

Measuring Step Gauges Using the NIST M48 CMM

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1.0 Abstract

The Moore M48 coordinate measuring machine (CMM) has provided NIST with unique and very flexible measurement capabilities for many years. The machine's state of the art performance was further improved following the move of the machine into the new Advanced Measurement Laboratory (AML) on the Gaithersburg, Maryland site. These improvements are particularly evident in the measurement of 1D step gauges of lengths approaching a meter. This paper will describe the measurement process currently used for these long 1D artifacts. The development of the data collection algorithms, data analysis techniques, and process control methods will be discussed. The impact of thermal issues, elastic deformation resulting from probe contact, gauge fixturing, and coordinate system generation and the impact of these considerations on the measurement uncertainty budget will be presented in detail.

2.0 NIST M48 CMM

The NIST M48 coordinate measuring machine [1,2] is shown in Figure 1. The CMM is currently operated as a three axis machine that can incorporate a rotary fourth axis if required. The motions of the X and Y machine axes (the table and carriage motions, respectively) are accomplished using a precision lead screw coupled with constant force springs on each axis to eliminate backlash motion. The table and carriage motions are restricted using twin V-ways and hundreds of precision cylindrical roller bearings. The machine design takes advantage of the high moving masses of the machine and the mechanical averaging of the bearings to provide extremely smooth and repeatable motion. The Z axis of the machine consists of a ceramic ram and constant force air bearings in a configuration that provides stable translation. The drive motor is decoupled from the RAM by using a threadless nut and flexure design that minimizes the effects of hysteresis during directional changes.



Figure 1. The NIST M48 coordinate measuring machine in the Advanced Measurement Laboratory.

The standard probe design is an induction type probe and provides short term repeatability as low as 7 nm, as shown in Table 1. The control system of the M48 CMM is designed to require the probe to touch artifact surfaces until a predetermined deflection is reached that corresponds to about a 1.0 Newton (N) applied force. The machine then reverses direction and backs away from the surface slowly, collecting data along the way to extrapolate the result to an undeformed condition. This level of applied force is routinely used for artifact measurement. The controller does allow for changes to the maximum deflection limits as well as approach and probing speeds. These features are valuable for reducing the force exerted on very delicate measurement features or surfaces where applied forces of 1.0 N would deflect or permanently damage the artifact. The short term repeatability of collected data is very stable in nearly all probing configurations.

MOTION	REPEATABILITY (NM)
X direction (table)	9
Y direction (carriage)	13
Z direction (RAM)	7

Table 1. The NIST M48 CMM short term repeatability performance.

The CMM laboratory housed within the AML at NIST is one of the most environmentally controlled laboratories in the world. The thermal environment maintains temperature stability of better than $\pm 0.01^{\circ}\text{C}$ over periods of 30 days or more. The relative humidity is also controlled

within a range of less than 5% during the same periods of time. This level of environmental control allows NIST to operate the M48 CMM for long, uninterrupted periods of time and monitor how the machine behaves independent of most environmental influences. This is particularly important for measuring long steel or ceramic step gauge artifacts.

The measuring volume of the NIST M48 is approximately 1200 mm x 750 mm x 300 mm. The stability of the machine error map and the accuracy of the mapped corrections allow for full use of this volume with no measurable degradation of performance around the periphery edges. Artifacts can be measured anywhere in the machine volume with consistent performance.

3.0 Control Standard Techniques and Uncertainty Development

The development of valid control data using an assortment of 1D and 2D artifacts is the most important component of the NIST M48 CMM's uncertainty analysis. Most of the work performed on the M48 consists of measurements of primary artifact standards with very few discrete part measurements. This allows NIST to use classic dimensional artifacts such as ring and plug gages, end standards or gage blocks, spherical standards, 1D step gages, and 2D ball plates and grid plates to quantify the reproducibility performance of the machine as well as the accuracy. Repetitive and redundant measurement of these artifacts over many years have developed very valuable process control parameters that are used to continuously and instantaneously monitor the output of the machine. Figure 2 is an example of current process control artifact data.

