



# Technical Notes

Issue 8 April 2012

## Lumen Maintenance Testing of Off-grid Lighting Products

This Technical Note covers methods for measuring lumen maintenance of LED based off-grid lighting products, focusing on low-cost methods to evaluate a product's ability to provide long-term lighting service.

*The Information contained in this article builds on previous Technical Notes, see also:  
<http://www.lightingafrica.org/resources/briefing-notes.html>*

### Introduction

Consistent luminous flux over the lifetime of an LED lighting product (referred to as lumen maintenance) is an important performance metric. Lighting designers, manufacturers, importers, as well as government and non-government organizations often require lumen maintenance data to evaluate product quality. For those who do not have specialized training and access to relatively high-cost photometric equipment, there exist simple, low-cost devices that can accurately measure LED lumen maintenance. Two such devices, a box-photometer and a tube-photometer, can be constructed of widely available materials, using basic tools, for \$250- \$350. In addition to being inexpensive, the tube- and box-photometers occupy little space, and a minimally trained operator can make lumen maintenance measurements quickly with both devices.

### LED Lumen Maintenance

LEDs do not tend to fail catastrophically. Instead, they experience an irreversible decrease in light output over time called '**lumen depreciation**'. The inverse of lumen depreciation, '**lumen maintenance**' is defined as the percentage of the initial luminous flux output remaining at a specified elapsed operating time.<sup>1</sup> For example, an LED product may lose 30% of its initial light output after running for 2000 hours. Its lumen maintenance would then be 70% at 2000 hours, also written as  $L_{70}$ . If the product instead retained 90% of its initial light output after 6000 hours of operation, its lumen maintenance would be " $L_{90}$  at 6000 hours".

Modern off-grid lighting technologies must be competitive on the basis of cost-per-time of lighting service if they are to be adopted by low-income consumers. Unfortunately, many low-quality LED

products exhibit such rapid lumen depreciation that the potential economic savings are never achieved. With this in mind, the Lighting Africa Quality Test Method (LA-QTM) and Initial Screening Method (LA-ISIM) include an off-grid lighting-specific method for measuring lumen maintenance that is derived from existing standards and internationally accepted methods. Examples of lumen maintenance plots for "stable" and rapidly depreciating lighting products are shown in Figures 1 and 2.

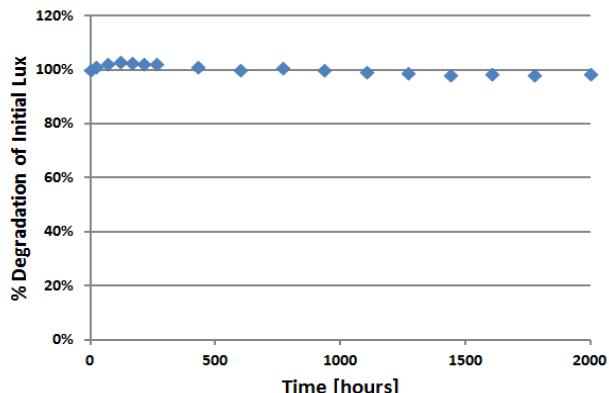


Figure 1. Lumen maintenance plot for a product that meets Lighting Africa minimum standards.

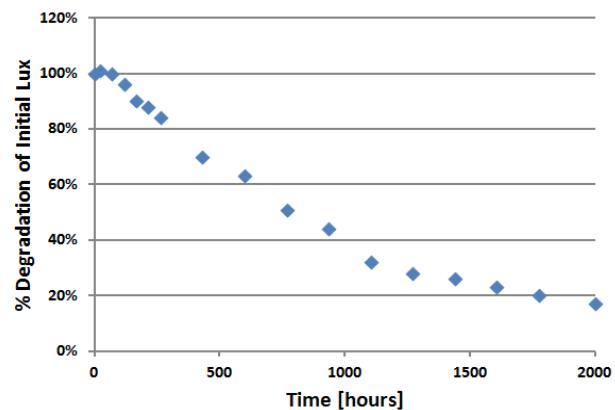


Figure 2. Lumen maintenance plot for a product that fails Lighting Africa minimum standards.

