CMM Performance Stability

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Purpose

This article explores the performance stability of a typical CMM based on 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 map data. The calibration of a CMM by SCI involves measuring and updating all compensation parameters so changes in the machine can be determined by simply comparing the changes to the map data following a calibration.

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 possible. 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.

Some like to separate calibration and certification when dealing with CMM's where calibration involves correcting errors and certification is just the measurement of the current state of the machine. In this authors opinion this is just word-salad. There may be some basis for this but, ignoring the semantics, it is not the expectation of the customer when requesting a calibration for their CMM regardless of what it is called. Companies in this line of work that do not update machines when needed should seek a new profession.

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CMM Calibration Using a Traditional Laser

Traditional lasers allow the measurement of 5 of the 6 axis parameters of the CMM. The 6^{th} axis parameter is typically 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.

The typical 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 meaning only updates to the axis scales and squareness would be sufficient. 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 without an 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 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 in 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 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 the 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 the calibration is a simpler process as all the compensation map parameters are measured and updated without the need for investigative measurements or other expert diagnostic skills from the technician. From a manufacturing point of view, with an interest in achieving 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 few 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.

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

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

Data		Value	Description
Total Samples		193	Total number of compensation maps used for the analysis.
Sample Distribution	Bridge	131	Number of bridge configured CMM's
	Gantry	38	Number of gantry configured CMM's
	Horizontal Arm	24	Number of horizontal arm configured CMM's
BnS CT2 map		109	Number of machines with a BnS CT2 error map
DEA Type 1 map		17	Number of machines with a DEA Type 1 error map
DEA Type 2 map		6	Number of machines with a DEA Type 2 error map
DEA Type 3 map		37	Number of machines with a DEA Type 3 error map
DEA Type 4 map		2	Number of machines with a DEA Type 4 error map
LK map		12	Number of machines with an LK error map
Renishaw map		3	Number of machines with a Renishaw error map
Other maps		7	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 included in this data that do not have annual calibration cycles.

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* compensation map. The gradient difference of the data between compensation map parameters is the basis for the analysis.

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 case where additional *update<n>* map files exist the highest number version is always used when comparing to the original *update0* map file.

Using *Compare Compensation Maps* utility the comparison is done automatically between the *As*

Found and *As Left* map data for all map parameters. The output of the comparison utility writes an entry to a CSV data file containing a set of differences in the form of a gradient for each compensation map parameter. Illustration 1 shows the comparison utility:

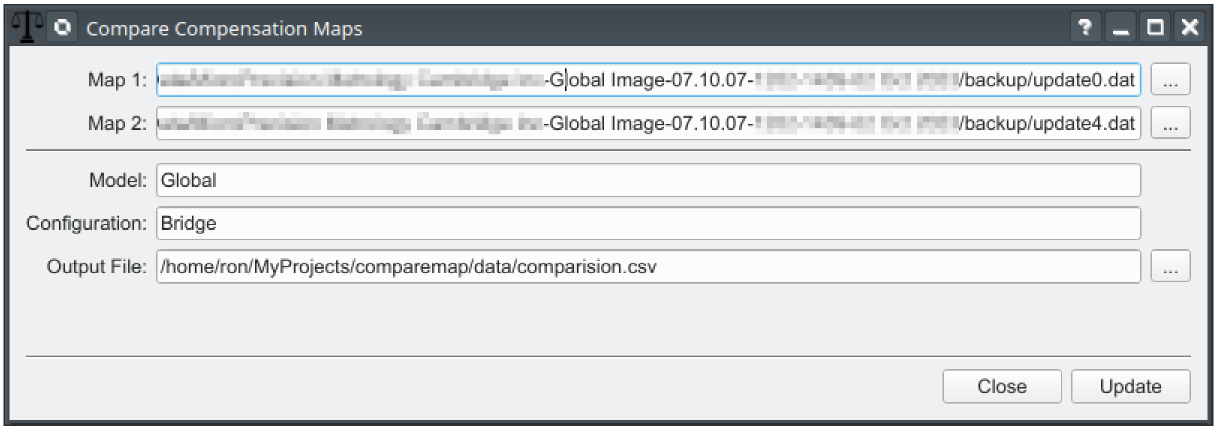
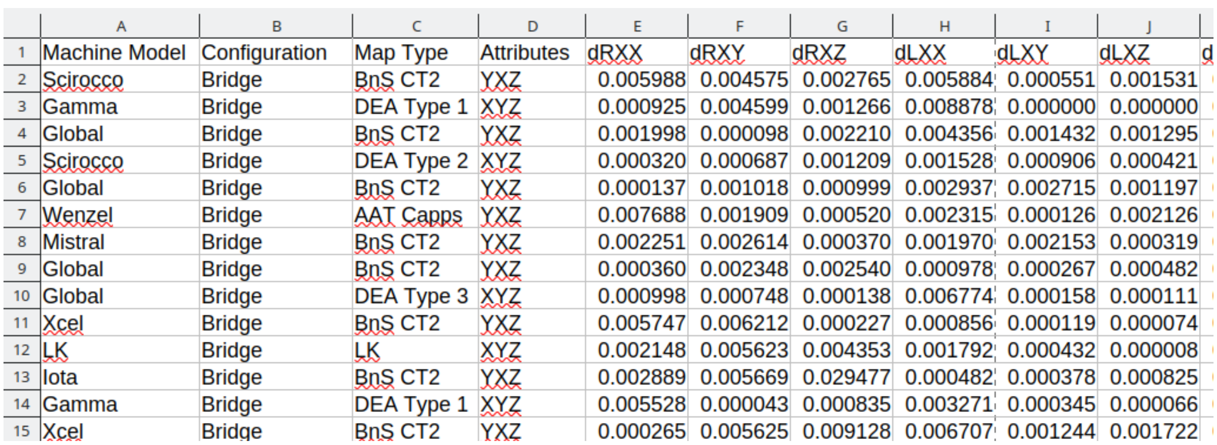


