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Luminance-to-Intensity Measurement Method

M. Finkle

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Introduction

The most difficult and interesting visibility problems solved with photometry are usually best referenced from the point of view of the observer and the perceived visual environment. Sometimes the necessary photometric measurements required to evaluate a situation or solve a problem cannot be made due to physical limitations of the measuring equipment. Perhaps the most common example of this occurs with illumination measurements. This also applies to source intensity estimations, calculated from illumination when the measurement distance is known. Illumination measurements of light-emitting traffic control devices, from the observers' perspective, are very difficult to achieve because of the low light levels encountered and the presence of light from other uncontrolled sources.

Recently, a method has been developed for estimating source intensity using a luminance meter in cases where the source is very small and does not fill the aperture of the luminance meter. The method involves measuring the target source with a luminance meter and using the resulting luminance measure to calculate the estimated intensity of the source. Similar to converting an illumination measure to intensity, this method requires that the measurement distance be known. In addition, the size of the luminance meter aperture must also be known.

Background

A luminance meter is designed to measure luminance. Because of the way luminance characterizes a light source, its value is independent of the distance from which it is measured. With a uniform extended light source this is easy to understand. The luminance meter views the source through a fixed viewing angle or aperture. As the distance between the source and luminance meter increases, the illumination on the meter photoreceptor from any infinitesimal point on the source decreases, following the inverse square law. However, the area viewed by the luminance meter increases with the square of distance, thereby increasing the number of points contributing to the measurement. Thus, the total amount of photons falling on the photoreceptor remains constant as long as the source fills the aperture of the luminance meter.

If the luminance meter is moved so far from the source that the source no longer fills the aperture, the illuminance from each infinitesimal point on the source will drop as stated previously, but the number of points

no longer increases proportionately. In fact, the number will remain constant if the source has a black background. Thus, the light falling on the photoreceptor will decrease, as will the luminance meter reading. In the extreme, the angle subtended by the light source will become very small and decrease very slowly. At this point, only the inverse square law will be in effect and the source will act as a point source. Under these conditions, the luminance meter would be measuring the effect of the inverse square law and, therefore, a form of illumination.

This discussion assumes that the photoreceptor reacts to light sources in a linear fashion and its sensitivity does not vary over its surface area. This is not the case with some types of receptors and illustrates the importance of laboratory validation before the luminance meter is used in the field.

Calculations

To calculate the total intensity from a target from the luminance measured, the familiar equation for luminance is rearranged to the following

$$I = L * A \quad (1)$$

where I = total intensity (cd); L = measured luminance (cd/m²); and A = area component(m²).

When the target is much smaller than the aperture of the luminance meter, the area component is the area encompassed by the aperture at the measurement distance. This area is found using the following equation

$$A = [(\tan(\text{APSIZE}) * D) / 2]^2 * \pi \quad (2)$$

where APSIZE = aperture size (radians or degrees) and D = distance between target and luminance meter (m).

If the target is larger than the aperture then the area component (A) in **Equation 1** is no longer the area enclosed by the aperture, but becomes the physical area of the target. In this case, the luminance of the area must be uniform.

When ambient lighting is a factor, such as during daytime measurements or anytime stray light sources enter the background, a second luminance measurement must be taken. The second measurement must be taken with the target "off." This measurement is subtracted from the "on" measurement and the resultant luminance is used to derive the intensity in **Equation 1**.

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Laboratory study

In order to validate the concept of the luminance-to-intensity measurement process, a small laboratory experiment was conducted at the Federal Highway Administration's Photometric Visibility Laboratory in McLean, VA. The objective of the experiment was to compare the estimated intensities of accurate illuminance and luminance measurements to determine the accuracy of the novel measurement method.

Equipment

The light measuring equipment consisted of precisely calibrated illuminance detectors and luminance meters. Illuminance measurements were taken with an LMT Photometer Head with a very fine level of adaption to the luminous efficiency curve $V(\lambda)$ of the human eye. The detector was connected to an LMT Digital Photocurrent Meter I 1000 which displayed the readings. An LMT Luminance Meter was used to collect the necessary luminance measurements. An Optronic Laboratories OL 453 calibration source was used as a target light source. The OL 453 was set up with a 1 inch diameter aperture and was powered by an OL 65DS precision current source at 5.407 A.

