# SOLID-STATE LIGHTING MEASUREMENT ASSURANCE PROGRAM SUMMARY WITH ANALYSIS OF METADATA

**Miller, C.C.,** Nadal, M., Ohno, Y., Tsai, B. and Zong, Y.[1]
[1] National Institute of Standards & Technology, Gaithersburg, MD USA
c.miller@nist.gov

## Abstract

The National Institute of Standards and Technology (NIST) began to offer proficiency testing for Solid-State Lighting (SSL) products through a Measurement Assurance Program (MAP) in 2010. This article communicates the results of the first version of the MAP in which 118 worldwide laboratories participated. Statistical analysis of how the laboratories' measurements compared to NIST's measurements are presented. In general, all the laboratory results are within +/- 4 % for total luminous flux and luminous efficacy measurements. The discussion provides reasons for any discrepancies or large uncertainty intervals found in the data. A major finding was that measurement differences of RMS current had a larger standard deviation and number of outliers than expected. Two possible explanations are (1) the discrepancies are due to issues with using 4-pole sockets, and (2) the large deviation is caused by some solid state lamps being sensitive to impedance and slew rate of AC power supplies.

*Keywords*: e.g. Photometry, Proficiency Testing, Solid-State Lighting

## 1 Introduction

In January 2010, the National Institute of Standards and Technology (NIST) began to offer a Measurement Assurance Program (MAP) for solid-state lighting (SSL) products to customers of the National Voluntary Laboratory Accreditation Program (NVLAP) Energy-Efficient Lighting Products (EELP) program[1] under the support of the United States Department of Energy (DOE). The MAP program provided proficiency testing complimenting laboratory accreditation to ensure that as SSL products became more prevalent, capable testing laboratories would be available to handle the volume of measurement work. At the request of the Energy Star program, in January 2011 the MAP was opened to any testing laboratories that wanted to participate, independent of accrediting body. As of December 2014, the first version of the MAP was closed with 118 participant laboratories representing 13 countries. The results of the comparison provide a snapshot of the capabilities of accredited laboratories worldwide. The participant laboratories include the United States (49 laboratories), China (45), Taiwan (9), Korea (4), Canada (3), the Netherlands, Brazil, Singapore, India, Malaysia, Hungary, Italy, and Germany.

Scope of the measurement assurance program covered the procedures described in Illuminating Engineers Society (IES) LM-79-08[2]. The following properties/quantities were measured for each artifact: total luminous flux (lm), RMS voltage (V) and current (A), electrical active power (W), luminous efficacy (lm/W), chromaticity coordinates (x, y), correlated color temperature (CCT) (K), and color rendering index (CRI) (Ra).

## 2 Artifact Characteristics

Six different types of lamp or luminaire were used in MAP as listed in Table 1. The F-lamp is a recessed ceiling luminaire (downlight) which was chosen because of its physical size (large enough to cause potential self-absorption concerns with sphere measurements) and because it has a feedback mechanism that measures the chromaticity of the emitted light (and light reflected into the luminaire) and adjusts the red light emitted to maintain a constant chromaticity. The L-lamp has a large remote phosphor that may cause potential self-absorption concerns in a small sphere measurement system. The S-lamp has a sharp peaked current wave that has a maximum when the voltage is at a maximum which makes the measurement of the current and power factor of the lamp challenging. The R-lamp is a 30°

spot lamp which requires the laboratory to correct for angular non-uniformity in a sphere measurement or angular sampling frequency for a goniometric based measurement. The I-lamp is a simple incandescent halogen lamp used to evaluate the luminous flux scale of the laboratory. These five lamps are operated with 120 V of 60 Hz AC electricity. The sixth lamp, T-lamp, is a 24 inch under cabinet type lamp which is operated with 0.2250 A of constant current DC electricity with an approximate compliance voltage of 12 V. The T-lamp has a high correlated color temperature near 7000 K.

**Table 1 – Test artifact identification, nominal CCT and rated electrical conditions**

| Identifier | Type | Nominal CCT | Rated voltage or current | Rated power |
|---|---|---|---|---|
| F-lamp | Directional | 3500 K | 120 V AC | 12 W |
| L-lamp | Omnidirectional | 2700 K | 120 V AC | 12.5 W |
| S-lamp | Omnidirectional | 2800 K | 120 V AC | 8 W |
| R-lamp | Spot lamp | 3000 K | 120 V AC | 8 W |
| T-lamp | Undercabinet tube | 8000 K | 0.225 A DC | 2.88 W |
| I-lamp | Incandescent | 2900 K | 120 V AC | 100 W |

## 3 MAP Structure and Analysis

The Measurement Assurance Program was conducted as a star-type comparison. Along with the measurement results each laboratory provided information on how they conducted the measurements and what equipment was used. The difference between the results of the laboratories' measurements and NIST's measurements for each of the eight properties/quantities was calculated and categorized by lamp type. This analysis provides a 'snapshot' of the lighting measurement community's capability to measure solid-state lighting products and is presented in such a way that an individual laboratory's results cannot be identified. Individual laboratories have received formal reports describing their particular results. With those reports, individual laboratories can determine where their results fit into the overall capabilities of the lighting measurement community.

