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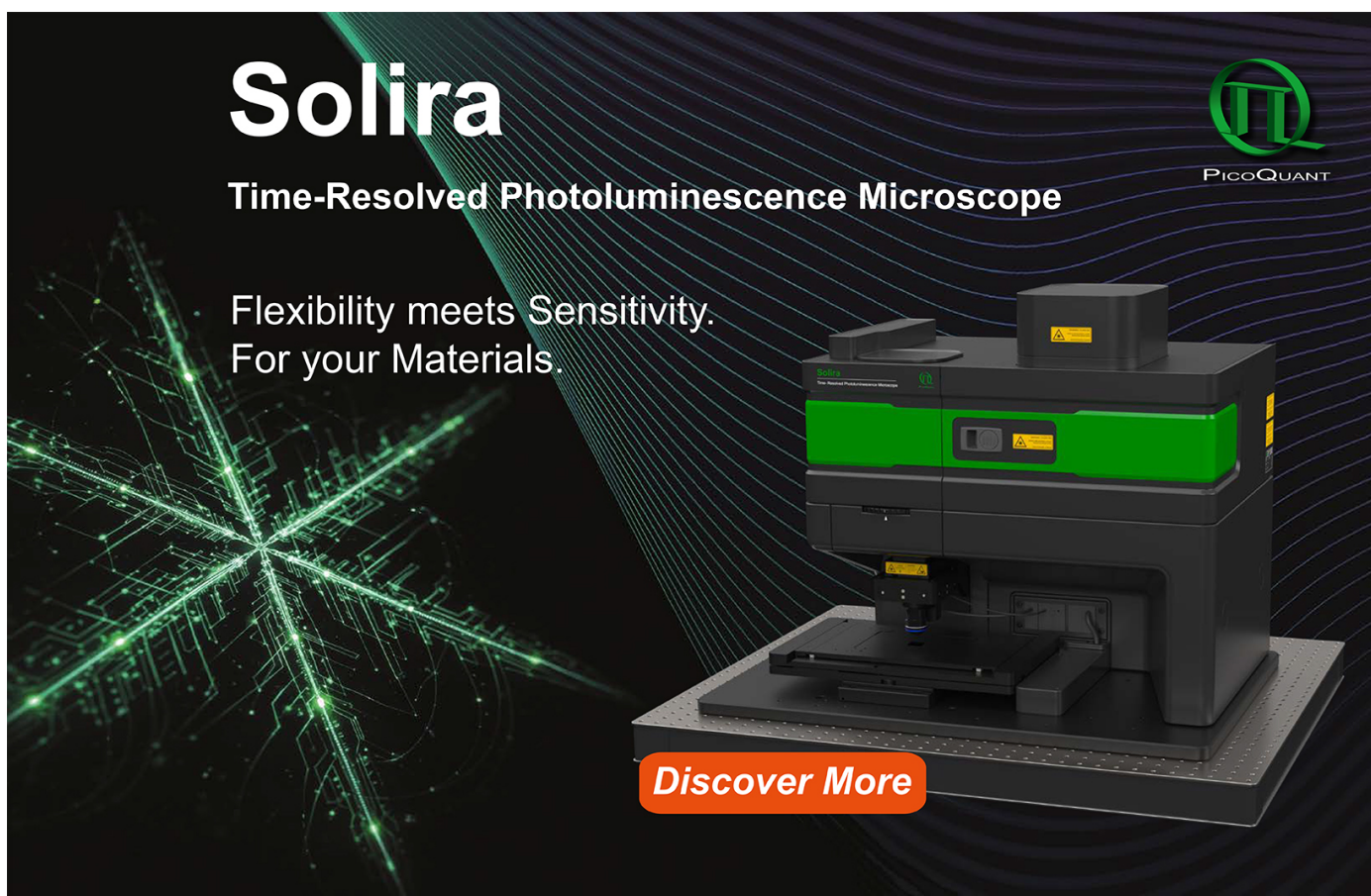
Validation of upgrades to the NIST M48 vision measurement system

To cite this article: Maxwell Pranievicz *et al* 2026 *Meas. Sci. Technol.* **37** 405012

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RECEIVED
28 April 2026

REVISED
2 September 2026

ACCEPTED FOR PUBLICATION
17 September 2026

PUBLISHED
8 October 2026

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Validation of upgrades to the NIST M48 vision measurement system

Maxwell Praniewicz^{*} , John R Stoup and Wei Ren

Dimensional Metrology Group, National Institute of Standards and Technology, Gaithersburg, MD, United States of America

^{*} Author to whom any correspondence should be addressed.

E-mail: maxwell.praniewicz@nist.gov

Keywords: calibration, length, vision, line-scale, grid-plate

Abstract

One-dimensional and two-dimensional vision artifacts are calibrated at NIST using the Dimensional Metrology Group's M48 vision measurement system. The vision system replaces the tactile probing system on the primary M48 CMM (coordinate measurement machine) with a camera system integrated into the CMM controller, combining the ultra-accurate 2D positioning of the M48 CMM with non-contact edge detection. Typical expanded measurement uncertainties ($k = 2$) are between 0.15–0.50 μm , dependent upon artifact quality. However, degradation of the hardware over time has made the system less reliable, causing long lead times for calibrations. Currently, resolution and image quality limit the artifacts which can be measured on the machine, and there is customer-based need to improve the scope of artifacts which can be measured. Line width limitations are currently 5 μm –10 μm and customer needs are pushing toward lines widths $\leq 5 \mu\text{m}$ and need greater flexibility in artifact illumination. This work details the first steps taken toward improving the reliability and capabilities of this system. Using the CTE of common glass vision artifacts, $8.0 \times 10^{-6} / ^\circ\text{C}$, the expanded measurement uncertainty ($k = 2$) is proposed as $0.092 \mu\text{m} + 1.2 \times 10^{-7} \text{ l}$ for one-dimensional measurements and $0.24 \mu\text{m} + 1.1 \times 10^{-7} \text{ l}$ for two-dimensional measurements. Measurements of long term NIST check standards and standard reference materials are used to validate these uncertainties.

1. Background

The dimensional metrology group (DMG) at the National Institute of Standards and Technology (NIST) realizes and disseminates the SI unit of length within the United States and to customers around the world. The primary means of this dissemination is the calibration of length artifacts ranging in size from micrometers to several meters. In the U.S. optical measurement systems often rely on calibrated artifacts (e.g. line scales, stage micrometers, grid plates). One-dimensional vision artifacts were previously calibrated at NIST using the NIST LSI (length scale interferometer) [1]. This system was capable of measuring scales up to 1 m in length with line widths down to 1 μm . While the final measurement uncertainty would be greatly dependent on artifact quality, uncertainties were often on the order of tens-of-nanometers. Two-dimensional vision artifacts (grid plates) were calibrated using retrofitted multi-axis coordinate measuring machines (CMMs) [2]. The measurement process for these artifacts has not changed significantly throughout the following decades, but has been improved significantly by improved artifact quality, camera technology, and CMM error mapping techniques. However, services using the LSI were halted in the 2010's due to turnover in NIST staff and equipment instability. Thus, the majority of vision artifact calibrations were transitioned over to using the CMM based measurement platform. In its current state, the vision measurement system is used on the Moore M48 CMMs in the DMG at NIST.

The NIST Moore M48 CMMs are ultra-accurate measuring systems and have been used extensively by the DMG not only for standard calibration activities [3], but for world class measurements of geometry [4–7]. The vision system replaces the tactile probing system on the M48 CMM with a camera

system alongside the CMM controller, combining the ultra-accurate 2D positioning of the M48 CMM with non-contact edge detection. Typical expanded measurement uncertainties ($k = 2$) using the current iteration of the system are between 0.15–0.50 μm , dependent upon artifact quality. However, degradation of the hardware over time has made the system less reliable, causing long lead times for calibrations. Currently, resolution and image quality limit the artifacts which can be measured on the machine, and there is customer-based need to improve the scope of artifacts which can be measured. Line width limitations are currently 5–10 μm and customer needs are pushing toward lines widths $\leq 5 \mu\text{m}$ and need greater flexibility in artifact illumination. This work will detail the first steps taken toward improving the reliability and capabilities of this system. Section 1 has described the background for the improvements needed. Section 2 describes the new modifications to the system, including the motivations behind the system design. Section 3 describes the measurement techniques employed in the measurement of artifacts, including the measurement of both one-dimensional and two-dimensional artifacts. Section 4 describes the uncertainty analysis for the measurement system, contrasting to the previous uncertainty budget for the system. Section 5 discusses measurement validation, including measurements of control check standards, including one-dimensional and two-dimensional artifacts.