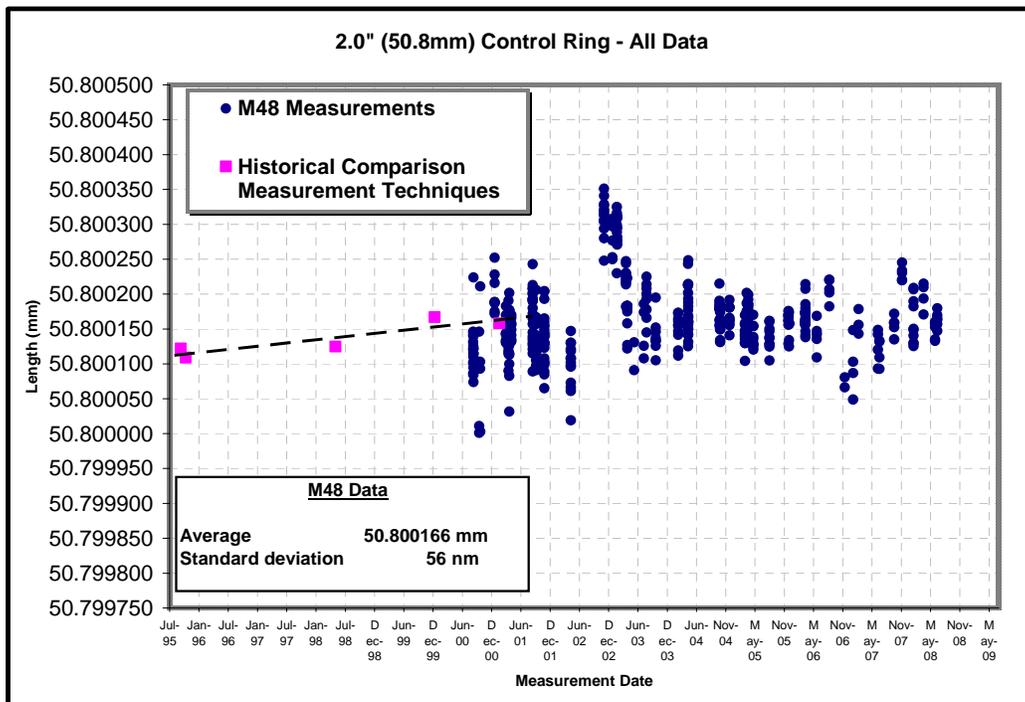


Figure 2. The control chart for an NIST reference ring gage.

The measurement uncertainty statements for the NIST M48 are developed by using the standard set of influences that exist for all measuring instruments and the internationally accepted techniques for combining them [3]. The complexity of the CMM measurement uncertainty is reduced by using control standard data. These provide an estimation of variability from machine influences too multifaceted to control or easily understand. The current 1D measurement uncertainty is calculated as:

$$U(k=2) = 0.11 \mu\text{m} + 0.2L \mu\text{m} \quad (L \text{ is in meters})$$

with a significant portion of the uncertainty coming from the long term performance of the control artifacts. The measurement uncertainty budget for step gauges will be specifically explored later in this article.

4.0 Step Gauge Measurement Technique

Achieving this level of measurement uncertainty on step gauges using the M48 coordinate measuring machine requires careful attention to established procedure and strong knowledge of the machine's capabilities, environment, and limitations. The exceptional M48 CMM laboratory environment is crucial to the accurate measurement of long step gauges with very low uncertainty. Consequently, the standard step gauge measurement procedures are designed to take advantage of the machine stability. The following sections describe the breakdown and importance of different aspects of the step gauge measurement process.

4.1 Gauge Fixturing and Setup

The process starts with very careful cleaning of the gauging surfaces with alcohol wipes and lint free brushes. All gauging surfaces are then inspected with an eyeloop to guarantee they are clean and dust free and to identify any damage at the gage points on the pucks. The M48 CMM operates at motion velocities of 4 mm/s or less to prevent unacceptable internal heating due to friction in the V-ways or lead screw drives. The time required to complete a full step gauge measurement is significant, and it is important that the data is not influenced by contamination or unexpected surface damage.

The gauge is then mounted on the machine in a way that is reproducible by client laboratories. Figure 3 shows two common types of step gauges mounted in the CMM measuring volume using different techniques. Moore-style step gauges require mounting on a straightedge to avoid bending of the measurement plane while other gauges require mounting on rolls at the points of minimum bending, or Bessel points. Other step gauge designs have permanent, fixed feet built into the gauge frame which assures a consistent mounting technique. The gauges are aligned directly with the CMM X-axis to minimize the CMM positioning motion to this axis only. This alignment also improves the probing repeatability by limiting the sensing motion to a single axis of the probe assembly. Light epoxy is used to carefully attach the gauge to the Bessel point feet. This prevents the gauge from rocking if the bottom is not flat. An NIST-owned one meter step

