CMM Performance Stability

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Purpose

This article explores the performance stability of a typical CMM from the changes in the compensation error map data collected from repeated calibration cycles. For an ideal CMM the geometry (shape of the axis) would not change at all so no updates would be theoretically required following the initial calibration of the CMM over the life of the machine. In practice, there are changes to the geometry of the CMM axis, as with all measurement instruments, so periodic updates are required to maintain a desired accuracy (measurement uncertainty) level.

The reasons for changes in the axis geometry of a CMM include, but are not limited to, the amount of use, the environment, the construction materials, the design or type of machine, and the treatment of the machine from the operators. It is believed that CMM manufacturers do long term stability studies but, to the best of my knowledge, that kind of information is not published.

The data used for the analysis of the performance stability is based on the changes in the CMM's compensation error map data. The calibration of a CMM by SCI involves measuring and updating all compensation parameters so changes in the axis geometry can be determined by simply subtracting the final compensation error map from the original and analyzing the difference.

CMM Calibration Overview

Calibration of a CMM involves updating the compensation error map with descriptions of the current angular and linear errors for each axis with the goal of having the resulting machine error as small as possilble. In the early days of CMM's, before compensation error maps existed, mechanical adjustments were necessary to remove all geometry error but, for a modern CMM, it is very rare to perform mechanical adjustments when calibrating a CMM.

Exceptions for mechanical adjustments can include: gantry machines where the foundation is still in the processing of curing resulting in large geometry errors in the CMM, horizontal arm machines with steel tables placed on a floor that is less than ideal or prone to motion from external sources, or any machine where there is an excessive amount of squareness error.

Thoroughly calibrating a CMM is a complex process. For a typical bridge style CMM there are 21 compensation parameters consisting of 3 angular corrections for each axis, 3 linear corrections for each axis, and three squareness corrections between the three machine axis.

Calibration of a CMM requires the use of suitable equipment and almost always involves a laser. Prior to the mid 2000's six parameter lasers were unknown and all CMM calibrations were done using a traditional one parameter laser system. Following the availability of six parameter lasers the calibration process is far easier, faster, and more complete then what could be done with a traditional laser system.

The general calibration process using the two types of laser systems is described in the following sections:

CMM Calibration Using a Traditional Laser

Traditional lasers allow the measurement of 5 of the 6 axis parameters of any CMM. The 6th axis parameter was measured using differential levels (X or Y axis roll) or by offset probes and a straight edge (Z axis roll). Each measurement requires a unique setup of the laser or a unique setup of other equipment necessary for data that the laser cannot handle.

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The normal approach when calibrating a CMM using a traditional laser starts with investigative measurements of the machine to determine the necessary scope of work. The ideal situation is that the investigative measurements don't reveal any geometry problems resulting in updates to only the axis scales and squareness is needed. For cases where other geometry problems are detected the technician must determine what compensation map parameters need to be updated to achieve a desired result. Properly selecting and interpreting investigative measurements require a good deal of experience and expertise from the technician.

Machines with no existing compensation error map is the worst case scenario when using a traditional laser system and supporting equipment. For this scenario the time necessary to collect all the data for the compensation error map will take approximately 3 days which includes all the necessary performance validation tests. For a novice technician the estimated amount of time increases depending on their skill level but, assuming the technician is skilled, doing this work is less than 3 days is unlikely (24 hrs in total, 3 days assumes 8 hour work days or 2 days of 12 hours each).

One observation from various CMM's over the years is that many of the compensation error map parameters are rarely updated when a traditional laser system is used. It is not uncommon to find machines where some of the map parameters are zero, the product of a simple linear gradient, or has not been updated in a very long time. These examples are very common and often done to reduce the amount of time required to calibrate a CMM.

CMM Calibration Using a Six Parameter Laser

Six parameter lasers are ideal for calibration of a CMM. They can, simultaneously, collect data for all angular and linear errors for any axis of a CMM. There is usually only one setup required and the data collection process is similar to the method used to collect scale data with a traditional laser system. There is the problem of data dependency where angular parameters impact measurement errors of the linear parameters but, with the right software, this is handled seamlessly.

With the use of a six parameter laser a calibration of a CMM is more of a process as all the compensation error map parameters are measured and updated without the need for investigative measurements. From a manufacturing point of view, with an interest in providing the best results possible in the field, this is ideal and reduces the level of training for the technician performing the work onsite. The only downside that I am aware of is that the cost of a six parameter laser is more than a traditional laser system.

Depending on the type of six parameter laser it may be necessary to use two setups in order to measure the Z axis roll. With a maximum setup count of 4 it is still easier than the 18 setups needed using a traditional laser and other supporting equipment.

Analysis Data

The data used for the analysis is from recent CMM calibrations over the past couple of years. The data used is restricted to cases where the previous compensation error map was known to be valid and complete which limits data to CMM calibrations previously performed by SCI or, in some cases, a reliable secondary source such as machines that were recently calibrated at the Hexagon factory.

The data chosen for this analysis is described in table 1.

Table 1: Summary of data used for analysis along with various characteristics.

Data	Value	Description
Samples	147	Total number of compensation maps used for the analysis.
Bridge CMM's	99	Number of bridge configured CMM's
Gantry CMM's	29	Number of gantry configured CMM's
Horizontal Arm CMM's	19	Number of horizontal arm configured CMM's
BnS CT2 map type	83	Number of machines with a BnS CT2 error map
DEA Type 1 map type	14	Number of machines with a DEA Type 1 error map
DEA Type 2 map type	4	Number of machines with a DEA Type 2 error map
DEA Type 3 map type	28	Number of machines with a DEA Type 3 error map
DEA Type 4 map type	2	Number of machines with a DEA Type 4 error map
LK map type	8	Number of machines with an LK error map
Renishaw map type	2	Number of machines with a Renishaw error map
Other map types	6	Number of machines with other error map types

The distribution of machine configurations such as bridge, gantry, or horizontal arm, should reflect on the ratio of installed machines in the field. All of the data is used for the analysis but, in some cases, results are separated based on the machine configuration when it makes sense to do so.

The majority of machines are on a 1 year calibration cycle. There is a small number of machines that were unintentionally included in this data that do not have annual calibration cycles. Future additions to the analysis data will only be from machines with a 1 year calibration cycle.

For compensation maps with 4 axis (DEA Type 4) only the first 3 axis are used for the analysis. This also applies to DEA maps with second scales and BnS maps containing non-zero deflection data.

Analysis Method

The method used to determine the changes in the CMM's geometry is to find the difference between the *As Found* and *As Left* error map then find the slope of the difference data to represent the change in each compensation error map parameter.

CMM's calibrated by SCI will have a minimum of four compensation error map files using the names *update0*, *update1*, *update2*, *update3*, and *update4*. The map with the name *update0* is always the original compensation map where *update1* is created following changes to the first kinematic axis, *update2* following the second kinematic axis, *update3* following changes to the third kinematic axis, and *update4* following the squareness update. Although rare, additional map files may exist for various reasons but most machines will have only the four map files. In the cases where additional *update<n>* map files exist the highest number version is always used when comparing to the original *update0* map file.

Using a purpose specific utility a comparison is done between the two compensation error map files representing the *As Found* and *As Left* data from every suitable CMM calibration. The output of the comparison utility adds an line entry to a CSV data file containing a set of differences in the form of a gradient for each compensation error map parameter. Illustration 1 shows the comparison utility:

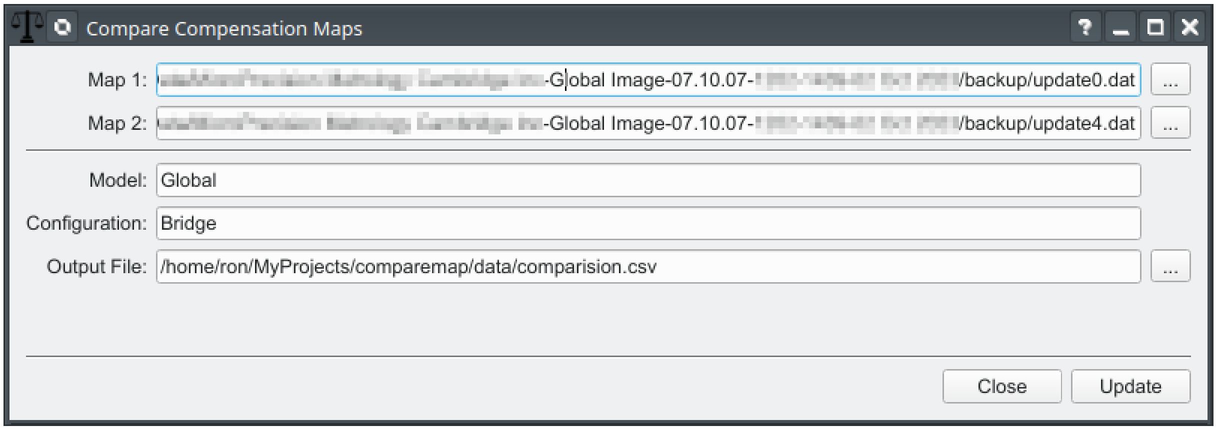

Illustration 1: Comparison generator utility. Some privileged information is grayed.