To determine whether the differences between measurements were normally distributed and therefore potentially coming from a random process, the values were ordered from smallest to largest and then plotted on a Normal Probability Plot (NPP).[3] This method uses theoretical normally distributed values (called "normal order statistic medians") as a horizontal axis to plot against the observed measurement differences. If the observed differences are normally distributed, then the resulting graph will be linear to a certain significance determined by the correlation coefficient and the number of data points.[4] For example, Fig. 1 shows the sequenced distribution of all the observed differences between laboratories' measurements and NIST's measurements of luminous flux, and Fig. 2 shows the NPP of the data in Fig. 1.

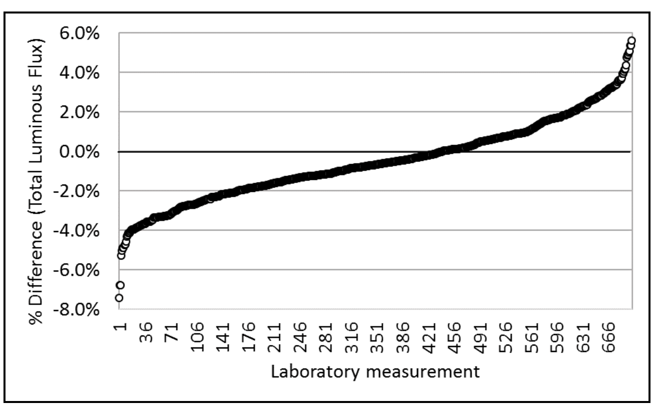


**Figure 1 – The sequenced distribution of all the observed differences in luminous flux measurements**


**Figure 2 – A Normal Probability Plot of all the observed differences in luminous flux measurements which has been fit to a linear function**

The NPP also provides the mean and standard deviation of the sequenced distribution as a result of the fit where the mean is estimated by the y-intercept and the standard deviation is approximated by the slope of the fit. The y-intercept of the graph shows how far the laboratories' measurements fall from NIST's measurements altogether. In this case, the intercept is -0.0054 meaning that in general, laboratories measured luminous flux about 0.54% lower than NIST. The standard deviation of the measured differences is ± 2.0 %. Another analysis step included is identifying any outliers in the data which were dealt with by using the method described in ASTM E 178-08.[5]

## 4 Results and Discussion

### 4.1 Luminous Flux

Fig. 3 shows a compilation of the normal probability plots for the difference of luminous flux for each lamp type. The difference, NIST's measurement minus the laboratory's measurement, is shown on the vertical axis and the normal order statistic medians are shown on the horizontal axis. Table 2 lists the standard deviations of the distributions in the figures above them, the overall bias/offset of laboratories' measurements compared to NIST's measurements, the number of data points in the distributions, the correlation coefficients of each linear fit, and the critical values for each distribution. Not included in Fig. 3 or the results in Table 2 is one data point identified as an outlier. The measurement made by a laboratory on an S type lamp may have been influenced by the S type artifact instability. The S type lamp in question was removed after this laboratory's measurement.

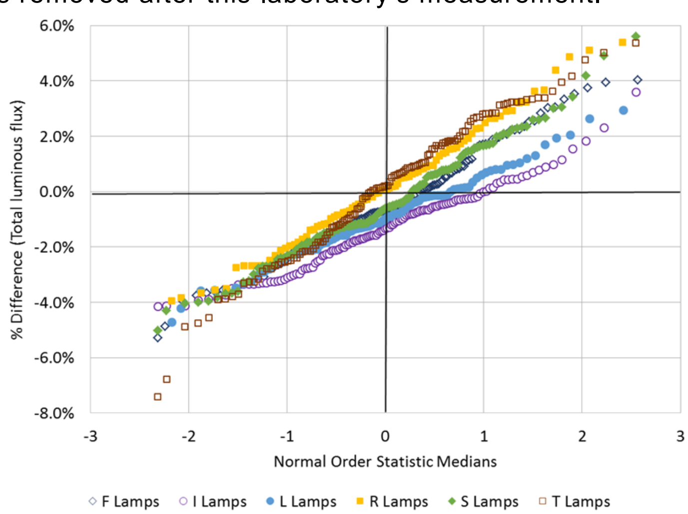


**Figure 3 – Normal Probability Plots of the percent differences in luminous flux measurements between the laboratories and NIST for each lamp type**

