Characterization of the Dimensions of Internal Gap in a Glass Artifact Using a Laser Triangulation Probe

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1. Introduction

The National Institute of Standards and Technology (NIST) Dimensional Metrology Group (DMG) develops and delivers unique and critical high-value dimensional measurements that promote industry innovation, ensure product quality, and are not commercially available. In some cases, we need to use multiple measuring systems to provide our customers with the needed measurement results. This paper is the story of one of these measurements that involved a number of different instruments and is typical of the complexity of many of our customer requests. Recently, NIST provided a measurement solution for characterizing the gap width of a new biotechnology absorbance spectrometry standard reference material (SRM). This SRM is a reduced path length validation absorption standard for Ultraviolet (UV) visible spectroscopic measurements. The SRM consists of a series of very small rectangular glass containers called cuvettes and has been developed for the biotechnology community's daily measurements of samples where the sample amount available is very limited: typically, samples include DNA, RNA, or an antibody. Identification of the exact substance by spectrometry measurements is based on how the substance absorbs light. The dimension of the gap between the inside walls of the cuvette is a critical characterization, therefore measurement of the gap width with low uncertainty is required.

2. Dimensional measurement challenge

2.1 Challenge

The Standard Reference Materials (SRMs) are transparent cuvettes made of fused quartz glass, 45 mm long and 10 mm wide, with gaps of three different widths, 2 mm, 1 mm, and 0.5 mm. An example of a cuvette is shown in Figure 1. Due to geometric imperfections during manufacture and assembly, the gap dimension does vary as a function of location (length), thus a rigorous characterization is needed. Dimensional Metrology Group (DMG) has several high-accuracy Coordinate Measuring Machines (CMMs) with a variety of probe sizes and configurations. However, as the gap width becomes smaller, the required probe diameter becomes smaller and subsequently the maximum probe shaft length becomes shorter in order to maintain required probe stiffness. The large aspect ratio of gap width-to-length thus presents a challenge for DMG using conventional touch-probe CMMs.

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2.2 The limitation of CMM touch probe

NIST's M48[1] CMM is recognized for its unparalleled accuracy over its measurement volume [1][2]. The 2 mm cuvette can be measured over its entire length by the M48 CMM using a probe with a 1.5 mm diameter tip and a 40 mm long shaft. This arrangement can easily provide the sub-micrometer level expanded uncertainties (k=2) required for the measurement. However, for the smaller cuvettes, the narrow opening limited the size of the tip that could be used. In addition, the smaller diameter tips require a very thin shaft with a much shorter useable length. The restricted probe length limited the accessible region to 1.25 mm of the 34 mm length desired. The CMM cuvette measurement also required the data to be collected at multiple probing forces. The thin glass walls of the cuvette may bend under the probing force and the elastic deformation of the glass needed to be characterized. The CMM data was extrapolated to an un-deformed result for the comparison with the non-contact system.

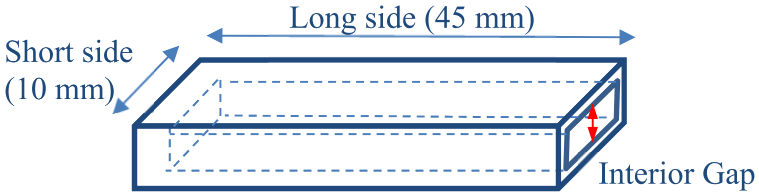


Figure 1. An example of cuvette

3. A Non-contact measurement technique

3.1 Introducing Laser Triangulation Probe

A laser triangulation probe is a non-contact measurement technology and is sometimes preferred over contact-probe technology when measuring delicate or hard to reach surfaces. The basic principle of triangulation is shown in Figure 2. A semiconductor laser emits the laser beam to the target. The light scattered from the surface of the target (seen as a small spot of light) is focused by the lens and forms an image on the light-receiving element which is either a CCD (charge-coupled device)/CMOS (complementary metal-oxide semiconductor) array or a PSD (position sensitive detector) element. The position of the beam spot on the receiving element varies with the distance to the target. This variation is evaluated and converted into a measurement of target position [3].