The comparison CSV data file created by the *Compare Compensation Maps* utility can be loaded into any spreadsheet program for processing and analysis. Illustration 2 shows the contents of the CSV data file when viewed in LibreOffice.

	A	B	C	D	E	F	G	H	I	J
1	Machine Model	Configuration	Map Type	Attributes	dRXX	dRXY	dRXZ	dLXX	dLXY	dLXZ
2	Scirocco	Bridge	BnS CT2	YXZ	0.005988	0.004575	0.002765	0.005884	0.000551	0.001531
3	Gamma	Bridge	DEA Type 1	XYZ	0.000925	0.004599	0.001266	0.008878	0.000000	0.000000
4	Global	Bridge	BnS CT2	YXZ	0.001998	0.000098	0.002210	0.004356	0.001432	0.001295
5	Scirocco	Bridge	DEA Type 2	XYZ	0.000320	0.000687	0.001209	0.001528	0.000906	0.000421
6	Global	Bridge	BnS CT2	YXZ	0.000137	0.001018	0.000999	0.002937	0.002715	0.001197
7	Wenzel	Bridge	AAT Capps	YXZ	0.007688	0.001909	0.000520	0.002315	0.000126	0.002126
8	Mistral	Bridge	BnS CT2	YXZ	0.002251	0.002614	0.000370	0.001970	0.002153	0.000319
9	Global	Bridge	BnS CT2	YXZ	0.000360	0.002348	0.002540	0.000978	0.000267	0.000482
10	Global	Bridge	DEA Type 3	XYZ	0.000998	0.000748	0.000138	0.006774	0.000158	0.000111
11	Xcel	Bridge	BnS CT2	YXZ	0.005747	0.006212	0.000227	0.000856	0.000119	0.000074
12	LK	Bridge	LK	XYZ	0.002148	0.005623	0.004353	0.001792	0.000432	0.000008
13	Iota	Bridge	BnS CT2	YXZ	0.002889	0.005669	0.029477	0.000482	0.000378	0.000825
14	Gamma	Bridge	DEA Type 1	XYZ	0.005528	0.000043	0.000835	0.003271	0.000345	0.000066
15	Xcel	Bridge	BnS CT2	YXZ	0.000265	0.005625	0.009128	0.006707	0.001244	0.001722

Illustration 2: Comparison data used for the analysis. Each error parameter is represented by a gradient.

The error entry for each compensation map parameter is the slope of the difference between the two sets of compensation map data. This comparison method is suitable for most of the compensation map parameters as changes observed in the field are almost always linear gradients. The only map parameters that are not suitable for this kind of comparison is straightness as slope errors are often removed (in some cases automatically) so any kind of slope comparison between straightness errors is meaningless.

The raw data from the map differences was sorted into error levels. Illustration 3 shows the frequency distribution data for the six compensation parameters of the X axis.

	A	B	C	D	E	F	G	H	I
1		Category		RX	RY	RZ	LX	LY	LZ
2	X Axis		0.0000	0	0	0	0	0	0
3		<0.005	0.0050	125	119	127	110	146	143
4		0.005-0.010	0.0100	22	22	13	25	1	3
5		0.010-0.015	0.0150	0	4	4	5	0	1
6		0.015-0.020	0.0200	0	1	0	2	0	0
7		0.020-0.025	0.0250	0	1	0	3	0	0
8		0.025-0.030	0.0300	0	0	1	1	0	0
9		0.030-0.035	0.0350	0	0	2	0	0	0
10		0.035-0.040	0.0400	0	0	0	1	0	0
11		0.040-0.045	0.0450	0	0	0	0	0	0
12		0.045-0.050	0.0500	0	0	0	0	0	0
13		0.050-0.055	0.0550	0	0	0	0	0	0
14		0.055-0.060	0.0600	0	0	0	0	0	0
15		0.060-0.065	0.0650	0	0	0	0	0	0
16		0.065-0.070	0.0700	0	0	0	0	0	0
17		0.070-0.075	0.0750	0	0	0	0	0	0
18		0.075-0.080	0.0800	0	0	0	0	0	0
19		0.080-0.085	0.0850	0	0	0	0	0	0
20		0.085-0.090	0.0900	0	0	0	0	0	0
21		0.090-0.095	0.0950	0	0	0	0	0	0
22		0.095-0.100	0.1000	0	0	0	0	0	0

Illustration 3: Count of compensation errors sorted into error ranges.

24	Count		< 0.010	147	141	140	135	147	146
25			0.010 – 0.020	0	5	4	7	0	1
26			>0.020	0	1	3	5	0	0
27		sum:		147	147	147	147	147	147
28	Stats		< 0.010	100.0%	95.9%	95.2%	91.8%	100.0%	99.3%
29			0.010 – 0.020	0.0%	3.4%	2.7%	4.8%	0.0%	0.7%
30			>0.020	0.0%	0.7%	2.0%	3.4%	0.0%	0.0%

Illustration 4: General analysis of the change in the error map.

One problem when comparing changes to the YZ or ZX squareness is that many CMM's have a functional axis system where Y is along the granite even though, internally, it is the X axis of the compensation error map. For example, a typical Global CMM setup with a DEA map defines this as the ZX squareness correction even though it is in the functional YZ plane of the CMM. Future versions of this document may try to separate this, if practical. There is some mixing of YZ and ZX squareness as a result.

Bridge CMM's with DEA compensation maps, regardless of the apparent axis system of the machine, use the kinematic of XYZ. A typical Global CMM with a DEA compensation error map with DEActiv compensation of the granite will correct the X axis pitch, ZX squareness, X scale, and X vertical straightness even through the operator of the CMM will see this as changes in the Y axis pitch, Y axis scale, YZ squareness, Y vertical straightness.

Analysis Results

The analysis is done by two methods. The first method looks at the average change for each of the compensation error map parameters where the second method only considers the maximum change of any compensation error map parameter. The slope of all compensation parameter differences are unsigned results ranging from zero (no change) to a positive maximum value.

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Average Changes

Table 2 list the average change of all angular and linear scale compensation parameters. The straightness data for each axis is not included as this data is either end-fit or slope corrected and does not represent changes in the machine axis.

Table 2: Average change of all angular and linear scale compensation parameters.

Compensation Axis	Compensation Parameter	Average Change in mm or mm/m
X	Rx	0.0023
	Ry	0.0031
	Rz	0.0032
	Scale	0.0044
Y	Rx	0.0011
	Ry	0.0009
	Rz	0.0033
	Scale	0.0037
Z	Rx	0.0041
	Ry	0.0011
	Rz	0.0049
	Scale	0.0013
X	XY Squareness	0.0006
Y	YZ Squareness	0.0002
Z	ZX Squareness	0.0042

Table 3 shows the distribution of errors at different error levels.

Table 3: Distribution of average change for angular and linear scale data at different error levels.

Error in mm or mm/m	Change at Specific Level
Less than 0.010	90.34%
Between 0.010 and 0.020	6.89%
Greater than 0.020	2.77%

Comparison of the straightness data could be done by comparing the range of the data and not the slope. Since slope comparison is the method used for this analysis no results from straightness are shown.