2. System description

The recent redesign of this system has been implemented to improve reliability and upgrade performance. The basic design of this system is shown in figure 1, and contains a compact collimating microscope, LED light source, low wattage camera, and image processing software. The overall design goals of the system were to improve the resolution and illumination consistency from the previous system, while minimizing the heat introduced into the measurement environment. A relatively low-wattage commercial CMOS (Basler acA2440-35um) camera was chosen to reduce the total energy input into the measurement system ($\sim 2.5 \text{ W}$), while having sufficient resolution (5 MP) to perform measurements. This camera utilizes a global shutter sensor, to reduce the potential for imaging artifacts. The camera is affixed using a commercial C-mount to a compact collimating microscope (Nikon CM-30L). This then allows the imaging system to use a wide range of imaging objectives. Magnification from 1x–50x can be used to obtain FOV of 8.45 mm $\times$ 7.07 mm to 0.17 mm $\times$ 0.14 mm and resolutions from 3.45 μm to 0.069 μm . This is a significant improvement over the previous camera which had a pixel size of 17 μm $\times$ 13 μm and a similar FOV.

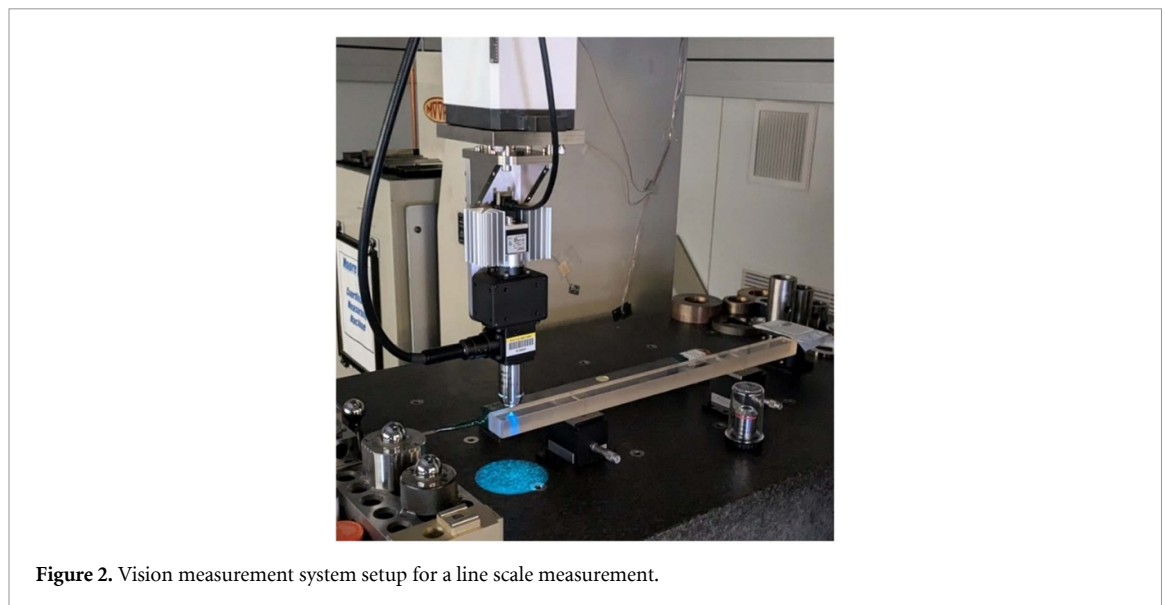
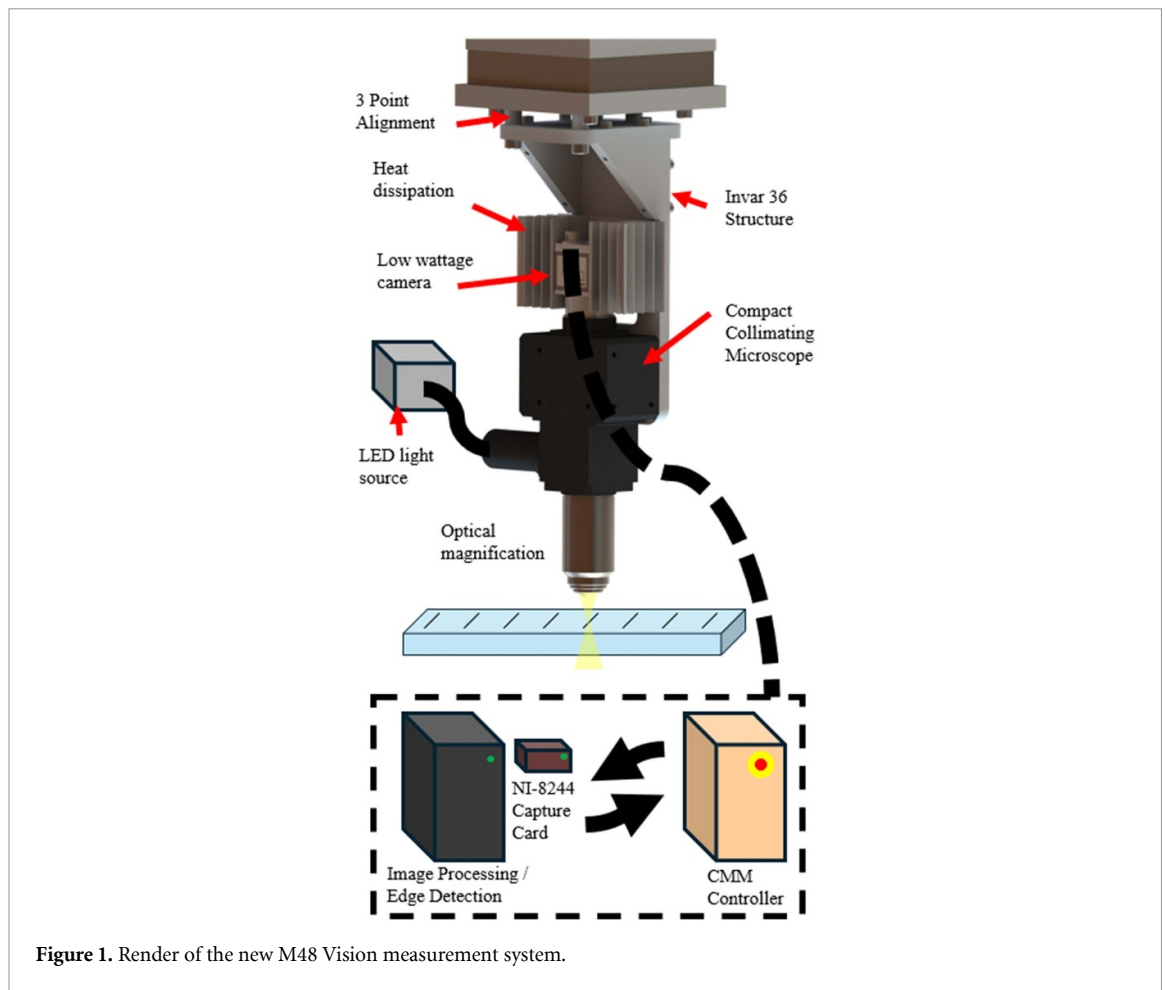
Through-optic lighting is supplied using a commercial white light LED source, which replaced the previous generation's halogen bulb illumination. This greatly improved consistency in light intensity and uniformity, contributing to improved image repeatability. No bottom lighting or ring lighting is currently available on this system, but most measurements can be completed using this reflected light configuration. To mitigate the impact of input heat on the measurement support structure, all components were machined from Invar 36. Since the coefficient of thermal expansion (CTE) of this material is nearly 0, there would be little asymmetric thermal expansion of the support structure to cause the image to drift over time. Addition heat sinks were also attached to the camera to mitigate heat buildup in the structure, which could potentially cause expansion (and therefore image distortion) in the camera mount. The three point mount from the structure to ram of the CMM allowed for angular adjustment of the structure to make the optical path coaxial with the Z motion of the CMM.