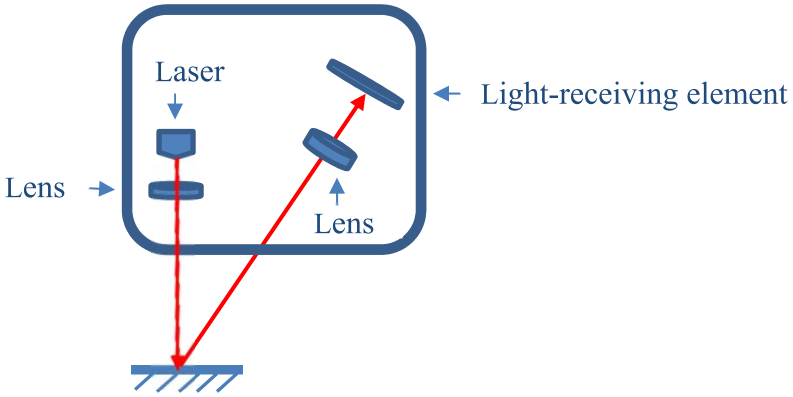


Figure 2. The principle of the triangulation probe

[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

We have used the triangulation probe for a number of projects where the measurement artifacts were not transparent and thus only one surface was measured. The gap measurement here, using a laser triangulation probe, is based on the location difference between spots generated at 2 of the 4 glass-air interfaces, specifically the two inner interfaces. The concept seems straight-forward but, in reality, deciphering which 2 spots represent the inner interfaces and extracting the distance between them was not simple.

3.2 System setup and measurement process

When measuring a diffuse-reflective target, we mount the laser triangulation probe head straight down and perpendicular to an X-Y stage as shown in Figure 2. The incident light hits the target and the reflected light intensity is uniform in all directions, and the light-receiver element can detect the target “image” and calculate the displacement of the target. However, the cuvette is made of fused quartz glass and is a specular-reflective target with most of the light being reflected at an angle equal to the incident angle. The light-receiver sensor in the triangulation probe head does not receive an adequate signal from the transparent surfaces if the probe head is mounted as in Figure. 2. Therefore, a different measurement setup for the triangulation probe head is introduced as shown in Figure 3. The probe head is mounted on a precision linear stage, along the Y axis of our setup, with the head tilted at an angle of 20 degrees, which is half of the original light receiving angle for this instrument configuration. The cuvettes with different gap sizes are laid on a small adjustable Z-axis vertical stage, which sits on a high precision air bearing linear stage, with its motion aligned in the X direction. The X-axis stage is moved at a speed of 100 mm/s during measurement, with the speed remaining reasonably constant.

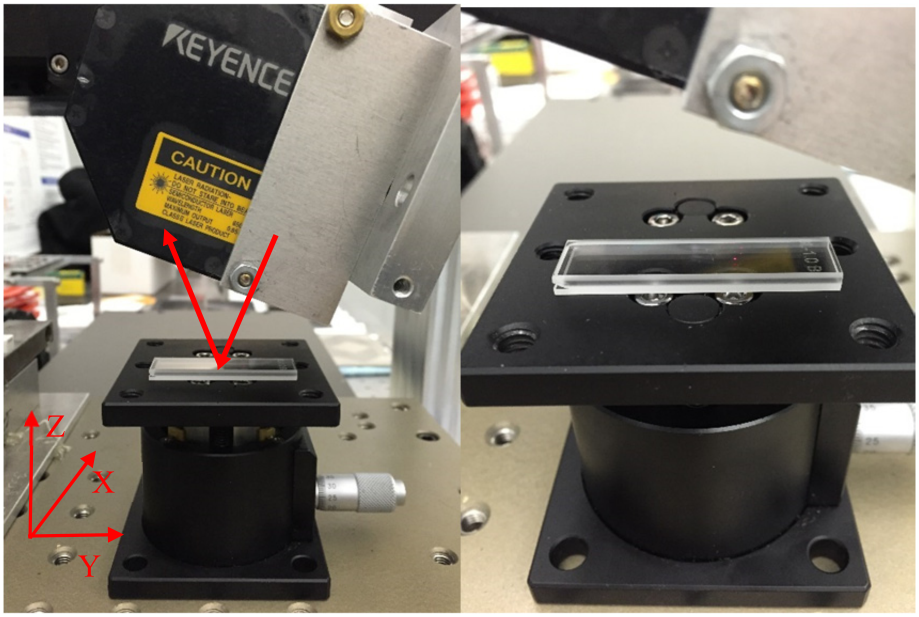
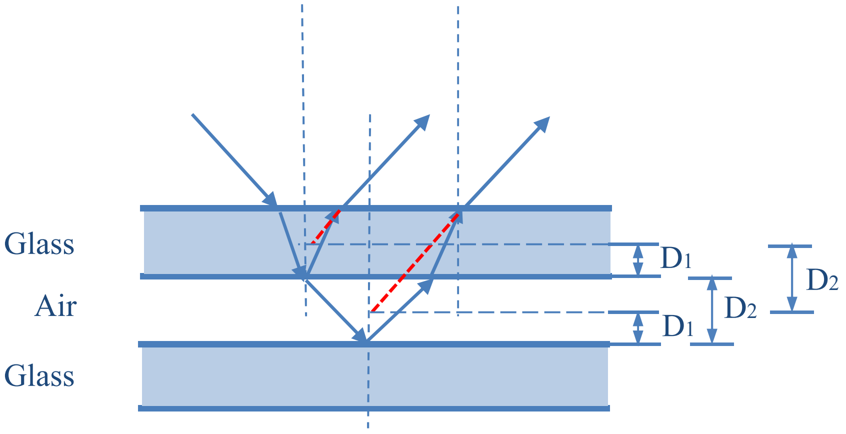