Results

After the light source was allowed to stabilize, illuminance measurements were taken at two distances to determine the intensity of the source. **Table 1** contains the results of the illuminance tests. With these results, the intensity of the calibration source was determined to be 4.55 cd.

Luminance measurements were taken 4.19 m from the light source. The LMT meter aperture was set to 1 degree. Using **Equation 2**, the area encompassed by the aperture at the measurement distance was calculated to be 0.004201 m². Three levels of ambient illumination were used during the luminance measurements. A totally darkened room, with overhead fluorescent lighting on, and with a high intensity flood light directed at the light source was used. The different levels were used to simulate different night and day ambient lighting conditions. In lighting conditions 2 and 3, a measurement with the source "off" is required and is subtracted from the "on" measurement. **Table 2** contains the results of the luminance testing. The estimated intensity was calculated using **Equation 1**.

The intensity estimated from the luminance measurements only varied by 8 percent from that derived from the illuminance readings. With these results, the laboratory experiment proved that the luminance-to-intensity method could produce accurate estimations of light source intensity.

Case studies

The need for a method to measure luminous intensity from light emitting sources arose from various research projects in which luminous intensity was the variable of interest. The intensity needed to be measured from the perspective of an observer, who was sometimes several hundred meters away from the source. The unknown or varying geometries encountered in the field made it impossible to estimate the intensity from a laboratory measurement. Furthermore, illuminance levels in the field were too low to measure reliably. Because of the novelty of the approach, the method had to be validated. The following case studies provide information on the validation processes that were used.

Equipment

The photometer used in the case studies was a Minolta LS-110 luminance meter. The LS-110 has a 1/3 degree aperture and a through-the-lens (TTL) viewing system which accurately indicates the area to be measured. The manual states that the optical system is designed to reduce flare so that measurements are "virtually unaffected by light sources outside the measurement area." It goes on to state that the actual amount of light that the meter picks up by a source outside the measurement area is less than 0.1 percent of the value that the meter would give if the source was in the measurement area. The meter uses a silicon photocell to measure the light, and is filtered to closely match the CIE Relative Photopic Luminosity Curve.

A Minolta T-1 illuminance meter was also used in the validation experiments. It uses a silicon photocell and is also filtered to closely match the CIE Relative Photopic Luminosity Curve. The meter has a measurement range of 0.01–99,900 lx.

Validity testing

Two potential problems may be identified with luminance measurements of objects smaller than the luminance meter aperture:

1. The viewing aperture is not the same as the measurement aperture (effect of flare).

Table 1—Illuminance testing results.

	Illuminance (lx)	Estimated intensity (cd)
Distance 1 [1.37 m]	2.43	4.56
Distance 2 [2.90 m]	0.54	4.54

Table 2—Luminance testing results.

Luminance off	Luminance on	Estimated intensity	
	(cd/m ²)	(cd/m ²)	(cd)
Lighting Condition 1	N/A	1168	4.90
Lighting Condition 2	5.0	1171	4.89
Lighting Condition 3	7.5	1176	4.91

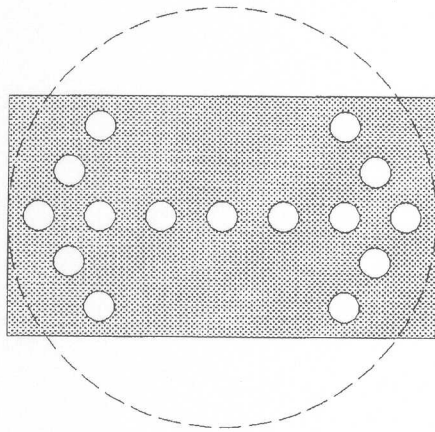


Figure 1—Illustration of how the arrow panel fills the aperture.

2. The sensitivity of the photoreceptor varies over the aperture area.

The effect of flare was accommodated by the manufacturer of the luminance meter. Therefore, the validity testing focused on the potential sensitivity problem and confirmation of the derived luminous intensity values with values calculated from illuminance measurements. Two types of experiments were conducted to validate the photometric technique. Vary the size of the target relative to the aperture. For example, when measuring a fixed target at different distances, the calculated intensity should remain constant. And from a fixed distance, measure the luminance and illuminance of the target. The intensity calculated via both metrics should be the same.

