International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

OP29

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

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DOI 10.25039/x46.2019.OP29

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

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

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DOI 10.25039/x46.2019.OP29

Abstract

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) under the support of the United States Department of Energy. 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. The results of the comparison provide a snapshot of the capabilities of 118 accredited laboratories worldwide. This presentation will focus specifically on comparing laboratories that used integrating spheres versus goniophotometers for photometric and colorimetric measurements. In general, the results for both measurement systems are within ±4% for total luminous flux and luminous efficacy measurements.

Keywords: Measurement Assurance Program, 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) 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. In December 2014, the first version of the MAP was closed with 118 participant laboratories representing 13 countries.

In January 2015, NIST started to offer a second version of the MAP (MAP2) with different SSL artefacts meant to evaluate the laboratory's capabilities. The MAP2 artefacts have been updated to represent the current SSL market and were selected to allow the laboratory to diagnose potential deficiencies in its measurement system or to provide diagnostics to improve the lighting measurement standards. MAP2 is expected to run for five years and is available to any testing laboratory for a service fee.

Both MAPs are conducted as a star-type comparison. Along with the measurement results, each laboratory provided information on their measurement protocol, laboratory equipment, and measurement traceability. The difference between 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 SSL 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 results.

In the United States, DOE has limited the measurements that qualify products for EPAct (Energy Policy Act) to just the ones of integrating sphere systems. This paper will show a statistical comparison of results from integrating sphere systems and goniophotometer systems revealing that statistically there is no difference.

2 General Results

The results of the MAP1 offered by NIST are a snapshot of lighting testing laboratories' capabilities to measure total luminous flux (lm), RMS voltage (V), current (A), electrical active power (W), luminous efficacy (lm/W), chromaticity coordinates (x, y), CCT (K), and CRI (Ra) according to the procedures described in IES LM-79-08 "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products". (IES, 2008) The results are for the measurements of 118 laboratories located worldwide between the years of 2010 and 2014 and were published in 2016. (Miller et al., 2016)

The results of the comparison are analysed using a normal probability plot. (NIST/SEMATECH, 2013a) The process begins by ordering the differences to the NIST values from smallest to largest. These differences are plot against theoretical normally distributed values (called normal order statistic medians). 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. To calculate the normal order statistic medians of a distribution, the uniform order statistic medians were calculated using equations (1), (2), and (3). The normal order statistic medians were calculated by taking the inverse of the normal cumulative distribution function also known as the percentage point function (NIST/SEMATECH, 2013b) for each of the uniform statistic medians where the mean of the normal cumulative distribution function is zero and the standard deviation is one.

$$U_i = (1 - U_n)\ for\ i = 1 \quad (1)$$

$$U_i = (i - 0.3175)/(n + 0.365)\ \ for\ i = 1, 2, 3, 4, \dots, n - 1 \quad (2)$$

$$U_i = 0.5^{1/n}\ for\ i = n \quad (3)$$

where

U_i is the uniform statistic median for an observed value i in the sequenced function of the differences;

n is the total number of observed values.

For example, Figure 1 shows the sequenced distribution of all the observed differences between laboratories' measurements and NIST's measurements of luminous flux, and Figure 2 shows the normal probability plot of the data in Figure 1.

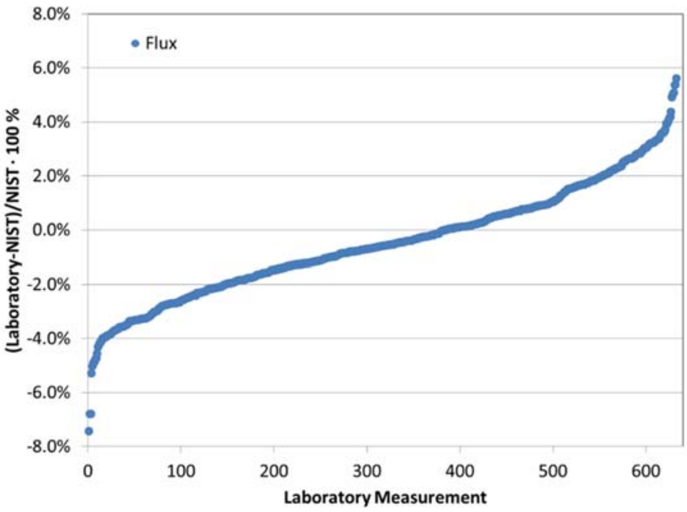

Figure 1 – The sequenced distribution of all the measured total luminous flux differences