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## Reference Test Methods

The test method established in LM-80-08 by the Illuminating Engineering Society (IES) serves as the primary methodological reference for determining the lumen maintenance of individual LED components. LM-80-08 specifies that an LED, LED array, or LED module must be operated for at least 6,000 hours, with data collection every 1,000 hours, resulting in a minimum of six measurements over the course of the test. These measurements are typically conducted with an integrating sphere-spectrophotometer system, as described by the International Commission on Illumination (CIE) technical report on the measurement of luminous flux (CIE 84-1989). LM-80-08 states that LEDs are to be driven at a constant current that is specified by the LED manufacturer, and must be regulated to within  $\pm 3\%$  of the rated value over the testing period. The ambient air temperature is maintained at  $25^{\circ}\text{C} \pm 2^{\circ}\text{C}$  and airflow must be minimized in order to reduce the effects of convective heat transfer away from the LED package. A lumen maintenance test report must include all of the operating conditions and the percent change in initial luminous flux at each measurement interval.

LM-80-08 is an accurate method for measuring the change in LED luminous flux for an LED source over time. Alterations to the LM-80-08 procedure have been incorporated into the LA-QTM and LA-ISM in order to allow and simplify testing of LED-based off-grid lighting products. These changes help distinguish between products that experience rapid lumen depreciation and those that are able to provide thousands of hours of lighting service while reducing the time, expense, and complexity of lifetime testing.

## Lumen Maintenance Testing Procedure

The Lighting Africa program specifies that the off-grid lighting product be continuously operated for a period of 500 hours for LA-ISM and 2,000 hours for LA-QTM.

The light output is measured at regular intervals using a fixed-geometry measurement cavity under constant conditions.<sup>2</sup> The light output is quantified in units of lumens (for luminous flux measurements) or lux (for illuminance measurements), depending on the type of testing device used.

For each light output measurement, the following must be reported:

- Relative light output (initial measurement divided by the measurement at a specific time interval)
- Operating time of the light source
- Ambient air temperature
- Current and voltage delivered to the light source

### Measurement frequency

The LA-QTM requires at least 17 light output measurements are conducted over the course of the test. The LA-ISM requires at least 6 light output measurements. The initial measurement is taken after a 20 minute warm up period in order for the light to reach steady state – if for any reason the power is interrupted during the warm up period, a new 20 minute warm up period must be given. The initial measurement should be repeated at least once to check for an erroneous measurement. The second measurement should be made 24 hours later to determine if the product is likely to experience extremely rapid lumen depreciation. If the relative luminous flux at the second measurement is approximately 95% or less, then the measurement frequency needs to be increased to capture the time at which  $L_{70}$  is reached. The LA-QTM indicates that the next five light output measurements should be taken at 48-hour intervals, which are then followed by measurements at one-week intervals. LA-ISM recommends that measurements be conducted at 100-hour intervals. Discretion must be exercised to determine the appropriate measurement frequency, according to the resolution desired as well as availability of equipment and operators.

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## Ambient conditions

The ambient air temperature must be maintained at  $25^{\circ}\text{C} \pm 3^{\circ}\text{C}$ , with minimal airflow. LEDs are temperature sensitive and large temperature fluctuations or excessive air flow can result in errors in lumen maintenance measurements.

## Power Supply

The device under test (DuT) battery is replaced by a DC power supply set to deliver constant voltage (measured **at the device**) equal to the nominal battery voltage. This voltage must be regulated to within  $\pm 3\%$  for the duration of the testing period and measured with an accuracy of  $\pm 0.2\%$  at each photometric measurement. The power supply should have a resolution of at least 0.01V and 0.001A, and be capable of remote voltage sensing (used with a 4-wire measurement technique) in order to compensate for resistance and voltage drops in wires and connections to the lighting device. For power supplies without remote sensing, the voltage can be measured very close to the lighting device under test to confirm that the voltage input is equal to the nominal battery voltage. Paired, multi-strand wire of the type typically used for speakers (18-22 AWG or 0.258 - 0.823 mm<sup>2</sup>) is acceptable for connecting the lighting product to the power supply – heavier gauge wire (>0.823 mm<sup>2</sup>) is preferred.