Case 1: Arrow panel visibility study

This section describes the method of luminous intensity measurement of arrow panels used in a portion of an NCHRP study on arrow panel visibility (Mace et al.).¹ The main purpose of that study was to establish the minimum luminous intensity levels that could be incorporated into a standard for arrow panels.

Luminous intensity levels were established using a Minolta LS-110 luminance meter. Since arrow panels are rectangular and the LS-110's aperture is circular, a portion of an arrow panel's background, as well as some of the surrounding background, entered into the field of view of the luminance meter, as shown in **Figure 1**. The

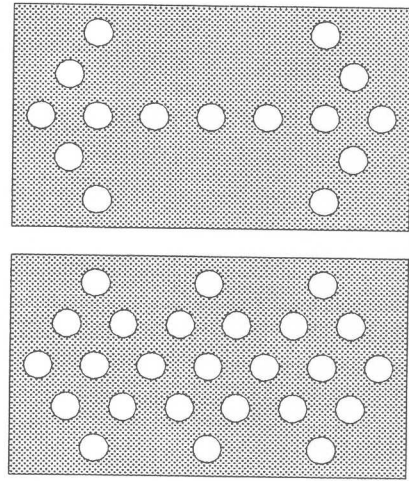


Figure 2—Fifteen- and 25-lamp configurations.

photometric measurements were, therefore, taken at night to ensure a uniform black background in the luminance meter aperture. Because the LS-110 luminance meter has a fixed aperture, the selection of a measuring distance was restricted by the length of the arrow and the size of the luminance meter aperture.

Experimentation

In order to validate the measurement process, both types of experiments described in the previous section were conducted. All tests were conducted on either a 25- or 15-lamp arrow panel, as shown in **Figure 2**.

The luminance measurement was converted into an average luminous intensity per lamp value by dividing the total intensity from the arrow panel, calculated with **Equation 1**, by the number of lamps in the measurement. Lamp intensity, expressed in candelas, was selected as the appropriate unit of measure as it is the standard method used to describe the luminous intensity distribution emitted by a lamp. In the case of an arrow panel, the total intensity is the summed contribution of several lamps. To derive the intensity of an individual lamp, the total intensity of the arrow panel is divided by the number of lamps used to create the display. This calculation assumes that each lamp contributes an equal portion of intensity, which is not necessarily true. The amount of light coming from each lamp may vary somewhat, due to manufacturer tolerances in lamps, lens color, and lamp hoods.

Changing target size in aperture due to distance

For this Type 1 experiment, the measurement target was an arrow panel located on a relatively straight and level section of roadway. This geometry reduced the effect of large changes in entrance angle as the distance was increased. Luminance measurements of the entire arrow panel display were taken at a minimum distance of 458 m. This is the distance at which the 2.1 m long arrow fills the LS-110's 1/3 degree aperture. As the distance from the

Table 3—Changing target size in aperture due to distance.

Distance	Luminance (m)	Intensity/lamp (cd/m ²) (cd)	Aperture filled (percent)
458	285	58	2.28
610	165	163	1.28
763	103	159	0.82
915	70	156	0.57
1068	50	151	0.42

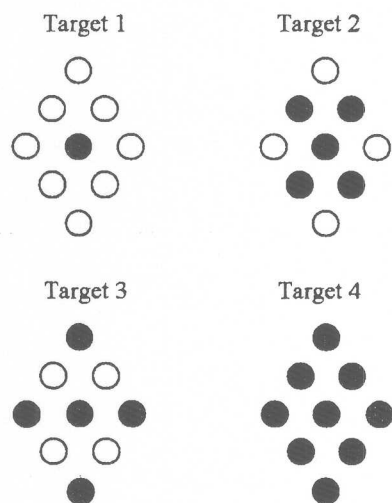


Figure 3—Test targets (shaded circles represent energized lamps).

arrow panel was increased, the size of the target in the aperture of the luminance meter decreased. Ideally, the calculated intensity of the target should have remained constant, regardless of the measurement distance.

The results of the test, shown in **Table 3**, indicate that the measurement procedure yielded relatively constant intensity per lamp values. Deviation in these values is very small and could have accumulated from a number of sources. The most likely sources would be geometric effects which influence the entrance angle from the observer to the arrow panel and atmospheric transmissivity. The percent of the aperture filled by lighted area is also shown in the table.