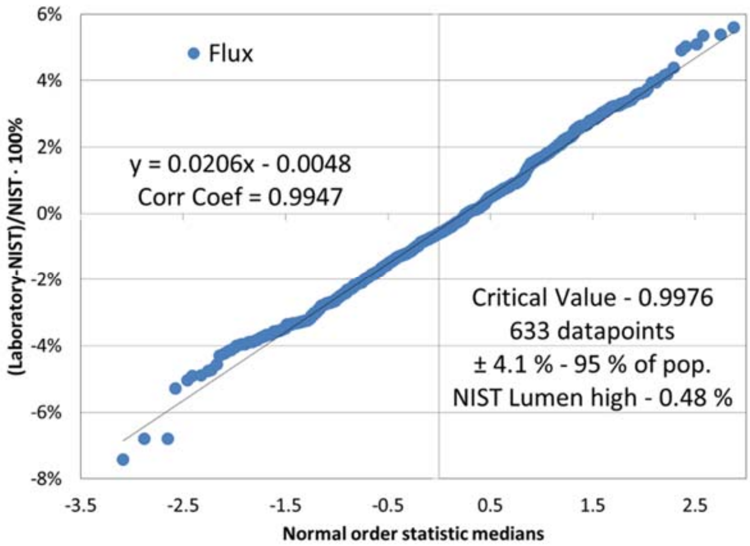

Figure 2 – A Normal Probability Plot of all the observed differences in luminous flux measurements which has been fit to a linear function.

The normal order statistic medians have been calculated using the method described above and plotted on the horizontal axis against the observed normalized differences. The hypothesis is that the measurement differences come from a normal distribution. The correlation coefficient R is calculated for the observed values with respect to a linear fit line. A critical value (NIST/SEMATECH, 2013c) is established based on the number of points and significance level. The correlation coefficient R is compared to the critical value and, based on the results, the normal distribution hypothesis can be confirmed or rejected. For Fig. 2 the number of points is 700 and the significance level is chosen as 5%, which gives a critical value of 0.9978. The correlation coefficient is $R = \sqrt{R^2}$ = 0.9963, which is lower than the critical value, meaning that the sequence does not come from a normal distribution. However, it is very close implying that the process is quite random.

The normal probability plot also provides the mean and standard deviation of the sequenced distribution because 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 −0.0048, meaning that, in general, laboratories measured luminous flux is about 0.48% lower than NIST. The standard deviation of the measured differences is ±2.1%.

In general, independent of the lamp type, laboratories were able to measure the total luminous flux and the luminous efficacy within ±4% (k = 2, representing a 95% confidence interval). The laboratories were able to measure the active power within ±1% (k = 2) for most of the lamps. The one type of lamp, which has an active feedback, and another type of lamp, which is a 12 V DC lamp (uncommon for many laboratories), have a larger spread.

3 Integrating Sphere Analysis

In addition to the measured quantities, a set of metadata was collected including the size of sphere. The results for total luminous flux was broken into three sets of data defined by integrating spheres with diameters smaller than 1.5 m, between 1.5 m and 2.0 m, and larger than 2.0 m for all the types of lamps. A normal probability plot was performed on the three sets of data. The results are presented in Table 1.