**Table 2 – Fit parameters for the luminous flux measurement differences for each lamp**

| Lamp Type | Standard Deviation | Bias/Offset | Number of Points | Correlation Coefficient | Critical Value |
|---|---|---|---|---|---|
| F | 1.93% | -0.54% | 135 | 0.9947 | 0.9897 |
| I | 1.47% | -1.37% | 129 | 0.9920 | 0.9897 |
| L | 1.53% | -0.94% | 89 | 0.9975 | 0.9850 |
| R | 2.12% | 0.15% | 88 | 0.9968 | 0.9850 |
| S | 1.99% | -0.43% | 129 | 0.9944 | 0.9897 |
| T | 2.47% | 0.04% | 128 | 0.9921 | 0.9897 |

The number of data points is larger than the number of laboratories participating because some laboratories used several measurement facilities (different spheres or sphere and goniometer). The L type and R type lamps were added after the initial roll out of the measurement assurance program. These lamps were found to be more stable than the initial lamps chosen.

For all the types of lamps the correlation coefficient is larger than the critical value; therefore, the hypothesis that the distributions do not come from a normal distribution cannot be rejected. The distribution of differences is well represented by a normal distribution which implies the data is generated by a random process. Using a sigma of 2 and the standard deviation of the fits, 95 % of the measurements are within ±4.0 %. The incandescent lamps which are operated on AC electricity are slightly better at ±3.0 %, and the T type lamp which has a very high correlated color temperature is slightly worse at ±5.0 %.

The bias shows the difference between the population and NIST. The average bias is 0.54 % which means laboratories typically measure lamps with lower lumen values than NIST. This is somewhat expected because as the calibration chain becomes longer and older in time, incandescent lamps which maintain the scale decrease in luminous flux. The positive bias for the R type lamp which is a spot lamp may be due to the angular non-uniformity of sphere responsivities. The larger negative bias for the I type lamp may be due to problems with 4-pole sockets used in the laboratories.

## 4.2 RMS Current

Fig. 4 shows a compilation of the NPP for the difference of RMS current for each lamp type. Not included in Fig. 4 or the results in Table 3 are the data points listed in Table 4 which were identified as outliers. An unexpected result of the MAP1 was the large standard deviation and the number of outliers identified for the measurement of current. The 30 measurements identified as outliers included the results from 19 different laboratories. For all the types of lamps the correlation coefficient is smaller than the critical values; therefore, the hypothesis that the distributions come from a normal distribution is rejected. The S type lamp was included in the MAP1 because of its current waveform and the standard deviation was twice any of the other type lamps. One laboratory was a consistent outlier and many times had the largest deviation; measuring a much larger current than NIST. This laboratory identified a wiring problem and has corrected the situation.

In Fig. 4 it visually appears that a fraction of the laboratories' measurements may result from a normal distribution while the standard deviation is larger than expected. In the wings of the distribution the deviation becomes larger quickly; therefore, there are two types of laboratories. The laboratories with the larger deviations may be due to wiring concerns where resistance, capacitance, or inductance out of the normally expected ranges is playing a role. NIST is conducting research to determine potential dependencies. Another possible explanation for the differences is improper implementation of using a 4-pole or Kelvin socket to eliminate junction potentials. If a laboratory is measuring the voltage drop across the lamp at a wiring junction outside of the sphere or perhaps at the power supply terminals, a voltage drop will be measured that includes the voltage drop across the lamp, at any junctions, and through the length of wire. The lamp will be operated at a lower than specified voltage.

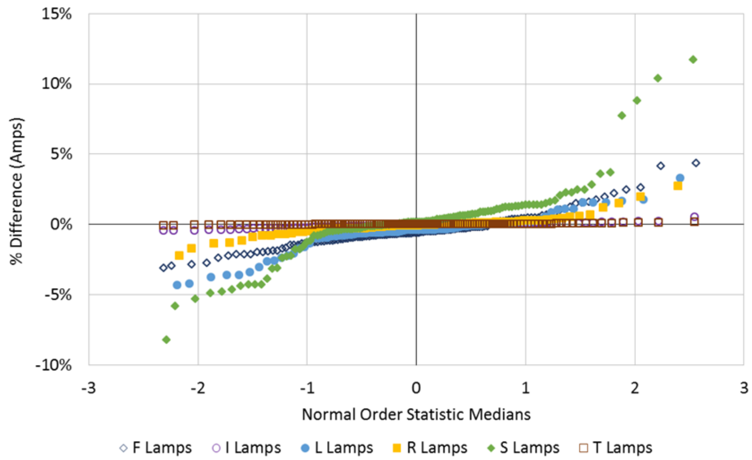


**Figure 4 – Normal Probability Plots for the differences in RMS current measurements for each lamp type except the T type lamp which is a difference in voltage measurements.**