3. Measurement technique/analysis

While an individual artifact will always need its own task specific measurement plan, the measurement procedures are generally classified as either one-dimensional scale measurements, or two-dimensional scale measurements. However, the procedures are generally similar in concept.

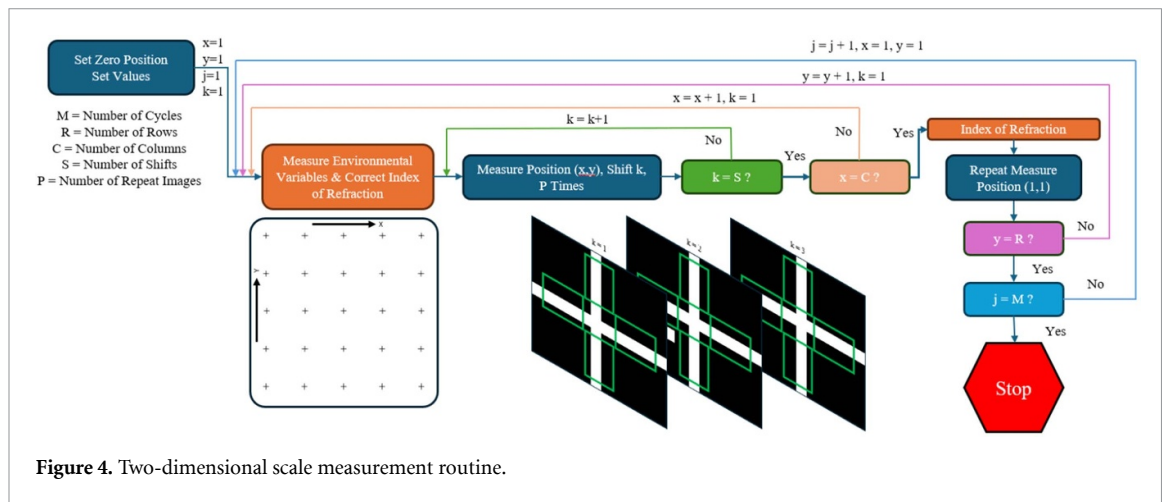
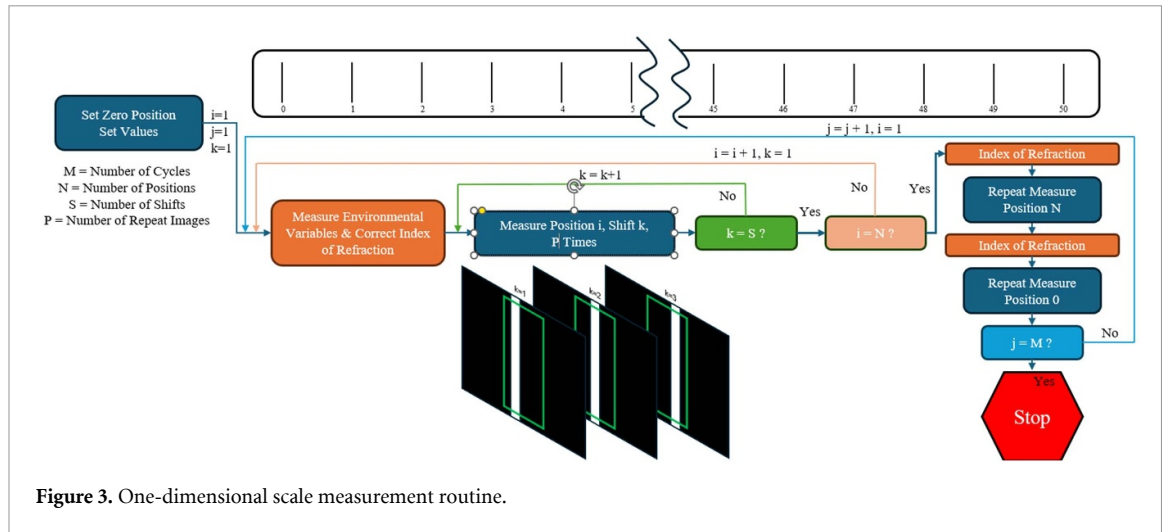
3.1. One-dimensional scale measurements

Since the M48 CMMs are fixed-bridge style machines [8], one dimensional artifacts are always oriented such that the measurement axis along the artifact is within the XY plane and is aligned with the X axis of the machine. This minimizes the contribution from machine geometric errors, since only one axis is moving during the measurement process. It also minimizes any vibrations or stresses imparted to the vision measurement system from the motion axes it is coupled to (Z,Y). Short one-dimensional scales (e.g. stage micrometers) are often supported on a flat plate using a tilt-turn stage, allowing for the adjustment of focus over the scale length (rotation about Y) and alignment of the scale to the X axis (rotation about Z). Longer one-dimensional scales (e.g. line scales) are supported on two Bessel points



to minimize the bending of the scale and provide a reproducible mounting condition. The two points are supported by Z axis adjustment stages, which are used to level the scale in the XY plane. The alignment of the scale is adjusted by laterally moving the adjustment stages. An example of a line scale measurement set-up is shown in figure 2.

After the scale is aligned within the measurement volume, the zero position of the scale is found either by positioning the system at the center of the zero line defined on the scale or at a location pre-defined through agreement with the gauge owner. Focus on the zero position is found by first manually



driving the machine to the Z position which visually maximizes the image sharpness, then adjusting the Z position by $0.5 \mu\text{m}$ increments to maximize the slope of the edge response function.

The measurement sequence begins by incrementally measuring each position from zero to the end of the gauge. The end position is then measured again, followed by a repeat measurement of the zero position. These repeats allow for the correction of any linear drift in the measurement process. This is defined as a measurement cycle, M , and is repeated multiple times to evaluate the repeatability of the process, shown schematically in figure 3. The measurements of the individual positions, N , are accomplished by driving the CMM to a predefined nominal position (defined by the nominal measurement lengths of the scale). The CMM then waits for a predetermined amount of time (generally 2 s) to allow for any residual oscillations of the measurement system to dampen. A signal is then set from the CMM software to the image acquisition system to begin its routine. It acquires the pre-set number, P of sequential images for processes. These repeat images are used to determine statistics regarding CMM positioning stability for each position measured. To transfer the CMM scale to the camera scale ($\mu\text{m pixel}^{-1}$), the graduation on the scale is translated several times, S , within the field of view at known increments on either side of the nominal position. This allows for an *in-situ* calibration of the length scale of the image at each measured position by dividing the number of pixels translated along the measurement direction by the known translation of the system.

The calculation of the line position within the image is completed using the National Instruments edge detection tools. Before the measurement process is begun, the user defines an ROI (region of interest) within the image, shown as the green box on the images in figure 3. The function then progresses from the top of the image and runs an edge detection function along each row (or skipping a predefined number of rows depending upon user inputs) to find the left and right edge of the line independently. These two edge points are then averaged to yield a center point. A line is then fit to these center points to represent the position of the line in the image. This fit line is then evaluated at the middle of the ROI in the Y direction to yield the X value of the line. Since the measurand is the position of the line, the

accuracy of the edge detection is minimally influential in the determination of the line center position, as edge detection bias will only symmetrically increase or decrease the width of the line.

The end result of the measurement process is an array of line positions in pixel coordinates which correspond to predefined nominal positions. The measurement result is then calculated by taking the difference between the measured pixel position and the position of the zero in the pixel coordinates multiplied by the pixel scale factor and added to predefined nominal position.

3.2. Two-dimensional scale measurements

Two-dimensional scale measurements performed by this system follow the same fundamental principles as one-dimensional scales, but included additional analysis steps for the second axis. Generally, the X or axis parallel to the direction of any writing or numbering pattern on the artifact, is aligned to the X axis of the machine. Plates are supported at the three points of minimum bending, unless otherwise specified by the customer [9]. The plate is leveled across these three points to be within the focus plane.

The measurement sequence is similar to that of the one-dimensional scales. The CMM moves to the measurement position, then waits for a predetermined amount of time (2 s) to allow for any residual oscillations of the measurement system to dampen. The zero position is first measured and continues to step in each increment along the first row of the grid, as seen schematically in figure 4. After the last position the row is measured, the zero position is measured again. The sequence then continues to the next row. This process repeats until all positions on the plate are measured. Again, this is defined as a measurement cycle, M . Like the one-directional measurements, a pre-set number of images, R , are captured for each position. The length scale of the machine is also transferred to the camera scale by translating the scale within the field of view S times. However, the image is translated in both X and Y for two-dimensional measurements.