During testing, test personnel should be aware of nominal drive current and voltage levels for DuT's. Any discrepancy between expected and actual current or voltage values should be noted, and the test apparatus should be inspected for possible causes. Since the testing provides a constant voltage, and not a constant current, it is not usually possible to regulate the power being delivered to the LED source(s). The DuT electronics regulate this power, and there can be significant drift in this power regulation that can affect the light output of the device.

## Orientation of the lighting product

Over the period of continuous illumination, the device under test should be oriented as it is intended for typical use, in order to replicate the heat transfer occurring during normal operation.

## **Recommended Testing Devices**

Lighting Africa recommends three different devices for measuring lumen maintenance of an off-grid lighting product, in order of decreasing cost and complexity:

- Integrating sphere-spectrometer system
- Self-built box-photometer
- Self-built tube-photometer

Below, is a short description of each method, including recommendations and advice for proper application.

## Integrating Sphere

An integrating sphere is a hollow sphere whose internal surface is a diffuse reflector that spatially integrates radiant flux.<sup>3</sup> While an integrating sphere is

the most complex and expensive option for determining lumen maintenance, it is also the most versatile and can be used for several other photometric measurements including: radiant and luminous flux, laser power, reflectance and transmittance of materials. A typical integrating sphere is shown below in Figure 3.



**Figure 3**  
Integrating sphere  
(<http://www.optronik.de/plm-is-its10.shtml>).

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An integrating sphere is advantageous for use in lumen maintenance testing because it is less susceptible than other cavities to measurement error associated with changes in the location and orientation of the light source within the cavity. Nonetheless, when conducting lumen maintenance measurements, the lighting product should be located in exactly the same alignment and orientation within the sphere to minimize the potential for this error.

The drawbacks of an integrating sphere, especially for users who do not specialize in photometry, include the relatively high cost of a sphere and associated components, the need for frequent calibration, relatively time-intensive measurements, the need for specialized training to operate the system and analyze the data, and relatively large spatial requirements (a 1m diameter integrating sphere, sufficient for testing most off-grid lighting products, typically occupies 4m<sup>2</sup> of floor space).

Accurate luminous flux measurements made with an integrating sphere require calibration of the system according to a ‘standard lamp’ of known radiant flux and correction of the lumen measurement to account for self-absorption of the body of the lighting product. The methods used to calibrate and correct luminous flux measurements made with an integrating sphere are not covered here, as they require a much more in-depth explanation, which will be covered in a forthcoming Technical Note.<sup>3</sup>

## Box-Photometer

A box-photometer is an integrating photometer employing an arbitrarily shaped, hollow box or cavity that can be used to compare the luminous flux of light sources of the same type. The box-photometer is useful and convenient for measuring the **relative** change in light output of a light source, as required to evaluate lumen maintenance. An interior view and a three dimensional rendering of a box-photometer are shown in Figure 4.<sup>4</sup>



Figure 4. Box-photometer (left: Interior view, right: 3-D view)

A typical low-cost box-photometer is a hollow box constructed of wood with the inner surfaces covered in white matte paint. Multiple coats of paint improve the uniformity and reflection of the walls. The finished interior surface is intended to reflect light as diffusely and homogeneously as possible. Care must be taken to apply the paint such that the surface texture is smooth. Midway up one corner of the box is a port that allows an illuminance meter sensor to “see” into the box. A baffle that is constructed of a thin, rigid material (0.5cm-thick plywood is appropriate) is placed in front of the sensor port so that light emitted from the device under test cannot shine directly on the sensor. The light source to be measured is placed on a stand that is located in the center of the box. When closed, the box must not allow any ambient light to enter. Refer to Appendix A for detailed plans for a box-photometer that is suitable for lumen maintenance testing of typical off-grid lighting products.