Figure 3. Triangulation probe setup for measuring a cuvette. The incident and reflected beam as a red line shows in the figure above.

The cuvette is mounted so that its short side is parallel to the X axis. We align the cuvette by stepping the laser spot along the Y axis near the edge and ensuring that the edge is at the same X position at different locations along the Y axis. A careful alignment is important for measuring the cuvette due to the offset calculation performed as part of the data analysis. A detailed explanation will be presented in section 3.3. The triangulation probe head is mounted in such a way that the incident and reflected beam form a triangle that lies in the YZ plane.

The measurement procedure is as follows. We first acquire a scan along the X axis at a Y position that is 0.5 mm from the open end of the cuvette. We compute the gap width for each position along the X axis and compute the average of multiple runs. We then step the probe another 0.5 mm along the Y axis, acquire a new scan along the X axis, and compute the average gap width, again from multiple runs. We repeat this process all the way down to 34 mm from the open end of the cuvette. From all the data, we obtain the gap width as a function of the location along the long side of the cuvette. The gap thickness is calculated using the multiple reflections obtained when the laser source is directed at each of the four cuvette surfaces.

Knowing that the laser beam is refracted when it passes through the cuvette, Snell’s law tells us that the amount of refraction can be related to the angle of the laser beam [4]. If we were interested in measuring the thickness of cuvette wall, the influence of refractive index of glass would need to be calculated. However, given that we are interested in measuring the gap between the glass plates we know both beams are refracted by exactly the same amount during each pass through the glass and the effects cancel as shown in Figure 4.



D_1 : Shifted distance due to refraction.
D_2 : Gap distance of cuvette.

Figure 4. Beam diagram for thickness measurement. The reflections from the top and bottom surfaces are omitted.

3.3 System validation

The system is validated by comparing the triangulation probe results with M48 CMM measurements made on a 2 mm cuvette, since the 2 mm cuvette can be measured over its entire length by the M48 CMM. Two aspects of the data are compared – the variation of the gap dimension as a function of location and the magnitude of the gap dimensions. The data in Figure 5 show that the variation of the gap dimension as a function of location is the same using both measurement techniques, thus verifying that the gap dimension is changing due to cuvette geometry and is not a function of the measurement technique. However, a systematic offset exists between the gap dimension reported by the two methods which is most likely related to the not precisely known angle between the laser and the cuvette surface. Instead of determining this angular error and correcting for it independently, we instead correct the triangulation results by this constant offset, effectively using the triangulation probe as a comparison measurement tool. This validation demonstrates that the laser triangulation probe method can be used as a comparison method but it does not free us from the need for reference measurements for gap dimension on the smaller cuvettes, since the magnitude of the correction will vary with gap size and the angle the laser makes with the cuvette surface.

