Integrating Sphere for Luminance Calibration

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Abstract

A digital camera can be used to measure and document scene luminance, providing the camera can be calibrated by photographing a source of known luminance.

This paper describes a low-cost, purpose-built integrating sphere which creates uniform, diffuse field of light at an opening in the sphere. The illuminance at this port can be measured using a low-cost luxmeter. The luminance is then a simple function of the illuminance and so the luminance of the shere port is a known value for camera calibration.

The integrating sphere has other applications, among them measuring the total output flux of a light source, and determining the reflectance of materials.

Figure 1: Integrating Sphere, showing latches, base and DC power jack for the LED light source.

1 Introduction

This project arose out of a need to measure the luminance of light pollution sources. A modern digital camera can be used for such measurements, but it requires calibration with a source of known luminance.

1. Suitable sources of standard luminance are available in the standards laboratories, but access is expensive[1].

2. A calibrated luminance meter is expensive. For example the Minolta LS-100 Luminance Meter costs about $3300 [1]. The Tektronix J16 Photometer with 6503 luminance probe is sometimes available for a reasonable price on the surplus market. Be prepared to replace the power supply (which is NiCad battery based). The luminance probe may require calibration.

3. A photographic spot meter can be used to measure exposure value. This can then be related to luminance [2]. A new spot meter is expensive, typically $800, but they are occasionally available used. We obtained a used Minolta-M spotmeter for $350.

4. An *illuminance* meter (measuring in lux or foot-candles) is an inexpensive instrument, costing about $60. See for example the Mastech LX1330B [3]. If luminance and illuminance can be related, then the calibration can be done with this instrument. That turns out to be the case.

   It can be shown (see reference [4] and section 7.2) that illuminance and luminance are related as :

   $$L = \frac{E}{\pi} \tag{1}$$

   where:

E	is the illuminance in lux
L	is the luminance in candela per metre^2

   For this equation to apply, the source of illumination must be uniform and diffuse which, it turns out, is available at the aperture of an integrating sphere.

2 The Integrating Sphere

The integrating sphere is a hollow sphere that is coated on the inside surface with a reflective, diffusing paint. The sphere is equipped with one or more measuring ports – in this case, a single opening. A light source is placed inside the sphere, shielded so that it is not directly visible from the measuring port. Light from the source reflects repeatedly from the sphere painted surface, resulting in a uniform light field over the interior surface. Viewed from the port, light intensity has equal magnitude irrespective of direction, that is, the light field is uniform and diffuse, as required by equation 1.

Consequently, it should be possible to relate illuminance and luminance by the following:

Figure 2: Integrating Sphere, Measuring Port Luminance

> The illuminance meter is placed in the diffuse light field at the output port the integrating sphere to measure E. The luminance L at the port opening is predicted according to equation 1. The port is then a calibrated source of luminance for a digital camera or luminance meter (figure 2).

[1] The National Research Council of Canada quoted $1800 to calibrate a luminance meter.

2.1 Construction

According to [5], to avoid significant impact on the operation of the sphere the port opening should be no more than 5% of the total area. For the instruments in our collection, the largest illuminance meter sensor area is 2.1 inches in diameter. A port of that diameter would require a sphere diameter of 11 inches diameter, minimum.

A suitable basis for the sphere was found at the local Ikea store, a 14 inch diameter stainless steel mixing bowl[2].

Each of these bowls has a 3 inch diameter flat at the base of the bowl. The flat base of one sphere was used for the port, which was opened with a 2.25 inch Greenlee chassis punch. The flat of the other sphere was pounded out match the curvature of the bowl. The pounding was accomplished with a 2"x4" wooden post, rounded at one end with a belt sander to roughly match the curvature of the bowl. The hammering was done with a sledge hammer over soft ground.

The inside of each bowl was painted with several coats of a matte white metal spray paint *Cloud 3*[3].

To align the two bowls, a 1 inch wide strip of thin sheet metal was pop-rivetted to the inside surface of the perifery of one of the bowls. To assemble the sphere, one slides the other bowl over this skirt. Four toggle latches[4] hold the bowls together.

The base was constructed using a 5.5 inch square by 0.75 inch clear pine block with furniture feet [5] implanted and pointing upward. This arrangement keeps the sphere from rolling about on the work surface. The sphere can be pointed at an arbitrary angle and will stay there[6]. Figure 1 shows the completed sphere on its base.

2.2 Light Source

Two different sources were tested in the original design of the sphere: an LED point source and an incandescent lamp. Subsequently these were replaced by an LED ring light, and then a distributed LED strip array.