Table 1 – Normal Probability Plot for Different Integrating Sphere Sizes

Diameter of Sphere	Number of measurements	95 % Confidence Interval	Bias	Correlation Coefficient	Critical value (5%)
< 1.5 m	123	± 4.6 %	-0.70 %	0.9962	0.9891
1.5 – 2.0 m	72	± 3.7 %	-0.47 %	0.9930	0.9862
> 2.0 m	349	± 3.6 %	-0.59 %	0.9941	0.9958

The critical values are very close to or less than the correlation coefficient implying that the distributions of the results are near normal. The 95 % confidence interval and bias for integrating spheres with diameters between 1.5 m and 2.0 m compared to integrating spheres greater than 2.0 m are not very different. This is expected because the SSL products distributed do not have large surface areas.

The 95 % confidence interval for the integrating spheres with diameters less than 1.5 m is 28 % larger than the other two sets. The self-absorption correction factor and near-field absorption uncertainties become critical as the integrating sphere diameter becomes smaller. This concern is supported by the increase in the bias in negative direction. The near-field absorption of the SSL products cannot be corrected, and the self-absorption correction factor appears to not capture the magnitude required to correct the measurements. Another factor, which is most prevalent with the lamp that has a large phosphor surface, is that the self-absorption correction factor is not measured properly because the spectral distribution of the auxiliary source is not equivalent to the source under test spectral distribution. For the auxiliary lamp measurement, the blue light in the spectrum is down converted by the phosphor causing a much larger signal when weighted by the photopic luminous efficacy function. This error causes the bias to be larger in the negative direction. For larger sources than measured in the MAP, these errors will have more significance in the larger integrating spheres

4 Goniophotometer Analysis

For goniophotometers the set of metadata was broken into two sets. The first set is goniophotometer with a measurement test distance less than 5 m and the second set is a measurement test distance greater than 5 m. A normal probability plot was performed on the two sets of data. The results are presented in Table 2.

Table 2 – Normal Probability Plot for Different Goniophotometer Sizes

Test Distance	Number of measurements	95 % Confidence Interval	Bias	Correlation Coefficient	Critical value (5%)
< 5 m	30	± 4.3 %	-0.43 %	0.9588	0.9634
> 5 m	42	± 5.0 %	-0.28 %	0.9837	0.9723

Goniophotometers with test distances larger than 5 m have a 16 % increase in the 95 % confidence interval and minimal change in the bias. The increase in confidence interval is most likely due to the percentage of imaginary sphere surface at a fixed distance that is sampled. The photometers in all the systems have a similar aperture area for collecting light, but as the distance increases the solid angle collected becomes smaller. The number of half planes and vertical angles collected is typically constant for all the systems; therefore, the percentage of sphere surface area sampled for larger test distance goniophotometers is much smaller. The reduced amount of sampled surface increases the significance of the model used to fit the space in between datapoints causing the uncertainty to increase.

5 Comparing Integrating Sphere and Goniophotometer Measurements

The question of which measurement system, an integrating sphere system or a goniophotometer system, is better depends on the SSL lamp or luminaire properties. Therefore, integrating sphere measurements versus goniophotometer measurements are compared for each SSL lamp type in the MAP.