Changing target size in aperture at a fixed distance

This experiment was a variation of the previous Type 1 experiment. In the first experiment the target remained constant and distance to the arrow panel varied, while in this test the target size changed and the distance was fixed. By changing the target size, the amount of light filling the aperture would vary. Because the targets were composed of lamps with an assumed equal intensity, the calculated intensity per lamp should have remained constant. Only the middle "diamond" of a 25-lamp arrow panel was used (**Figure 2**). The luminance meter was located 244 m from the arrow panel, so that the "diamond" was just within the meter's aperture. **Figure 3** shows the different targets used in the test.

Table 4—Changing target size in aperture at a fixed distance (244 m).

Target ID	Luminance (cd/m ²)	Total intensity (cd)	Intensity/lamp (cd)	Aperture filled (percent)
1	140	221	221	0.8
2	680	1075	215	4.0
3	645	1020	204	4.0
4	1130	1782	198	7.2

Table 4 contains the results of the second experiment. The intensity per lamp is calculated from the measured luminance using **Equation 1** and divided by the number of lamps used in the target. Here again, the aperture-filled quantity is a measure of the lighted area within the area enclosed by the aperture at the measurement distance. The results show that the deviation in the intensity per lamp between the stimuli is small.

The reason why the intensity per lamp value is decreasing as the number of lamps in the aperture increases is due to the assumption that all lamps contribute equally to the total intensity. An explanation of this follows:

1. It is assumed that Target 1 is measured on-axis with the meter.
2. Target 1 has only one lamp turned on and therefore the total intensity calculated from **Equation 1** is also the intensity per lamp value.
3. When more lamps are turned on, as with the other three targets, the individual lamp intensities add together to produce a total intensity. These lamps are not on-axis and do not contribute as much as Target 1 lamp.
4. Dividing the result of **Equation 1** by the number of lamps assumes that the individual contributions of all lamps is equal. This assumption is incorrect because a lamp that is on-axis with the meter gives a higher intensity than a lamp that is off-axis. As more off-axis lamps are added, this error increases.

Comparing illuminance to luminance derived intensities

In order to achieve illuminance measurements high enough to provide a reliable comparison with luminance measurements, luminance and illuminance readings were taken at 153 m and 61 m from the arrow panel. Because of the short distances used in this Type 2 experiment, only two targets were small enough to fit within the luminance meter aperture. These were Targets 1 and 2 of the previous tests. **Table 5** contains the total intensities calculated from illuminance and luminance at both distances, as well as the recorded illuminance readings.

Even though the deviation in the readings is small—15 percent for Target 1 and 3 percent for Target 2—a large portion of the deviation is due to the fact that the illuminance measurements were very close to the lower threshold of the illuminance meter. In fact, the readings had only one significant digit. Documentation for the meter states that it is accurate to ± 1 digit in the last displayed position. This means that the intensities obtained by measuring illuminance could vary as much as ± 40 cd.

Case 2: Symbolic traffic signal study

This case study is from a FHWA



Figure 4—Illustration of how different signals fill the meter aperture.

research project studying the visibility of symbolic traffic signals (Mace et al., Pennak and Finkle).^{2,3} These signals included lane use, turn arrow, and pedestrian control signals. A field study was used to determine the effect of luminous intensity on the visibility of pedestrian signals in hopes that a lower intensity would provide adequate visibility along with a reduction in the required electrical power and, therefore, a cost savings. Nineteen different signal types and configurations were used in the study, including incandescent, fiberoptic, and LED light sources. Symbolic and textual "WALK" and "DONT WALK" were represented on a mix of 9 and 12 inch (230 and 300 mm) signal sizes. As with the previous case study, the exact geometry between the signals and the observers was unknown. **Figure 4** shows how various pedestrian signals were measured with the luminance meter.

Experimentation

Because of time constraints, only a handful of the signals were used in the validation experiments. **Table 6** describes the signals that were used and gives an ID code for identification in this document. The luminous intensity of each signal was calculated from nighttime luminance readings, here again to ensure a uniform black background. The Minolta LS-110's 1/3 degree aperture forced the measurement distance of the 12 inch (300 mm) signals to 53 m, which was used for the 9 inch (230 mm) signals as well.