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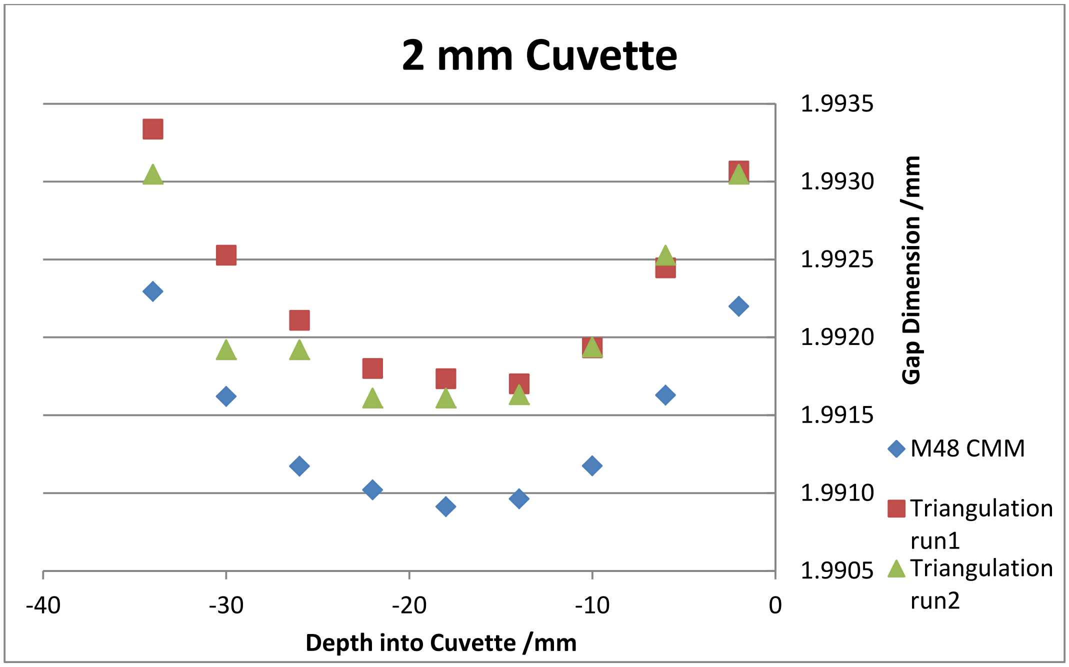

Figure 5. Measurement results for 2 mm cuvette

3.4 Measurement of Smaller Cuvettes

For the smaller cuvettes, we use the largest CMM probe that will fit in the gap to maximize the depth within the cuvette that can be measured with the M48 CMM. For the 0.5 mm cuvette, we used a 300 µm diameter probe, the smallest effective probe that the CMM can use without shaft breakage. As concluded from the system validation, the M48 measurements serve as the reference for making corrections to the triangulation probe results for the two smaller cuvettes. This is not done without some concern for the validity of the corrected data due to the limited depth of overlap between the M48 and triangulation probe measurements. With this concern, we incorporated an additional check by using the Mitutoyo[1] UMAP ULTRA350 Dual-Probe Micro-Feature CMM [5]. This special purpose CMM has multiple probes, one with a 100 µm diameter probe on an 80 µm diameter shaft that is 10 mm long and a second probe with a 30 µm diameter probe on a 20 µm diameter shaft that is 2 mm long. For this measurement, the larger of the two UMAP probes was used.

Figure 6 shows the measurement results for all three processes and the extent of overlap, limited in the case of the physical probes, by the probe shaft length. The M48 measures the gap to a depth of 1.25 mm from open end and the UMAP measures the gap to a depth of 8.5 mm from the open end. Comparison of the results in Figure 6 show that all three systems see a similar variation in gap geometry, which supports applying a systematic correction to the triangulation probe results using the M48 results as a reference. Upon closer examination to the data presented in Figure 7, the slope of triangulation probe and the M48 data match within 29 nm/mm in the overlap region. Although the UMAP data shows an increasing gap dimension as a function of depth like the other results, the slope is not nearly as close of a match. This observation is not a surprise in that the UMAP probe often exhibits errors that are function of depth due to sidewall-probe stem interactions that result from the shaft having a diameter only 10 µm smaller than the probe. As more and more of the shaft is exposed to the part sidewall, the interaction forces increasingly affect the trigger point. This trend could be removed by measuring the 2 mm cuvette with the UMAP probe then extracting the depth dependent correction using the M48 data, but the 2 mm cuvette was no longer available by the time the decision was made to include the UMAP. Ultimately, we concluded that all comparisons were useful and we could confidently use the triangulation data for measuring the smaller cuvettes, correcting systematic differences based on overlap measurements with the M48, even though the overlap region was only a small fraction of the gap depth.

