

# IN-SITU CALIBRATION OF TEMPERATURE COMPENSATION SYSTEMS USING DIFFERENTIAL LENGTH MEASUREMENTS

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## INTRODUCTION

Temperature variation can significantly impact dimensional measurements, and therefore many modern dimensional measuring instruments are equipped with built-in temperature compensation systems. These systems operate in real time during measurements and compensate for the linear thermal expansion of both the measuring instrument scales and the measured workpiece. Temperature compensation systems come standard on many instruments, such as the coordinate measuring machine (CMM).

A Mitutoyo Legex CMM was installed at Mitutoyo America's calibration lab in Plymouth, Michigan, for the purposes of doing a variety of high accuracy dimensional calibration and inspection work. One of the goals of the Legex CMM implementation was to calibrate length gages with a very low uncertainty. A large variety of length gages were considered, including step gages, length bars, linescales, ball bars, and also rings, plugs, and spheres.

Being a commercial lab, another goal of the CMM implementation was high throughput of the calibration process to reduce operational cost. The most practical solution was to use the Legex as designed, including the use of the built-in temperature compensation system. Concern existed on whether the desired uncertainty could be achieved using a standard CMM, particularly since the target uncertainty was less than the accuracy specifications of the Legex. A preliminary uncertainty budget indicated that the ability to properly measure the temperature of the length gages was critical. Since it was desired to use the temperature compensation system on the Legex, various methods were explored to calibrate and implement the system with the smallest possible uncertainty.

The final implemented solution on the Legex is a bit unique. The technique does not involve traditional thermometry methods but instead uses differential measurements of two calibrated length standards with significantly different coefficients of thermal expansion (CTE). The result is a calibration of the temperature compensation system following the same manner in which the system is actually used. The technique is straightforward to implement and has the potential to reduce dimensional measuring uncertainty associated with the combined calibration and usage of the temperature compensation system. Experimental results showed that an uncertainty of 50 mK is practical and that an uncertainty of less than 15 mK is possible. The results were verified through intercomparison of length measurements with the National Institute of Standards and Technology (NIST).

## LENGTH CALIBRATION USING CMMs

CMMs have a long history of being used for the calibration of length gages. In some cases, the CMM has been equipped with an external laser interferometer [1-5]. This approach reduces the CMM to a one-dimensional measuring instrument, which would not meet the flexible needs of the Legex CMM in the Plymouth Calibration Laboratory. Another method that has been utilized involves careful error mapping and correcting the geometric errors of the CMM [6,7]; the implementation of the Legex CMM is similar to this method.

Regardless of the method utilized, the CMMs discussed in [1-7] were all located in precision temperature controlled environments. In addition, various types of temperature measurement systems were utilized to record the temperature of the measuring scale and the length gages during calibration. Understanding

the uncertainty of these systems, as implemented, is critical to understanding the overall uncertainty of the measurement process. The calibration of these temperature measuring systems can also be a challenge, for example see [6], as these systems must be calibrated on the CMM. Even with precise temperature controlled rooms and temperature measuring and compensation systems, the largest sources of uncertainty in most longer length calibrations are still related to temperature [2-6].

It is also possible to use a CMM as a mechanical comparator. Following this approach, length gages are calibrated via comparison to calibrated master gages made of similar materials. This method, which is common in applications like gage block calibration, can be very accurate but limits the range of possible measurement applications for the CMM.

### LEGEX CMM IMPLEMENTATION

A Mitutoyo Legex 910 CMM was implemented in the Plymouth Calibration Laboratory of Mitutoyo America as shown in Figure 1. One of the reasons a Legex CMM was chosen is that the machine is designed to be largely insensitive to thermal variations. In particular, the measuring scales are made of CLEARCERAM-Z, which has an ultra-low CTE of  $0.08 \times 10^{-6}/K$  [8]. Unlike the methods presented in [1-7], which require precise measurement and correction of the machine and scale temperature, the only significant temperature related concern with the Legex is workpiece temperature measurement.



FIGURE 1. The Legex CMM (on left) in the Plymouth Calibration Laboratory of Mitutoyo America.

The Legex CMM has a built-in temperature compensation system. The workpiece sensors are thermistors encased in brass blocks, as shown in Figure 2. These two sensors are placed on workpieces during measurement and

software is used to compensate for linear thermal expansion in three-dimensional space.