Relative light output measurements with a box-photometer do not require calibration or device-specific corrections to deliver quick and accurate results. Since no calibration or correction is required, the light source is simply placed in the center of the box and the illuminance measured by the lux/foot-candle meter is recorded. It is extremely important that for each illuminance measurement, the light is placed in the box in exactly the same location, with exactly the same orientation. Even the slightest adjustment in the location or orientation of the light source between measurements can result in significant error in the relative light output measurements.

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Two approaches can be taken when using the box-photometer to conduct lumen maintenance measurements. The box can be dedicated to a single light source, or the device can be used to measure multiple light sources.

## Dedicated box-photometer

A single product sample remains in the box for the entire duration of the test. The benefit of dedicating the box to a single light is that the product can be fixed in the box, thereby reducing the possibility of measurement error due to changes in alignment. In addition, if a lux meter with data logging capability is used, then the illuminance can be continuously monitored and recorded with minimal operator effort. Care should be taken to check that the light source does not build up heat within the cavity, as this can affect both the source and the sensor. Most off-grid products, however, will not dissipate enough power to have significant thermal effects in the box.

## Box-photometer for multiple samples

The box is used to measure multiple lighting products that are operated outside of the box between measurements. Using the box-photometer to intermittently measure multiple samples is more common than the “dedicated” approach, as it greatly increases the testing throughput of the box-photometer. In this case, the test operator must take extreme care to place the light in exactly the same location and orientation for each subsequent measurement. Several methods can be used to ensure replicate product placement within the box, including:

- using a photo for reference that shows the placement of the light
- using a custom jig within the box that holds the light in exactly the same orientation
- marks on the product and test stand to assist in placement and alignment

## Measuring luminous flux with a box-photometer

Luminous flux is usually measured with an integrating sphere in accordance with CIE 84-1989. However, if an integrating sphere is not available, a box-photometer can be used for measuring luminous flux. In practice, however, measuring lumen output with a box-photometer is not recommended since it is relatively cumbersome and inherently more error prone than an integrating sphere-spectrometer system. Modern lighting laboratories generally rely on integrating spheres to make lumen measurements on account of the ease of use, measurement accuracy, and minimal impact of spatial irregularities.

## Tube-Photometer

A tube-photometer is a simple, hand-made device used to measure the **relative** change in illuminance of a light source over time. The apparatus consists of a tube with a cap at one end. The end cap fits snugly on the tube such that it holds the illuminance meter sensor in a fixed position and restricts stray light from entering the tube. Light emitted by a lamp under test is directed into the open end of the tube and the illuminance incident on the sensor head is measured by the lux meter. A diagram of the tube-photometer is shown in Figure 5.

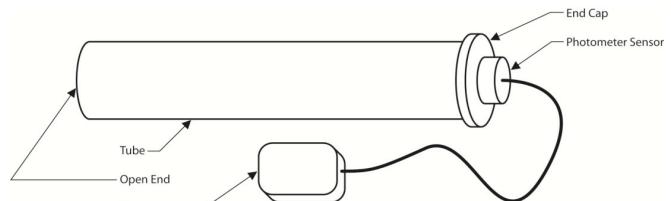


Figure 5. Drawing of a tube-photometer, indicating the basic device components.

Materials for the tube and end cap can be procured at very low cost, often free of cost. Cardboard tubes that are commonly used in rolls of fabric, paper and plastic sheets tend to be widely available and inexpensive, if not free. Alternatively, inexpensive plastic pipe can be used. A typical tube diameter is 6

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cm and an appropriate length for the tube-photometer is 0.5 m, although these dimensions do not need to be strictly adhered to. Ideally, the end cap is machined from a rigid material like wood or plastic that fits snugly into the tube and mates with the photometer sensor such that the sensor is fixed in place. Research has shown that if precise machining equipment is not available, an acceptable end cap can be simply constructed from cardboard and packaging tape.<sup>5</sup> Refer to Appendix B for instructions for constructing the end cap.