Only a Type 2 experiment, comparison of luminance and illuminance derived intensities, was conducted. Based on the results of the previous case study, Type 1 and 2 experiments were dropped. Also included was a comparison of nighttime to daytime luminance derived intensity values. The daytime luminance measurement

Table 6—Description of signals used in validation experiments.

Signal ID	Description
B	12-inch orange incandescent hand
C	12-inch white incandescent man
F	12-inch white fiberoptic man
G	12-inch orange fiber optic hand
H	12-inch white fiberoptic "WALK"
I	12-inch orange fiberoptic "DONT WALK"
J2	9-inch orange incandescent hand
K2	9-inch white incandescent man
L	9-inch green incandescent hand
M	9-inch white incandescent hand
N	9-inch orange incandescent man
O	9-inch red incandescent hand

process included a "signal off" measurement which was subtracted from the "signal on" measurement before conversion to luminous intensity.

Comparing illuminance and luminance derived intensities

Nighttime luminance and illuminance measurements were taken at 53 m from the signals. Due to the presence of overhead lighting, an "off" illuminance measure was taken and subtracted from the "on" measure. The luminance measures did not require an "off" measure because the "off" readings were negligible when compared to the "on" readings. **Table 7** contains the results of the experiment.

The differences in the results are small and could easily be explained by measurement and equipment tolerances. As in the previous case study, the illuminance measurements are close to the lower threshold of the meter.

Comparing nighttime and daytime luminance derived intensities

The purpose of this experiment was to determine if the luminance-to-intensity method could be used during the day in bright ambient conditions. The experiment involved taking luminance measurements of the pedestrian signals from 53 m. Because of the high ambient light levels, an "off" measurement was taken and subtracted from the "on" measurement. These two measures were taken with as little delay as possible between them. A change in the ambient light levels from one measurement to the next corrupts the entire process. **Table 8** contains the results of the experiment.

Table 5—Comparing illuminance and luminance derived intensities.

Target ID	61 m			153 m		
	Illuminance (lx)	Intensity by Illuminance	Intensity by luminance	Illuminance (lux)	Intensity by illuminance	Intensity by luminance
1	0.05	186	2142	N/A (too low)	—	—
2	N/A (too close)	—	—	0.05	1170	1135

Table 7—Comparing illuminance and luminance derived intensities.

Signal ID	Luminance on (cd/m ²)	Calculated intensity (cd)	Illuminance off (lx)	Illuminance on (lx)	Calculated intensity (cd)
J2	2364	176.4	0.09	0.15	168.8
K2	1652	123.3	0.07	0.12	140.7
M	2466	184.0	0.08	0.15	196.1
N	1845	137.7	0.08	0.13	140.7

Table 8—Daytime and nighttime measurements.

Signal ID	Daytime		Nighttime		
	Luminance [off] (cd/m ²)	Luminance [on] (cd/m ²)	Calculated intensity (cd)	Luminance [on] (cd/m ²)	Calculated intensity (cd)
B	370	1223	63.7	772	57.6
C	538	1028	36.6	548	40.9
F	572	2964	111.4	372	102.4
G	592	3576	222.7	2937	219.2
H	780	3173	178.6	2231	166.5
I	826	3143	172.9	2359	176.0
L	975	2014	77.6	1144	85.4
O	930	1450	38.8	504	37.6

The results indicate that daytime measurements can be taken as accurately as nighttime measurements. Again, it must be noted that the daytime "off" and "on" measurements must be taken within a few seconds of one another.

Applications

Human factor experiments geared toward understanding the role of luminous intensity in visibility could benefit from this intensity measurement process. Most field research settings make a more conventional intensity measurement impossible.

For practical applications, the ability to measure the luminous intensity of light-emitting traffic control devices during the daytime with a luminance meter would give traffic engineers a convenient and simple way to take in-service measurements.

Conclusion

The results of the different tests satisfactorily validate the luminance-to-intensity measurement procedure. Until an instrument that is better suited becomes available, it has been shown that a luminance meter can be used for making such field measurements during the day or night. It is, however, unknown as to whether certain luminance meters may be more appropriate than others. For instance, the meter used in these case studies utilized a silicon photocell and not a phototransistor. A phototransistor behaves differently and could alter the results of the tests. Another important consideration is color sensitivity. Color sensitivity is a characteristic of the luminance meter and must be taken into account for both

proper luminance and luminance-to-intensity measurements. Many photometers allow the use of color-correction factors which could be used to correct measurements for color effects.