Illustration 1: Comparison generator utility. Some privileged information is grayed.

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	d
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 absolute 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 are likely meaningless.

The raw data from the map differences was sorted into error ranges. 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	140	141	140	136	168	167
4		0.005-0.010	0.0100	29	26	22	25	1	2
5		0.010-0.015	0.0150	1	2	5	4	1	1
6		0.015-0.020	0.0200	0	0	0	3	0	0
7		0.020-0.025	0.0250	0	1	0	0	0	0
8		0.025-0.030	0.0300	0	0	1	1	0	0
9		0.030-0.035	0.0350	0	0	0	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	1	0	0	0
14		0.055-0.060	0.0600	0	0	1	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
23									

Illustration 3: Compensation map differences sorted into error ranges.

24	Count		< 0.010	191	189	185	183	192	192
25			0.010 – 0.020	2	3	5	8	1	1
26			>0.020	0	1	3	2	0	0
27		sum:		193	193	193	193	193	193
28	Stats		< 0.010	99.0%	97.9%	95.9%	94.8%	99.5%	99.5%
29			0.010 – 0.020	1.0%	1.6%	2.6%	4.1%	0.5%	0.5%
30			>0.020	0.0%	0.5%	1.6%	1.0%	0.0%	0.0%

Illustration 4: General analysis of the change in the compensation map data.

One problem when comparing changes in the compensation map data is the kinematic axis order for bridge machines. Most standard CMM's have the Y axis as the first axis where some models such as LK have the X axis the first axis. In order to improve reliability of the comparison data maps that have a kinematic of XYZ have the errors transposed to the equivalent YXZ counterpart. For example, a machine with kinematic of XYZ and a change in the X axis scale (the granite axis) would actually be considered to be a change in the Y axis scale of a machine with a kinematic of YXZ. It was decided to convert all data into the kinematic or YXZ as this is the most common used axis convention. This should eliminate any bias due to differences in axis material between the X and Y axis of a CMM and other common characteristics.

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 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 from 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	0.0027
	Ry	0.0028
	Rz	0.0036
	Scale	0.0037
Y	Rx	0.0039
	Ry	0.0032
	Rz	0.0033
	Scale	0.0052
Z	Rx	0.0061
	Ry	0.0054
	Rz	0.0077
	Scale	0.0037
X	XY Squareness	0.0064
Y	YZ Squareness	0.0108
Z	ZX Squareness	0.0071

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	87.53%
Between 0.010 and 0.020	8.84%
Greater than 0.020	3.63%

An interesting note is the largest change in squareness on a CMM is the YZ axis. This is partially due to the change in the first axis (granite) pitch due to a change in the temperature gradient top to bottom. Granite does not conduct heat well and has an expansion coefficient around 8 um/m/C so it behaves like a bimetallic spring when there is a thermal gradient. It is such a common problem that many newer CMM's actively correct for this by using correction tables and measurements from temperature sensors top and bottom of the granite axis.