2.2.1 LED Point Source

The LED light source[7] is concentrated into a small emitting area. The LED was operated from a constant-current source[8] at a current of 360mA. The LED source ran quite hot (about 60°C) and as a consequence the light output decreased by some 10% while warming up. With some help from translucent plastic over the LED, the integrating sphere was surprisingly effective in diffusing this point source and the sphere aperture was uniformly illuminated. If the LED is allowed to warm up, and the aperture illuminance is measured shortly before being used as a calibration source, then it would probably be acceptable. However, we were concerned that the light output was excessively dependent on the temperature of the LED source.

2.2.2 Incandescent Lamp

The incandescent light source was a 60 watt incandescent lamp[9], nominal output 550 lumens. A sheet-metal shield blocked directed light from the lamp reaching the port. The aperture illumination was sufficiently uniform.

The incandescent lamp is operated from the AC line. Unfortunately, due to the limited thermal inertia of the lamp filament, the incandescent lamp output varies by some 10% at a rate of 120 times per second (period, 8.3 milliseconds). Figure 3 shows a recording of a photodiode detecting the lamp

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[2] Ikea #000.572.26, $17 each.

[3] Krylon Outdoor Spaces 42904 Cloud (SHERWIN-WILLIAMS CANADA INC. KRYLON Products Group Vaughan, ON L4K 4T8. The manufacturer gives the tristimus coordinates for this paint as X:74.67, Y:79.32, Z:85.63)

[4] Lee Valley Part Number 00S5590, Stainless steel Draw Latch.

[5] Lee Valley Part Number 00H5001 Levelling Glide.

[6] This construction might make the basis for a *portaball* type telescope: `http://www.mag1instruments.com/index.php`.

[7] LedEngin part number LZ4-40CW10, available from Newark Electronics, price $29.00 reference [6].

[8] Digikey DKSB1003A, $26.00

[9] Philips *Duramax*, part #129411.

output, measured with a Syscomp CGR-201 oscilloscope. A camera exposure that is much less than this interval will sample this variation at some random instant, introducing an uncertainty of 10% into the measurement of luminance.

The ripple will have no effect if the shutter interval is equal to the period of the ripple waveform, in this case, 1/120 second[10]. Then the exposure is integrated over one period, regardless of where the exposure begins and ends in the ripple cycle. Unfortunately, that limits exposure adjustments to aperture and ISO, which is highly inconvenient.

The light output L of an incandescent lamp is related to the line voltage V according to $L \propto V^{3.4}$ [7]. Consequently a 10% change in line voltage would result in a 40% change in light output. Ideally, the line voltage should be regulated or adjusted to the same value each time, or the aperture needs to be calibrated for each use, with the hope that the line voltage does not change during a measurement.