These facts, and others, must be considered before such atypical use of luminance meters becomes accepted. Any luminance meter used in the luminance-to-intensity procedure should be carefully tested beforehand.

Acknowledgments

The author thanks John Arens of FHWA for his technical contributions and assistance with the laboratory study.

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Discussion

When the luminance-to-illuminance measurement method was first considered, the primary concern was with pedestrian crossing signals having very uniform luminance over the signal. Mr. Finkle then applied this principle to relatively uniform light sources used in

Table A—Results of outdoor experiment.

Setup, distance and viewing direction	Luminance meter used	Luminance with signal on (cd/m ²)	Luminance with signal off (cd/m ²)	Luminance due to signal (cd/m ²)	Total area seen by meter (m ²)	Luminous signal intensity (cd)
1A; 61.3; west	Minolta 1 degree	412	253	159	0.890	142
1B; 61.3 m; west	LMT 1 degree	422	252	170	0.890	151
1C; 61.3 m; west	LMT 20 ft	1794	292	1502	0.0989	148
2A; 29.3 m; west	Minolta 1 degree	845	173	672	0.0205	138
2B; 29.3 m; north	LMT 1 degree	903	198	705	0.0205	145
2C; 29.3 m; north	LMT 20 ft	4570	138	4432	0.228	101
3A; 21.0 m; east	Minolta 1 degree	1650	372	1278	0.1055	135
3B; 21.0 m; east	LMT 1 degree	1747	421	1326	0.1055	140
3C; 21.0 m; east	LMT 20 ft	5300	137	5163	0.0117	60
4A; 25.6 m; south	Minolta 1 degree	2100	1450	650	0.1568	102
4B; 26.5 m; south	LMT 1 degree	2480	1645	835	0.1568	131
4C; 25.6 m; south	LMT 20 ft	4470	181	4289	0.0174	75

Note: The area of an 8-inch traffic signal face is 0.082 m²

arrow boards. When he considered this approach to traffic signals, I became quite concerned about the reliability of this method. Intuitively, I felt measuring traffic signals was beyond the capability of this concept, primarily because of the geometric setup necessary to make good measurements and the impact of high ambient luminance levels surrounding a traffic signal during daytime.

Being a doubting Thomas, I attempted to see how this would work in the field on a bright day. We measured an 8 inch red traffic signal head in the lab and found its luminous intensity to be 135 cd at 2.5 degrees down and straight on. We then mounted this unit outdoors such that we could locate a luminance meter 2.5 degrees below the horizontal, looking at the signal with different backgrounds and at different distances. The results are tabulated in Table A.

The results clearly indicate the viability of the proposed method for field measurements when some errors are acceptable and certain conditions are met. Several precautions, however, must be met. The distance and geometry from the meter to the signal must be accurately measured. The meter aperture used must take in a larger area than the signal. The meter used, especially for measuring red signals, must have good photopic correction at the red end of the spectrum. The normal ± 1.5 –2 percent accuracy to the CIE Photopic Curve stated by the meter manufacturers applies to the area under the curve; the meter may well be off by as much as 50–100 percent near the ends of the visible spectrum. It must be calibrated for the color to be measured. How does the author propose to assure field measurements, done by maintenance crews will meet the above precautionary conditions?

The author is to be congratulated for a new and novel way to measure signals in the field.

J. Arens

Federal Highway Administration

Author's response

To J. Arens

I am glad that Mr. Arens was able to successfully utilize the luminance-to-intensity measurement method for his field test. As he indicates, the measurement accuracy is limited by the characteristics of the luminance meter, especially color correction characteristics. This is also true of conventional luminance measurements. The meter must be satisfactorily calibrated to the color of the measurement stimulus. Distance and aperture size are also important to the method and must be noted accurately. The geometry, however, is not of importance for general use of the measurement method. It only becomes important when field measurements, using the luminance-to-intensity method, are compared with laboratory intensity measurements. For the measurements to be equivalent, the geometries must also be equivalent.

As with any measurement method, a proper procedure must be followed to ensure the validity of the results. Such a procedure should be established before any maintenance crews use this method for measuring light sources.