



Advanced Particle Sizing Technique for Development of High-Accuracy Scanner Calibration Standards

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Advanced Particle Sizing Technique for Development of High-Accuracy Scanner Calibration Standards

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Abstract: This report describes a new technique developed by The Scatter Works, Inc. (TSW) to accurately size particles by their light scattering characteristics. Current particle sizing methods have a high degree of uncertainty associated with their stated size, which impacts the calibration of defect scanners in operation at most fabs. The new technique measures the angle resolved light scattering from polystyrene latex spheres (PSLSs) deposited on bare Si wafers, and computes several parameters that provide an accurate measurement of the true PSLs size when used in particular combinations. Three different sets of particles certified by the National Institute of Standards and Technology (NIST) were compared with the new technique; good agreement was obtained with the NIST particles. TSW also established a parameter that is easier to obtain experimentally and also has a low uncertainty. This "B" revision of the document has been declassified, but otherwise is identical to the prior version.

Keywords: Angle Resolved Scattering, Particle Detection, Polystyrene

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1 EXECUTIVE SUMMARY

This report describes work by The Scatter Works, Inc. (TSW) to establish a new technique for accurately sizing particles by their light scattering characteristics. Particle standards in use today have a high degree of uncertainty associated with their stated size. This impacts the calibration of defect scanners in operation at most fabs. Usually, yield engineers prioritize defect issues on the basis of reported particle size. Inaccuracies in these reports could lead to wasted time and effort on non-issues, besides documenting problems incorrectly. The new technique measures the angle resolved light scattering from polystyrene latex spheres (PSLSs) deposited on bare Si wafers and computes several parameters that provide an accurate measurement of true PSLs size in particular combinations. Three different sets of particles certified by the National Institute of Standards and Technology (NIST) were compared with the new technique, and good agreement was obtained with the NIST particles. TSW also established a parameter that is easier to obtain experimentally and also has a low uncertainty. Two sets of two wafers each, with accurately sized PSLs deposited on them, were delivered to SEMATECH for evaluation of the technique and future use in scanner calibration.

2 INTRODUCTION

Particle scanners, used to detect contamination on wafer surfaces, operate by sensing scattered light from particles as a laser is scanned over the surface. Accurately sized particles are needed to calibrate semiconductor industry particle scanners, and PSLs are deposited on the wafer surface for this purpose. Although in most cases the diameter of these spheres is known only to about 10%, it varies from 1% to 25%, depending on sphere size and sphere manufacturer [1]. Because the scatter varies significantly with sphere diameter, knowing the true diameter of a PSL is an important calibration issue.

3 PROJECT OVERVIEW

The project had several well-defined tasks, as follows:

- Using NIST-sized PSLs, confirm and optimize the sizing technique.
- With a review from NIST, find the uncertainty in the sizing technique.
- Use the technique to size additional PSL diameters.
- Create two eight-diameter sets of sized PSL standards for SEMATECH.
- Use best efforts to obtain and measure real-world particles.
- Work with NIST to make the sizing technique NIST-traceable.
- Use best efforts to make the sized PSL standards commercially available.

TSW used five different NIST-sized particles; of these, only three were used as comparisons. One was only an estimated NIST value, and another proved to be unsuitable for the measurement technique because it had an unusually wide variation in particle diameter in the sample. The best of these, the NIST 100 nm standard reference material (SRM), was very well sized ($\pm 1\%$ uncertainty). TSW concentrated on this one to optimize the sizing technique. During the project, about 100 depositions were made and several hundred complete angle-resolved scattering instrument (CASI) scans were taken.

The technique, in all its variations, consists of taking CASI scatterometer data of a PSL deposition and using it to evaluate a particle diameter sensitive parameter. This parameter was then used with a scattering model that relates the parameter to particle diameter. The model diameter that corresponds to the measured parameter value is chosen as the sized diameter. The concept is simple, but optimizing it is more difficult because of the number of possible combinations in incident angle, scattering angle and polarization, as well as the number of parameter definitions. Four different parameters were seriously investigated in an effort to find one that combined ease of measurement with low uncertainty. In all cases, the parameter evaluation involves choosing specific measurement points and combining them with other measurement data, through simple arithmetic to obtain the parameter.