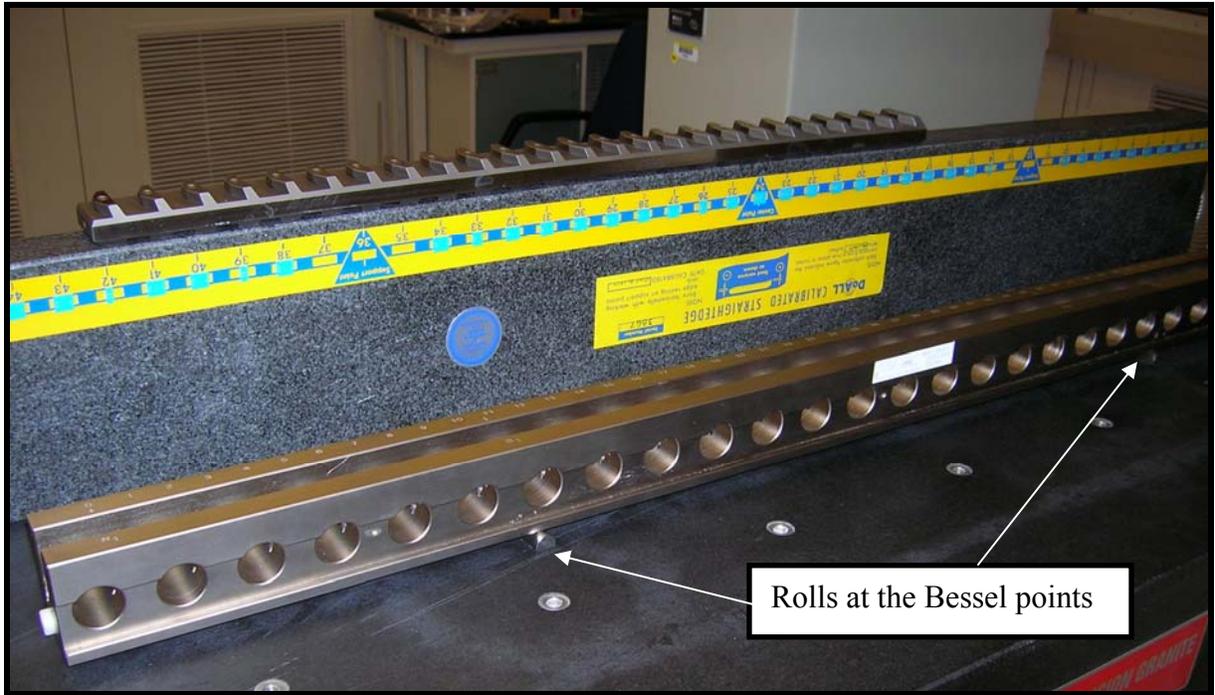


Figure 3. Moore gauge freely mounted on a precision straightedge. KOBA gauges mounted on rolls at the Bessel points.

gauge is also mounted on the machine table as a real time control standard. Although the NIST gauge is always aligned with the CMM X-axis, the position of the gauge on the table is constantly varied to sample any position-dependent errors that may exist resulting from uncorrected motion errors in the machine error map. Several temperature sensors are positioned around the gauges to monitor temperature gradients and the changes to these gradients as the table moves during measurement.

4.2 Coordinate System Development

The development of the gauge coordinate system can have a significant impact on the reproducibility of step gauge measurements. The interactions between poor geometry or damaged gauge reference surfaces and machine-related variables such as positioning accuracy and probe sphere diameter can result in variability in the location of the reference origin and the direction of the gauge axis. These effects can be greatly amplified if small features of limited area are used to create the gauge axis requirements. The components of the coordinate system must be selected carefully and identified so they can be duplicated for future measurements if required. The physical design of some step gauges provides good reference surfaces for locating the long axis and reference origin, while other gauge styles are less consistent and require careful thought when choosing reference locations. For the most reproducible work, coordinate system design can be specified by the client or end user.

At NIST, the development of a step gauge coordinate system relies on a technique that uses high quality symmetrical surfaces on the gauge. Examples of these are shown in Figures 4 and 5. Knowledge of the gauge manufacturing process is useful for determining if these symmetrical