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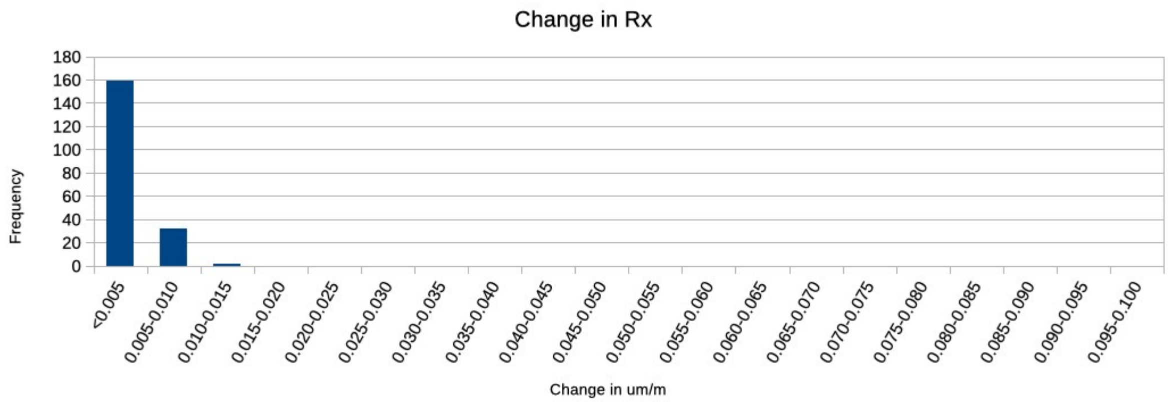
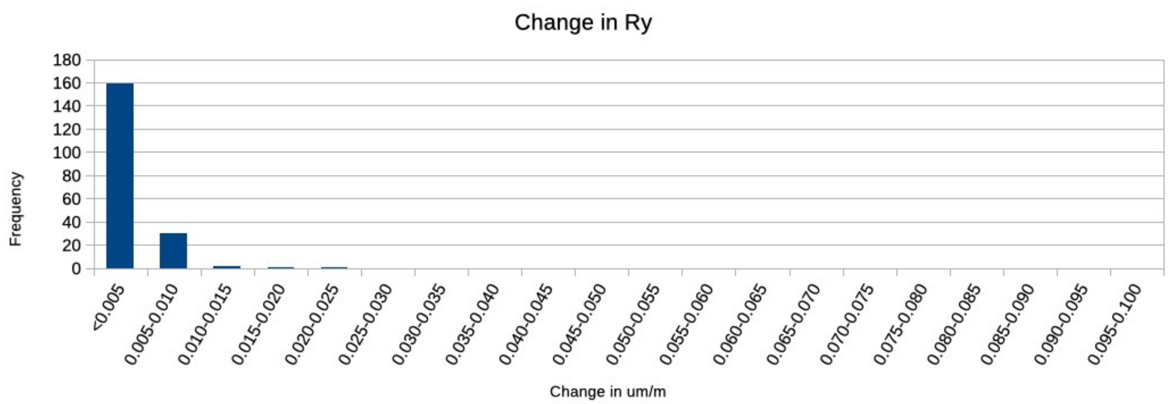
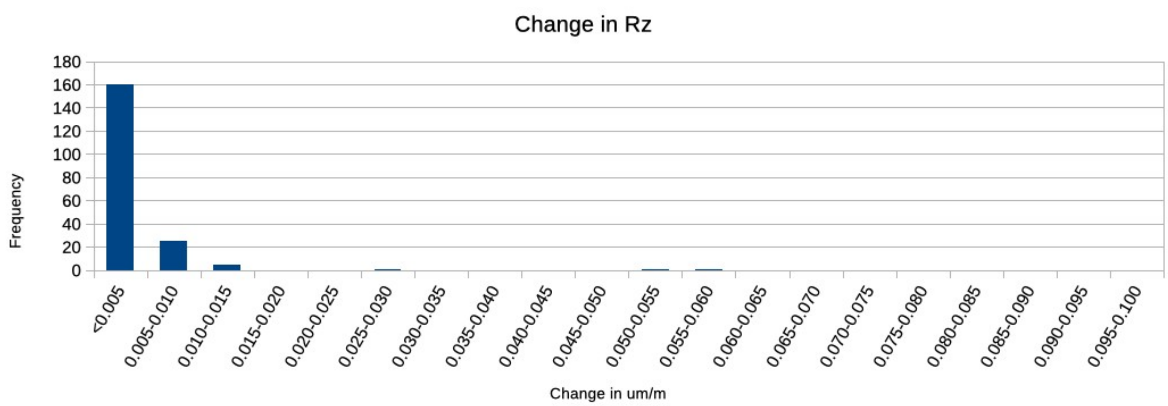
X Axis Changes:







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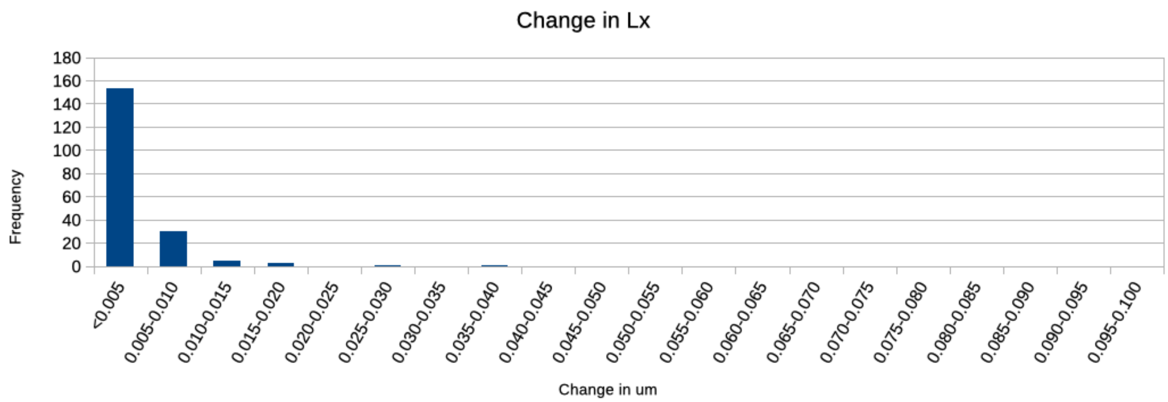
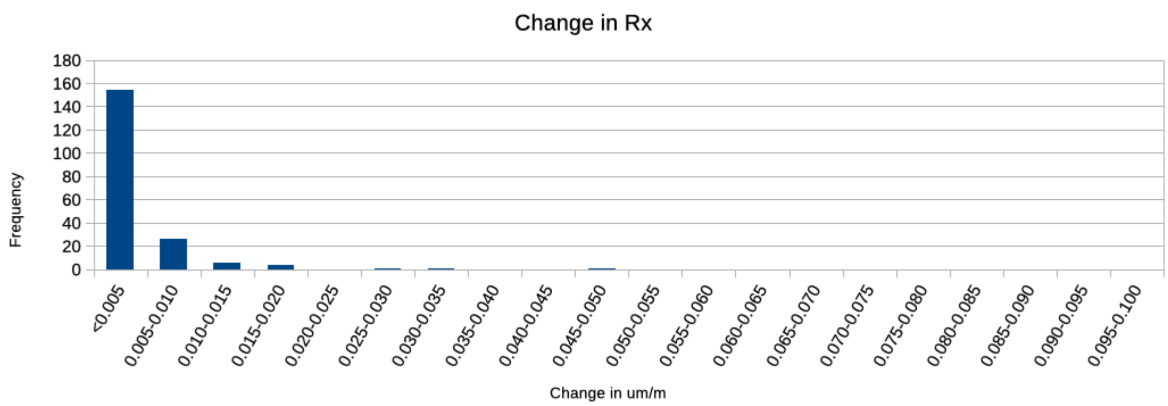