At a midterm presentation, results were presented using three parameters called Tom, Dick and Harry. Uncertainty analysis started after good agreement was obtained with the NIST particles. Following that report, a parameter that is easier to obtain experimentally and that has a low uncertainty also was investigated. This became the preferred parameter, and was named Simple Simon because of its ease of measurement. (Because of patent issues, this report will not reveal exact details of parameter calculations.)

TSW delivered two sets of standards to SEMATECH, each consisting of two wafers with four spot depositions of sized PSLs on them. The diameters are 64.4 nm, 76.4 nm, 91.0 nm, 100.3 nm, 126 nm, 156.5 nm, 215.9 nm, and 290.4 nm. TSW has been unable to obtain real-world particles with diameters 100 nm or smaller. Since it is clear that this is a key research issue, it will be a top priority as commercialization is pursued.

TSW's attempts to make sized PSLs commercially available through an arrangement with their partner organization, ADE Optical Systems in Charlotte, NC, have so far failed. Another arrangement that looks more promising and that will make sized PSLs easily available to SEMATECH members (as well other members of the semiconductor industry) is being pursued. This will involve building particle deposition equipment and installing it at SEMATECH for use by SEMATECH technical projects, with potential commercialization through the Advanced Tool Development Facility (ATDF) marketing organization.

The uncertainty analysis is a key factor in using the sizing technique to produce NIST traceable standards (see Appendix A for NIST comments). Other than lab time, most project hours were spent in this activity.

4 ANALYSIS OF MEASUREMENT UNCERTAINTY

TSW identified several sources of uncertainty that impacted all four parameters seriously investigated. These uncertainties involve particle index, incident angle, scatter measurement angles and measured scatter intensities. These uncertainties are described below, along with the method by which their effects on a measured parameter were evaluated. Results for Simple Simon also are presented.

In general, the sources of uncertainty can be classified as Type A or Type B, and the distinction is important. Type A uncertainties are caused by more or less random changes in the process. For example, in the case at hand, the ability to measure scatter angle and source incident angles is important as these variables occur in parameter evaluation. An outer bound was determined for the accuracy of determining these values experimentally. Adding them in quadrature, which accounts for the fact that it would be rare for all of them to reach a maximum in the same

measurement, combines independent Type A uncertainties. The resultant uncertainty is 1σ , or one standard deviation value. Doubling this value gives the 2σ value found here.

Another source of Type A uncertainty is repeatability. This is found by calculating the standard deviation of a set of N measurements and dividing by N . In this case, this value was found for the 100 nm particles, and the same percentage uncertainty for all other calculated particle diameters was used.

Type B uncertainties are different in that they are caused by unknown values that do not change randomly, or result from knowledgeable estimates instead of averaging. For example, the uncertainty in particle index is a factor investigated below. It is understood that exactly the right value is not being used, but it also is known that the value does not change randomly during the measurements. Type B uncertainties also are added in quadrature.

In some cases, small measurement corrections can be evaluated. For Simple Simon, it was determined that the small distribution in particle size, within a deposition, caused such an error. In this case, uncertainty in distribution width became a Type A uncertainty, although it was so small that it was ignored in these calculations. Discussions of the significant sources of uncertainty follow.

4.1 Particle Index Uncertainty (Type B)

The nominal particle index is a function of wavelength and perhaps to a smaller extent PSL sphere diameter. A paper by Mulholland et al. [2] provides a method to calculate the index at any wavelength, using the Bateman dispersion relation. Details of this calculation are shown in Appendix B. For this effort, a value of 1.59 was chosen for 488 nm, and 1.58 for 633 nm. An index uncertainty of ± 0.01 for both wavelengths was used, which is constant with the max./min. limits found in Appendix B. This is a type B uncertainty, but the direction in which the error occurs is not known.

The model was used to evaluate the effects of index uncertainty on the defined parameters. Identical input variables are entered into the model twice, except that the particle index is changed by 0.01. The resulting variation in the calculated parameter, P , allows calculation of dP/dn .