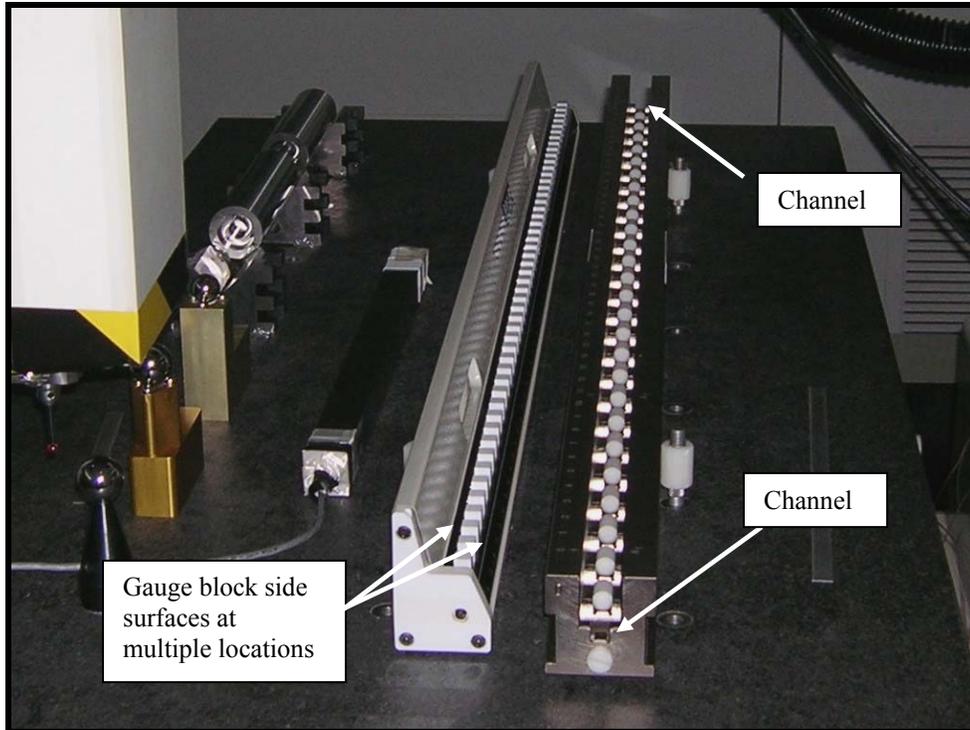


Figure 4. Symmetrical surfaces used for coordinate system development.

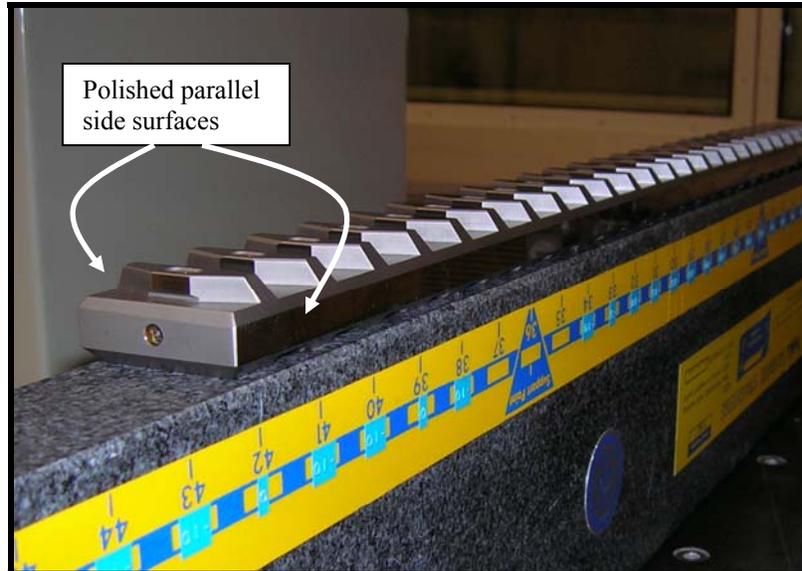


Figure 5. Symmetrical surfaces used for coordinate system development.

surfaces are sufficiently aligned perpendicular to the puck faces. Some gauges use cylindrical pucks that are pressed into long, machined channels. Others are created by wringing gauge blocks together offset in such a way that the step surfaces are produced along the length of the gauge. Still other gauges are machined from a monolithic piece of material. Each of these

designs requires different approaches to assure that the long axis direction is determined correctly.

Another important aspect of the coordinate system is the origin definition at the center of the puck face. In cases where the pucks are installed individually, the puck vertical position and its vertical tilt alignment in the channel may vary significantly and result in systematic differences depending on the direction and height from the channel of the calculated gauge axis as shown in Figure 6. This is also a potential problem for monolithic gauges where the planar direction of the machined gauging surface could vary between each step. This is less of a problem for gauge block derived step gauges where the wringing of good quality block surfaces assures a high degree of parallelism between step faces.