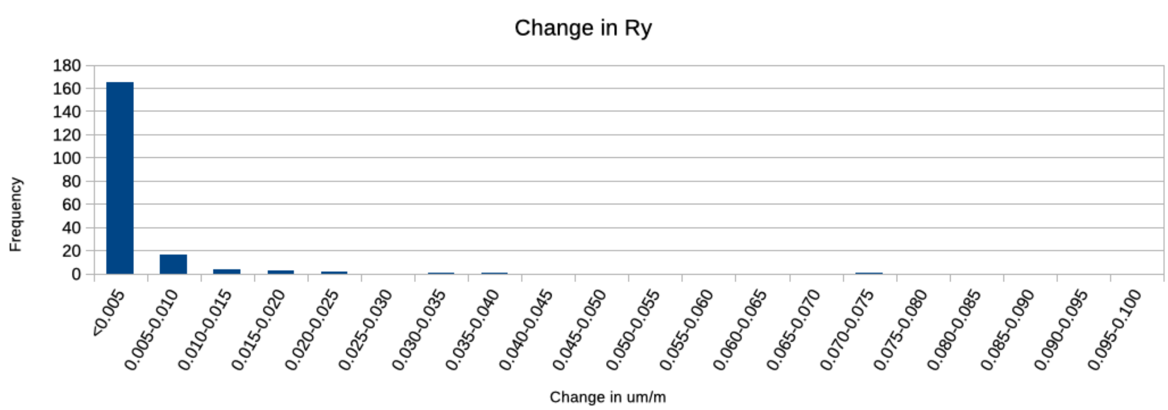
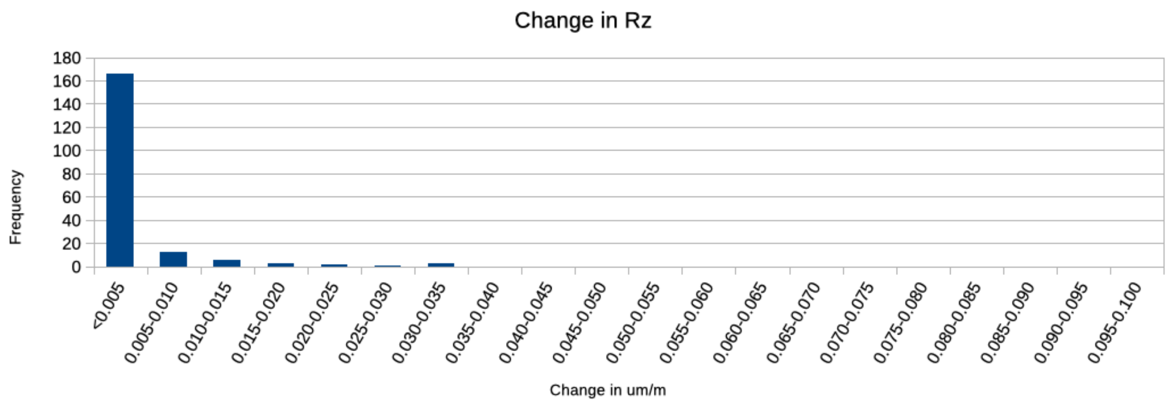
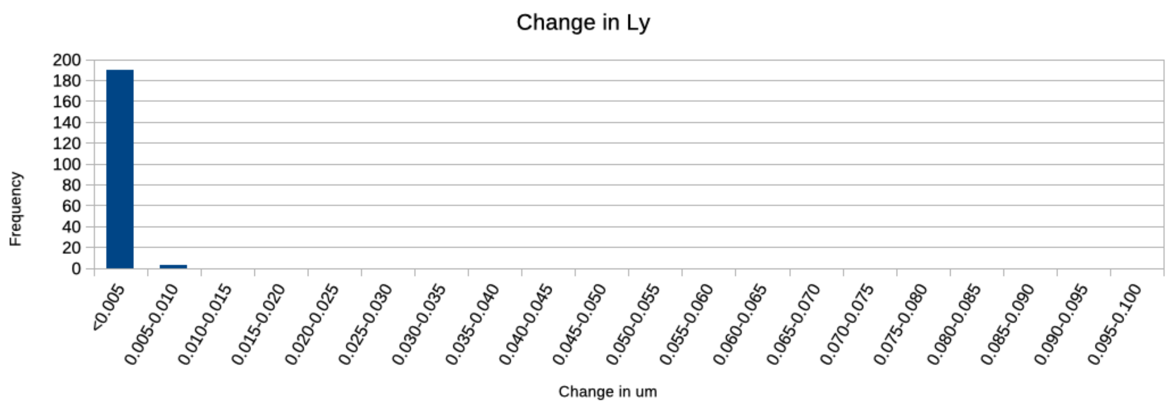