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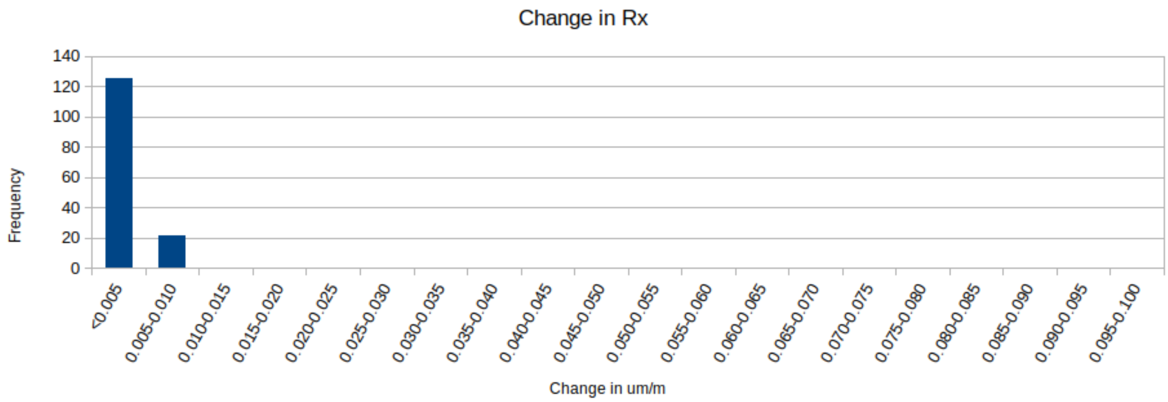
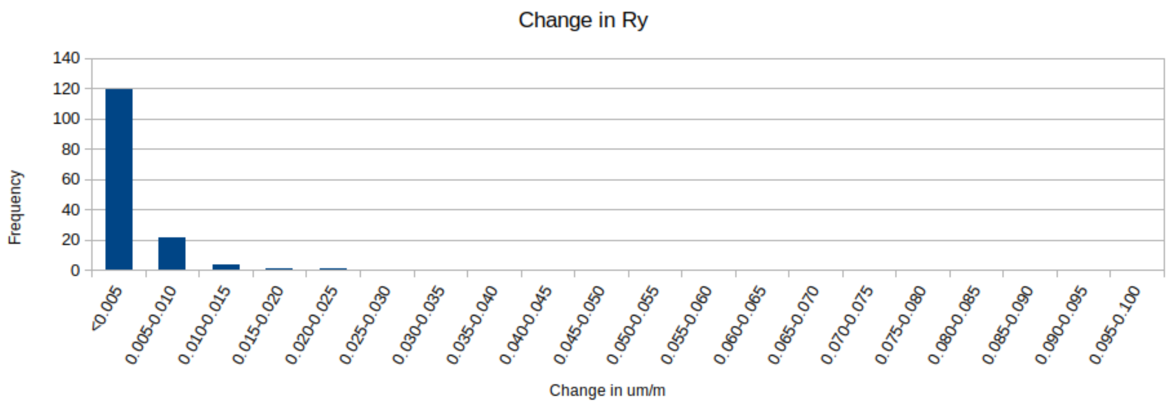
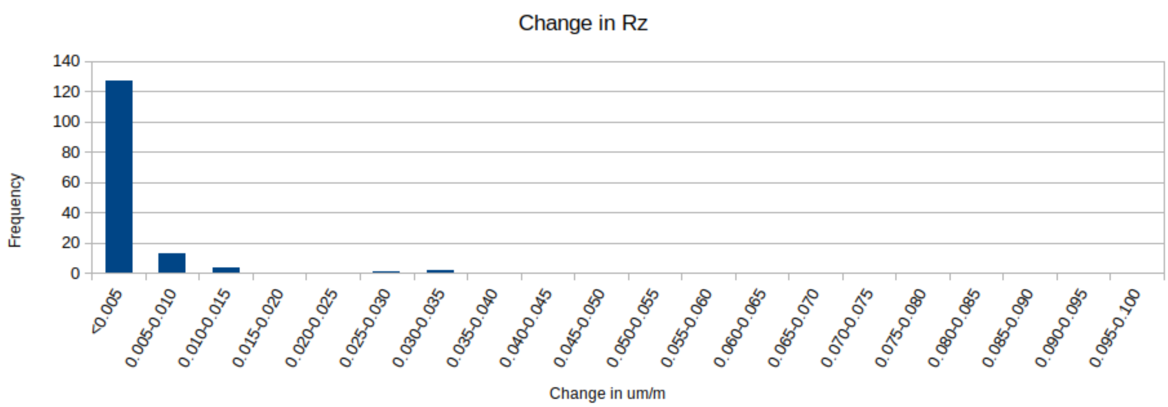
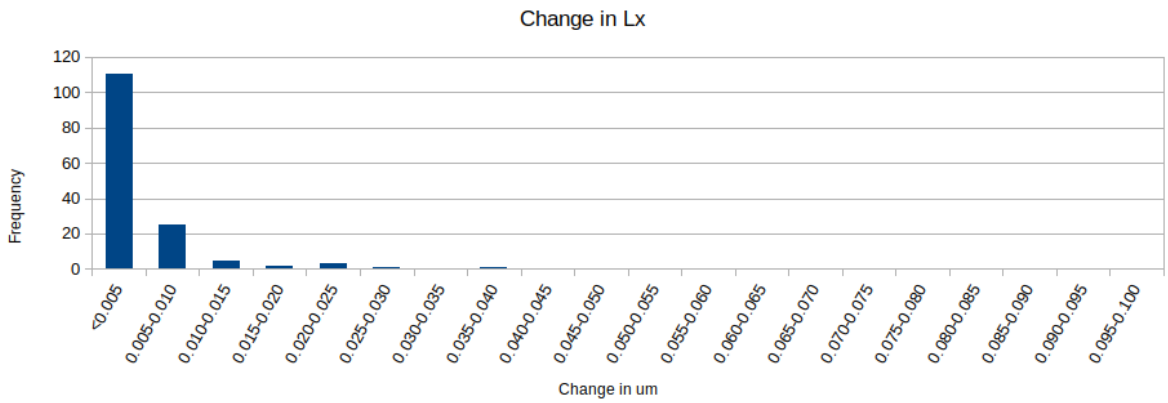
X Axis Changes:

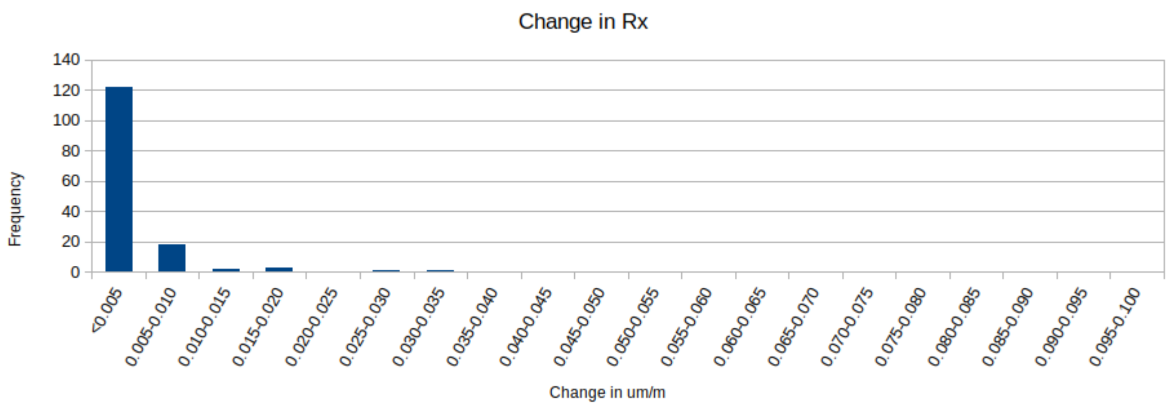


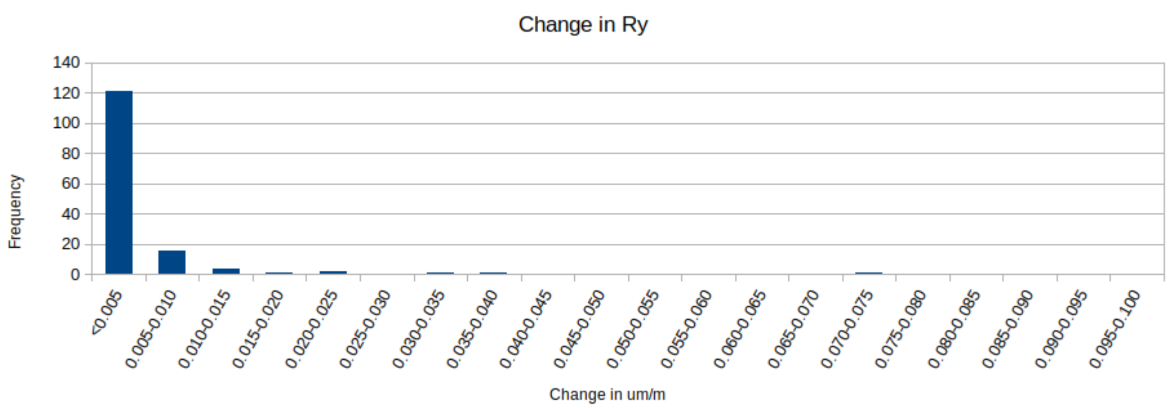


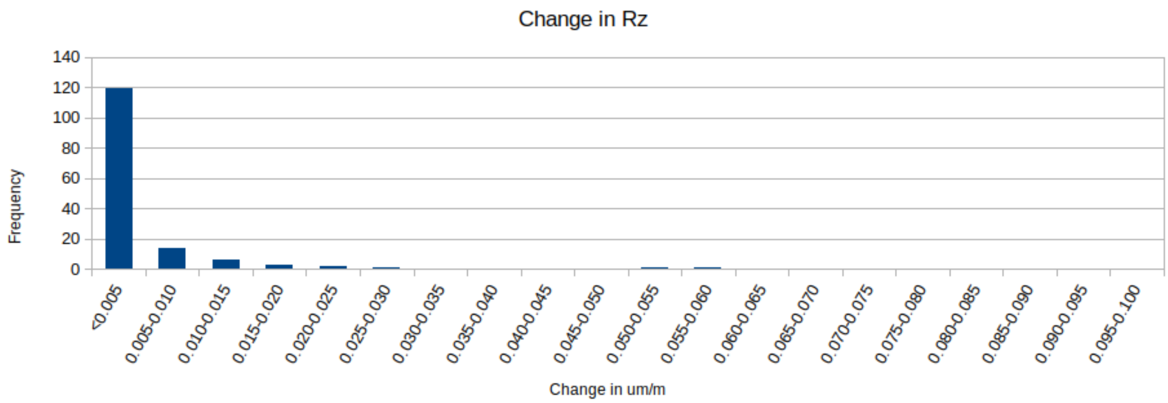


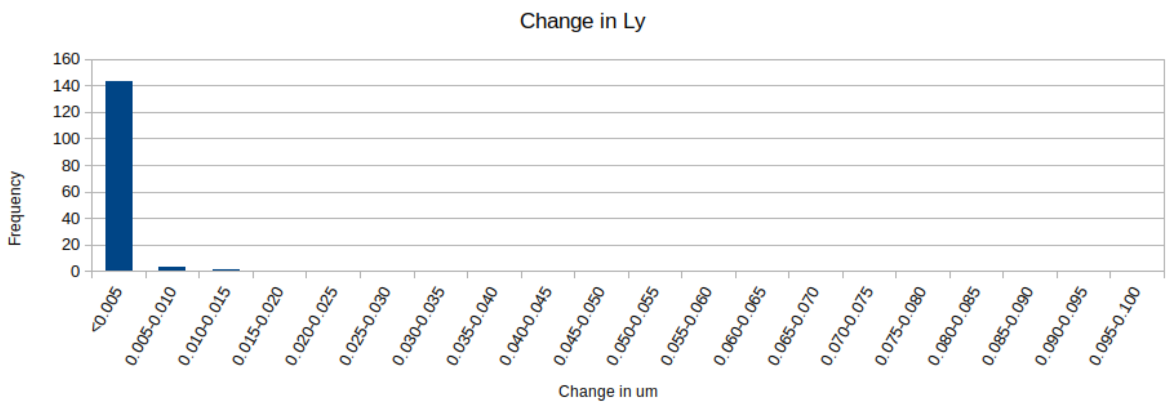


Y Axis Changes:

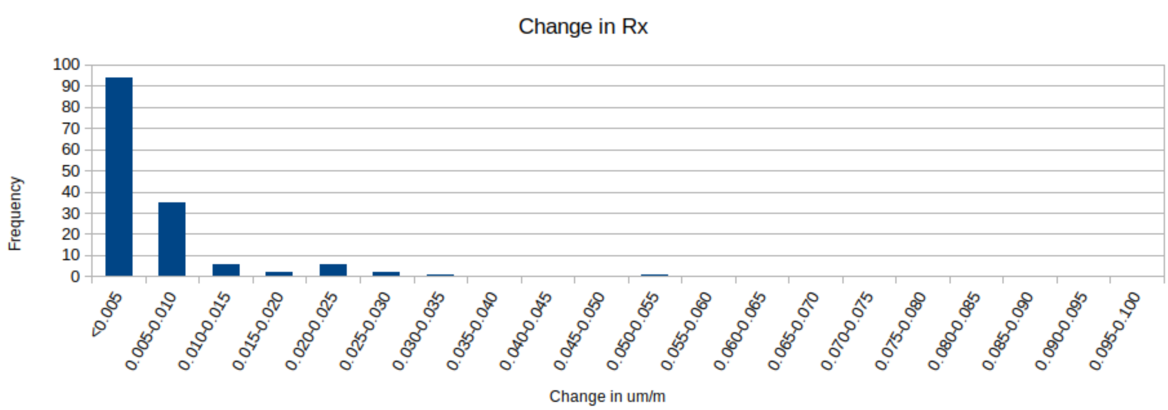








Z Axis Changes:



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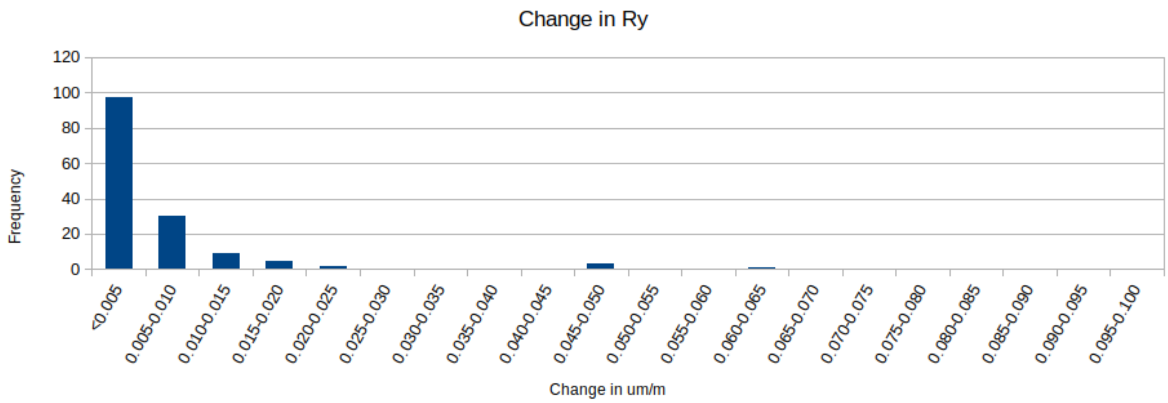