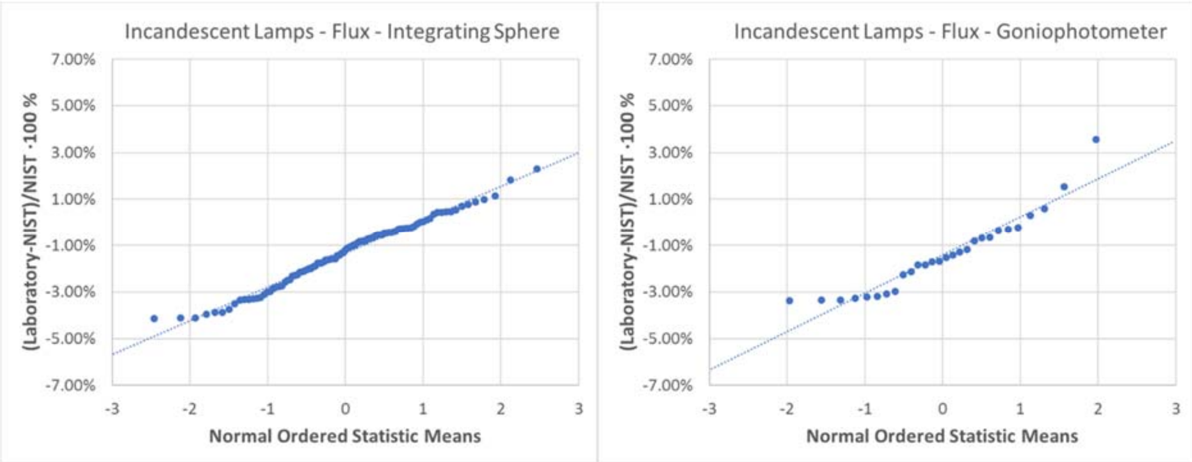

Figure 3 – Normal probability plots comparing integrating sphere measurements to goniophotometer measurements for the halogen-incandescent lamp in the MAP

Figure 3 shows the normal probability plot analysis for the 60 W halogen-incandescent lamp in the MAP set and Table 3 shows the numeric results. The larger than average bias is due to a 4-pole socket problem in many laboratories. Many of the measurement systems were not connected correctly. The voltage measurement across the lamp was not measured directly at the lamp socket. The second version of the MAP has a 11 V, 4.1 A incandescent lamp that when measured with AC voltage control highlights the 4-pole socket problem is present.

Table 3 – Normal Probability Plot for Halogen-Incandescent Lamp

Type	Number of measurements	Standard Deviation	Bias
Integrating Sphere	99	1.44 %	-1.34 %
Goniophotometer	28	1.64 %	-1.42 %

The standard deviation for the integrating sphere measurements and goniophotometer measurements appear similar but are they statistically indifferent. To determine if two variances are equal the F-test was applied. (NIST/SEMATECH, 2013d) The hypothesis of the test is that the variances are equal, $H_0\colon \sigma_1^2 = \sigma_2^2$. The two-tailed version tests against the alternative that the variances are not equal, $H_a\colon \sigma_1^2 \neq \sigma_2^2$. The test statistic is

$$F = s_1^2/s_2^2 \tag{4}$$

where

s_1^2 and s_2^2 are the sample variances.

The more this ratio deviates from one, the stronger the evidence for unequal population variances. The hypothesis that the two variances are equal is rejected if

$$F < F_{1-\frac{\alpha}{2},N_1-1,N_2-1} \text{ or } F < F_{\frac{\alpha}{2},N_1-1,N_2-1} \tag{4}$$

where

F_{α,N_1-1,N_2-1} is the critical value of the *F*-distribution with $N_1 - 1$ and $N_2 - 1$ degrees of freedom and a significance level of α. (NIST/SEMATECH, 2013e)

The *F*-statistic for the halogen-incandescent lamp is 0.771 and *F*(0.025, 98,27) = 0.572 and *F*(0.975, 98,27) = 1.946. The test does not disprove that the variances are not equal; therefore, for isotropic sources like the halogen-incandescent lamp the total luminous flux measurement using integrating sphere systems or goniophotometer systems in the MAP are the same.

Table 4 shows the normal probability plot analysis for four types of lamps in the MAP. The F-type was chosen for its stability & reproducibility and because it has a chromaticity feedback control. The L-type was chosen because it has a large remote phosphor and a hybrid current wave which has a sharp peak on top of a sinusoidal wave. The R-type lamp has a narrow beam. The T-type lamp is an undercabinet light with a very high correlated color temperature approaching 7500 K.

The *F*-statistic is within the F-test limits set by a 95 % significance level for all the types of lamps included in the MAP sets. Therefore, for lamps and small luminaires there is no statistical difference in the variance of measurements. For the R-type lamp the bias is significantly different for the two measurement methods. The most likely reason is that the angular distance between datapoints for the narrow beam lamp is too large. The interpolation model is over estimating the total luminous flux.