Y Axis Changes:

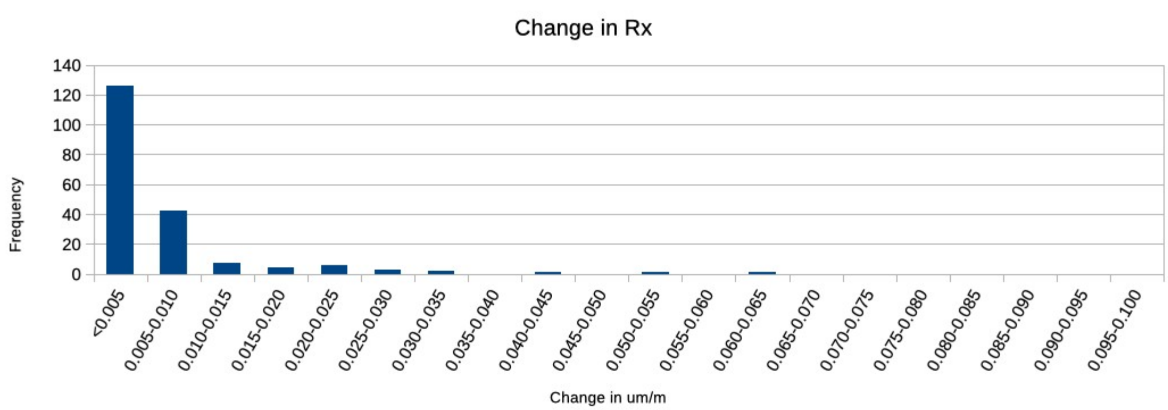


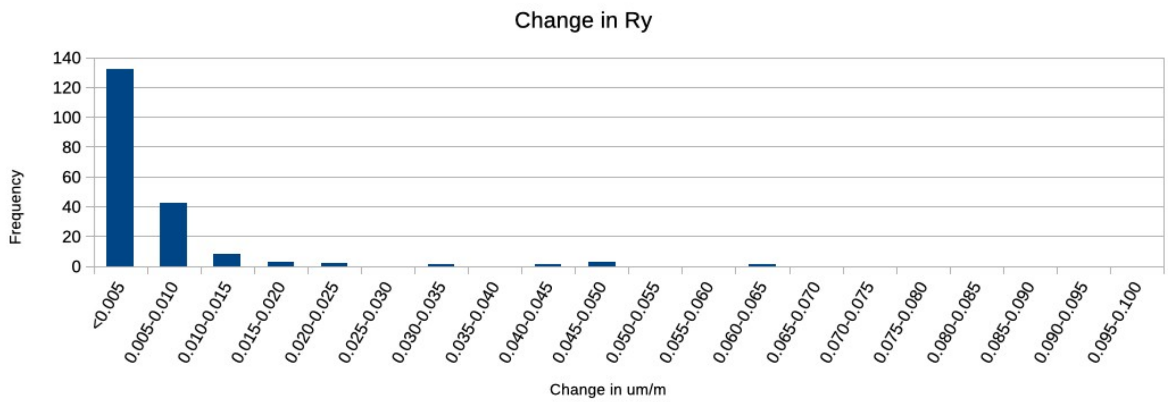


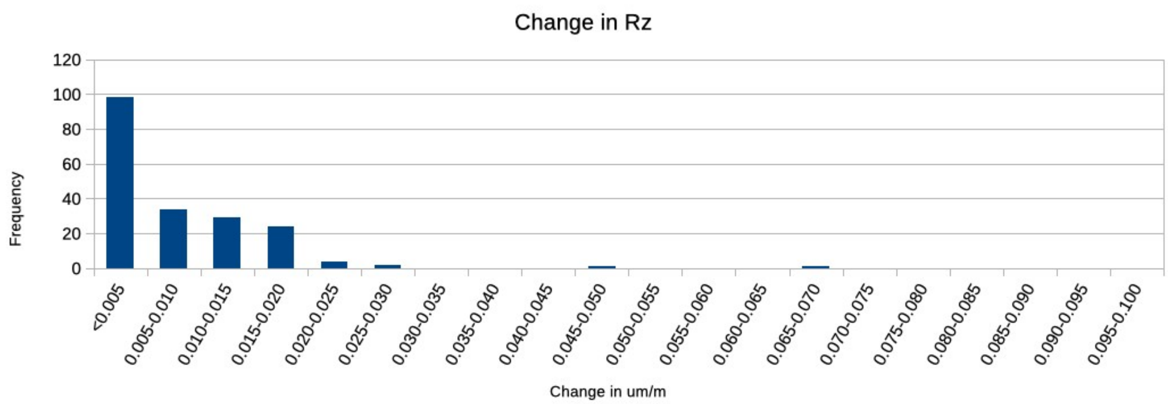


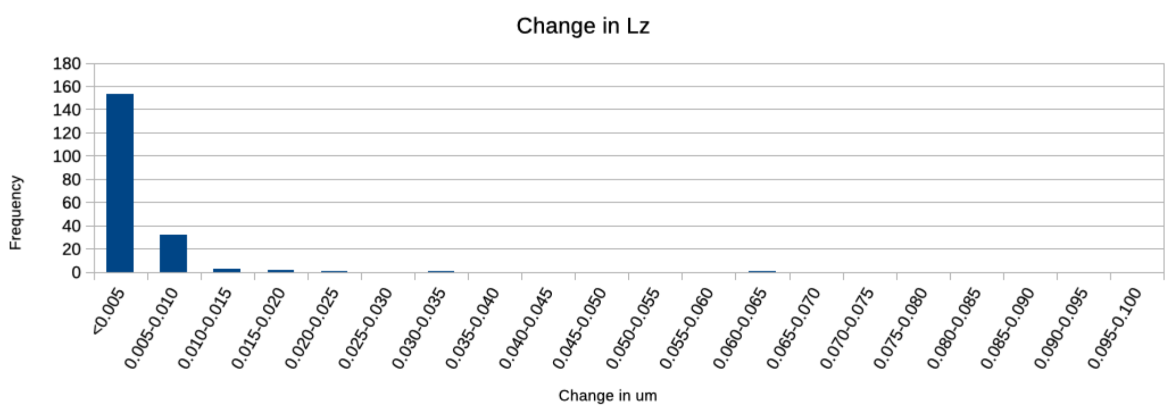


Z Axis Changes:

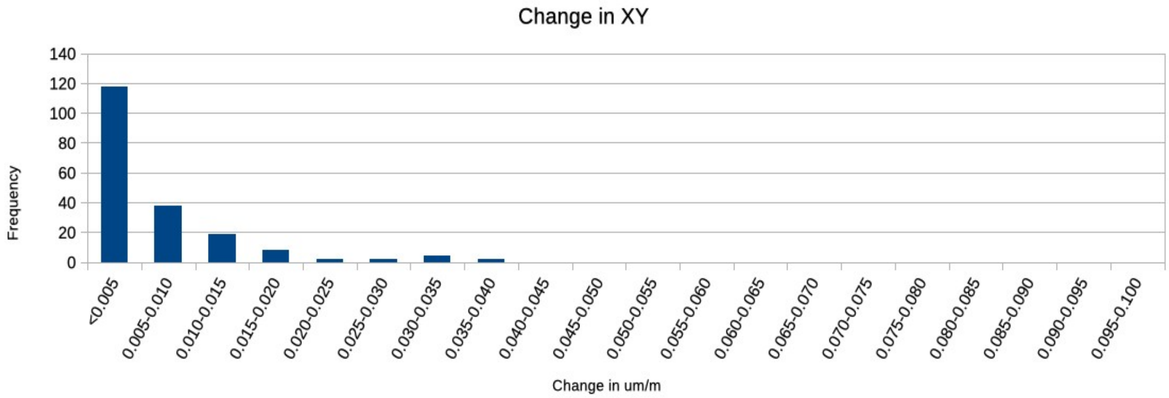


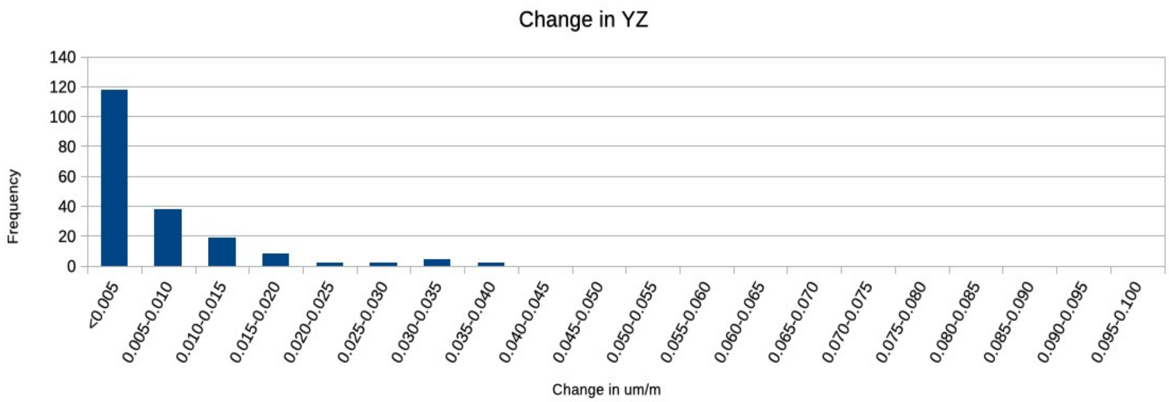

Change in Ry
Frequency
0
20
40
60
80
100
120
140
<0.005
0.005-0.010
0.010-0.015
0.015-0.020
0.020-0.025
0.025-0.030
0.030-0.035
0.035-0.040
0.040-0.045
0.045-0.050
0.050-0.055
0.055-0.060
0.060-0.065
0.065-0.070
0.070-0.075
0.075-0.080
0.080-0.085
0.085-0.090
0.090-0.095
0.095-0.100
Change in um/m

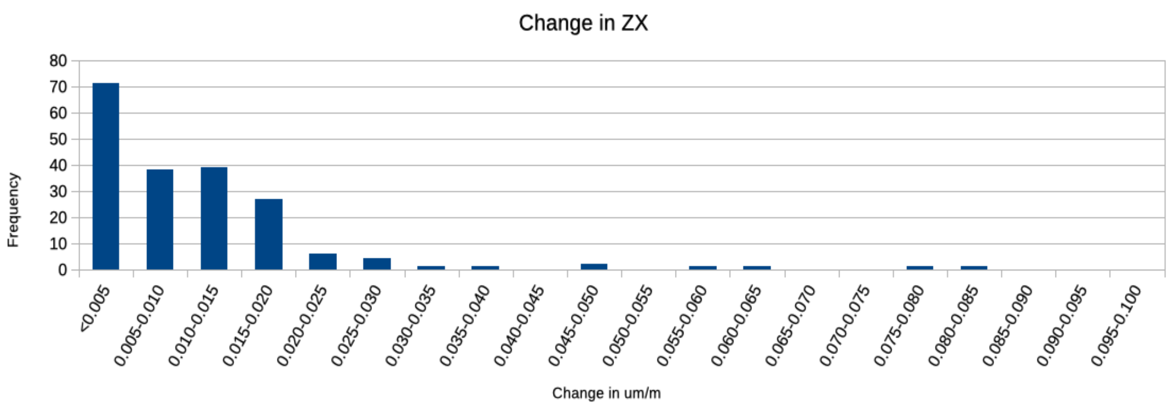

Change in Rz
Frequency
0
20
40
60
80
100
120
<0.005
0.005-0.010
0.010-0.015
0.015-0.020
0.020-0.025
0.025-0.030
0.030-0.035
0.035-0.040
0.040-0.045
0.045-0.050
0.050-0.055
0.055-0.060
0.060-0.065
0.065-0.070
0.070-0.075
0.075-0.080
0.080-0.085
0.085-0.090
0.090-0.095
0.095-0.100
Change in um/m


Change in Lz
Frequency
0
20
40
60
80
100
120
140
160
180
<0.005
0.005-0.010
0.010-0.015
0.015-0.020
0.020-0.025
0.025-0.030
0.030-0.035
0.035-0.040
0.040-0.045
0.045-0.050
0.050-0.055
0.055-0.060
0.060-0.065
0.065-0.070
0.070-0.075
0.075-0.080
0.080-0.085
0.085-0.090
0.090-0.095
0.095-0.100
Change in um

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.

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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	24.35%
Between 0.010 and 0.020	44.04%
Between 0.020 and 0.030	16.58%
Between 0.030 and 0.040	6.22%
Between 0.040 and 0.050	3.63%
Greater than 0.050	5.18%

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.