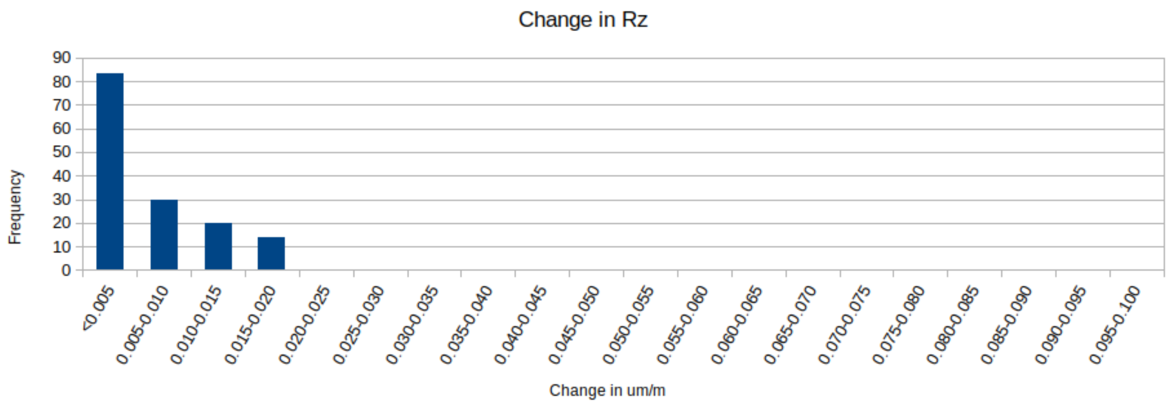

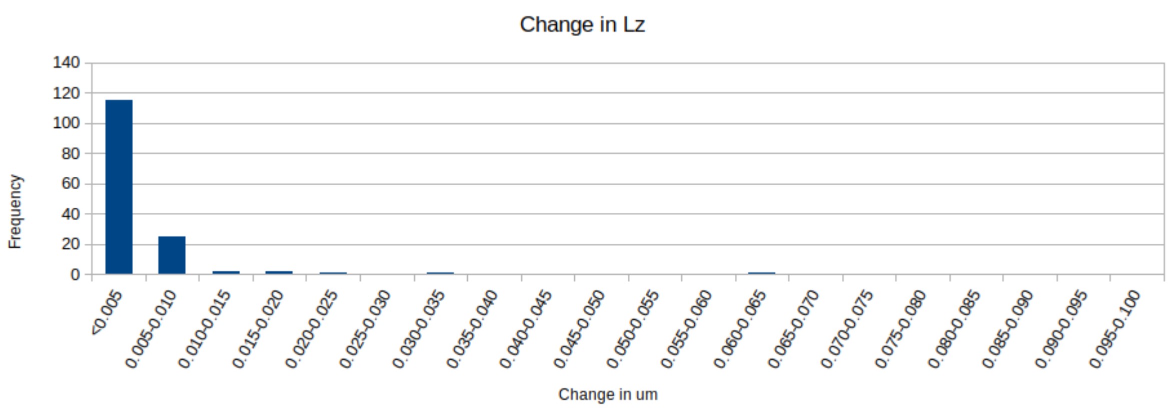

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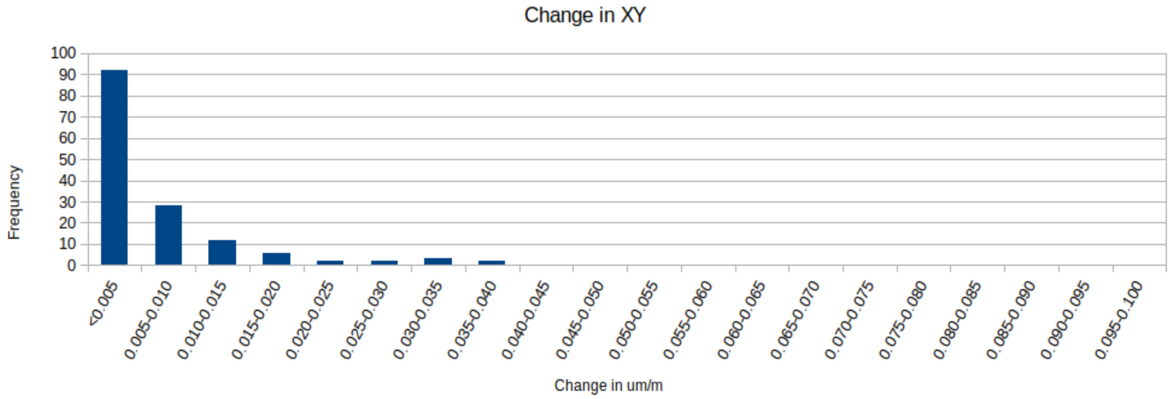
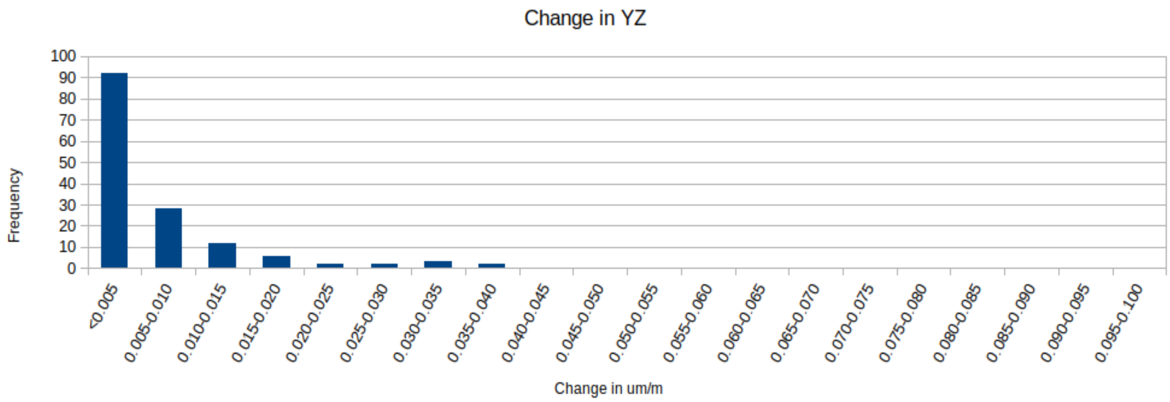
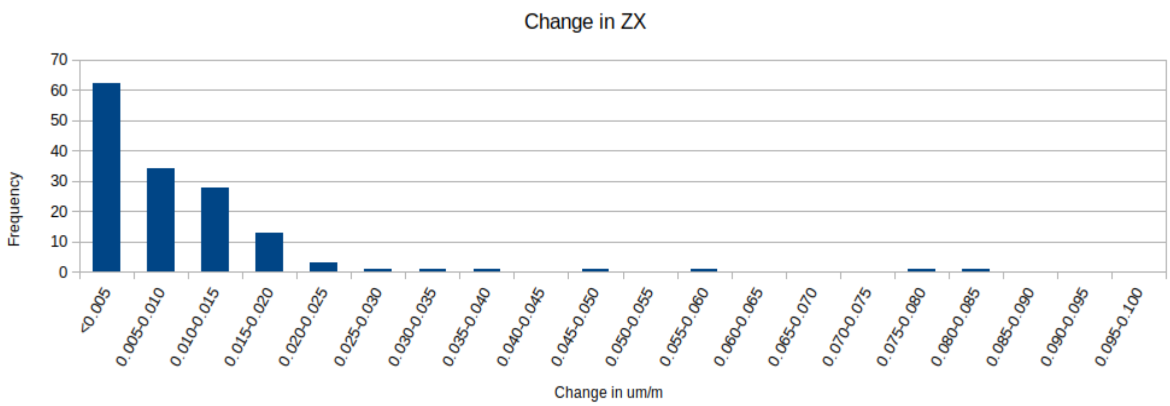
Squareness Changes:







Due to the location of the rotation points of the compensation error map the amount of linear scale data may not represent the observed measurement error on a CMM. It is not unusual to see a linear scale error when collecting data but end up with this completely removed following updates to one or more angular parameters.

Maximum Change

Table 4 describes the maximum change for all angular compensation parameters and linear scale for all configurations of CMM's. Unlike the changes described by the average data this will single out any single parameter change in a machine such as a change in pitch or a scale error. This is probably more realistic to machine stability as any single change can have far reaching impact on the CMM performance.

As a general rule of thumb, changes below 10 um or 10 um/m is considered to be no significant change. The majority of machines will have one or more changes in the range of 10 um or 10 um/m to 40 um or 40 um/m. Changes above 40 um or 40 um/m drop off and become uncommon.

The general limits are exactly that, general limits. They are chosen based on typical requirements of CMM's installed in a variety of environments. For high-end CMM's these limits obviously don't apply.

Table 4: Distribution of maximum change of angular and linear scale data at different error levels for all configurations.

Maximum Error in mm or mm/m	Change at Specific Level for All CMM Configurations
Less than 0.010	27.21%
Between 0.010 and 0.020	42.86%
Between 0.020 and 0.030	14.97%
Between 0.030 and 0.040	7.48%
Between 0.040 and 0.050	2.72%
Greater than 0.050	4.76%

Based on the data from table 4, 1 in 4 CMM's will have changes to all compensation parameters below 10 um or 10 um/m. Illustration 5 shows the distribution of the maximum change in machine errors relative to a set of error limits.

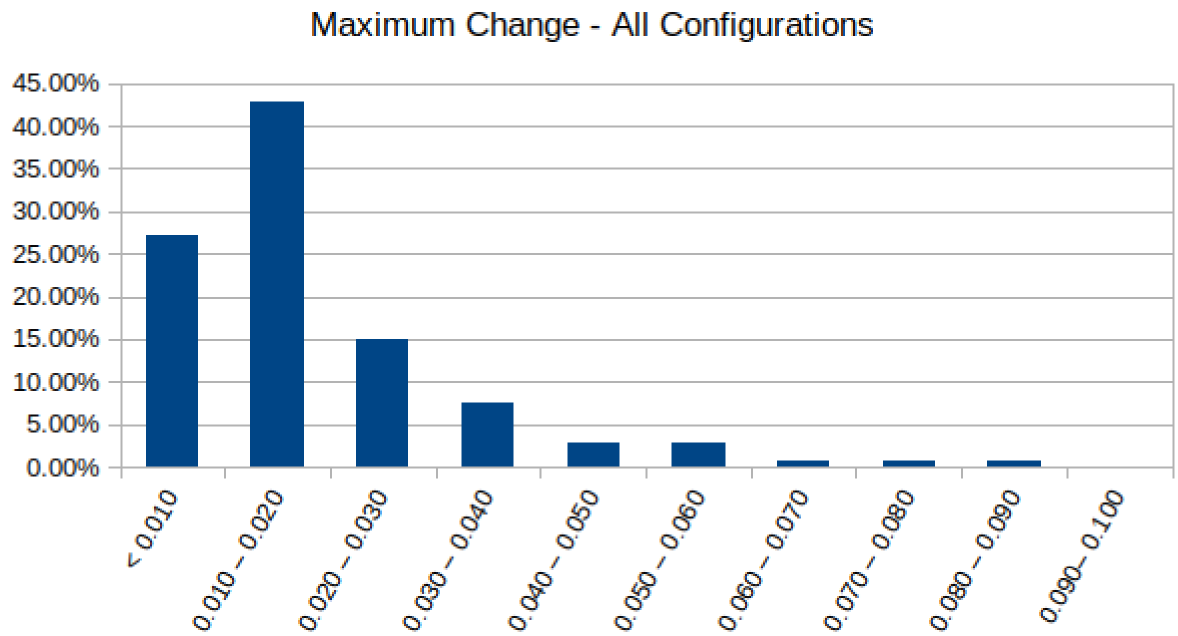


Illustration 5: Maximum change distribution.