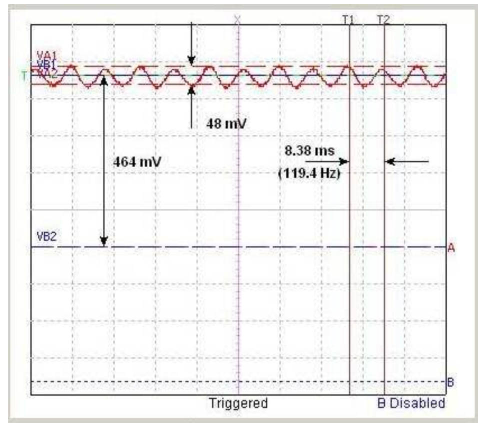


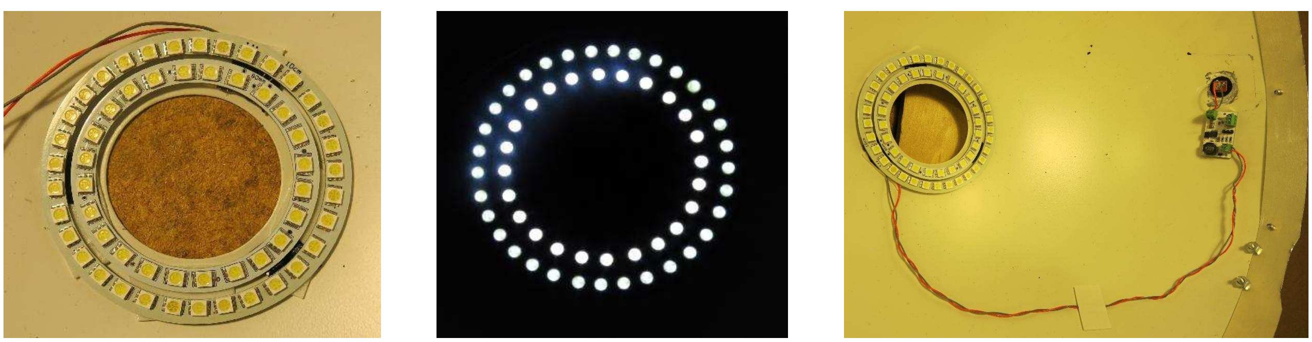
Figure 3: Incandescent Lamp Flicker

The incandescent lamp source is a simple, inexpensive source for the integrating sphere. However, as a result of the ripple and line voltage sensitivity it is not well suited for predictable and consistent measurements.

2.2.3 Ring LED Source

The ring illumination is provided by two rings of LEDs, 8 and 10 centimetres in diameter as shown in figure 4(a)[11]. Each ring consists of strings of LEDs wired in parallel. Each LED string consists of 3 LEDs and a series resistor. The 8 centimeter ring contains 8 strings of LEDs, the 10cm ring contains 11 strings of LEDs.

The rings were mounted inside the sphere using double-sided foam tape, located around the aperture, facing the rear of the sphere.



(a) Ring LEDs (b) Illuminated (c) Wiring with Driver Board

Figure 4: Ring LED Source

The two rings are connected in parallel, and operated from the constant current supply described previously in section 2.2.1[12]. The total current is set to 360mA, giving an LED current of 19mA. The

[10] Alternatively, one could power the lamp from 117VDC. Unfortunately, such a supply is not usually ready to hand in the standard electronics lab.

[11] These units were found in the basement electronics department of College Home Hardware, 290 College Street, Toronto. Toronto electronics enthusiasts will recognize this as the latest location for Supremetronic stock.

[12] The LM317 integrated circuit regulator is inexpensive and readily available, and can be configured as a current source.

resistors in the LED ring ensure that the current is distributed approximately equally in each string, which results in equal illumination from each LED (figure 4(b)). The voltage across the LED rings is about 10 volts at 360mA.

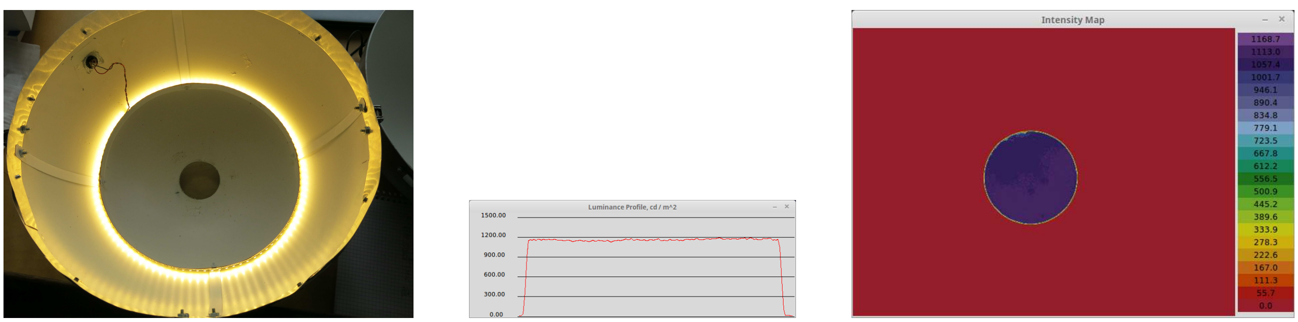
The suggested operation of these LED rings is from a 12 volt DC source. It was found in practice that the slightest variation of output voltage resulted in substantial change in light output. Current drive is much more stable. In this case, the LED driver board regulates the current at 360mA, and the driver board is fed by an 18 volt DC regulated voltage wall adaptor so the LED current should be immune to changes in line voltage or LED voltage.

In the ring illuminator, the light output is distributed over 56 LEDs, compared to one LED in the point source of section 2.2.1. Consequently the temperature rise in each LED of the ring is much less, about 15°C above ambient, compared to 40°C above ambient for the point-source LED. The warmup drift is then much less in the ring illuminator. The light output is within 1% of its final value in 2 minutes, and 0.1% of its final value in 6 minutes. As a consequence, the source is ready to be used almost immediately after it is turned on and is unlikely to drift substantially with ambient temperature.

