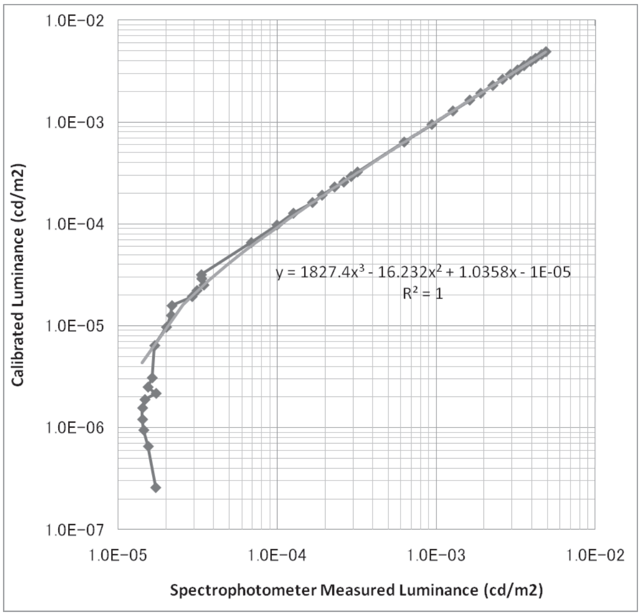


Fig. 8 Calibration of the commercial spectrophotometer.

made by a commercial spectrophotometer. This spectrophotometer is guaranteed in the luminance range higher than 10^{-3} cd/m^2. So, values in the meshed area of Fig. 6 are uncertified.

Therefore, we calculate the accurate L2/L1 ratio by using values at higher than 10^{-3} cd/m^2 of L2 luminance. From this ratio, we derived the luminance corresponding to the original photometer's raw data. The results are shown in Fig. 7.

Figure 7 shows that this apparatus can realize calibrated light of luminance down to the middle range of 10^{-6} cd/m^2 level by deriving L2 from the L1 luminance.

From Fig. 7, we can say this apparatus has an ability of realizing calibrated light of luminance down to the mid-

Table 1 Maximum sensitivities of the original photometer and the commercial spectrophotometer.

	Measured Value	Calibrated Luminance
Original Photometer	6.0×10^{-1}[mV]*	5.95×10^{-6}[cd/m^2]
Commercial Spectrophotometer	2.0×10^{-5} [cd/m^2]	1.07×10^{-5} [cd/m^2]

* after offset voltage correction

dle range of 10^{-6} cd/m^2 level by deriving L2 from the L1 luminance.

2.3 Calibration Experiment of a Commercial Spectrophotometer

We tested a method to calibrate a commercial spectrophotometer using the double integrating sphere reference light source.

Figure 8 shows the fitted curve of the relationship between the measurements made by the commercial spectrophotometer and the calibrated luminance of the second sphere. This curve can be used in the range greater than 2×10^{-5} cd/m^2. At lower levels, this spectrophotometer can indicate only that the luminance is less than 1×10^{-5} cd/m^2.

Table 1 shows the maximum sensitivity of our original photometer and the commercial spectrophotometer. This table shows that luminances down to 1.0×10^{-5} cd/m^2 can be measured by the commercial spectrophotometer with calibration.

3. Display Measurement Using a Dark Sphere

To eliminate the influence of the low luminance light in the surround, we put a dark sphere between the panel and the measuring instrument. We prepared two hemispherical Styrofoam shells of 400 mm diameter to make this dark sphere [2]. The inner surfaces of the hemispherical shells were sprayed with black paint to reduce reflections of light as much as possible. Windows were cut open in both the shells on the panel side and on the measurement instrument side to let light through. The dark sphere was completed by attaching the shells together. Figure 9 shows the photograph of the dark sphere and darkness inside.

Using the dark sphere made in this way, only the emitted rays nearly normal to the display panel can enter the window of the measuring instrument, and all the other stray and flare lights caused by multiple internal reflection in the panel cover glass are attenuated inside the sphere and do not influence the measurement result.

We examined the effects of using the dark sphere by measuring the luminance of uniform dark gray levels for 4 types of TV display panels: LCDs with a CCFL backlight and with an LED backlight, a plasma TV, and an OLED TV. The results are shown in Fig. 10.

The luminance in Fig. 10 were obtained by applying the calibrated values from Fig. 6.

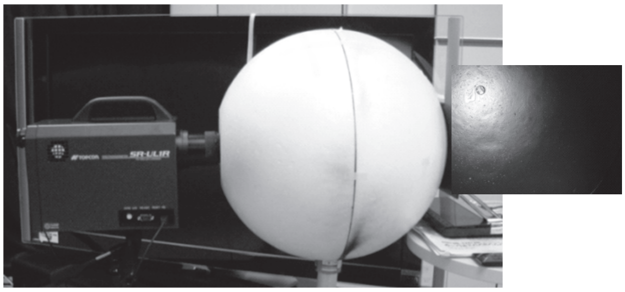


Fig. 9 Dark sphere and appearance inside.

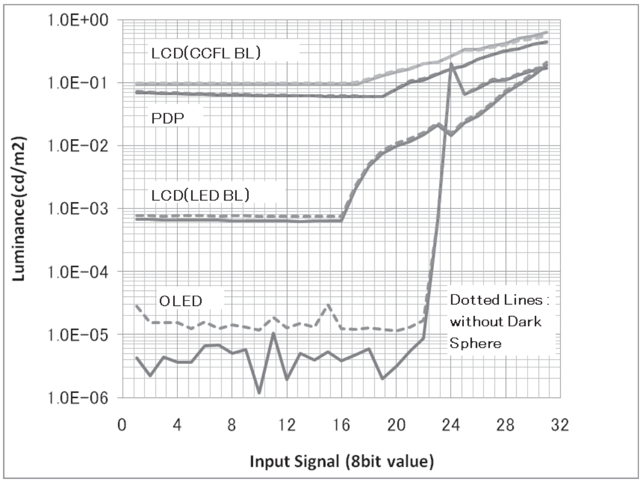


Fig. 10 Luminance of the low-luminance gradations of display panels (Calibrated values).