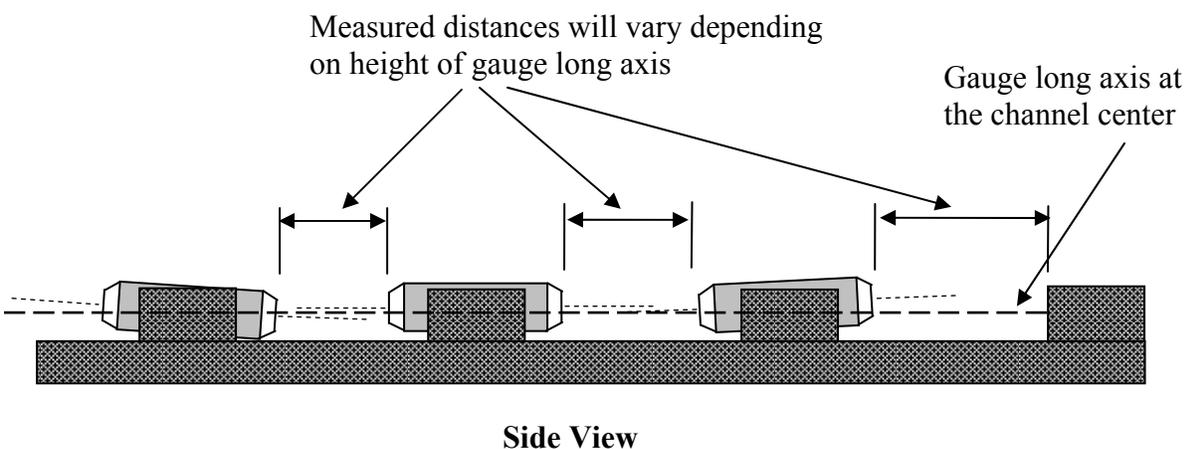


Figure 6. Step gauge puck tilt and vertical alignment can affect measured distances as a result of decisions made during gauge coordinate system development.

In some instances, it may be necessary to measure the step gauge using different coordinate systems derived in different ways to properly sample the variability from the coordinate system generation process. Tests on good quality step gauges have shown that the fluctuation of gauge origin position can easily vary fifty micrometers depending on the surfaces sampled during coordinate system generation. Additionally, the gauge long axis direction can easily vary by as much as 0.1 degrees (6 arc-minutes) and results in a length dependent effect of 0.15 $\mu\text{m}/\text{meter}$.

4.3 Designing a Measurement Plan

The step gauge measurement plan used at NIST is designed to test for, or negate, the effects of thermal gradient and environmental stability, thermal drift, contamination, fixturing stability, and bi-directional probing errors during the data collection. These errors affect the measurement in real time, and are generally considered to be gauge or test specific effects. If properly developed, the measurement plan can provide solid statistical data for the CMM measuring process and provide high quality evidence for the CMM measurement uncertainty budget.

The plan starts with a probe sphere diameter calibration using calibrated sphere standards. Following the calibration of stem bending characteristics using a commonly available CMM sphere, a set of two or three precision tooling balls are measured for two point diameter along the X-axis of the CMM. These spheres are measured independently by NIST using interferometric techniques [4] along a single, reproducible diametrical axis. This measured two point diameter is then aligned precisely with the CMM X-axis. The multiple master spheres provide a redundant measurement of effective 1-D probe ball diameter and samples this measurement in more than one location within the machine measuring volume. The data from these measurements provide a good estimate of effective probe diameter and its variability as it relates to different artifacts, surfaces, and positions on the CMM table. The sphere to sphere differences can also be compared to the actual calibrated differences to give a good statistical indication of how the CMM behaves in an artifact comparison methodology where elastic deformation, thermal effects, and probe related effects are mostly negligible.



Figure 7. CMM calibration sphere and precision stainless steel master spheres, in magnetic kinematic mounts, on the CMM table.

Another critical issue when measuring step gauges comprised of dozens of gauging surfaces is contamination and dust. One technique to monitor this is to design the measurement procedure to measure each puck face multiple times during each test. This provides good data on short term repeatability of the measurement system and reveals evidence of contamination or dirt on the gauging surfaces of the puck faces. As the gauge measurement progresses, the different puck face data sets should be consistent with each other with similar variability, dependent on the level of performance of the CMM. These methods provide a large sampling of very short term repeatability data for the CMM and probe combination and can easily and quickly reveal unexpected problems with the CMM performance. The data can also be used to determine

expectations about performance levels and some components for the CMM measurement uncertainty budget.

Thermal drift of the machine during data collection can be a large source of variability if not monitored carefully. For long step gauges, NIST uses a technique of repeated and systematic measuring of the reference surface to track the drift of the machine coordinate system during data collection. The reference point on the first puck is measured at the beginning of the step gauge procedure, and then repeated after approximately every fifth puck. Analyzing this reference point data allows for a stability assessment of the CMM measuring volume and to verify that the artifact did not move relative to the origin of the CMM scales. If the data does indicate a drift of the reference point, any linear drift can be easily removed using regression analysis, and the remaining residual errors provide a good estimate of the medium-term (1 to 2 hour) CMM repeatability performance.