**Table 3 – Fit parameters for the current measurement differences for each lamp.**

| Lamp Type | Standard Deviation | Bias/Offset | Number of Points | Correlation Coefficient | Critical Value |
|---|---|---|---|---|---|
| | RMS Current | | | | |
| F | 1.18% | -0.46% | 134 | 0.9581 | 0.9897 |
| I | 0.15% | -0.09% | 127 | 0.9791 | 0.9897 |
| L | 1.31% | -0.57% | 89 | 0.9405 | 0.9857 |
| R | 0.65% | -0.09% | 84 | 0.9156 | 0.9850 |
| S | 2.59% | 0.13% | 124 | 0.8937 | 0.9889 |
| | RMS Voltage | | | | |
| T | 0.75% | 0.02% | 127 | 0.9573 | 0.9897 |

**Table 4 – Measurement differences that were determined to be outliers.**

| Lamp Type | Outlier 1 | Outlier 2 | Outlier 3 | Outlier 4 | Outlier 5 |
|---|---|---|---|---|---|
| | RMS Current | | | | |
| F | 18.7 % | 9.68 % | 5.76 % | -5.17 % | |
| I | 0.62 % | -0.58 % | -0.81 % | -0.93 % | -1.37 % |
| L | 4.55 % | -4.43 % | | | |
| R | 17.9 % | 12.5 % | 10.4 % | 6.86 % | -3.82 % |
| S | 20.9 % | 19.1 % | 18.1 % | 17.9 % | 14.5 % |
| | 12.5 % | -13.1 % | -13.3 % | -13.8 % | -29.0 % |
| | RMS Voltage | | | | |
| T | 11.4 % | 4.22 % | 3.84 % | 3.58 % | |

## 5 Conclusions and Future Work

The results of the Measurement Assurance Program offered by NIST are a 'snapshot' of lighting testing laboratories' capabilities to measure total luminous flux (lm), RMS voltage (V) and current (A), electrical active power (W), luminous efficacy (lm/W), chromaticity coordinates (x, y), CCT (K), and CRI (Ra) according to IES LM-79-08. The results are for the measurements of 118 laboratories located worldwide between the years of 2010 and 2014.

In general, independent of the lamp type, the laboratories that participated in MAP were able to measure the total luminous flux and the luminous efficacy within ± 4 % (variance of the distribution, capturing 95 % of the measurements). The laboratories were able to measure the active power within ± 1 % (k = 2) for most of the lamps. The F type lamp which has an active feedback and the T type lamp which is a 12 V DC lamp (uncommon for many laboratories) have a larger spread.

The somewhat surprising result was the large spread for the measurement of RMS current, ± 5 % (k = 2) for the S type lamp. This large spread has motivated research in this area. One conclusion is that many laboratories may have issues with 4-pole sockets. A specific lamp has been included in the second version of the MAP to investigate 4-pole socket problems. Additionally, some of the early results reveal that a select set of solid state lamps are sensitive to the impedance and slew rate of the AC power supplies, which is not specified in LM-79. Additional research is required in this area to help the testing community reach more consistent results.The CCT, chromaticity coordinates and CRI results showed standard deviations that were on the order of the expected uncertainty of these measurements.

In January 2015, NIST started to offer a second version of the MAP (MAP 2) with different SSL artifacts meant to evaluate the laboratory's capabilities. The new version has a set of proficiency artifacts for a laboratory to measure, and the laboratory will be graded for passing or failing for each artifact. The MAP 2 artifacts were selected to allow the laboratory to diagnose potential deficiencies in its measurement system or to provide diagnostics to improve the lighting measurement standards. MAP 2 is expected to run for three years and is available to any testing laboratory for a service fee. MAP 2 has three options: A – SSL products, B – SSL products with 2 different 4 foot LED tubes, and C –SSL products along with 4 compact fluorescent lamps (CFLs) (with or without 4 foot LED tubes). Not every laboratory has the capability to measure lighting products 4-foot-long, so the 4 foot tubes are not part of the proficiency test grading.

## References

[1] Miller, C.C., Crickenberger, J., NIST Handbook 150-1, 2010 Ed., National Voluntary Laboratory Accreditation Program – Energy Efficient Lighting Products, Dec. 2010.

[2] Illuminating Engineering Society, LM-79-08, “Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products”, 2008.

[3] NIST. 2013. Engineering Statistics Handbook. 1.3.3.21 Normal Probability Plot. http://www.itl.nist.gov/div898/handbook/eda/section3/normprpl.htm, accessed 2016-01-08.

[4] NIST. 2013. Engineering Statistics Handbook. 1.3.6.7.6. Critical Values of the Normal PPCC Distribution. http://www.itl.nist.gov/div898/handbook/eda/section3/eda3676.htm, accessed 2016-01-08.

[5] ASTM. 2008. Standard Practice for Dealing with Outlying Observations. West Conshohocken (PA): ATSM E178-08.