2.2.4 LED Strip Array

With the near-completion of the *Luma* software, it became apparent that the non-uniformity of the sphere illumination was aversely affecting calibration results. The LED ring emitters described in section 2.2.3 are not completely uniform and they illuminate the rear of the sphere (the area that is viewed through the aperture) directly, rather than being diffused.

As a consequence of this non-uniform illumination a profile line measurement showed a variation of about 25% . A temporary arrangement of cardboard and aluminum foil was then used to deflect the ring illumination to the side walls of the sphere, and the variation reduced to 9%, at the expense of less illumination. This indicated that diffusing the LED illumination would make it more uniform, so we constructed the arrangement shown in figure 5(a).



(a) Sphere Interior (b) Horizontal Profile (c) Intensity Map

Figure 5: LED Strip Source

The LED support structure is a 10 inch (25.4 cm) diameter ring, one inch (2.54 cm) in height. This is held in place by 4 straps which attach to the same bolts holding the latches. The LED strip (Lee Valley part 00U4108, 120 LEDs per metre) is attached to the ring by its adhesive backing. With this arrangement, the LEDs face the sphere wall, which is at a 45 degree angle to the LED output. Consequently, illumination on the rear wall of the sphere does not come directly from an LED but has undergone at least one diffuse reflection.

Connection to the LED strip is brought to a connector on the sphere [13]. A regulated 12 volt supply (Syscomp PSM-101) operates the LEDs, which require a total operating current of 730mA.

Unfortunately, as a linear regulator, it runs quite hot and the output current changes significantly with temperature. The Digikey DKSB1003A recommended for this application is a switching regulator and runs cold. The output current does not change over time.

[13] A 12 volt DC power supply for LED strips is also available from the Lee Valley. However, it has an output ripple of 0.5 volts at 120Hz, which is unacceptable for this application.

At a power supply setting of 12 volts, the illuminance at the aperture is about 4000 lux.

The profile line for the LED strip illumination is shown in figure 5(b). The variation is about 4%, a substantial improvement over previous arrangements. Figure 5(c) shows the intensity map of the aperture. The aperture false-colour is two colours only, which suggests reasonable uniformity.

3 Comparison of Sphere Light Sources

Experience with various light sources in the integrating sphere leads to the following observations:

- A single high intensity LED emitter can supply sufficient light for the sphere. However, even with a heatsink, the temperature and light output change significantly during warm up.
- A single incandescent lamp will work (and is the traditional source for an integrating sphere) but it heats the interior of the sphere and the light output varies at the line frequency.
- One or more LED rings have the advantage of circular symmetry but the LED outputs are not uniform to the degree required by this application and result in a non-uniform field when directed to the rear of the sphere. However, because the light output is spread over a number of LEDs, it does not suffer from the heating drift problem of a single LED emitter.
- A string of LEDs, aimed at the sphere walls, generates a uniform field on the rear wall of the sphere. There is no measureable drift in light output after power-on. The light output is significantly higher than the incandescent lamp, single LED or ring LED sources. The LED string can be dimmed when the string is powered by a variable DC supply.

4 Luminance Calibration: Results

We measured the illuminance at the port with two luxmeters and calculated the corresponding value of luminance. We also measured luminance directly with a luminance meter, and an exposure spotmeter.

The Minolta spotmeter wmeasures *exposure value* EV. For an ASA (film speed) setting of 100, Minolta relates the luminance L to the exposure value as equation 2:

$$L = 0.14 \times 2^{EV} \text{ candela/metre}^2 \tag{2}$$

The measured value of EV was 11.9 Then the measured luminance is:

$$L = 0.14 \times 2^{EV} = 0.14 \times 2^{11.9} = 535 \text{ candela/metre}^2$$

An exposure value of 11.9 could be anywhere between 11.85 and 11.95, so the equivalent luminance could be anywhere between 516 to 553 candela/metre^2.

The results are summarized as follows:

Instrument	Measurement	Reading	Luminance, cd/m^2
Tektronix J16 with 6511 probe	Illuminance	1596 lux	508
Mastech LX1330B	Illuminance	1580 lux	503
Tektronix J16 with 6503 probe	Luminance	525cd/m^2	525
Minolta Model M	Exposure Value	11.9	535
Average			517

The results for luminance are within 3% of the average value.

5 Verification of Results Using SQM-LU Sky Quality Meter

The Unihedron Sky Quality Meter SQM-LU is generally intended for measuring the background light of a night sky [24]. It can however be used as a moderate to low-level luminance meter. This is useful because the SQM-LU is inexpensive when purchased new, and it (or a similar instrument) can often be borrowed from an astronomy club.