Thermal drift of the artifact during data collection is also important where the time involved to complete a full gauge measurement can be long. This thermal effect can be monitored by combining the CMM measuring volume drift procedure described above with a linear drift eliminating measurement design. For long step gauges, the design can be as simple as an “out and back” routine of measuring each puck, from the beginning reference puck to the end puck, then reversing direction and returning to the original reference puck in the same method. Combining this measurement design with systematic re-measurements of the reference puck provides a full assessment of thermal influences on both the CMM and the gauge during data collection. Figure 8 shows reference puck data from a typical step gauge measurement where both sides of the reference puck were measured 11 times using an out and back routine. The linear trend due to thermal drift can be easily removed to reveal the uncorrected variability from random thermal influences on the machine and artifact.

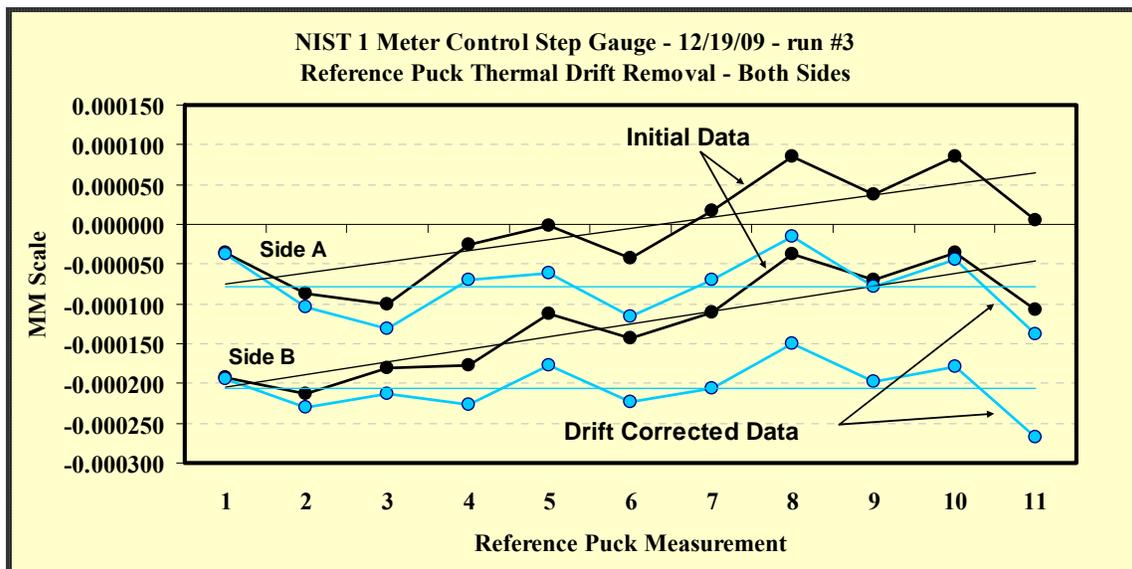


Figure 8. The removal of linear thermal drift from reference puck data in a step gauge measurement.

Multiple data collection cycles using a drift assessing measurement design can provide valuable information as to the CMM length dependent performance. Multiple measuring cycles, including re-establishment of the step gauge coordinate system, combines the effects of several sources of error into the measurement data. These include the thermal gradient fluctuations along the gauge length, thermal stability of the CMM measuring volume as a function of room HVAC performance, probe sphere diameter determination and any length dependent effects generated from the variable gauge surface sampling data used for the coordinate system generation. This procedure provides a good estimate of the performance of the CMM over a one to two week period and allows for the operator to make an informed assessment of whether the CMM performance is consistent with past results. The redundant data also provides extra opportunities to check for intermittent effects of dirt and dust contamination.