Unlike the integrating sphere and box-photometer, the luminous flux of a light source cannot be determined by the tube-photometer. The tube-photometer is used solely for evaluating the lumen depreciation characteristics of a light source. By placing the device under test flush with the open end of the tube, the orientation and distance of the light source from the sensor head can be replicated for each illuminance reading taken throughout the lumen maintenance test. As long as the same orientation between the light source and sensor is maintained for each reading, an accurate measurement of relative change in luminous flux can be achieved.

Similar to the box-photometer, the tube-photometer can be dedicated to measuring the lumen maintenance of a single light source, or used to measure multiple test samples.

## Dedicated tube-photometer

A tube-photometer is dedicated to a single light that is fixed to the open end of the tube. Extreme care must be taken to affix the test product to the tube such that repositioning does not occur between measurements.

## Tube-photometer for multiple test samples

A single tube-photometer is used to measure multiple product samples that are not attached to the open

end of the tube. Rather, the test operator holds the light source flush to the open end of the tube. Maintaining the light source flush with the tube, the operator makes slight adjustments to the angle between the light source and the tube, searching for the maximum illuminance measured by the light meter. **This approach requires a meter that has the ability to record and display the maximum illuminance reading.** The test operator continues “searching” until the maximum illuminance reading displayed on the light meter no longer increases for any orientation of the device under test. For highly directional light sources like small task lights and torches (flashlights), all of the emitted light can be shined into the open end of the tube. Wider distribution light sources (lanterns/ambient lights) may require the operator to select a specific region in which to search for the maximum illuminance.

When using this approach, the test operator must search diligently for the maximum value, only recording the max lux value when all orientations of the light source have been evaluated. The operator must also prevent stray light from entering the tube by covering the light source and tube opening with an opaque cloth or by taking the measurement in a dark room.

## **Box- and Tube-Photometer Reliability**

An analysis of the box- and tube-photometer confirms that the devices can be used to accurately measure the relative change in light output of typical off-grid lighting products.<sup>5</sup> The study compares relative light output measurements made with the box and tube to those made with an integrating sphere. Results indicate that these methods are acceptable substitutes for an integrating sphere when conducting lumen maintenance measurements of light sources with varying physical shapes, sizes, lumen outputs, and spatial light distributions.

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The analysis does warn that errors can result from improper use of the tube- and box-photometers. Specifically, test operators must take care to avoid changes in the light source location and orientation within the box. When testing multiple samples, the operator must be aware of error due to false identification of the maximum illuminance. These errors can be avoided by repeating the measurement procedure and training test operators in the proper use of the equipment.

## Absolute vs. Relative Testing

Relative testing measures the change in a measured test quantity. For lumen maintenance testing, the procedures described herein measure the relative change in light output of a light source over a set time period. Equipment calibrations are less stringent for relative tests than for absolute tests.

Absolute testing, as the name implies, measures absolute quantities (lumens, lux, etc. represent quantities of visible light). Absolute test results require calibrated instruments that have been properly checked and adjusted for accuracy. Ultimately, a properly calibrated instrument will have its calibration performance ‘traceable’ to a proper standard maintained by a professional standards organization.

For example, an illuminance meter may be out of calibration and ‘off’ by 5 lux. Absolute measurements will thus be inaccurate. However, this same meter may be used to measure the change in lux (as during a lumen maintenance test) as long as it is stable and no change has occurred to the meter during the test period (so it must remain 5 lux ‘off’ at the end of the test, too). In this way, relative testing can cancel the error in calibration of the test equipment.