The meter reads out in *magnitudes per square arcsecond* (MPSAS). The Unihedron web page gives the conversion formula as follows:

$$L = 10.8 \times 10^4 \times 10^{-0.4M}$$

where L is the luminance in candela per square metre and M is the sky quality in magnitudes per square arcsecond.

Measurement into the sphere port using the SQM-LU Sky Quality Meter generated a reading of 5.93 MPSAS. Converting to luminance, using the formula given above, yeilds a luminance of 458 cd/m^2.

The illuminance at the port entrance, using a Mastech MS6612T illuminance meter (luxmeter) generates a reading of 1468 lux. Converting that to luminance by dividing by π gives a result of 467 cd/m^2. This is within 2% of the result obtained using the SQM-LU.

The fact that these two values of luminance were obtained by completely different instruments and calculations creates confidence that the techniques for measuring luminance that we describe here are reliable and accurate[14].

6 Summary

It is possible to create a predictable source of luminance with relatively modest equipment and minimal expense. One needs a low-cost illuminance meter (luxmeter) and an integrating sphere similar to the unit described in this paper.

The integrating sphere port then creates luminance at the port that is uniform, diffuse and reasonably predictable, that could be used for calibration of a luminance meter, spot light meter, or digital camera.

7 Notes

7.1 Integrating Sphere: Flux and Illuminance

The output luminous flux ϕ of the lamp undergoes a series of reflections. With each reflection, it is diminished by the reflectance of the sphere surface ρ. Consequently the flux returned from the surface of the sphere, ϕ_{int}, is

$$\begin{aligned} \phi_{int} &= \phi \cdot \rho + \phi \cdot \rho^2 + \phi \cdot \rho^3 + \ldots \\ &= \phi(\rho + \rho^2 + \rho^3 + \ldots) \end{aligned} \tag{3}$$

It can be shown [8] that

$$x + x^2 + x^3 = \frac{x}{1 - x}$$

Using that relationship in equation 3 we have:

$$\phi_{int} = \phi \left(\frac{\rho}{1 - \rho} \right) \tag{4}$$

[14] Alert readers will notice that the port luminance has changed from 503 cd/m^2 to 458 cd/m^2 between sections 4 and 5. The time between these two sets of measurements is at least two years, so we attribute the difference to aging of the LED ring. This change in values emphasizes the importance of measuring the luminance on a regular basis.

The illuminance E is equal to the flux ϕ_{int} given in equation 4 divided by the surface area of the sphere, A_s. (This assumes the area of the port is negligible, ie, under 5% of the total).

$$E = \frac{\phi}{A_s} \frac{\rho}{1 - \rho} \quad (5)$$

This is the illuminance on the interior surface of the sphere, which is observed from the sphere port. For a source of given flux, the illuminance at the port increases with a smaller sphere.

The quantity

$$\frac{\rho}{1 - \rho}$$

is known as the *sphere multiplier* and given the symbol M. A larger value of multiplier results in greater illuminance at the output port and improves the uniformity of the light field in the sphere. However, with a large multiplier a small change in reflectivity (due to dust, deterioration of the paint coating, or change in wavelength of the light source) then has a large effect on the sphere calibration [9].

7.2 Integrating Sphere: Illuminance and Luminance

Referring to figure 6, consider that there is an emitting area dA on the inside of the sphere. Then by Lambert's Law of Cosines [10], the intensity of the light emitted is

$$dI = dA \; L \cos(\theta) \quad (6)$$

where:

- dI is the intensity of light emitted by area dA, candela (lumens per steradian)
- dA is small patch of area on the interior surface of the sphere, metres^2
- L is the luminance of the patch, candela per metre squared
- θ is the angle between the emitted light and the normal to the surface, as shown in figure 6.