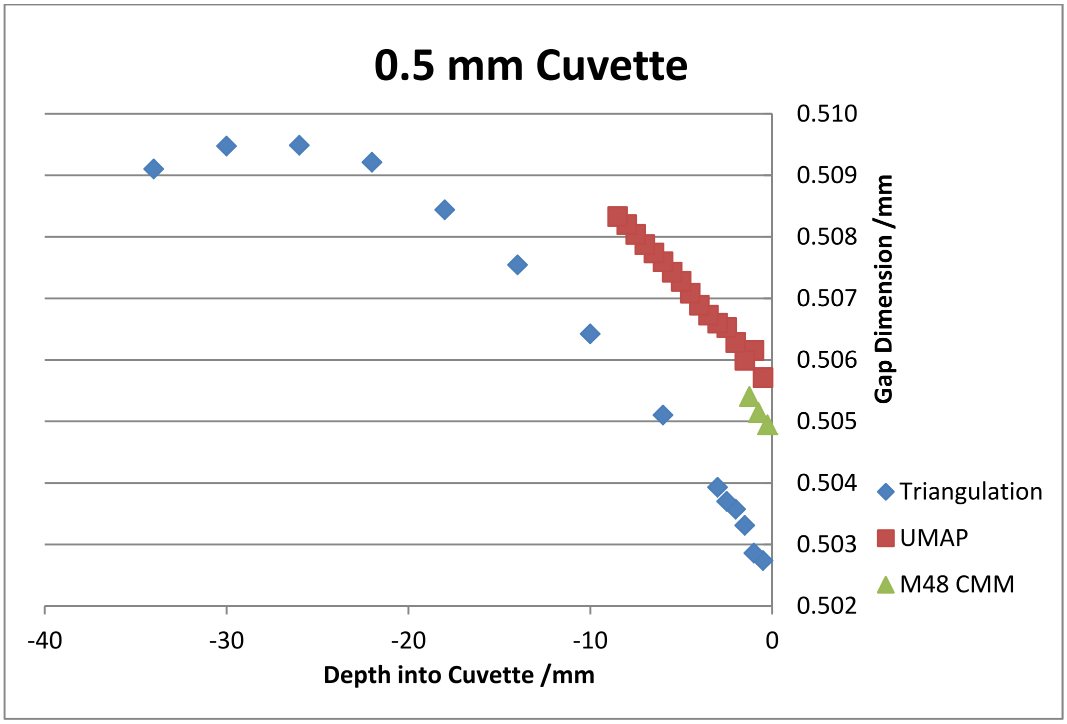

Figure 6. Measurement results for 0.5 mm cuvette

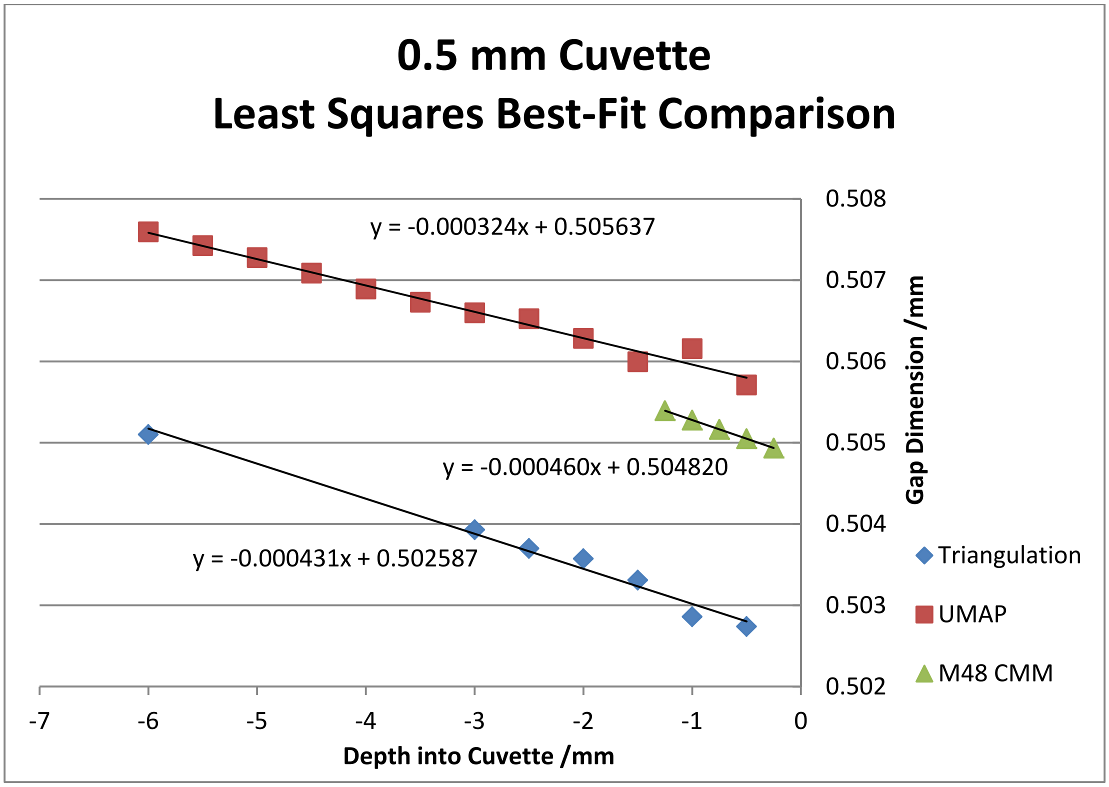

Figure 7. Linear plots for 0.5 mm cuvette

3.5 Data Analysis and Uncertainty

Both the 1 mm and 0.5 mm cuvettes were measured using two different methods, a high accuracy M48 CMM and a laser triangulation probe. Because of the small gap widths, the CMM could only measure down 1.25 mm into these cuvette openings. The laser triangulation probe collected 3,800 points across the width of the cuvette, and each collection of 3,800 points was referred to as a line or profile. The cuvette was translated along the Y direction, the long dimension of the cuvette, and the line scan was repeated at 14 different levels, 0.5 mm to 34 mm from the open end of the cuvette. The accessible depths were then measured with the M48 CMM and used to correct the small bias in the laser triangulation probe data. The bias corrections were based on the average gap dimension across the width.

The short-term reproducibility of the laser triangulation probe is 0.1 µm and, from the comparison data between the M48 and the triangulation measurement system, the standard error of each comparison correction is 0.3 µm, which includes the triangulation probe repeatability. We will call this u_1. The M48 CMM, which is used as the reference for these comparison measurements, has a standard uncertainty of 0.1 µm, which we will call u_2. Other sources of error are negligible. Combining these standard uncertainties, u_1 and u_2 in quadrature yields a combined standard, u_c, of 0.32 µm. With a coverage factor of k=2, the expanded uncertainty, U, then becomes ± 0.64 µm.

4. Conclusion