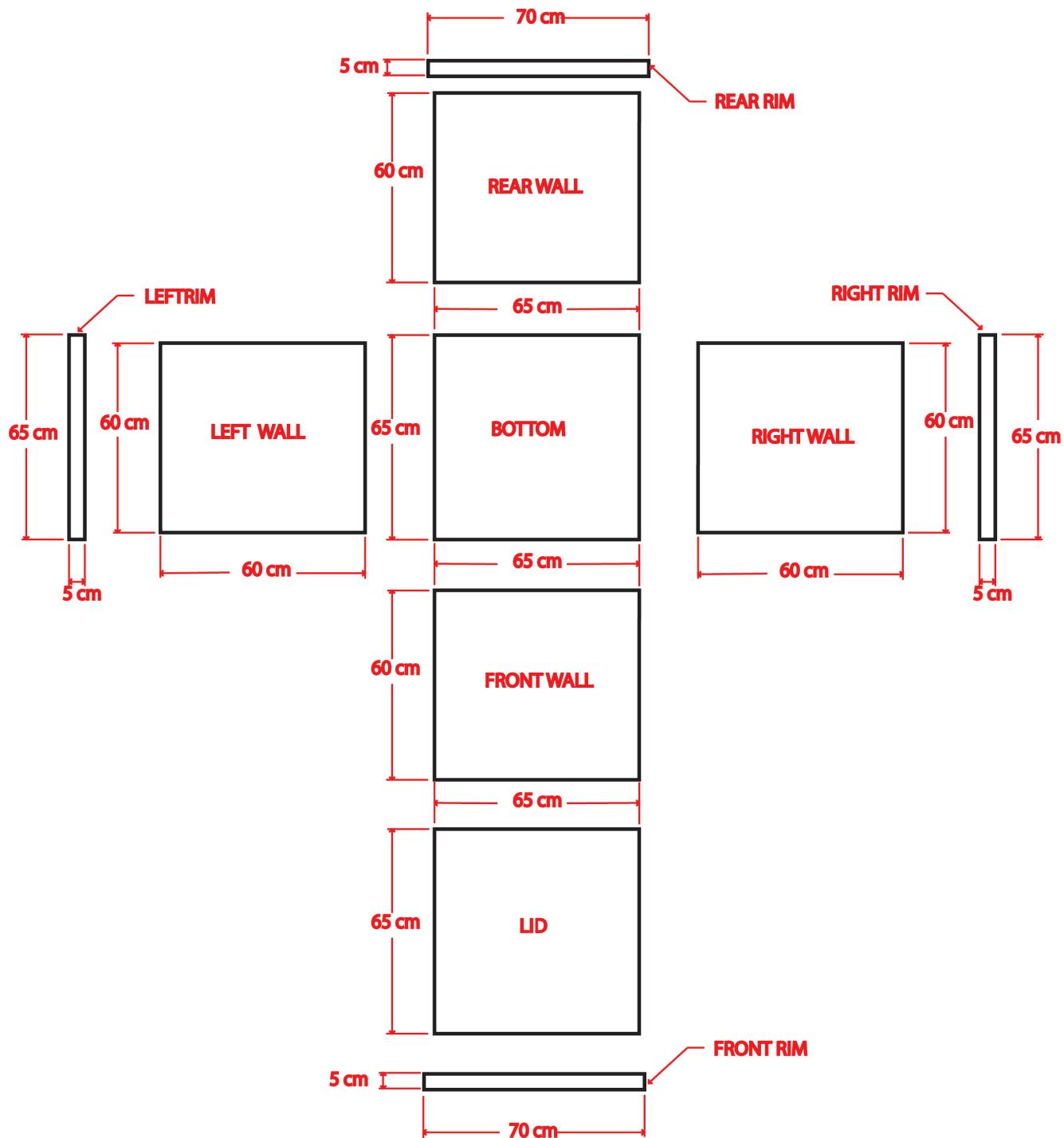
## Conclusion

Lumen maintenance is a critical performance metric that must be measured when evaluating the quality of LED-based lighting products. The box- and tube-photometer are simple and affordable devices that can be constructed and used by non-specialized technicians to accurately measure lumen maintenance. Relative lumen maintenance measurements made with the box and tube require less calibration than absolute measurements. The accuracy measurements made with these devices, however, is highly dependent on stable operating conditions as well as consistent location and orientation of the light source.