Table 2 Average luminance of levels 1-17 levels (Range below black).

TV Type	With Dark Sphere[cd/m^2]	Without Dark Sphere[cd/m^2]	Stray Light[cd/m^2] (ratio)
OLED	(1×10^{-5})	1.6×10^{-5}	about1.6×10^{-5} (>60%)
LCD(LED BL)	6.48×10^{-4}	7.61×10^{-4}	1.13×10^{-4} (17%)
LCD(CCFL BL)	9.32×10^{-2}	9.91×10^{-2}	0.59×10^{-2} (6%)
PDP	6.38×10^{-2}	6.56×10^{-2}	0.18×10^{-2} (3%)

There are clear differences between the luminances with and without the dark sphere for the OLED TV and for the LCD with LED backlight.

Table 2 shows the calibrated luminances of the black levels of TVs calculated from the averages of the luminances for input signal levels from 1 to 15.

The measured values for the OLED TV using the dark sphere are in the range below 1×10^{-5} cd/m^2 which is the background level of the spectrophotometer. Therefore these data are uncertain and we can judge only that the luminances are less than 1×10^{-5} cd/m^2. We can estimate that the stray light is less than 1.6×10^{-5} cd/m^2 from the luminance without the dark sphere. Therefore the stray light from surround is less than 1.6×10^{-5} cd/m^2 and the stray light from the display panel is zero.

The stray light for the LCD TV with LED backlight can be calculated as 1.13×10^{-4} cd/m^2 from the difference between the results of measurements using the two methods of measuring of the display panel. The origin of its stray light can be divided into the surround and the panel, which account for 14% and 86%, respectively.

We can also calculate the stray lights from the LCD TV with CCFL backlight and the PDP TV. However, because the differences of the luminances between the two methods are small compared to with the luminance of the measuring spot, the differences in the values of the luminances are in the range of error.

Therefore, by using the dark sphere, we can estimate the luminances of the stray lights from the surround and from the panel and eliminate the effects of their presence.

4. Conclusion

We succeeded to make a standard calibrated light source by using the double integrating sphere system in the range higher than 2×10^{-5} cd/m^2, and to calibrate a commercial spectrophotometer, whose the accuracy is specified above 1×10^{-3} cd/m^2, in the range down to 10^{-5} cd/m^2.

We were also able to improve the luminance measurements of display panels in the ultra low luminance range by using the dark sphere to eliminate the stray lights from both the panel and the surround.

Acknowledgments

This research was supported in part by the New Energy and Industrial Technology Development Organization, Japan (NEDO).

References

[1] S. Kubota, T. Matsumoto, and T. Shimura, "An integrating sphere system to realize very-low-luminance reference light sources," IDW'08, vol.3, pp.2115–2118, 2008.
[2] K. Saiki, S. Tsuboi, and H. Hayashi, "Assemblage and application of a field integrating sphere for flat field," The Japanese Society for Planetary Science, vol.10, pp.126–135, 2001.
[3] E.F. Kelley, G.R. Jones, and T.A. Germer, "The three components of reflection," Information Display, SID, vol.10, pp.24–29, 1998.
[4] E.F. Kelley, G.R. Jones, and T.A. Germer, "Display reflectance model based on the BRDF," Displays, vol.19, no.1, pp.27–34, June 1998.
[5] The Illuminating Engineering Institute of Japan, Hikari no Keisoku Manual, pp.239–242, 1990.
[6] JCSS, Technical Requirements Application Indicator, Registration Division: Light, 2006.

Tatsuhiko Matsumoto is a researcher at the Sony Corporation. He received the M.S. degree in material science from the University of Tokyo in 1997. He joined Sony Corporation in 1997. He spent 2007 to 2009 at the Institute of Industrial Science of the University of Tokyo as a project researcher of Sony Chair of Color Science. His research interests include color rendering technology of visual components. He is a member of the Society for Information Display (SID), and the Institute of Image Information and Television Engineers (ITE).

Shigeo Kubota received B.S. and Doctor of Engineering Degree from the University of Tokyo in 1971 and 1986 respectively. He joined Sony Corporation in 1971. He was invited to the Institute of Industrial Science, the University of Tokyo as a project professor of Sony Chair of Color Science in 2007. His research interests include optical science such as incoherent and coherent optical metrology. He is a member of the Optical Society of Japan (OSJ) and the Optical Society of America.

Tsutomu Shimura received Ph.D. degree from the University of Tokyo 1987. He has been working at the Institute of Industrial Science, the University of Tokyo since 1987, and now is a Professor. His main research field is photorefractive effects, holographic data storage, and applications of nonlinear optics.

Shuichi Haga received M.S. degree in material science from Nagaoka University of Technology in 1983. He joined Sony Corporation in 1983. Now he engages in evaluation of visual quality of display device.

Takehiro Nakatsue received B.S. degree in applied physics from Tokyo Institute of Technology in 1980. He joined Sony Corporation in 1990. Now, he engages in evaluation and improvement of visual products applying the visual engineering.

Junichi Ohsako received the M.S. degree from the University of Electro-Communications in 1981. He joined Sony Corporation in 1981. Now he engages in development of UX Systems as General Manager.