4.2 Incident Angle and Scatter Angle Uncertainties (Type A)

The incident angle rotation stage moves in increments of 0.01 degrees, and the scatter measurement receiver moves in increments of 0.001 degrees. It is not easy to measure absolute accuracy of these stages. However, the combined uncertainty can be measured by centering the receiver (to less than 0.01 degrees using a very small aperture) on the reflected specular beam, moving the sample through an angle, and then moving the receiver through the angle necessary to re-center the beam. The change in receiver angle should be exactly twice the change in sample angle. Deviations from this are caused by uncertainties in the angular changes made in these stages as well as other errors (centering accuracy and sample offset). In any case, the result provides an outer bound for the angular uncertainties in these stages. When this measurement was performed, the largest deviation that was recorded after several attempts was 0.06 degree. In the worst case, 0.1 degree is the uncertainty for both of these angles, but it is likely that both are smaller than 0.05 degree. The θ_s uncertainty in P was evaluated by moving both measurement points in the same direction, which is the most likely way for this error to occur. Again, the

model was used to determine the effect of angle deviations on the calculation of P. Typically, 0.1 degree variations are used to evaluate $dP/d\theta_i$ and $dP/d\theta_s$.

4.3 Scatter Intensity Uncertainties (Type A and Type B)

The absolute value of the measured scatter is unimportant, as the result always can be defined as a ratio after the background scatter has been subtracted out. Thus, both first order gain and offset errors are removed. However, one should be concerned about small “second order” variations that do not ratio out. Three such contributions to parameter uncertainty have been identified and are considered here. These are caused by nonlinearity of the photo-multiplier tube (PMT) detector (Type A), the presence of a narrow distribution of particle diameters in the measured deposition (a correction and a Type A uncertainty), and the variation of the scattered field across the receiver aperture (Type B).

The PMT uncertainty is caused by a nonlinearity of about 1% over wide ranges. For these parameter definitions, large changes in intensity between data points selected to evaluate the parameters were avoided, so the nonlinearity contribution will be small. A minimum value of 0.2% and a maximum value of 1.0% was used for this uncertainty. Between these limits, a simple formula was devised that varied the contribution according to the relative values of the data points used. This uncertainty must be applied to all measurements used in defining a parameter, so it was applied twice in the Simple Simon calculation.

If all of the illuminated particles in the deposition are not quite the same size, then the measured intensity may be slightly shifted away from the value associated with the average diameter because the scattered intensity is not linear with diameter. As a result, the measured intensity is slightly off the center value. A model was constructed to predict this offset error. It depends on particle diameter and width of the diameter distribution. The standard deviation in particle diameter for the NIST 100 nm SRM is 2.2%, and the corresponding correction associated with this effect is +0.3 nm. This could be used as a correction to the calculated particle diameter. It can be pointed out that for the comparisons with NIST, the TSW sizes were always slightly smaller; these positive corrections would narrow that small gap. For example, the TSW 100.3 nm particle would increase to 100.6 nm, just under the 100.7 nm NIST value. After several discussions with NIST, it was decided to make the corrections. These changes were made after the standards were delivered to SEMATECH, and are reflected in the diameters reported at that time.

Variation of the scattered field across the aperture can be estimated by analyzing the steepest observed slope found in the model (about 1 decade in 50 degrees). This Type B uncertainty is analyzed in Appendix C. The resulting “convolution error” is 0.035% and makes almost no difference in the evaluation of all four parameters. In fact, in some cases the effect will be much smaller yet; as for some parameters, opposing effects cause cancellation. This effect was ignored.