## References

1. For more information about the LED lumen depreciation and lifetime, refer to Issue 2 of Lighting Africa Briefing Notes: *LED Lumen Depreciation and Lifetime*
2. Refer to the Lighting Africa Quality Test Method (LA-QTM) for a complete description of the *Long-Term Lumen Degradation Test*, available for download at [www.lightingafrica.org](http://www.lightingafrica.org)
3. Labsphere. (2008). *A Guide to Integrating Sphere Theory and Applications*. Retrieved January 2011. <http://www.labsphere.com/uploads/technicalguides/a-guide-to-integrating-sphere-theory-and-applications.pdf>
4. Basic instructions for construction of a box-photometer are included in Lighting Africa Quality Test Method (LA-QTM) available for download at [www.lightingafrica.org](http://www.lightingafrica.org)
5. Carlsen, C. (2011). *Analysis of Low-cost testing methods for LED lumen maintenance of off-grid lighting products*. Humboldt State University <http://humboldt-dspace.calstate.edu/handle/2148/766>

# PHOTOMETER BOX MAIN PIECES FOR ASSEMBLY

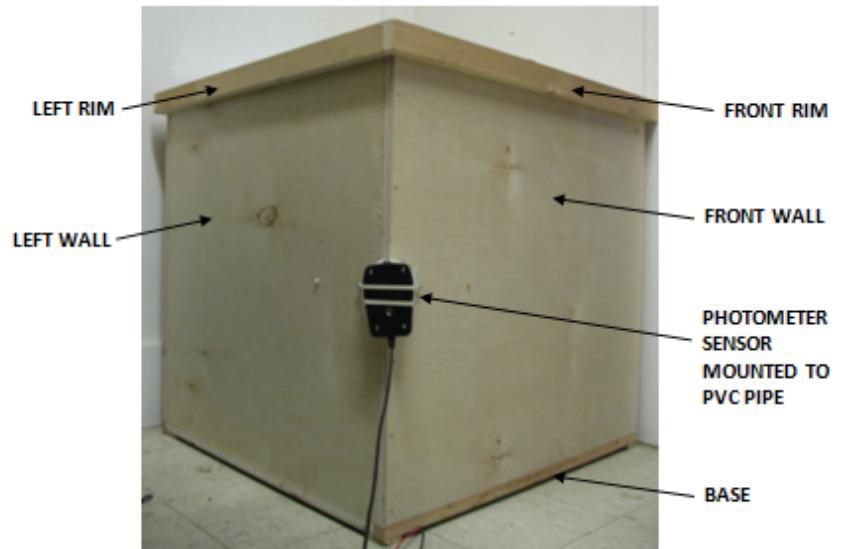
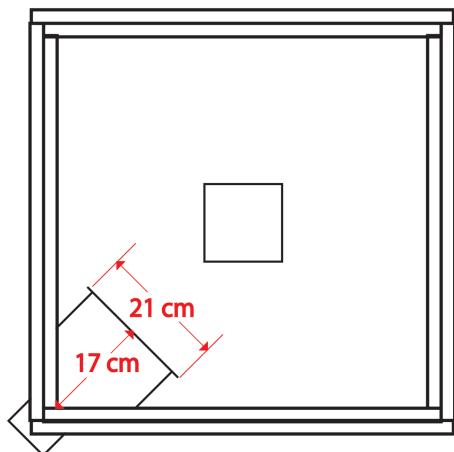