For larger luminaires the near field conditions and angular dependencies of the first bounce of integrating spheres may become problematic. For larger luminaires the cosine response of the photometer and the physical limitations of the mirror may become problematic. NIST is planning within the next two years to conduct a limited luminaire MAP among testing laboratories.

Table 4 – Normal Probability Plot for F, L, R, and T Type Lamps

Measurement System	Standard Deviation	Bias	$F_{\frac{\alpha}{2},N_1-1,N_2-1}$	$F_{1-\frac{\alpha}{2},N_1-1,N_2-1}$	F_{Stat}
F-type					
Integrating Sphere	1.92 %	-0.50 %	F(0.025,106,27) = 0.593	F(0.975,106,27) = 1.840	1.138
Goniophotometer	1.80 %	-0.80 %			
L-type					
Integrating Sphere	1.49 %	-0.96 %	F(0.025,72,13) = 0.488	F(0.975,72,13) = 2.592	0.550
Goniophotometer	2.01 %	-0.81 %			
R-type					
Integrating Sphere	2.03 %	-0.23 %	F(0.025,68,16) = 0.506	F(0.975,68,16) = 2.363	0.981
Goniophotometer	2.05 %	1.82 %			
T-type					
Integrating Sphere	2.38 %	-0.11 %	F(0.025,98,26) = 0.572	F(0.975,98,26) = 1.946	0.674
Goniophotometer	2.90 %	-0.51 %			

6 Operating Position Dependencies

Another measurement concern in recent years is comparing results from Type-C goniophotometers (IES, 2001) as defined by LM-75 where the rotational axis is aligned with gravity and what will be referred to in the revision of LM-75 as Type-D where the rotational axis is horizontal and therefore parallel to gravity. For a Type-C the thermal properties of the luminaire do not change as it is rotated perpendicular to gravity. For a Type-D the thermal properties of the luminaire change as it is rotated causing the LEDs to operate at different temperatures depending on position. Measurements on a Type-D goniophotometers require correction factors or measurements to correct the results to compare to Type-C goniophotometers.

Measurements were made in the NIST absolute integrating sphere with SSL lamps oriented at various angles with respect to gravity. Initially the SSL lamp is stabilized in a base up configuration, as it would be in a Type-C goniophotometer. Type-D goniophotometers require a special procedure and correction for stabilization. Figure 4 shows an example of an SSL lamp mounted in the NIST absolute integrating sphere. Each SSL lamp has a calibrated thermistor to measure the operating temperature of the LEDs as the SSL lamp is rotated with respect to gravity. The SSL lamps used are directional. The distribution of the SSL lamps was mapped onto the integrating sphere responsivity to eliminate this uncertainty component.

Figure 4 - SSL lamp mounted in NIST absolute integrating sphere at an angle with respect to gravity.

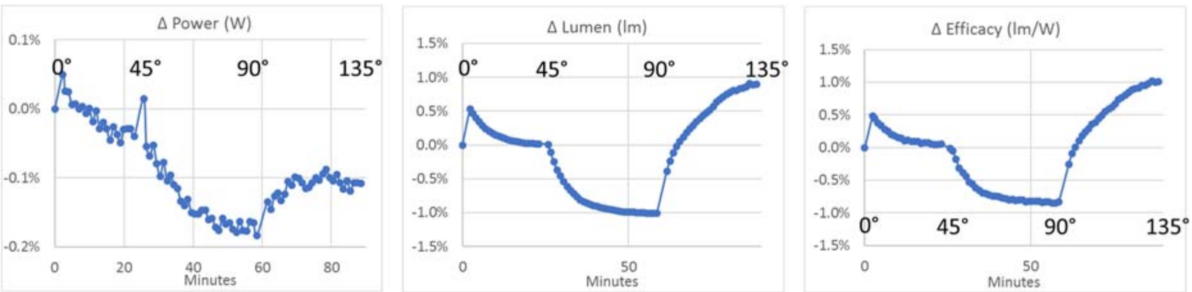

Figure 5 - Electrical power, total luminous flux, and luminous efficacy with respect to time - R-type lamp