The Plymouth Lab was concerned with the uncertainty in the use of this temperature compensation system. Sources of uncertainty include calibration of the system, radiant influences, contact with the measured workpiece, soak-out, and self-heating. Instead of attempting to estimate these challenging sources of uncertainty, as well as implementing traditional thermometry calibration techniques on-site, such as temperature baths, the laboratory decided to calibrate the system using a novel technique of differential length measurements.



FIGURE 2. Workpiece temperature sensors.

### DIFFERENTIAL LENGTH MEASUREMENTS

The workpiece temperature measurement and compensation system on the Legex CMM comes with a calibration from the CMM factory. The factory calibration is done using a temperature chamber that cycles the system over a range of temperatures to determine a calibration offset and slope. Since the Legex is used over a small temperature range,  $20 \pm 0.5^\circ C$ , the only significant concern is the calibration of the offset. This is done using a technique of differential length measurements. The technique requires two calibrated length gages, i.e. length standards, of nominally the same length, with different, and known, CTEs. The two length gages are then measured on the CMM using the temperature compensation system as it is normally used. The gages are placed in the same nominal location on the CMM to reduce variation from the CMM geometry. On the Legex, the two length gages are placed very near each other with two temperature sensors between them, as shown in Figure 3.

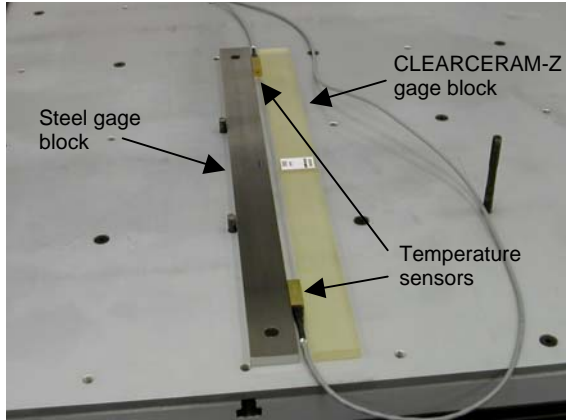


FIGURE 3. Setup for the in-situ calibration of the workpiece temperature system.

The change in length of either gage due to the influence of temperature can be expressed by:

$$\Delta L = L(T-20)\alpha \quad (1)$$

where  $L$  is the nominal length,  $T$  is the measured temperature, and  $\alpha$  is the CTE of the length gage. If the two gages have the same nominal length and are measured as shown in Figure 3 such that they have the same temperature, then the error in the temperature system can be determined by:

$$\Delta T = (\Delta L/L)(\alpha_2 - \alpha_1)^{-1} \quad (2)$$

This error,  $\Delta T$ , can then be used to adjust the offset of the temperature measuring system. The temperature compensation system is therefore calibrated, in-situ, in the same manner in which it is used for subsequent measurements. The temperature related concerns mentioned earlier are thus reduced or eliminated. The calibration process can also be easily repeated.

The traceability of this in-situ calibration of the temperature measuring system comes completely from the calibration of the length gages. The traceability depends on the calibration of the lengths of the two gages and also the knowledge of their CTEs. No additional calibrated thermometer is required.

## EXPERIMENTAL RESULTS

The temperature system on the Legex CMM in the Plymouth Lab was calibrated using the differential length measurement technique. The initial implementation utilized a steel gage block calibrated at NIST and a CLEARCERAM-Z gage block calibrated at NRC. Both gage blocks had a

nominal length of 500 mm. The uncertainty of the process, as shown in Table 1, was estimated to be around 50 mK. The uncertainty of the temperature system can then be used in the estimation of the uncertainty for length measurements. For the majority of length gages, the uncertainty of the Legex CMM at the Plymouth Lab has been estimated to be a very adequate  $U = (0.25 + 0.7L/1000)$  micrometers (at  $k=2$ ). This result is significantly influenced by the calibration of the temperature system.

TABLE 1. Uncertainty of the in-situ calibration of the temperature measurement system.

Uncertainty Source	Standard Uncertainty (nm)
Steel gage block, length calibration	82.5
Steel gage block, knowledge of the CTE ( $10.8 \times 10^{-6}/K$ )	62.5
Low CTE gage block, length calibration	25.5
Low CTE gage block, knowledge of the CTE ( $0.08 \times 10^{-6}/K$ )	1.0
Process reproducibility	75.0
Combined standard uncertainty = 130 nm	
Expanded uncertainty ( $k=2$ ) = 260 nm	
Applying the length uncertainty to equation (2): $U = 48.5$ mK	

Shortly after the implementation of the in-situ temperature system calibration technique on the Legex, the Plymouth laboratory was involved with an intercomparison measurement of a step gage organized by NIST. The final results of this intercomparison were never published, but the results were made available to the participants. The timing of the intercomparison provided an opportunity to independently test the Legex and the temperature system calibration. The setup for the step gage measurements is shown in Figure 4.