Although the laser triangulation probe is not an absolute measurement, we devised a creative approach using multiple measurement techniques at our disposal to extend our measurement capabilities to solve a critical measurement request. This method used the laser triangulation probe as a comparator with the M48 CMM as the reference based on the overlap where the two processes could measure the same measurand. As the primary means of validation for the approach to measure 0.5 mm and 1 mm cuvettes, we used comparison measurements on an near identical item, the 2 mm cuvette, for which both technologies could measure the entire item. In addition, out of an abundance of caution, we also used a third measurement system, the Mitutoyo UMAP ULTRA350 Microfeature CMM, to give support to the notion that we could extrapolate our correction from a very small overlap between the two methods on the 0.5 mm and 1.0 mm cuvettes to the remaining 90 % or more of the measurement results produced by the laser triangulation probe. The high degree of accuracy of the cuvette gap measurements, resulted in an expanded uncertainty for the SRM's absorbance as a function of pathlength of less than 0.08 %, which exceeded expectations.

Lastly, it is important to note that the results reported represent the average gap across the width of the cuvette face at the specified depth. The data from both the M48 and the laser triangulation probe revealed that there was significant geometry variation across the width. The reported uncertainty assumes that the laser spot during the absorbance spectrometry measurements is relatively well centered on the cuvette face. If this is not the case, the user would need to incorporate additional uncertainty to cover geometry based variability caused by misalignment relative to the center where the reference measurements and uncertainty are valid.

5. Acknowledgments

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6. References

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