Table 5 describes the maximum change for all angular compensation parameters and linear scale for only bridge CMM's.

Table 5: Distribution of maximum change of angular and linear scale data at different error levels for bridge configurations only.

Maximum Error in mm or mm/m	Change at Specific Level for Bridge CMM Configurations
Less than 0.010	33.33%
Between 0.010 and 0.020	48.48%
Between 0.020 and 0.030	8.08%
Between 0.030 and 0.040	3.03%
Between 0.040 and 0.050	3.03%
Greater than 0.050	4.04%

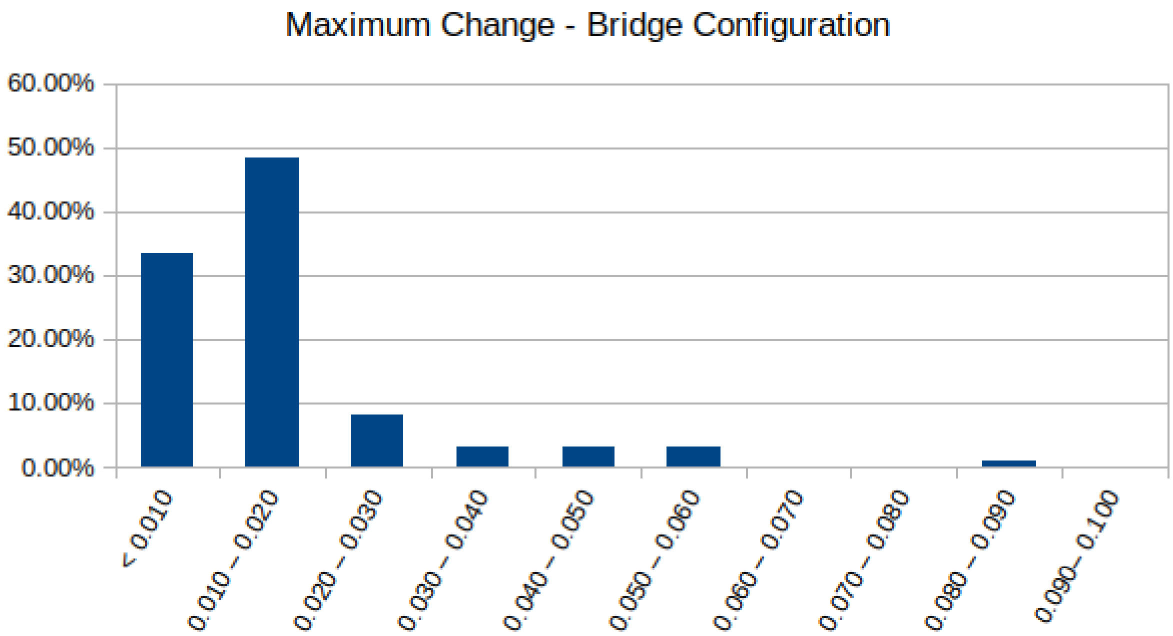


Illustration 6: Maximum change distribution for only bridge machines.

Table 6 describes the maximum change for all angular compensation parameters and linear scale for non-bridge CMM's.

Table 6: Distribution of maximum change of angular and linear scale data at different error levels for non-bridge configurations.

Maximum Error in mm or mm/m	Change at Specific Level for Non-Bridge CMM Configurations
Less than 0.010	14.58%
Between 0.010 and 0.020	31.25%
Between 0.020 and 0.030	29.17%
Between 0.030 and 0.040	16.67%
Between 0.040 and 0.050	2.08%
Greater than 0.050	6.25%

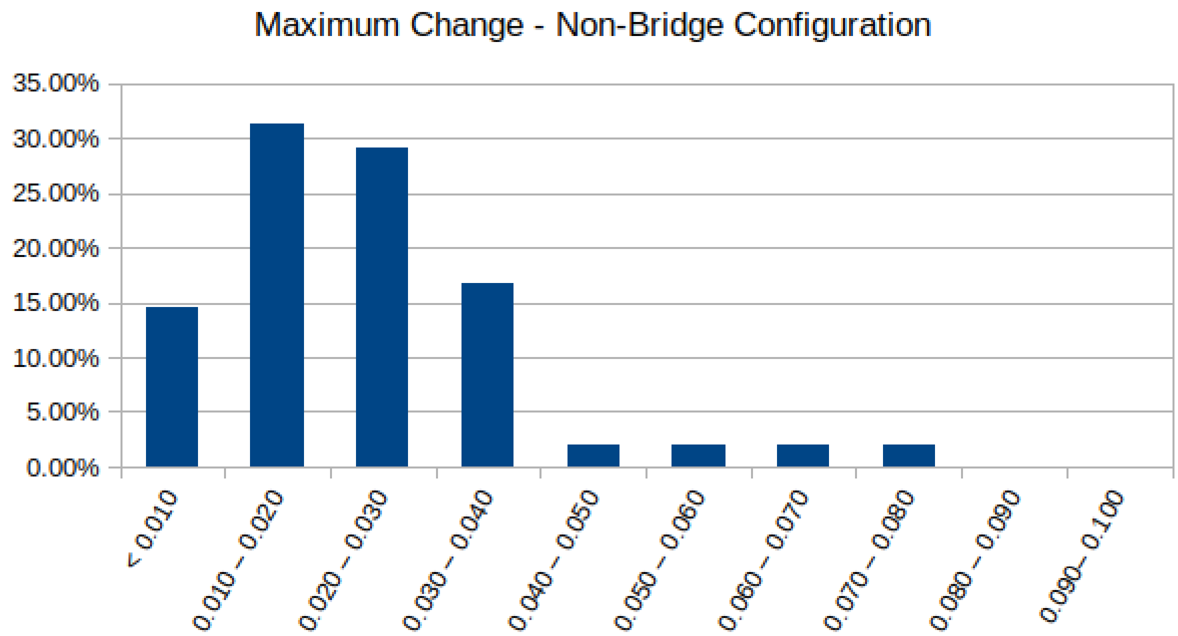


Illustration 7: Maximum change distribution for non-bridge CMM's.

As expected, bridge CMM's are more stable than gantry and horizontal arm CMM's. Gantry and horizontal arm CMM's are often influenced by the foundation the machine is placed on. Gantry CMM's, even with a proper foundation, will change for the first several years until the foundation has fully cured.

Performance Testing

The impact on the performance of a CMM was tested on a simulated 12.22.10 CMM with measurements following ISO/IEC 10360-2:2009 (ASME B89.4.10360-2:2008). Two sets of performance tests were created where the results from the first test used a CMM with average errors described in table 2 and the second test only had a Y axis pitch error of 10 um/m and no other machine errors. Illustration 8 shows the measurement pattern used to test the performance of the CMM.

The second test was chosen based on how common it is to find bridge CMM's with changes to the first axis pitch. Granite does not conduct heat very well and has an expansion coefficient around 8 um/m/°C so when there is a change in the vertical temperature gradient of the granite it changes shape in a way similar to how a bimetallic spring works.

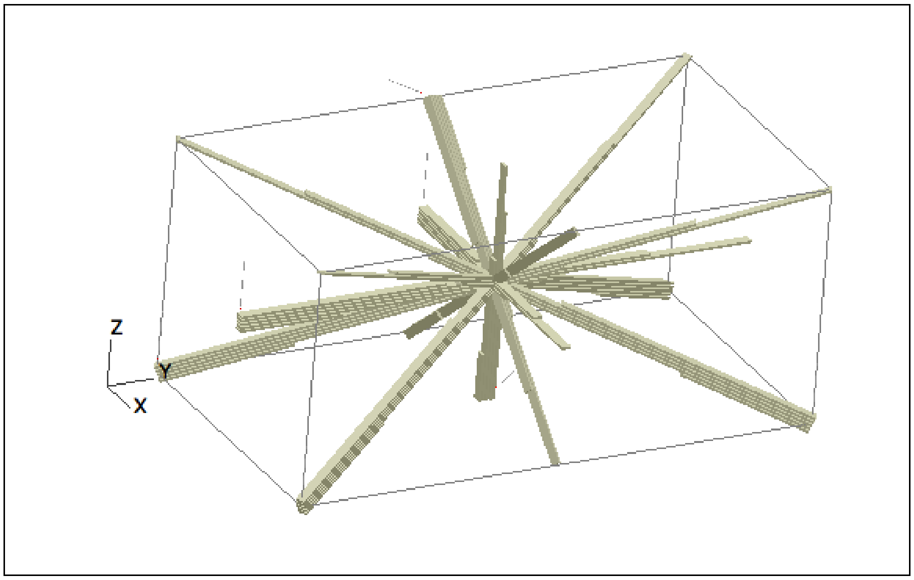


Illustration 8: Performance test measurement pattern following 10360-2.