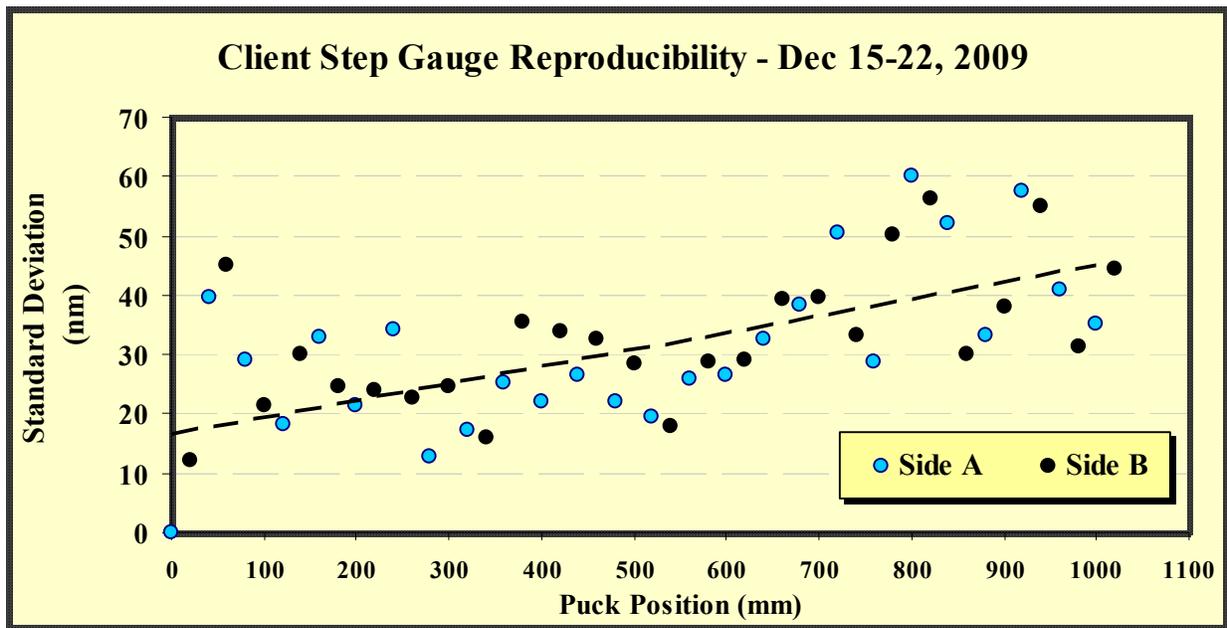


Figure 9. Gauge reproducibility graph for a typical client step gauge. Consistent performance from both sides of the pucks indicates good control over bi-directional probing errors.

It is important to differentiate this gauge reproducibility data from the complete measurement system long term reproducibility. Data derived from only one step gauge provides information about the measurement of only that single gauge, during that particular day or week. The data is very useful for verifying that the CMM and the step gauge are performing as expected over this short period of time. Figure 9 shows this data for a client step gauge. Typical results are at a level of about

$$\sigma_{\text{gauge reproducibility}} = 0.02 \mu\text{m} + 0.02 * L \mu\text{m} \quad (L \text{ is in meters})$$

The constant and length dependent effects can be isolated easily from this data. Gauge reproducibility data however does not included many important effects that affect a CMM measurement on a much longer cycle. Figure 10 shows the system reproducibility graph of the NIST control step gauge from data collected between 2004 and 2010. It is evident from the graphs that data from any single setup and measurement can not capture many important error

sources that affect the measurement process on a multi-year timeframe. These include effects from fixturing and gauge alignment to the machine axis, gauge temperature sampling errors, some CMM positioning effects, probe effects resulting from variable probe ball diameter and stem length and how they interact with surface finishes of gauges, CMM error map influences from seasonal humidity and pressure trends, residual measuring face cleaning effects, and probe alignment effects resulting from probe head remounting. The value of the system reproducibility data is evident since these types of errors would be very difficult to quantify for measurement uncertainty calculations.