The results of the intercomparison are shown in Figure 5. (While the intercomparison involved a number of labs, only the Legex deviations from the NIST results are shown.) Figure 5 shows the Legex deviations, the Legex uncertainty, and the uncertainty of the NIST calibration. The deviations, most of which are within the uncertainty from NIST, are also only about 50% or less of the estimated uncertainty of the Legex process. The most important finding, however, is that the results show no linear error, which is often indicative of temperature measurement issues. These results provide some confirmation of the Legex process and the in-situ calibration of its temperature measuring system.

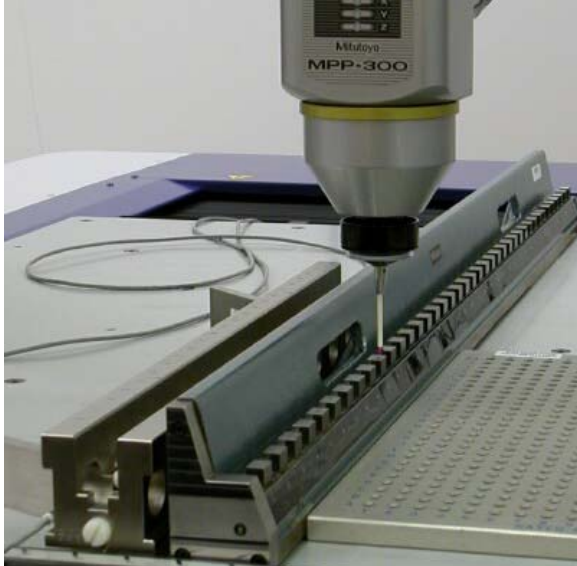


FIGURE 4. Setup for the calibration of the step gage as part of the intercomparison with NIST. The shorter Koba gage on the left is being calibrated. The Mitutoyo step gage on the right is a check standard.

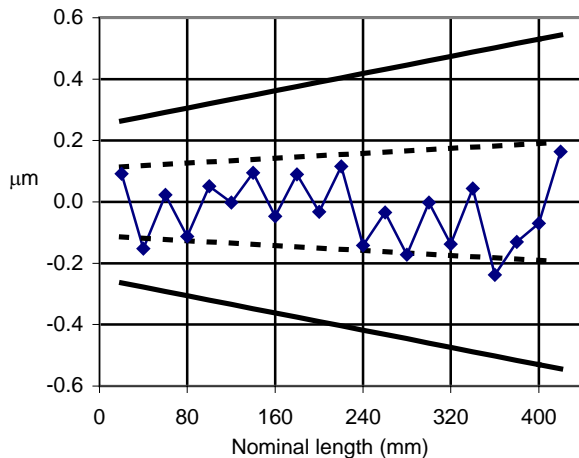


FIGURE 5. Results of the intercomparison with NIST. The solid lines are the Legex uncertainty and the dotted lines are the NIST uncertainty.

### FUTURE WORK

The uncertainty analysis shown in Table 1 was based on initial work using length gages that were readily available at the time. Further research has led to the potential uncertainty budget shown in Table 2. This is a best uncertainty based on possible improvements to the temperature calibration process. The changes include a higher accuracy calibration of the steel gage block, including the calibration of its CTE, and additional measurements to improve reproducibility. The results indicate that an uncertainty of less than 15 mK is possible.

TABLE 2. Potential uncertainty improvements.

Uncertainty Source	Standard Uncertainty (nm)
Steel gage block, length calibration	23.3
Steel gage block, knowledge of the CTE ( $10.8 \times 10^{-6}/K$ )	6.3
Low CTE gage block, length calibration	25.5
Low CTE gage block, knowledge of the CTE ( $0.08 \times 10^{-6}/K$ )	1.0
Process reproducibility	10.0
Combined standard uncertainty = 36.5 nm	
Expanded uncertainty ( $k=2$ ) = 73 nm	
Applying the length uncertainty to equation (2): $U = 13.6 \text{ mK}$	

### SUMMARY AND CONCLUSIONS

A unique, yet straightforward, technique was presented for the in-situ calibration of built-in temperature compensation systems in the field of dimensional metrology. The technique uses differential length measurements of two length gages of significantly different CTEs. The technique avoids many thermometry calibration issues and results in the temperature system being calibrated in a manner similar to how it is used in subsequent dimensional measurements.

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