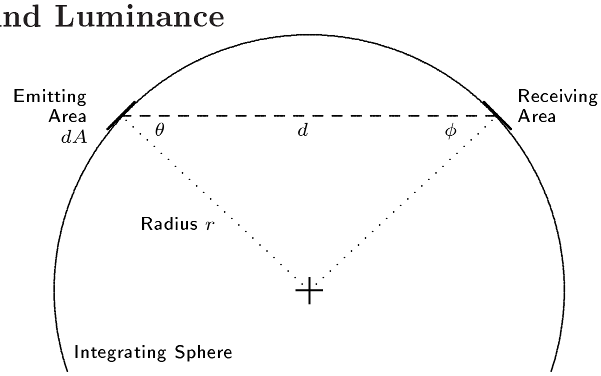


Figure 6: Illuminance and Luminance in the Sphere

At the receiving area, the illuminance is equal to the incident intensity divided by the distance squared (according to the inverse square law) and again subject to Lambert's Law of Cosines:

$$dE = \frac{dI \cos(\phi)}{d^2} \quad (7)$$

where:

- dE is the illuminance on the receiving area, lumens per metre^2 (lux)
- dI is the light intensity emitted from area dA, lumens per steradian (candela)
- ϕ is the angle between the received light and the normal to the surface, as shown in figure 6.

By geometry, since this is the interior of a sphere the angles θ and ϕ are equal. As well, the distance d is given by equation 8:

$$d = 2r \cos(\theta) \quad (8)$$

where r is the sphere radius.

Collapsing equations 6,7 and 8, we find for the illuminance:

$$dE = \frac{LdA}{4r^2} \quad (9)$$

This is the illuminance at any point in the sphere interior, created by the luminance of the patch area. Notice that this is a constant value of illuminance, independent of position or angle.

To relate the illuminance and luminance, integrate equation 9 over the area of the sphere. Then the incremental area da is replaced by the total sphere area, $4\pi r^2$.

$$\begin{aligned} E &= \int_{sphere} \frac{LdA}{4r^2} \\ &= \frac{L(4\pi r^2)}{4r^2} \\ &= \pi L \end{aligned} \quad (10)$$

7.3 Measuring Luminous Flux of the Sources

The integrating sphere is commonly used to measure the total output luminous flux of a light source. A light source will likely produce an output that varies by direction. To determine the total light output, one could plot the output of the light source, generate a three-dimensional function for the light output, and then integrate (average) that function over the surface of the sphere.

The integrating sphere makes that unnecessary. The illuminance at the port may be shown (see section 7.1) to be related to the total output flux of the lamp by equation 11:

$$E = \frac{\phi}{A_s} \frac{\rho}{1-\rho} \quad (11)$$

where:

E	is the illuminance at the sphere port in lux
ϕ	is the total luminous output flux of the lamp, in lumens
A_s	is the total surface area of the sphere in metres^2, equal to $4\pi {r_s}^2$, where r_s is the radius of the sphere in metres.
ρ	is the reflectance of the surface.

If the reflectance ρ is known, then the total output flux ϕ of the lamp, in lumens, is determined by the illuminance at the port E, in lux.

For example, in the case of the LED point source (section 2.2.1) without its diffusing filter the illuminance E at the sphere port is 3260 lux. The surface area A_s of the sphere is 0.397 metres^2. The reflectance ρ under LED illumination is 0.77. Rearranging equation 11 to solve for flux ϕ and plugging in these values, we have:

$$\begin{aligned} \phi &= A_s E \left(\frac{1-\rho}{\rho}\right) \\ &= 0.397 \times 3260 \times \frac{1-0.77}{0.77} \\ &= 386 \text{ lumens} \end{aligned}$$

According to the data sheet, the output of the LED source will be between 228 and 446 lumens.

With known values of output flux for a given source, we could rearrange equation 11 to enter the values of illuminance and sphere surface area, and solve for the reflectance of the sphere interior. However, the nameplate values of lamp and LED source can be dramatically different from their true output. (At one point, we experimented with a compact fluorescent lamp (CFL) which had a nameplate rating of 600 lumens. A measurement of the total flux output showed 863 lumens, an increase over the nameplate value of 140%[15].) Furthermore, measuring the total flux output is not simple, since most sources do not have a spherical distribution.

7.4 Applications for the Integrating Sphere

The integrating sphere was useful in this application because it produces a uniform, diffuse light field of predictable luminance. There are many other applications:

Mixing Colours Helmlinger [12] shows how to build an integrating sphere for demonstration of mixing colours from red, green and blue LEDs.

Luminous Output from LED Flashlight Reference [13] describes construction of a small integrating sphere, used to measure the light output of LED flashlights.

Laser Power Output Reference [14] describes a number of applications, among them the measurement of laser optical power, measurement of transmittance and reflectance, and the testing of imaging systems.

7.5 Acknowledgements

Special thanks to my colleagues Gabriel Guillen, who participated in helpful discussions on this topic, and Axel Jacobs, who pointed out the luminance ripple effect and a formula error in the first draft of this paper.

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