4.4 Repeatability

Measurement of the NIST 100s were repeated five times, using the same incident angle and deposition to determine the ability to repeat the measurement and its effect on the determination of PSL diameter. Table 1 shows the results of the five measurements, the calculated mean diameter and the root mean square (RMS) deviation from the mean. The mean of 100.28 nm rounds up to 100.3 nm and the RMS deviation is only 0.055 nm, which is less than an angstrom. The resulting addition to uncertainty would be $0.055/\sqrt{5} = 0.025$ nm for five scans, which is very

small compared to the other uncertainty values. One larger diameter (156.5 nm) was measured twice using two different light wavelengths. The same result was obtained for the diameter, but different uncertainty values emerged. In the end, a repeatability contribution to uncertainty of 0.1% was used for all particles, which is a little larger than the value of 0.055% indicated by the measurements on one particle. Table 1 shows contribution to sizing uncertainty from very low repeatability of measurements.

Table 1 Contribution to Sizing Uncertainty from Low Repeatability of Measurements

Simple Simon			
Trial	Parameter	Diameter	Sq'd. Diff.
1	0.6150	100.21	0.0049
2	0.6172	100.30	0.0004
3	0.6153	100.22	0.0036
4	0.6181	100.34	0.0036
5	0.6179	100.33	0.0025
	Mean	100.28 nm	

4.5 Determination of Parameter Contribution to Diameter Uncertainty

The various contributions to the uncertainty in P are found by multiplying each sensitivity by the corresponding parameter uncertainty ($\Delta P = dP/dx\Delta x$). The relationship between diameter uncertainty and parameter uncertainty is found from the model by allowing the diameter to vary a small amount and calculating dD/dP . This has to be determined for every particle size and for every measurement configuration. Multiplying this factor times the parameter uncertainty gives the diameter uncertainty associated with this measurement source ($\Delta D = dD/dP \Delta P$).

4.6 Determination of Diameter Uncertainty

Because the Type A uncertainties are independent, their contributions are added in quadrature. The Type B contributions are evaluated in the same manner, and also are added in quadrature to the Type As. The result is the total 1σ uncertainty in the parameter, ΔD . The 2σ uncertainty in diameter (sometimes called the expanded uncertainty) is found in a straightforward manner as $2\Delta D$ and defines a range of 95% certainty.

Uncertainty computations were developed on a spreadsheet for the research project, but eventually this will be added to the model to avoid wasting time or making calculation errors. This will allow the model to be used more easily to explore measurement situations that reduce uncertainty.

4.6.1 Example: The NIST 100 nm SRM

One NIST particle evaluated was the 100 nm NIST SRM 1963. It has been evaluated at NIST to have a diameter of $100.7 \text{ nm} \pm 1 \text{ nm}$. The uncertainty analysis, using the technique described above on measurements of the same particle, is shown in Table 2.

Table 2 100 nm NIST SRM 1963 Particle Measured 100.6 ± 0.7 nm

100.6 PSLs [488/40/-60/5]	
Nom. Diameter =	100.6
Nom. Parameter =	0.6183
Dia./Param. Uncert. =	38.90

Type/Variable	Source/Calc.	Variable Uncertainty	Param./Var. Differential	Diameter Uncertainty
A/Incid Angle	CASI/Equation	0.1	0.053	0.2062
A/Scatter Angle	CASI/Equation	0.1	0.035	0.1362
A/Linearity	CASI/Equation	0.41%	1.237	0.1966
B/Part Index	NIST/Model	0.01	0.110	0.0428
B/Convolution	Data/MathCad	0.03%	1.237	0.0144
A/Repeatability	100 nm meas.	0.10%	--	0.1006

2 σ (Expanded) Particle Diameter Uncertainty in nm

5 SUMMARY OF TSW MEASUREMENT RESULTS

5.1 TSW Particle Sizing Results

Eight diameters were determined using Simple Simon and delivered to SEMATECH as depositions. The TSW measured diameter and calculated uncertainties in nanometers are given in Table 3. The particles below 175 nm in diameter were measured with a 488 nm Argon laser, and those over 150 nm were measured with a 633 nm laser. Particle #6 (157.0 nm) was measured at both wavelengths and designated as 6a and 6b.