The calculation of the position in two-dimensional measurements is highly dependent on the marker geometry. The majority of artifacts measured use a cross geometry (two intersecting perpendicular lines) as the individual markers, so that process is described here. Four regions of interest are defined on the cross, one for each leg of the cross. For the top and bottom sections of the cross, the same edge detection algorithm is used to find the center points of the line in the X direction. The center points of the top and bottom section are combined into one data set, and a line is fit to this data set. The same is completed for the left and right sections of the cross; the center of the edges are found in Y and a line is fit to the center points. The position of the cross is defined as the intersection point between the horizontal and vertical lines of the cross.

After one measurement cycle is completed, the artifact is rotated 90° within the measurement volume and measured a second time. Because the X axis of the machine is fundamentally trusted more than the Y axis due to its stability, reversal techniques are used to minimize any additional error contribution and residual rigid body errors of the measuring machine [10]. While previous iterations of this system used the method described in Hocken and Borchardt [11], the simplifications in this method to allow for simpler computation assume small angle rotations and ignore second order terms. This work solves this nonlinear system of equations using an iterative solver. First, both data sets must be shifted such that the center point (or middle of the data for an even grid) is at the origin (0,0). The solver minimizes φ , in equation (1), by using the input of the measurement at two positions X_1 and X_2 , where X_2 is nominally the 90° rotation of X_1 . However, due to squareness errors, α , scale mismatch between the two axes, γ , error in the 90° rotation, β , and translational errors, ε_x and ε_y , this will not be the case. Thus, X'_1 is defined in equation (2).

$$\varphi = \sqrt{\sum_N^i (X_{1,i} - X'_{1,i})^2} \quad (1)$$

$$X'_1 = AB^{-1}A^{-1}X_2 + \varepsilon \quad (2)$$

$$A = \begin{bmatrix} 1 & -\alpha \\ 0 & 1 - \gamma \end{bmatrix} \quad (3)$$

$$B = \begin{bmatrix} \cos(\frac{\pi}{2} + \beta) & -\sin(\frac{\pi}{2} + \beta) \\ -\sin(\frac{\pi}{2} + \beta) & \cos(\frac{\pi}{2} + \beta) \end{bmatrix} \quad (4)$$

$$\varepsilon = \begin{bmatrix} \varepsilon_x & \varepsilon_y \end{bmatrix}. \quad (5)$$

After these error parameters are calculated using the iterative solver, they are then used to calculate the undeformed plate geometry in both positions.

$$X_{f,1} = A^{-1}X_1 \quad (6)$$

$$X_{f,2} = B^{-1}A^{-1}X_2 + \varepsilon. \quad (7)$$

Since either calculation is a valid solution for the final undistorted values of the artifact, X_{Final} , they are averaged to achieve the final value in order to reduce and residual error. A factor of $\varepsilon/2$ is subtracted such that the reference point has coordinates (0,0).

$$X_{\text{Final}} = \frac{1}{2}(X_{f,1} + X_{f,2}) - \frac{\varepsilon}{2}. \quad (8)$$

4. Uncertainty analysis

The uncertainty budgets for one-dimensional and two-dimensional vision measurements using the Moore M48 are very similar in their components, with only minor differences occurring in a few terms. Therefore, all components of the uncertainty will be presented in one section, with the differences between one-dimensional and two-dimensional noted.

4.1. Uncertainty budget components

This section details the contribution from each term in the uncertainty budget

4.1.1. Machine staging uncertainty

Along the X and Y axes, the CMM staging uncertainty is assessed by analyzing the one-dimensional variability of a fixed location. Vision system staging is different from tactile probing as tactile probing does not require the CMM to stop and hold a fixed position. It has been observed that the CMM controller is susceptible to small systematic offsets during staging. These are estimated to be no more than 0.02 μm for one-dimensional measurements. For two-dimensional measurements, this is estimated to be no more than 0.04 μm . In the future, as more control measurements are collected on our vision control artifacts using different locations on the machine, these errors may become sampled in the control artifact reproducibility.

4.1.2. Error-mapping process and accuracy

The CMM is error-mapped using an external laser system. The temperature difference between the two beams is small, ± 0.020 $^{\circ}\text{C}$, giving an associated error of 0.02 $\mu\text{m}/\text{m}$. The atmospheric pressure difference between the two beams, no more than 200 mm apart in height, is negligible.

The traceable mapping laser frequency has a calibration standard uncertainty of 2.3×10^{-9} μm . However, the stability of the laser over time is a much larger contributor to this uncertainty. If the laser is only calibrated every several years, a reasonable estimate of this uncertainty is 1.0×10^{-8} . Statistical analysis has been performed on the quality of the error map as applied by the CMM controller. These tests reveal errors such as mapping beam alignment, and low frequency map accuracy at spacings of 25 mm. The standard uncertainty of the mapping process accuracy is estimated to be ± 0.02 $\mu\text{m} + 0.02 \times 10^{-6}$ L. The error map smoothness is quite good and linear interpolation between the measured points, 25 mm apart, is indistinguishable from the map reproducibility cited above.

4.1.3. Check standard and history reproducibility

We have measured many control artifacts on the same machines for over 15 years and have high quality check standard data (many hundreds of measurements of long end standards, control step gauges of different types, etc) as well as hundreds of measurements of check standard ring and plug gauges. We also have measurements on two-dimensional vision plates, two-dimensional ball plates, and one-dimensional line scales. The data is analyzed for each specific M48 CMM and the data shows a one-dimensional vision reproducibility for low CTE artifacts with high quality lines of ± 0.03 $\mu\text{m} + 0.03 \times 10^{-6}$ L. For L two-dimensional vision reproducibility for low CTE artifacts with high quality lines of ± 0.10 $\mu\text{m} + 0.04 \times 10^{-6}$ L. Though, this uncertainty will likely be improved in the future due to these improvements presented in this work.

4.1.4. Index of refraction calculation

The wavelength compensation has two parts. First the current wavelength is calculated from independent readings of atmospheric pressure, temperature and humidity using standalone, calibrated instrumentation. During data collection, the wavelength compensation is updated periodically using the current accepted Edlén Equation to convert pressure, temperature, and humidity to a wavelength correction. The uncertainty in the Edlén equation from work at NIST is estimated to be accurate to 0.015 $\mu\text{m}/\text{m}$.

Because we have less than 10 recalibrations of the temperature, pressure, and humidity instruments that make up the weather station, the variability due to these sensors is not yet adequately sampled in the reproducibility data and are addressed individually. The thermometer calibration history shows the sensors 'as found' condition at calibration to have a standard deviation of 0.006 $^{\circ}\text{C}$. More importantly, the thermal gradients during operation are measured to be about ± 0.020 $^{\circ}\text{C}$ along the interferometry path and are generally systematic in distribution. Using this and the dependence of the refractive index on the temperature we get a standard-length uncertainty of 0.02 $\mu\text{m}/\text{m}$. The humidity uncertainty of 2% gives a length uncertainty of about 0.017 $\mu\text{m}/\text{m}$. The standard uncertainty in pressure does not come primarily from the pressure sensor calibration, which has a standard uncertainty of 2.1 Pa. The pressure in the CMM laboratory is the one environmental condition that cannot be controlled and kept stable over long periods of time like temperature and humidity. The laser frequency is updated using the Edlén Equation at periodic intervals. During those intervals, the pressure fluctuates up to about 15 Pa before a new update is conducted. This gives a length uncertainty of about 0.041 $\mu\text{m}/\text{m}$ during the CMM operation.

4.1.5. Temperature related uncertainty

There are three other sources of uncertainty associated with thermal expansion and temperature measurement. First is the uncertainty in the thermometer calibration. The thermometer is calibrated to an accuracy of 0.0015 $^{\circ}\text{C}$, resulting in a standard uncertainty of about 0.012 $\mu\text{m}/\text{m}$, if using the common CTE of $8.0 \times 10^{-6}/^{\circ}\text{C}$. The thermal gradients that exist on the table are controlled within a range of about 0.009 $^{\circ}\text{C}$. Using the half width in a rectangular distribution, this results in a standard uncertainty of about 0.040 $\mu\text{m}/\text{m}$, if using the same CTE as previously stated. For low CTE glass, these sources are negligible.