Performance Results Using All Average Errors

The following shows the results of simulated measurements on a 12.22.10 CMM with the machine setup to use the average errors described in table 2:

```
ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            Position 1
Probe Offset:    0.0000, 0.0000, -200.0000
Start Position: 1200.0000, 0.0000, -1200.0000
Test Axis:       -0.444749590, 0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
  540.0000   540.0013     0.0013
 1080.0000  1080.0024     0.0024
 1620.0000  1620.0034     0.0034
 2160.0000  2160.0043     0.0043
 2700.0000  2700.0051     0.0051

Max Error:  0.0051
Min Error:  0.0013

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            Position 2
Probe Offset:    0.0000, 0.0000, -200.0000
Start Position: 1200.0000, 2200.0000, -1200.0000
Test Axis:       -0.444749590, -0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
```

```
  540.0000   540.0042     0.0042
 1080.0000  1080.0079     0.0079
 1620.0000  1620.0111     0.0111
 2160.0000  2160.0138     0.0138
 2700.0000  2700.0159     0.0159

Max Error:  0.0159
Min Error:  0.0042

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:           Position 3
Probe Offset:   0.0000, 0.0000, -200.0000
Start Position: 0.0000, 2200.0000, -1200.0000
Test Axis:      0.444749590, -0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
  540.0000   540.0014     0.0014
 1080.0000  1080.0032     0.0032
 1620.0000  1620.0054     0.0054
 2160.0000  2160.0081     0.0081
 2700.0000  2700.0113     0.0113

Max Error:  0.0113
Min Error:  0.0014

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:           Position 4
Probe Offset:   0.0000, 0.0000, -200.0000
Start Position: 0.0000, 0.0000, -1200.0000
Test Axis:      0.444749590, 0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
  540.0000   540.0035     0.0035
 1080.0000  1080.0071     0.0071
 1620.0000  1620.0108     0.0108
 2160.0000  2160.0147     0.0147
 2700.0000  2700.0187     0.0187

Max Error:  0.0187
Min Error:  0.0035

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:           Position 5
Probe Offset:   0.0000, 0.0000, -200.0000
Start Position: 0.0000, 1100.0000, -700.0000
Test Axis:      1.000000000, 0.000000000, 0.000000000
```

```
   Nominal     Actual      Dev
-----------------------------------------------------------------------
  240.0000   240.0005     0.0005
  480.0000   480.0011     0.0011
  720.0000   720.0016     0.0016
  960.0000   960.0021     0.0021
 1200.0000  1200.0027     0.0027

Max Error:  0.0027
Min Error:  0.0005

ISO 10360-2 Measurement
-----------------------------------------------------------------------
Name:            Position 6
Probe Offset:    0.0000, 0.0000, -200.0000
Start Position: 600.0000, 0.0000, -700.0000
Test Axis:       0.000000000, 1.000000000, 0.000000000

   Nominal     Actual      Dev
-----------------------------------------------------------------------
  440.0000   440.0028     0.0028
  880.0000   880.0057     0.0057
 1320.0000  1320.0085     0.0085
 1760.0000  1760.0114     0.0114
 2200.0000  2200.0142     0.0142

Max Error:  0.0142
Min Error:  0.0028

ISO 10360-2 Measurement
-----------------------------------------------------------------------
Name:            Position 7
Probe Offset:    0.0000, -100.0000, -80.0000
Start Position: 600.0000, 1000.0000, -1080.0000
Test Axis:       0.000000000, 0.000000000, 1.000000000

   Nominal     Actual      Dev
-----------------------------------------------------------------------
  200.0000   199.9999    -0.0001
  400.0000   399.9998    -0.0002
  600.0000   599.9998    -0.0002
  800.0000   799.9997    -0.0003
 1000.0000   999.9996    -0.0004

Max Error: -0.0001
Min Error: -0.0004

ISO 10360-2 Measurement
-----------------------------------------------------------------------
Name:            Position D1
Probe Offset:    0.0000, -150.0000, -80.0000
Start Position: 0.0000, 950.0000, -1080.0000
Test Axis:       0.768221280, 0.000000000, 0.640184400
```



```
   Nominal     Actual      Dev
----------------------------------------------------------------------
  312.0000   312.0010     0.0010
  624.0000   624.0022     0.0022
  936.0000   936.0036     0.0036
 1248.0000  1248.0051     0.0051
 1560.0000  1560.0067     0.0067

Max Error:  0.0067
Min Error:  0.0010

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:           Position D2
Probe Offset:   0.0000, 150.0000, -80.0000
Start Position: 0.0000, 1250.0000, -80.0000
Test Axis:      0.768221280, 0.000000000, -0.640184400

   Nominal     Actual      Dev
----------------------------------------------------------------------
  312.0000   311.9999    -0.0001
  624.0000   623.9997    -0.0003
  936.0000   935.9994    -0.0006
 1248.0000  1247.9991    -0.0009
 1560.0000  1559.9987    -0.0013

Max Error: -0.0001
Min Error: -0.0013
```

Table 7: Results of 10360-2 performance test using a machine with average errors.

10360-2	Nominal	Actual	Deviation
Average Errors	200	199.9999	-0.0001
	240	240.0005	0.0005
	312	312.0010	0.0010
	312	311.9999	-0.0001
	400	399.9998	-0.0002
	440	440.0028	0.0028
	480	480.0011	0.0011
	540	540.0013	0.0013
	540	540.0042	0.0042
	540	540.0014	0.0014
	540	540.0035	0.0035
	600	599.9998	-0.0002
	624	624.0022	0.0022
	624	623.9997	-0.0003
	720	720.0016	0.0016
	800	799.9997	-0.0003
	880	880.0057	0.0057
	936	936.0036	0.0036

	936	935.9994	-0.0006
	960	960.0021	0.0021
	1000	999.9996	-0.0004
	1080	1080.0024	0.0024
	1080	1080.0079	0.0079
	1080	1080.0032	0.0032
	1080	1080.0071	0.0071
	1200	1200.0027	0.0027
	1248	1248.0051	0.0051
	1248	1247.9991	-0.0009
	1320	1320.0085	0.0085
	1560	1560.0067	0.0067
	1560	1559.9987	-0.0013
	1620	1620.0034	0.0034
	1620	1620.0111	0.0111
	1620	1620.0054	0.0054
	1620	1620.0108	0.0108
	1760	1760.0114	0.0114
	2160	2160.0043	0.0043
	2160	2160.0138	0.0138
	2160	2160.0081	0.0081
	2160	2160.0147	0.0147
	2200	2200.0142	0.0142
	2700	2700.0051	0.0051
	2700	2700.0159	0.0159
	2700	2700.0113	0.0113
	2700	2700.0187	0.0187
Stats	Min		-0.0013
	Max		0.0187
	Range		0.0200
	Std.Dev		0.0052