The SSL lamps were measured at 45°, 90°, and 135° with respect to the 0° alignment with gravity. The electrical power and total luminous flux were measured with respect to time after the stabilization period. Figure 5 shows the change in electrical power, total luminous flux, and luminous efficacy for an R-type lamp. For this SSL lamp when the orientation is changed the electrical power changes very little compared to many laboratories' uncertainty. The total luminous flux changes very rapidly and smoothly stabilizes over time. The magnitude of the change is from -1 % to +1 % causing a larger component of uncertainty compared to testing laboratories. The operating temperature of the SSL lamp at the different operating orientations is in Table 5. For this lamp the luminous intensity distribution is simply corrected by using a monitoring detector that continuously views the SSL lamp at a given orientation, or by developing a correction curve based on the operating temperature.

Table 5 – LED Operating Temperature of an R-type lamp

Orientation Angle	0°	45°	90°	135°
Temperature (°C)	60.1	61.5	65.0	59.5

Not all lamps can be corrected by monitoring the luminous intensity at a given angle. Figure 6 shows the change in electrical power, total luminous flux, and luminous efficacy for an E-type lamp. The E-type lamp was chosen for its electrical properties which are very sensitive to system resistance and reactance. The operating temperature of the SSL lamp at the different operating orientations is in Table 6. For this lamp the total luminous flux changes with orientation with a smaller magnitude than the R-type lamp. However, the electrical power changes by several percent. The luminous efficacy changes and does not track the change in total luminous flux.

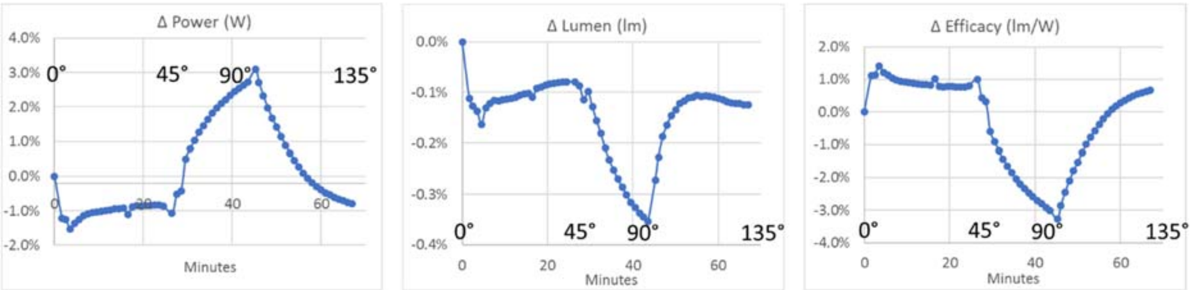

Figure 6 - Electrical power, total luminous flux, and luminous efficacy with respect to time - E-type lamp

To use a Type-D goniophotometer requires significant analysis and additional measurements for an SSL lamp under test compared to a Type-C goniophotometer.

Table 6 – LED Operating Temperature of an E-type lamp

Orientation Angle	0°	45°	90°	135°
Temperature (°C)	52.1	53.1	61.9	52.3

7 Summary

The results of the MAP for SSL products offered by NIST were analysed for measurement variation using integrating spheres and goniophotometer systems. As expected the smaller the integrating sphere diameter the greater the potential for variation in measurements. The larger the test distance for goniophotometers the more likely the deviation in measurements without a decrease in angular sampling interval.

The total luminous flux results were also analysed comparing the variance of measurement using an integrate sphere system versus a goniophotometer system using the *F*-test. The comparison reveals that for the SSL lamps used in the MAP set show no statistical difference between integrating sphere and goniophotometer systems used to measure total luminous flux.

Acknowledgements

The authors want to thank their colleague Yuqin Zong for support and numerous contributions on this research.

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