Table 3 Uncertainty Measurements for PSL Spheres Deposited by TSW on Wafers Delivered to SEMATECH

#	NIST Dia. & Uncert. (nm)	TSW Dia. & Uncert. (nm)	Largest Uncertainty/Comment
1	Not Evaluated	64.6 ± 1.0	Scatter Angle
2	76.1 (Estimate)	76.6 ± 0.6	Incident Angle
3	Not Evaluated	91.3 ± 0.9	Linearity
4	100.7 ± 1.0	100.6 ± 0.7	Incident Angle
5	126.9 ± 1.4	126.4 ± 0.7	Incident Angle
6a	Not Evaluated	157.0 ± 2.8	Linearity/488 nm
6b	Not Evaluated	157.0 ± 0.9	Incident Angle/633 nm
7	217.7 ± 3.4	216.5 ± 1.9	Linearity
8	Not Evaluated	291.3 ± 3.6	Index & Linearity/Can Be Lowered

The TSW uncertainties are large enough to include the NIST mean value in each case. Each TSW value has been increased by 0.3% to account for the correction associated with particle size distribution. The value 0.3% was found for the 100.7 nm NIST SRM and was used here to make a small correction for each size measured.

6 NIST TRACEABILITY

There are two different views regarding the uncertainties needed to report NIST traceability. The most conservative approach is to combine the experimental uncertainties (from Table 4) with the NIST uncertainties through quadrature addition. This approach is summarized below. NIST uncertainties were available for only three particles. These were reduced to percentage differences and used to estimate the uncertainties that might be obtained at NIST if the other particles had been measured there. The result of using these additional uncertainties is shown in Table 4 as Traceable Uncertainty in the far right hand column.

Table 4 Uncertainty Analysis for NIST Traceability of New Technique

#	NIST Dia.	Meas. Uncert.	Est. Uncert.	TSW Dia.	Meas. Uncert.	Traceable Uncert.
1	No Value	—	± 0.6	64.6	± 1.0	± 1.2
2	76.1	Est.	± 0.8	76.6	± 0.6	± 1.0
3	No Value	—	± 0.9	91.3	± 0.9	± 1.3
5	100.7	± 1	—	100.6	± 0.7	± 1.2
6	126.9	± 1.4	—	126.4	± 0.7	± 1.6
6a	No Value	—	± 1.7	157.0	± 2.8	± 3.3
6b	No Value	—	± 1.7	157.0	± 0.9	± 2.0
7	217.7	± 3.4	--	216.5	± 1.9	± 3.9
8	No Value	—	± 4.5	291.3	± 3.6	± 5.8

7 REFERENCES

- [1] Mulholland, G.W., et al.: *Measurement of the 100 nm NIST SRM[®] 1963 by Differential Mobility Analysis*. NIST, 1998.
- [2] Mulholland, G.W., A. W. Hartman, G. G. Hembree, Egon Marx, T. R Lettieri: "Development of a One-Micrometer-Diameter Particle Size Standard Reference Material," *J. of Res. NBS*, vol. 90, N1 p3 (1985).

APPENDIX A

NIST Statement on the TSW Measurement Technique and Measurement Calculations

Traceability to NIST of The Scatter Works, Inc. Particle Sizing Measurements

The Scatter Works Inc. (TSW) has developed a methodology for sizing particles on a surface based on a combination of light scattering intensity as a function of angle and a theoretical model for computing the scattering intensity. The exact details of the choice of angles and the theoretical model are not given by The Scatter Works because of a pending patent.

The calibration particles deposited by TSW consist of eight particle sizes ranging from the smallest size of 64.6 nm to the largest of 291.3 nm. A key element of the traceability is The Scatter Works' use of the NIST SRM 1963 with a diameter of $100.7 \text{ nm} \pm 0.95 \text{ nm}$ as its primary calibration size. This is a convenient particle size, because it is in the middle of the size range for the calibration particles. This material is also one of the eight particle sizes deposited on the wafer.

Two other particle samples for which there is a NIST publication describing the measurement and uncertainty were used by TSW. One size is $126.9 \text{ nm} \pm 1.4 \text{ nm}$ and the other $217.7 \text{ nm} \pm 3.4 \text{ nm}$. These sizes have a slightly larger uncertainty than the 100 nm SRM because their measurement is based on the calibration of the measurement instrument within the 100 nm particles.