Performance Results Using Max Error

The following shows the results of simulated measurements on a 12.22.10 CMM with the machine setup with only a pitch error of 10 um/m in the Y axis:

```
ISO 10360-2 Measurement
-----------------------------------------------------------------------
Name:           Position 1
Probe Offset:   0.0000, 0.0000, -200.0000
Start Position: 1200.0000, 0.0000, -1200.0000
Test Axis:      -0.444749590, 0.815374248, 0.370624658

   Nominal     Actual      Dev
-----------------------------------------------------------------------
  540.0000   540.0018     0.0018
 1080.0000  1080.0031     0.0031
```

```
 1620.0000  1620.0039     0.0039
 2160.0000  2160.0041     0.0041
 2700.0000  2700.0038     0.0038

Max Error:  0.0041
Min Error:  0.0018

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            Position 2
Probe Offset:    0.0000, 0.0000, -200.0000
Start Position: 1200.0000, 2200.0000, -1200.0000
Test Axis:       -0.444749590, -0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
  540.0000   540.0061     0.0061
 1080.0000  1080.0112     0.0112
 1620.0000  1620.0155     0.0155
 2160.0000  2160.0188     0.0188
 2700.0000  2700.0213     0.0213

Max Error:  0.0213
Min Error:  0.0061

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            Position 3
Probe Offset:    0.0000, 0.0000, -200.0000
Start Position: 0.0000, 2200.0000, -1200.0000
Test Axis:       0.444749590, -0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
  540.0000   540.0047     0.0047
 1080.0000  1080.0089     0.0089
 1620.0000  1620.0125     0.0125
 2160.0000  2160.0156     0.0156
 2700.0000  2700.0182     0.0182

Max Error:  0.0182
Min Error:  0.0047

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            Position 4
Probe Offset:    0.0000, 0.0000, -200.0000
Start Position: 0.0000, 0.0000, -1200.0000
Test Axis:       0.444749590, 0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
```



```
   540.0000   540.0032     0.0032
  1080.0000  1080.0055     0.0055
  1620.0000  1620.0069     0.0069
  2160.0000  2160.0074     0.0074
  2700.0000  2700.0070     0.0070

Max Error:  0.0074
Min Error:  0.0032

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            Position 5
Probe Offset:    0.0000, 0.0000, -200.0000
Start Position: 0.0000, 1100.0000, -700.0000
Test Axis:       1.000000000, 0.000000000, 0.000000000

   Nominal     Actual      Dev
----------------------------------------------------------------------
   240.0000   240.0000     0.0000
   480.0000   480.0000     0.0000
   720.0000   720.0000     0.0000
   960.0000   960.0000     0.0000
  1200.0000  1200.0000     0.0000

Max Error:  0.0000
Min Error:  0.0000

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            Position 6
Probe Offset:    0.0000, 0.0000, -200.0000
Start Position: 600.0000, 0.0000, -700.0000
Test Axis:       0.000000000, 1.000000000, 0.000000000

   Nominal     Actual      Dev
----------------------------------------------------------------------
   440.0000   440.0031     0.0031
   880.0000   880.0062     0.0062
  1320.0000  1320.0092     0.0092
  1760.0000  1760.0123     0.0123
  2200.0000  2200.0154     0.0154

Max Error:  0.0154
Min Error:  0.0031

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            Position 7
Probe Offset:    0.0000, -100.0000, -80.0000
Start Position: 600.0000, 1000.0000, -1080.0000
Test Axis:       0.000000000, 0.000000000, 1.000000000

   Nominal     Actual      Dev
```



```
--------------------------------------------------------------------
   200.0000   200.0000    -0.0000
   400.0000   400.0000    -0.0000
   600.0000   600.0000    -0.0000
   800.0000   800.0000    -0.0000
  1000.0000  1000.0000    -0.0000

Max Error: -0.0000
Min Error: -0.0000

ISO 10360-2 Measurement
--------------------------------------------------------------------
Name:            Position D 1
Probe Offset:    0.0000, -150.0000, -80.0000
Start Position: 0.0000, 950.0000, -1080.0000
Test Axis:       0.768221280, 0.000000000, 0.640184400

   Nominal     Actual      Dev
--------------------------------------------------------------------
   312.0000   311.9999    -0.0001
   624.0000   623.9999    -0.0001
   936.0000   935.9998    -0.0002
  1248.0000  1247.9998    -0.0002
  1560.0000  1559.9997    -0.0003

Max Error: -0.0001
Min Error: -0.0003

ISO 10360-2 Measurement
--------------------------------------------------------------------
Name:            Position D 2
Probe Offset:    0.0000, 150.0000, -80.0000
Start Position: 0.0000, 1250.0000, -80.0000
Test Axis:       0.768221280, 0.000000000, -0.640184400

   Nominal     Actual      Dev
--------------------------------------------------------------------
   312.0000   311.9999    -0.0001
   624.0000   623.9999    -0.0001
   936.0000   935.9998    -0.0002
  1248.0000  1247.9998    -0.0002
  1560.0000  1559.9997    -0.0003

Max Error: -0.0001
Min Error: -0.0003
```

Table 8: Results of 10360-2 performance test using a machine with a Y pitch error of 10 um/m.

10360-2	Nominal	Actual	Deviation
Max Error	200	200.0000	0.0000
	240	240.0000	0.0000
	312	311.9999	-0.0001
	312	311.9999	-0.0001

	400	400.0000	0.0000
	440	440.0031	0.0031
	480	480.0000	0.0000
	540	540.0018	0.0018
	540	540.0061	0.0061
	540	540.0047	0.0047
	540	540.0032	0.0032
	600	600.0000	0.0000
	624	623.9999	-0.0001
	624	623.9999	-0.0001
	720	720.0000	0.0000
	800	800.0000	0.0000
	880	880.0062	0.0062
	936	935.9998	-0.0002
	936	935.9998	-0.0002
	960	960.0000	0.0000
	1000	1000.0000	0.0000
	1080	1080.0031	0.0031
	1080	1080.0112	0.0112
	1080	1080.0089	0.0089
	1080	1080.0055	0.0055
	1200	1200.0000	0.0000
	1248	1247.9998	-0.0002
	1248	1247.9998	-0.0002
	1320	1320.0092	0.0092
	1560	1559.9997	-0.0003
	1560	1559.9997	-0.0003
	1620	1620.0039	0.0039
	1620	1620.0155	0.0155
	1620	1620.0125	0.0125
	1620	1620.0069	0.0069
	1760	1760.0123	0.0123
	2160	2160.0041	0.0041
	2160	2160.0188	0.0188
	2160	2160.0156	0.0156
	2160	2160.0074	0.0074
	2200	2200.0154	0.0154
	2700	2700.0038	0.0038
	2700	2700.0213	0.0213
	2700	2700.0182	0.0182
	2700	2700.0070	0.0070
Stats	Min		-0.0003
	Max		0.0213
	Range		0.0216
	Std.Dev		0.0062

CMM Performance Stability

Performance Specifications

The specifications for a typical 12.22.10 CMM would be 3+4L um (L in meters). Using this specifications the deviations from the two sets of simulated tests exceeding the tolerance are shown in table 9.

Table 9: Comparison of deviation to tolerance. Only results out of tolerance are displayed.

Nominal	Tolerance	Avg OOT	Max OOT
200	0.0038		
240	0.0040		
312	0.0042		
312	0.0042		
400	0.0046		
440	0.0048		
480	0.0049		
540	0.0052		
540	0.0052		0.0009
540	0.0052		
540	0.0052		
600	0.0054		
624	0.0055		
624	0.0055		
720	0.0059		
800	0.0062		
880	0.0065		
936	0.0067		
936	0.0067		
960	0.0068		
1000	0.0070		
1080	0.0073		
1080	0.0073	0.0006	0.0039
1080	0.0073		0.0016
1080	0.0073		
1200	0.0078		
1248	0.0080		
1248	0.0080		
1320	0.0083	0.0002	0.0009
1560	0.0092		
1560	0.0092		
1620	0.0095		
1620	0.0095	0.0016	0.0060
1620	0.0095		0.0030
1620	0.0095	0.0013	
1760	0.0100	0.0014	0.0023
2160	0.0116		
2160	0.0116	0.0022	0.0072
2160	0.0116		0.0040
2160	0.0116	0.0031	

2200	0.0118	0.0024	0.0036
2700	0.0138		
2700	0.0138	0.0021	0.0075
2700	0.0138		0.0044
2700	0.0138	0.0049	
Stats	Min	0.0002	0.0009
	Max	0.0049	0.0075
	Std.Dev	0.0013	0.0022

The specification of 3+4L um (L in meters) is on the lower end of the range of specifications. A typical gantry CMM could be in the range of 10+10L um (L in meters) and horizontal arm CMM's usually start around 15+15L (L in meters) and increase dramatically based on the length of the Y axis.

Summary

Based on the observed changes in CMM's between regular calibration cycles roughly 1 in 4 would have changes below a limit that would result in the machine measuring outside of specification where bridge machines are less likely to change as compared to gantry or horizontal arm CMM's.

The general limit used for change comparison of 10 um or 10 um/m appears to be in the ball-park for a general purpose rule-of-thumb limit. For larger machines or CMM's such as horizontal arms this limit is on the low side and likely on the high side for bridge machines. This limit does not apply to high end CMM's.

Machines that have a single significant error such as a change in the Y axis pitch of a typical bridge CMM can be just as bad as machines with numerous, smaller, errors covering all axis of the CMM. When using a traditional laser system and relying on investigative measurements to decide on the update strategy it can be very tricky. It may be a case where the investigative measurements show reasonably good results but, when everything is combined, you end up with a machine that does not meet the specification goal.

Revision History

Revision	*Date*	*Reason*
1	Oct 11, 2023	Initial Release