The uncertainty in the thermal expansion coefficient of the artifact depends on the artifact. For artifacts without exact expansion coefficients measured, we take an uncertainty value of $\pm 0.5 \times 10^{-6}/^{\circ}\text{C}$. The uncertainty in the length measurement also depends on the difference between the measurement temperature and 20 $^{\circ}\text{C}$. The M48 room maintains the artifact between 19.97 $^{\circ}\text{C}$ and 20.03 $^{\circ}\text{C}$, leading to an uncertainty of about 0.015 $\mu\text{m}/\text{m}$. Again, for low CTE glass, these sources are negligible.

4.1.6. Line edge geometry and focus

The flatness of the gauging surfaces and the quality of the gauge lines can affect the uncertainty of the measurement. High quality lines of less than 25 μm in width generally perform the best using these systems using higher powered objectives. Wider 250 μm lines usually have lower edge quality and require low power objectives that add uncertainty due to focusing performance and variability due to the line edge sampling. These effects are estimated from experimental data for each customer artifact and put in the budget as required. Also, the thickness of the glass artifacts and the gage support configuration can affect the quality of the vision system focus as the artifact is measured. Our system does not adjust camera position to maintain constant focus. All errors resulting from defocusing as a consequence of surface flatness issues are contained in the results. These types of errors are minimized by measuring the line centers where any defocusing should affect both edges equally. For high quality one-dimensional artifacts, these effects are estimated to be 0.02 μm . For high quality two-dimensional artifacts, these effects are estimated to be 0.05 μm .

4.2. One-dimensional and two-dimensional uncertainty

The final tabulated uncertainty budgets for one-dimensional and two-dimensional vision measurements on the M48 CMMs, shown in tables 1 and 2. In order to present a linear statement of uncertainty to our customers in the form of $A + BL$, the individual terms listed in the budget are not added in quadrature. Instead, the length independent terms are summed in quadrature to yield A . The length dependent terms are then summed in quadrature to yield B' . B is then calculated by subtracting A from B' . This linearization only overestimates the uncertainty throughout the full range of measurement. For one-dimensional scale measurements, this method over estimates the expanded uncertainty ($k = 2$) at

Table 1. One-dimensional uncertainty budget, assuming $\alpha = 8.0 \times 10^{-6}/^{\circ}\text{C}$.

Component description	Standard uncertainty	Sensitivity coefficient	Length uncertainty	
			Fixed	Length dependent
M48 2D staging uncertainty	0.020 μm	1	0.02 μm	
Temperature difference in beam paths during error mapping	0.020 $^{\circ}\text{C}$	$9.3 \times 10^{-7} L$		$2.0 \times 10^{-8} L$
Mapping laser frequency calibration	1×10^{-8}	L		$1 \times 10^{-8} L$
Error mapping process—method accuracy		1	0.02 μm	$2.0 \times 10^{-8} L$
Measurement reproducibility from Low CTE Control 2d vision artifacts (fixturing stability, unmapped positioning errors, contaminants, gauge alignment, CMM drift, map stability)		1	0.03 μm	$3.0 \times 10^{-8} L$
Edlén equation	1.5×10^{-8}	L		$1.5 \times 10^{-8} L$
Index of Refraction: Air Temp	0.020 $^{\circ}\text{C}$	$9.3 \times 10^{-7} L$		$2.0 \times 10^{-8} L$
Index of Refraction: Air Pressure	15 Pa	$2.7 \times 10^{-9} L$		$4.1 \times 10^{-8} L$
Index of refraction: humidity	2%	$1 \times 10^{-8} L$		$1.7 \times 10^{-8} L$
Thermometer accuracy	0.0015 $^{\circ}\text{C}$	αL		$1.2 \times 10^{-8} L$
Gauge temp/gradient Measurement	0.005 $^{\circ}\text{C}$	αL		$4.0 \times 10^{-8} L$
Coefficient of thermal expansion	0.5×10^{-6}	0.03 L		$1.5 \times 10^{-8} L$
Lighting and focusing variability (systematic behavior)		1	0.02 μm	
Combined standard uncertainty, u_c			0.046 μm	$5.9 \times 10^{-8} L$
Expanded uncertainty, $U (k = 2)$			0.092 μm	$1.2 \times 10^{-7} L$

Table 2. Two-dimensional uncertainty budget, assuming $\alpha = 8.0 \times 10^{-6}/^{\circ}\text{C}$.

Component description	Standard uncertainty	Sensitivity coefficient	Length uncertainty	
			Fixed	Length dependent
M48 2D staging uncertainty	0.040 μm	1	0.04 μm	
Temperature difference in beam paths during error mapping	0.020 $^{\circ}\text{C}$	$9.3 \times 10^{-7} L$		$2.0 \times 10^{-8} L$
Mapping laser frequency calibration	1.0×10^{-8}	L		$1.0 \times 10^{-8} L$
Error mapping process—method Accuracy		1	0.02 μm	$2.0 \times 10^{-8} L$
Measurement reproducibility from Low CTE Control 2d Vision		1	0.10 μm	$4.0 \times 10^{-8} L$
Artifacts (fixturing stability, unmapped positioning errors, contaminants, gauge alignment, CMM drift, map stability)				
Edlén equation	1.5×10^{-8}	L		$1.5 \times 10^{-8} L$
Index of refraction: air temp	0.020 $^{\circ}\text{C}$	$9.3 \times 10^{-7} L$		$2.0 \times 10^{-8} L$
Index of refraction: air pressure	15 Pa	$2.7 \times 10^{-9} L$		$4.1 \times 10^{-8} L$
Index of refraction: humidity	2%	$1.0 \times 10^{-8} L$		$1.7 \times 10^{-8} L$
Thermometer accuracy	0.0015 $^{\circ}\text{C}$	αL		$1.2 \times 10^{-8} L$
Gauge temp/gradient Measurement	0.005 $^{\circ}\text{C}$	αL		$4.0 \times 10^{-8} L$
Coefficient of thermal expansion	0.5×10^{-6}	0.03 L		$1.5 \times 10^{-8} L$
Lighting and focusing variability (systematic behavior)		1	0.05 μm	
Combined standard uncertainty, u_c			0.12 μm	$5.4 \times 10^{-8} L$
Expanded uncertainty, $U (k = 2)$			0.24 μm	$1.1 \times 10^{-7} L$

a maximum of 0.011 μm at $L = 0.4$ m. For two-dimensional scale measurements, this method over estimates the expanded uncertainty ($k = 2$) at a maximum of 0.008 μm at $L = 0.46$ m. Using these budgets, the expanded uncertainty ($k = 2$) for a high quality 1 mm glass stage micrometer is 0.092 μm . For a 600 mm glass line scale, the expanded uncertainty ($k = 2$) is 0.163 μm . For a 130 mm $\times$ 130 mm glass grid plate, the expanded uncertainty ($k = 2$) over the longest diagonal would be 0.261 μm .

5. Measurement validation

Testing of this system was completed using NIST check standards.