There are two requirements for TSW to establish traceability to NIST. The first is the use of a NIST certified calibration artifact for diameter. This requirement is satisfied by use of the SRM 1963 and the two other particle sizes characterized by NIST based on the SRM 1963. The second requirement is that a quantitative uncertainty assessment of the measurements be made. This is discussed below.

While TSW does not explain the exact details of its measurements, it has identified the Type A and Type B uncertainties in their measurements, given the magnitudes of the individual components, and computed their effects individually on the diameter. They have computed the total Type A and Type B uncertainty, combined them in quadrature to obtain a total uncertainty, and then multiplied by 2 to obtain an expanded uncertainty, which is often termed a 2σ uncertainty.

The Type A uncertainty components consist of the measurement repeatability, the uncertainty in the incident and scattering angle, and the nonlinearity of the detector.

The Type B uncertainties arise from the uncertainties in the following quantities: the refractive index of the particles, the aperture function, and the NIST calibration particles. The methodology used in estimating the uncertainties and combining them is based on NIST Technical Note 1297. Model calculations were carried out to determine the effect of the width of the size distribution on the apparent mean size. The measured results were corrected for this small effect (0.3%). The uncertainty associated with the width of the size distribution was not included in the uncertainty assessment because the effect itself is almost negligible.

Three of the samples studied have been sized at NIST so that the NIST values for the particle size and uncertainty estimates can be used directly. The difference between TSW and the NIST measurements is small with percent differences of 0.1% for the 100 nm particles, 0.4% for the 126.9 nm particles, and 0.6% for the 217.7 nm particles. The good agreement between the two

sets of measurements provides confidence in TSW's measurement method. It is noted that TSW's particle size is systematically smaller than the NIST size, but the difference is at most half the NIST measurement uncertainty.

There are five other sizes. One of the sizes is 157.0 nm, which is between two of the NIST measured sizes. For this size, the closest NIST particle size of 126.9 is used as the basis for the uncertainty for the traceable standard. The relative combined uncertainty (1σ) for this particle size is 0.0057%. This value is used in computing the total Type B uncertainty for the 157.0 nm particles.

For the 291.3 nm particle size, which is 33% larger than the largest NIST particles, the relative combined uncertainty of the NIST 217.7 nm particles is used in computing the total Type B uncertainty. This size has the advantages of being narrowly distributed with a CV (coefficient of variation) of 0.015. This represents the smallest CV among the eight particle sizes.

A similar procedure is used for the 91.3 nm, 76.6 nm, and the 64.6 nm particle sizes. The combined relative uncertainty of 0.0047% for the 100 nm SRM is used in computing the total Type B uncertainty for these three sizes. At NIST, nine sets of measurements have been made on the same particle samples as the 76.6 nm size and the result is a mean value of 76.1 nm. The uncertainty analysis has not been carried out for these measurements and the results have not been published. However, it is still of interest that the TSW value is in close agreement with this preliminary NIST value.

The combined relative uncertainty for the 100 nm SRM is also used in computing the Type B uncertainty for the 64.6 nm particle size. The expanded uncertainty is computed in the same manner as for the other sizes. This is a reasonable first estimate for the uncertainty; however, it would be recognized that the uncertainty has a larger "uncertainty" than the other sizes because of a number of factors that become more important as the particle size decreases. First the relative thickness of a residue layer on the surface of the particle increases as the particle size decreases. The residue arises from the nonvolatile impurities in the droplet containing the particle. The difference in optical properties between the polystyrene sphere and the reasoned will affect the light scattering by the particle. Secondly, the particle shape may be distorted on the surface as a result of the van der Waal forces between the particle and the surface. There is qualitative evidence of such an effect for 30 nm polystyrene spheres. thirdly, the size distribution for this particle size is larger than the other sizes with a CV greater than 0.06. It is likely that there are deviations from a Gaussian shape. The effect of these factors on the uncertainty analysis have not been made.