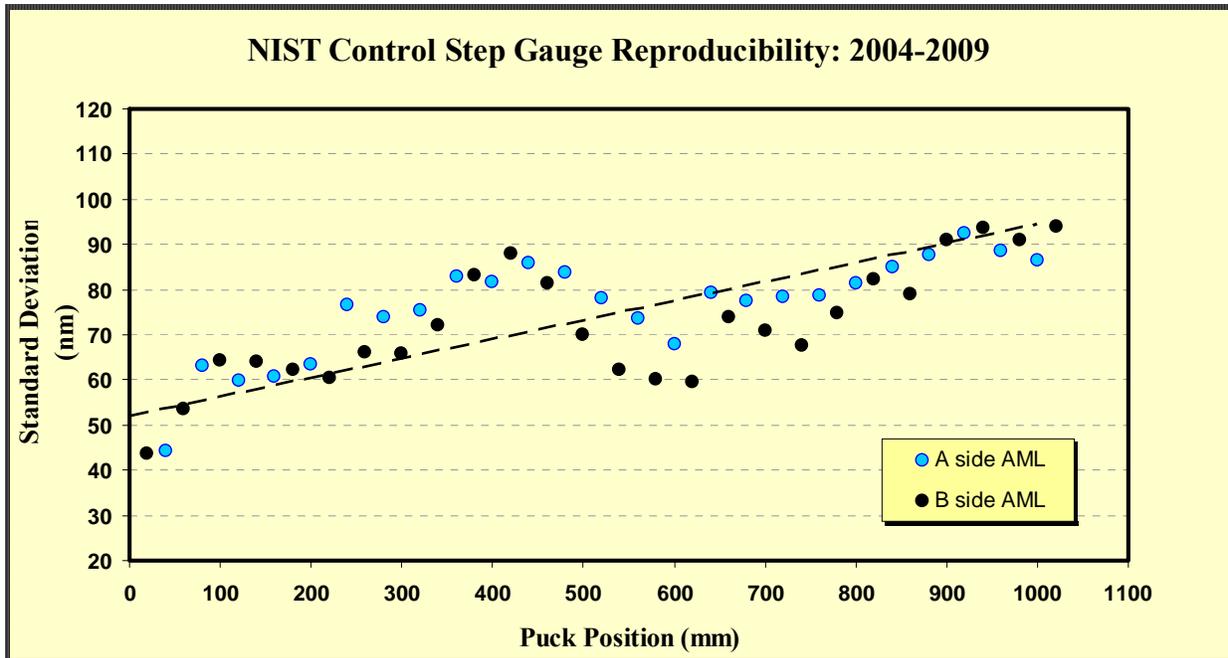


Figure 10. System reproducibility graph derived from 6 years of measuring the NIST control step gauge. These results compile over 30 different gauge mountings and more than 100 individual sets of data.

5.0 Measurement Uncertainty

Although the system reproducibility data derived from the control artifacts absorbs many sources of measurement error, there are still additional error sources that may need to be assessed or estimated independently. At NIST, these errors sources include thermometer, barometer, and hydrometer accuracy, and CMM error map and scale accuracy. Eventually, some of these errors can be absorbed into the system reproducibility data of the control standards, but only if the recalibration cycles of the instruments are short enough to sample 5-10 recalibrations or mappings.

Other uncertainty components are specific to the client artifact and must be estimated. These include deformation for non-steel surfaces, gauge coefficient of thermal expansion (CTE) related errors, and coordinate system generation decisions if the client gauge measurement procedure is not specifically designed to sample them. Systematic error related to gauge fixturing must also

be addressed if the client gauge is not remounted during data collection or if the fixturing techniques and decisions are not specified in the client report of calibration. In some cases, specific fixturing can be defined into the measurand and subsequently not be included as a source of uncertainty. However, the reproducibility of that fixturing must still be tested if variables still exist. It can also be argued that the re-mounting of the control step gauge provides a reasonable estimate of the client step gauge fixturing uncertainty, and that the effect is sampled in the system reproducibility data. This decision must be made carefully, as the specific geometry of different gauges may not behave in the same way when fixtured for measurement.

Finally, some error components are systematic error sources that cannot be sampled into reproducibility data. Examples of these would be the equations for the calculation of the index of refraction for air and for elastic deformation. Uncertainty estimates for these formulas are usually contained in their documentation [5,6,7].

M48 Uncertainty Budget 1D/ 2D Measurements			
Source	Calculation	μm	ppm
1. Residual Positioning	Multiple rotations of 2D artifacts	0.04	
2. Temperature difference in mapping beam paths	.02°C maximum difference		0.01
3. Laser Frequency Difference	2×10^{-8}		0.02
4. Measurement Reproducibility	7 years of data on rings, plugs, step gages	0.04	0.04
5. Edlén Equation	International accepted		0.03
6. Index of Refraction – Air Temp	$\pm 0.006^\circ\text{C}$ beam path accuracy		0.01
7. Index of Refraction - Air Press	± 10 Pascal accuracy		0.04
8. Index of Refraction – Humidity	$\pm 4\%$ accuracy		0.03
9. Temperature Accuracy	$0.003^\circ\text{C} \times 12 \mu\text{m}/\text{m}$		0.04
10. CTE	$0.05^\circ\text{C} \times 1 \mu\text{m}/\text{m}$		0.05
11. Contact Deformation	Bi-directional, material	0.002	
12. Gage Surface Geometry	CSY generation error	0.004	

$$U (k=2) = 0.11 + 0.20 \times 10^{-6} L \mu\text{m}$$

Where L = 1 meter

Figure 11. The NIST step gauge uncertainty budget.

The current uncertainty budget for NIST step gauge measurements is shown in Figure 11. It is possible that the error components for the environmental sensors will be absorbed into the reproducibility term in the near future.

6.0 Conclusions

The measurement of step gauges at NIST is an extensive effort that relies heavily on the performance of control artifacts to estimate long term reproducibility of the process. The M48 CMM is capable of very high precision work, but one must be careful not to infer too much from data collected over a relatively short period of time. It must also be noted that long term gauge material stability is not addressed, as this can be wildly variable depending on the environment,

use frequency, and abuse of the gauges by clients. With proper design and good metrology practice, 1-D step gauges can be ideal artifacts for the transfer and verification of scale accuracy in large coordinate measuring machines.

7.0 References

1. Trade names and company products mentioned in the text does not imply recommendation or endorsement by the National Institute of Standards and Technology.
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