5.1. One-dimensional measurement validation

The one-dimensional measurement procedures were validated using a Mitutoyo HL-500 mm line scale, which has >15 years of calibration history at NIST. This scale is marked using 4 μm wide lines and is made of Zerodur, which has a CTE of $(0.00 \pm 0.02) \times 10^{-6}/^{\circ}\text{C}$. This scale was setup according to the

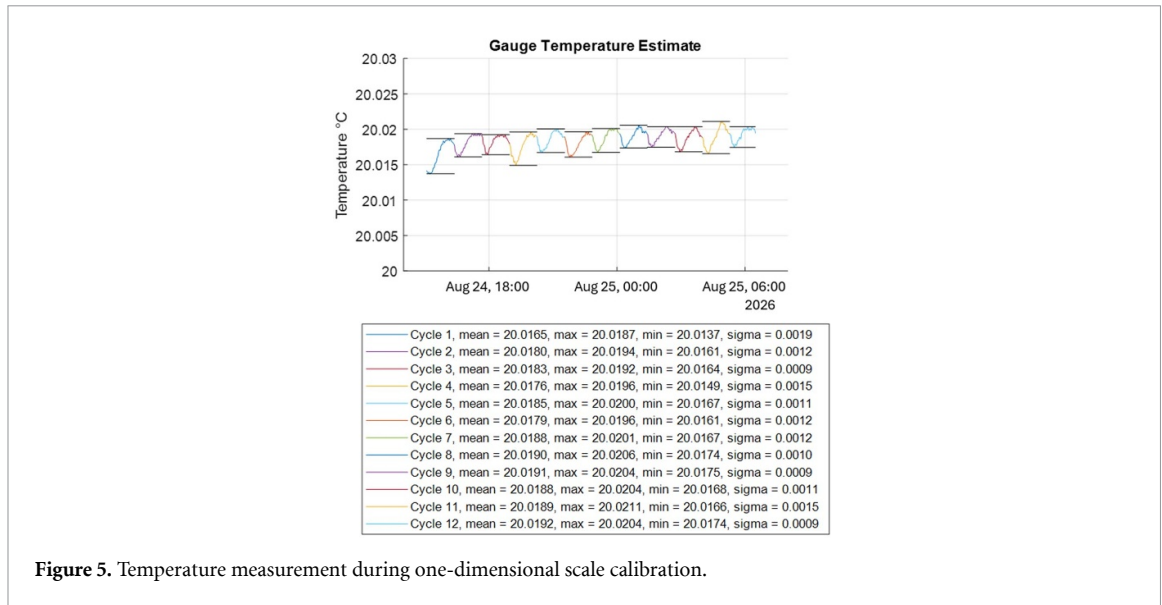


Figure 5. Temperature measurement during one-dimensional scale calibration.

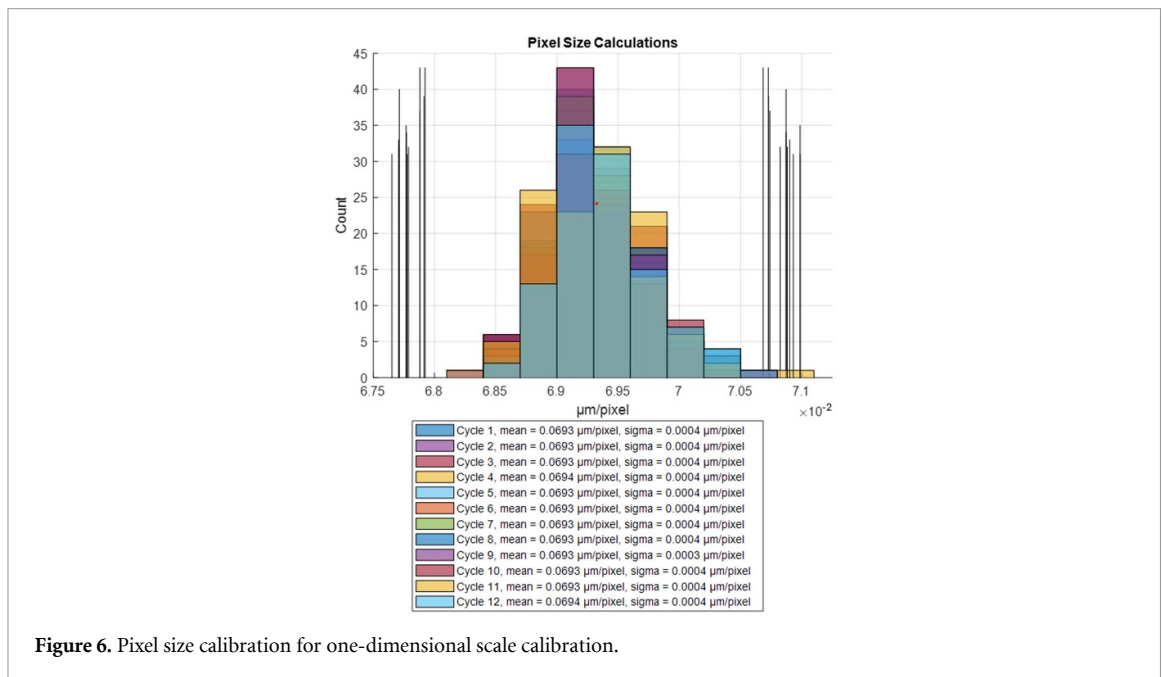
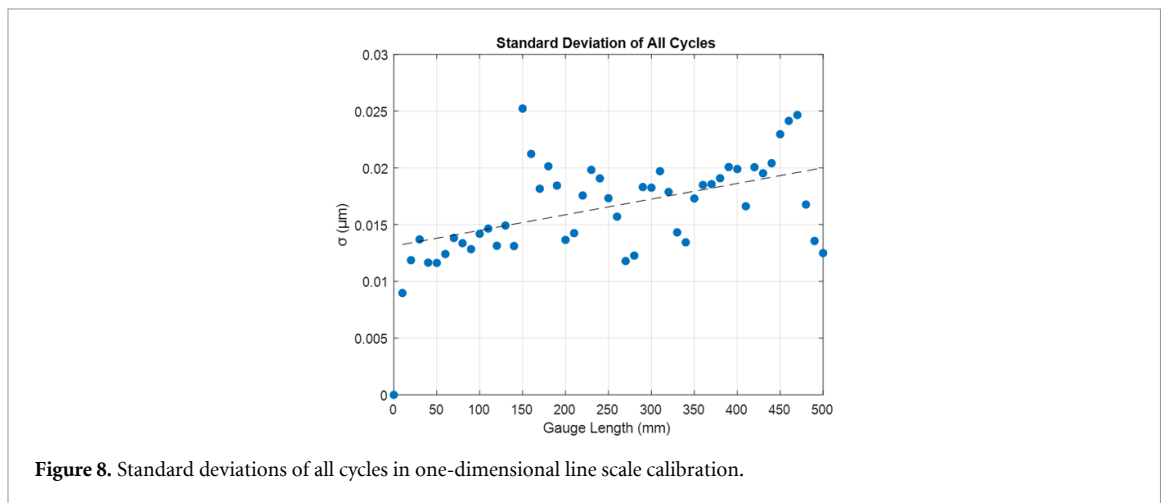
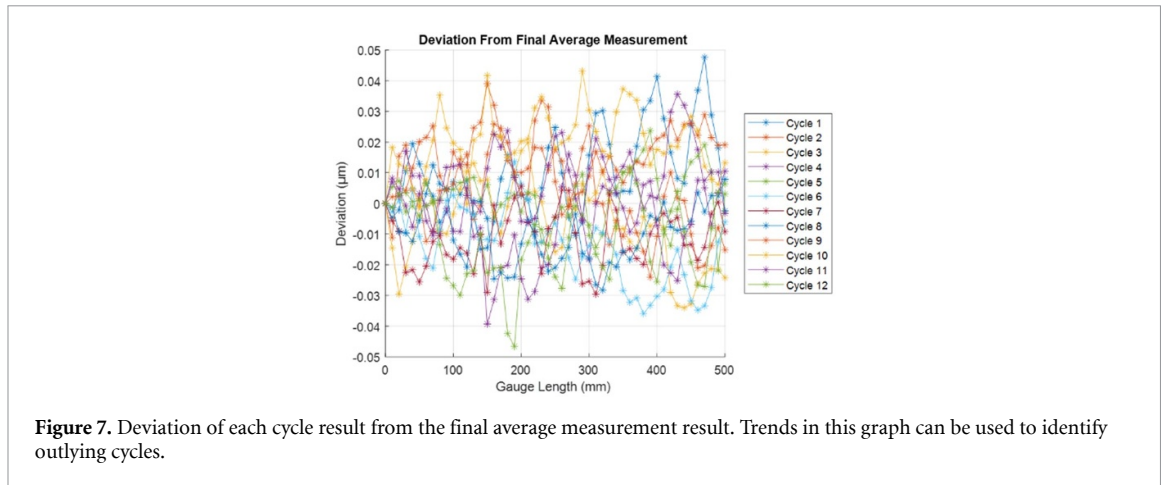


Figure 6. Pixel size calibration for one-dimensional scale calibration.

previously described procedure with the following measurement parameters; $M = 12$, $R = 15$, $S = 3$, $N = 51$, a known shift size of $2 \mu\text{m}$, and a $50\times$ objective.