Conclusion

The eight particle sizes measured by The Scatter Works and reported in this document are traceable to NIST based on the comprehensive uncertainty analysis carried out by TSW and on their use of the NIST SRM 1963, the 100 nm calibration particles, and of two other particle samples sized by NISR. "The Final Report on the Particle Sizing Project" submitted by John Stover and Craig Scheer is consistent with the NIST Traceability Policy.



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APPENDIX B

Calculation of PSL Refractive Index as a Function of Wavelength

Calculation of PSL Refractive Index as a Function of Wavelength

A dispersion relationship and measurement extremes from reference 2 are used used to determine limits for the PSL index of refraction at our measurement wavelengths.

$b := 1.0087 \cdot 10^4$ The Bateman Constant $\lambda := 450, 455, 650$

$\lambda_{ref} := 441.6$ The wavelength of reference 2.

Minimum Values

$a1 := 1.58 - \frac{b}{\lambda_{ref}^2}$ Calculation of the constant "a" from reference data.

$n1(\lambda) := a1 + \frac{b}{\lambda^2}$ The dispersion relationship.

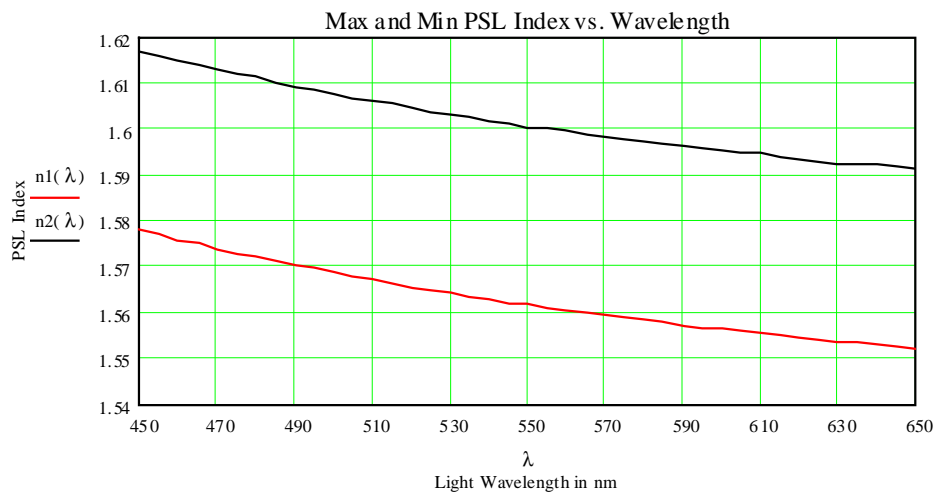
$n1(488) = 1.571$ Max and min values at the measurement wavelengths.
 $n1(633) = 1.553$

Maximum Values

$a2 := 1.619 - \frac{b}{\lambda_{ref}^2}$

$n2(\lambda) := a2 + \frac{b}{\lambda^2}$

$n2(488) = 1.61$
 $n2(633) = 1.592$



The commonly used values of 1.59 and 1.58 for wavelengths of 488 nm and 633 nm respectively fall well within the extremes suggested by reference 2. It seemed reasonable to use the common values and assign an uncertainty of 0.01.

APPENDIX C Convolution Errors

Convolution Errors

Addresses the problem of integration over the aperture as it traverses a signal region that changes exponentially with exponent n . The aperture width is W (in degrees), the actual power density is $p(\theta)$ and the measured power density is $p_m(\theta)$.

$$n1 := \frac{1}{50}$$

$$p1(\theta) := 10^{n1\theta}$$

$$p1m(\theta, W) := \int_{\theta - \frac{W}{2}}^{\theta + \frac{W}{2}} \frac{p1(\beta)}{W} d\beta$$

$$\Delta p1(\theta, W) := \left| \frac{p1m(\theta, W) - p1(\theta)}{p1(\theta)} \right|$$

$$\Delta p1(50, 2) = 3.535 \cdot 10^{-4}$$

This is the fractional change in measured versus actual BRDF (or DSC). It is smaller than the non-linearity of the PMT itself (approx. 0.005) when evaluated at a maximum observed value of $n=1$ decade/50deg is used. It can be ignored in the uncertainty calculations.

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