## APPENDIX A: Box-Photometer Construction

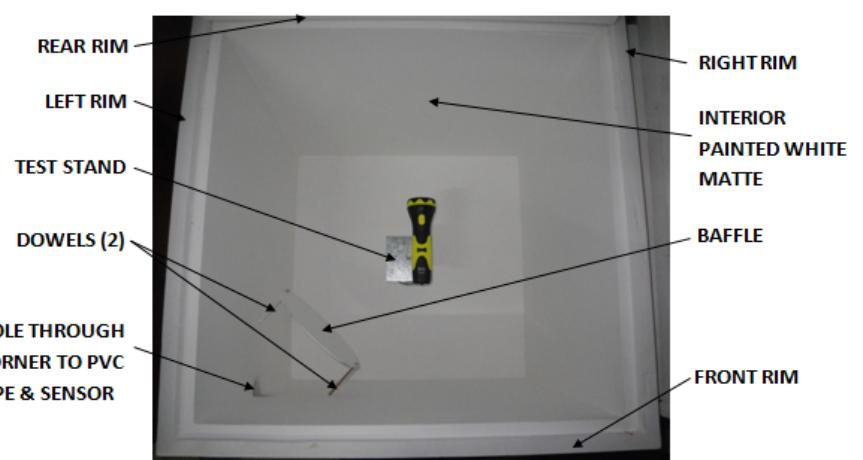
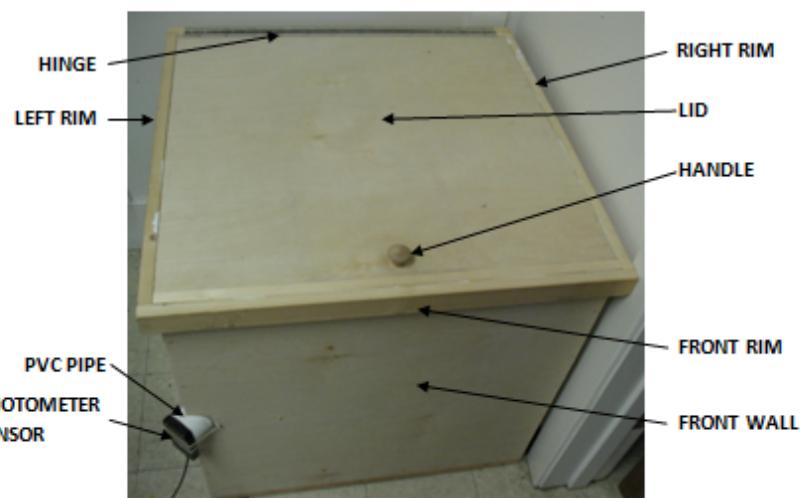
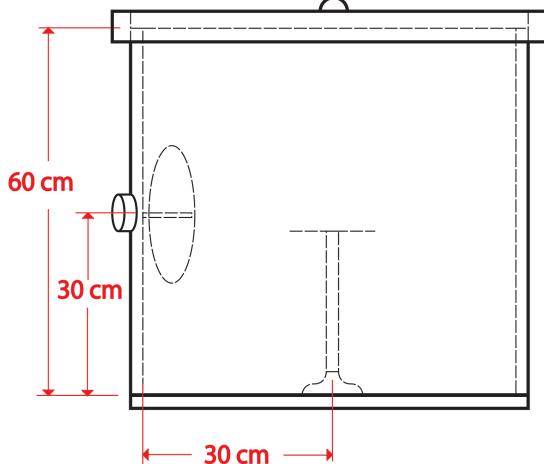
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TOP VIEW - INSIDE



FRONT VIEW



## **APPENDIX B: Tube-Photometer Construction**

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#### **TUBE-PHOTOMETER END CAP**

A tube-photometer end cap is required to hold the light meter sensor in place and to restrict ambient light from entering into the tube from one end. The end cap is preferably made of a rigid material (typically wood), but an equally acceptable end cap can be fashioned from cardboard and adhesive tape if precision woodworking tools are not available. A lathe is typically required to fabricate a wood end cap. The cardboard end cap can be crafted using a utility knife and adhesive tape. For both types of end cap, great care must be taken to cut the cap to the precise measurements of the light meter sensor diameter and tube diameter to ensure tight fits. Photos of a wood and cardboard end cap for the tube-photometer are included below as a reference.