Figure 5 shows the measurement of the gauge temperature throughout the course of the measurement process. The mean temperature of the gauge over all measurement cycles was 20.0184°C and the maximum deviation from this mean was $\pm 0.0047^\circ\text{C}$. These results are well within the process limits defined in the uncertainty budget for deviation from 20°C . These results indicate the thermal gradient is within our requirements, as the oscillations in temperature indicate slight thermal gradient variations as the gauge is moving along the X axis during the measurement procedure. Furthermore, the potential effects of thermal deviations are expected to be minimal due to the low CTE of the scale.

Figure 6 presents a histogram of the results in the pixel size calibration to transfer the interferometric scale of the movement axes to the camera scale. Nominally, the scaled pixel size using a $50\times$ objective and the manufacturer stated pixel size of $3.45 \mu\text{m}$ should be $0.069 \mu\text{m}$. The results below indicate an average pixel size through all measurement cycles of $0.0693 \mu\text{m}$. The results from the individual cycles, plotted as different color histogram groupings, appear as normal distribution for all calculations. The standard deviation for these calculations is 0.4 nm , indicating excellent repeatability in this scale transfer over the 216 individual calculations in each cycle. This is a significant improvement over the previous system, which had an average image repeatability of approximately 5 nm .



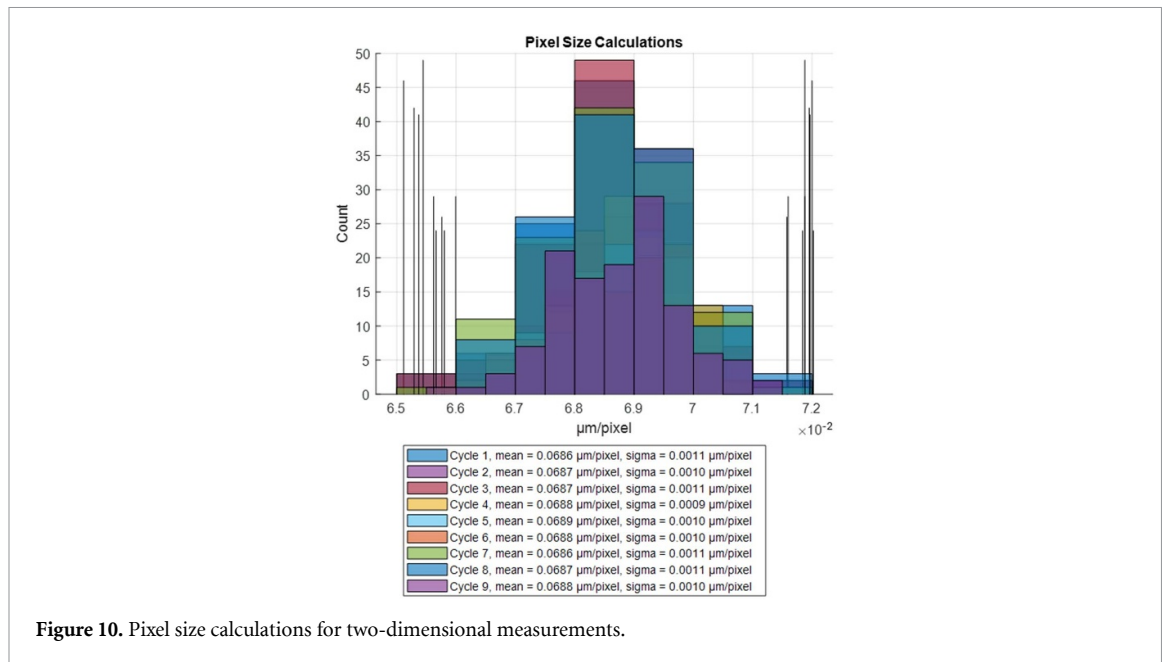
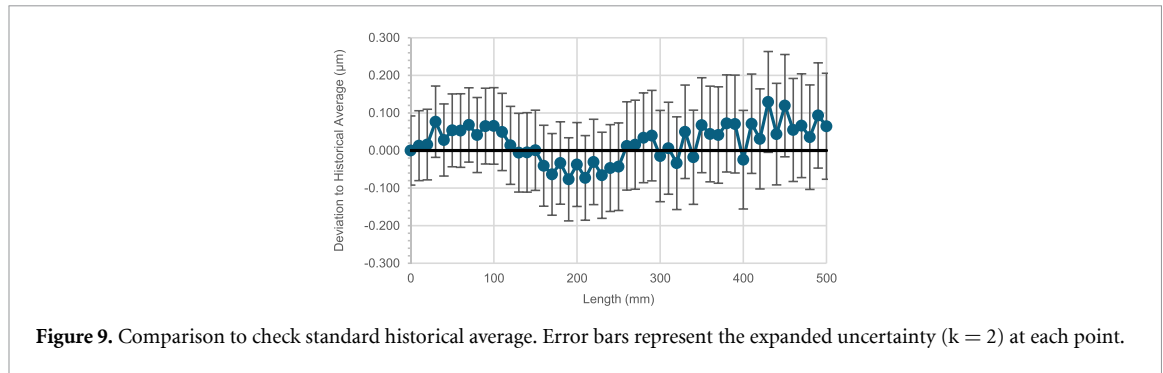
Figures 7 and 8 indicate the final performance metrics from the measurement procedure. Figure 7 shows the final results of each cycle compared to the final average measurement results, which is the average of the 12 cycles (assuming that each cycle is an equally valid measurement). This graph can indicate outlying cycles, either due to machine warm up or thermal settling (typically seen in the first cycle). Here, there are no apparent trends to the data. While cycle 3 does appear to be marginally higher than the others, this amount of variation is expected, and will be averaged with 11 other cycles. Biases this small could be attributed to minor inflections in pressure trends in the middle of the cycle, causing only portions of the cycle not to repeat with the others. Even still, this is well within the stated uncertainty.

Figure 8 shows the standard deviation at each measured position along the gauge for the 12 measurement cycles. The linear fit to these values is from the 10 mm position to the end of the gauge, so that the 0 position (which is always zero in each cycle) does not influence the fit. The fit result is $0.014 \mu\text{m} + 1.379 \times 10^{-8} \text{ L}$, again well within the uncertainty. These results all indicate excellent performance of the system within an individual measurement process. However, they do not provide any information regarding the accuracy of the scale.

The accuracy of the scale is monitored by comparing the measurement results to history of check standards. The history of this gauge overtime can be evaluated for drift to determine the current reference value for the scale. The reference value was compared to the current measurements using the new system. The estimate of expanded measurement uncertainty ($k = 2$) for this scale is $0.092 \mu\text{m} + 9.9 \times 10^{-8} \text{ L}$. Figure 9 shows these measurements compared to the historical average. All the expanded uncertainty ($k = 2$) overlaps the reference value at every point, indicating good agreement and reliability of the instrument scale.

5.2. Two-dimensional measurement validation

The two-dimensional measurement procedure was validated using a NIST SRM5001 Two-Dimensional Grid Photomask Standard. These SRMs are 27×27 grid plates with a nominal 5 mm pitch between positions. The measurands evaluated at each position are $18 \mu\text{m} \times 18 \mu\text{m}$ boxes with $2 \mu\text{m}$ linewidths.



The grid is etched chrome on fused silica, which has an estimated CTE of $0.5 \times 10^{-6}/^{\circ}\text{C}$ [12]. The expanded uncertainty ($k = 2$) of the calibrated positions according to the SRM's calibration certificate is $0.0174 \text{ nm} + 7.0 \times 10^{-8} \text{ L}$. A subset of these points, a 5×5 grid at 30 mm intervals, beginning at position A1, were chosen to evaluate the measurement process. The procedure was executed with the following measurement parameters; $M = 9$, $P = 15$, $S = 3$, $R = 5$, $C = 5$, a known shift size of 0.5 μm , and a 50x objective. This plate was also measured in a 0° and 90° orientation to execute the reversal procedure to minimize error.

Figure 10 displays the average pixel size through all measurement cycles of 0.0687 μm . The results from the individual cycles, again appear normal, but exhibit standard deviations of up to 1.1 nm. While slightly higher than one-dimensional measurements, this still indicates excellent repeatability in this scale transfer over the 62 individual calculations in each cycle.

Figures 11–13 display the final performance metrics for the 0° position measurement. The first cycle has been removed from the data set, as the Y axis exhibits a slightly longer warmup behavior than the X axis. This is discounted by only using cycles 2–9 in the result calculation. Cycles 2 and 4 in the X data do appear to exhibit different trends to the rest of the measurement cycles. Cycles 7 and 8 in the Y data also appear to follow different trends. However, these deviations are well within the uncertainty and are even close to the uncertainty in positioning of the CMM itself. Thus, they are not discounted from the dataset.

Figure 13 shows the standard deviations for the 0° measurement process. The x axis here indicates similar, if not slightly better performance to that in the one-dimensional scale measurements. The Y axis, as theorized, does not appear to perform as well over shorter lengths, due to more components in the kinematic chain susceptible to positioning errors. This further validates the need for reversal processes to reduce uncertainty. The plate was rotated 90° and measured again. The results for this measurement are omitted here for the sake of brevity, but similar process performance was observed.

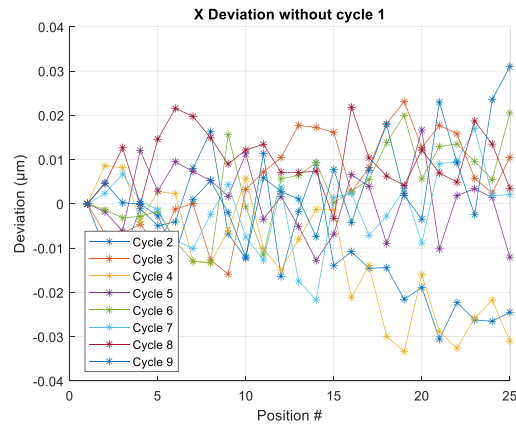


Figure 11. X axis deviation to final average measurement. Cycle 1 not included due to machine warm up behavior.

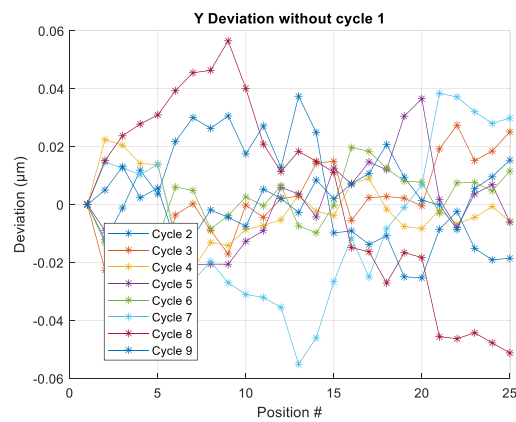


Figure 12. Y axis deviation to final average measurement. Cycle 1 not included due to machine warm up behavior.

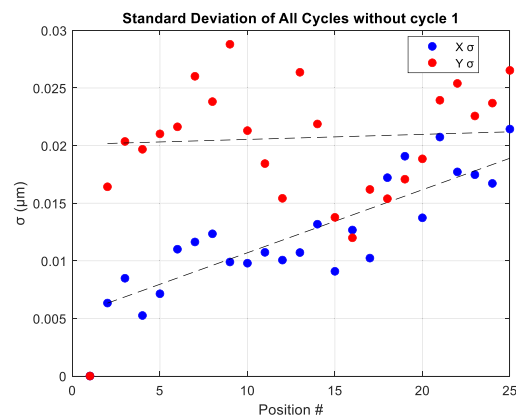


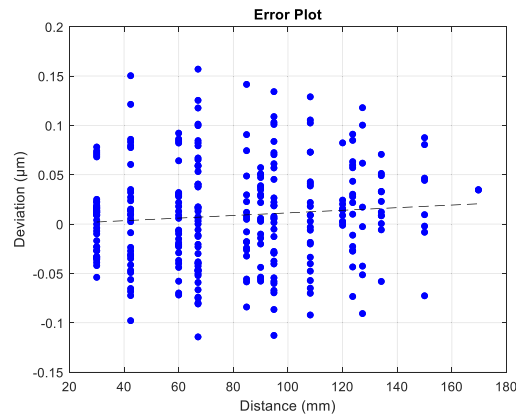
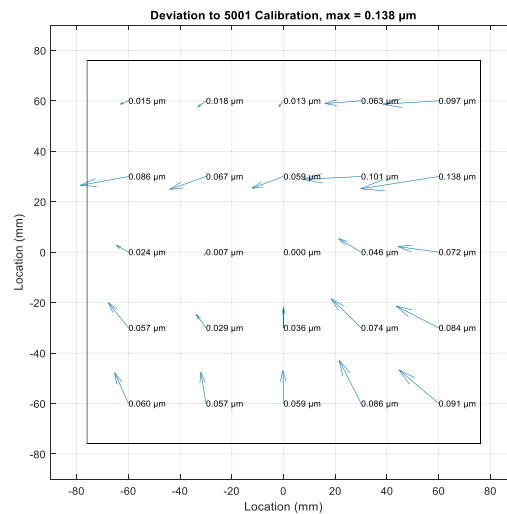
Figure 13. Standard deviations of all cycles in two-dimensional grid plate calibration.

The 0° and 90° results were combined using the procedure described above. This resulted in the error values listed in table 3. The low α and γ values indicate very little residual error in the machine geometry. Low β error indicates that the artifact was well aligned in the machine volume between each position. The calculated translation errors are also very low, indicating little shift between the center of the two datasets.

The error residuals of the reversal are calculated by taking the difference between all pairs of grid points in the two final data sets, $X_{f,1}$ and $X_{f,2}$. Figure 14 plots these residuals errors as a function of length. Since there are only 25 points, the points appear sparsely separated along the X scale, as there

Table 3. Calculated error values from grid plate reversal procedure.

Error	Calculated value
Squareness error, α	-6.4×10^{-7} rad
Scale mismatch, γ	-1.0×10^{-8} mm/mm
Rotation error, β	-3.8×10^{-6} rad
X translation, ε_x	2.3×10^{-5} mm
Y translation, ε_y	2.6×10^{-5} mm

**Figure 14.** Residual error plot from the reversal of SRM 5001 measurement.**Figure 15.** Point by point deviation between the presented M48 Vision calibration and original calibration certificate for NIST SRM 5001 3021 162.

are only so many discrete lengths. However, no real linear trends are observed, indicating no scale mis-corrections between the two data sets. The maximum of the residuals was $0.157 \mu\text{m}$, with the mean and standard deviation being 9 nm and 52 nm , respectively.

Figure 15 displays the deviation between the M48 Vision calibration of this grid plate and the original calibration certificate. The vectors indicate the direction and relative magnitude of the deviations with the magnitude value printed next to each position. Clear trends are visible within the deviation plot. The maximum deviation is measured to be $0.138 \mu\text{m}$. The distances calculated here are from the center position, so the maximum distance to assess the measurement uncertainty is 84.85 mm . Substituting the CTE of $0.5 \times 10^{-6} / ^\circ\text{C}$ into the budget presented in table 2, the uncertainty over this distance is $0.249 \mu\text{m}$. Future measurements of this grid and remapping of CMM motions may be able to discern the source of trends visible in the data.

These results indicate that the implemented upgrades have improved the reliability and operability of the vision measurement system without reducing performance. In fact, the improvements will likely improve the reproducibility of the system over time, therefore reducing uncertainty in the future as more check standard measurements are performed.

6. Conclusion

This work presented a validation of the newly implemented one-dimensional and two-dimensional vision artifact calibration system within the DMG at NIST. Using the CTE of common glass vision artifacts, $8.0 \times 10^{-6} / ^\circ\text{C}$, the expanded measurement uncertainty ($k = 2$) is proposed as $0.092 \mu\text{m} + 1.2 \times 10^{-7} \text{ l}$ for one-dimensional measurements and $0.24 \mu\text{m} + 1.1 \times 10^{-7} \text{ l}$ for two dimensional measurements. The results indicate measurement performance well within the uncertainty. It is anticipated that the presented uncertainty will reduce in the future, as the reproducibility of the new system is evaluated over time using check standard measurements.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iDs

Maxwell Praniewicz  0000-0001-8800-4126

John R Stoup  0000-0003-3189-0889

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