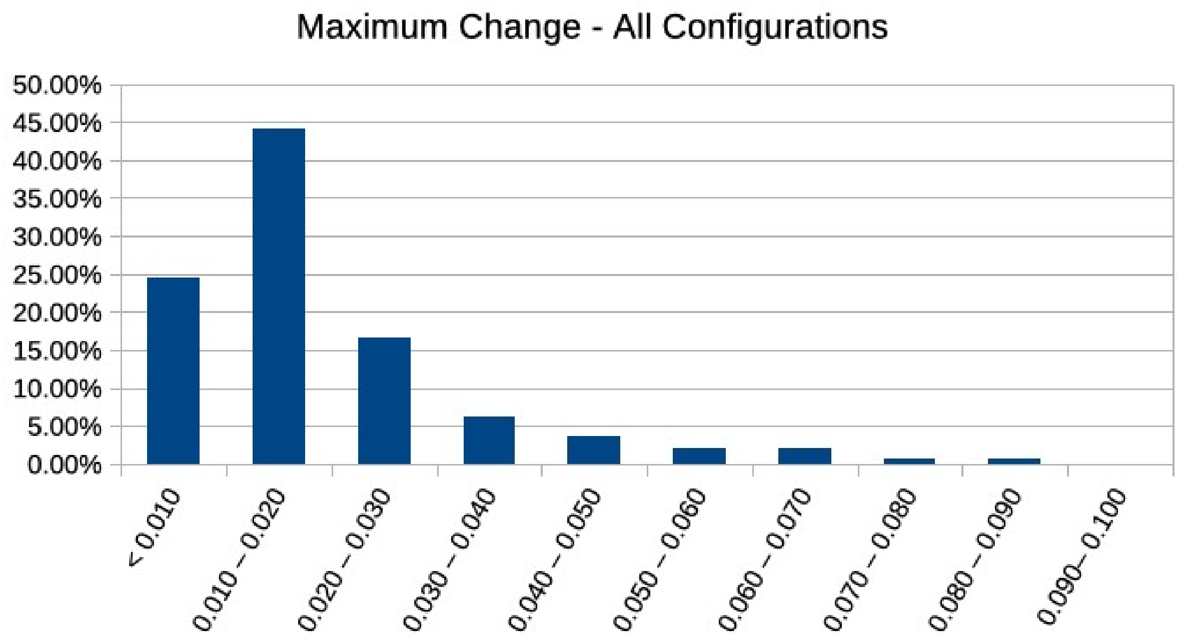

Illustration 5: Maximum change distribution.

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	29.01%
Between 0.010 and 0.020	48.09%
Between 0.020 and 0.030	11.45%
Between 0.030 and 0.040	3.05%
Between 0.040 and 0.050	3.82%
Greater than 0.050	4.58%

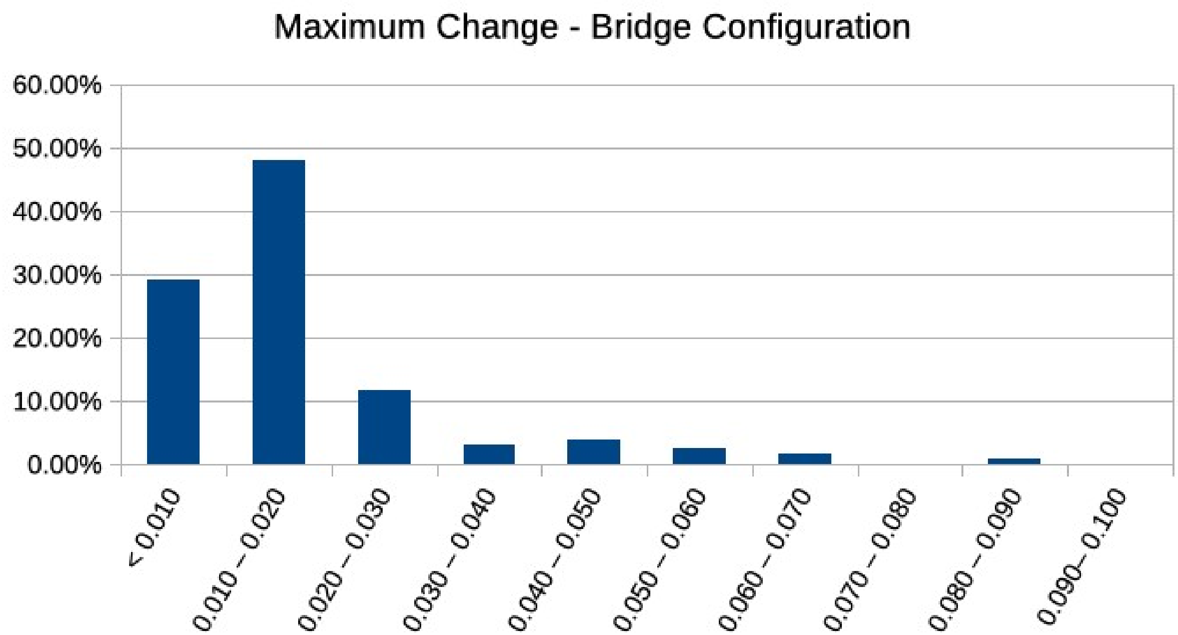

Illustration 6: Maximum change distribution for only bridge machines.

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	14.52%
Between 0.010 and 0.020	35.48%
Between 0.020 and 0.030	27.42%
Between 0.030 and 0.040	12.90%
Between 0.040 and 0.050	3.23%
Greater than 0.050	6.45%

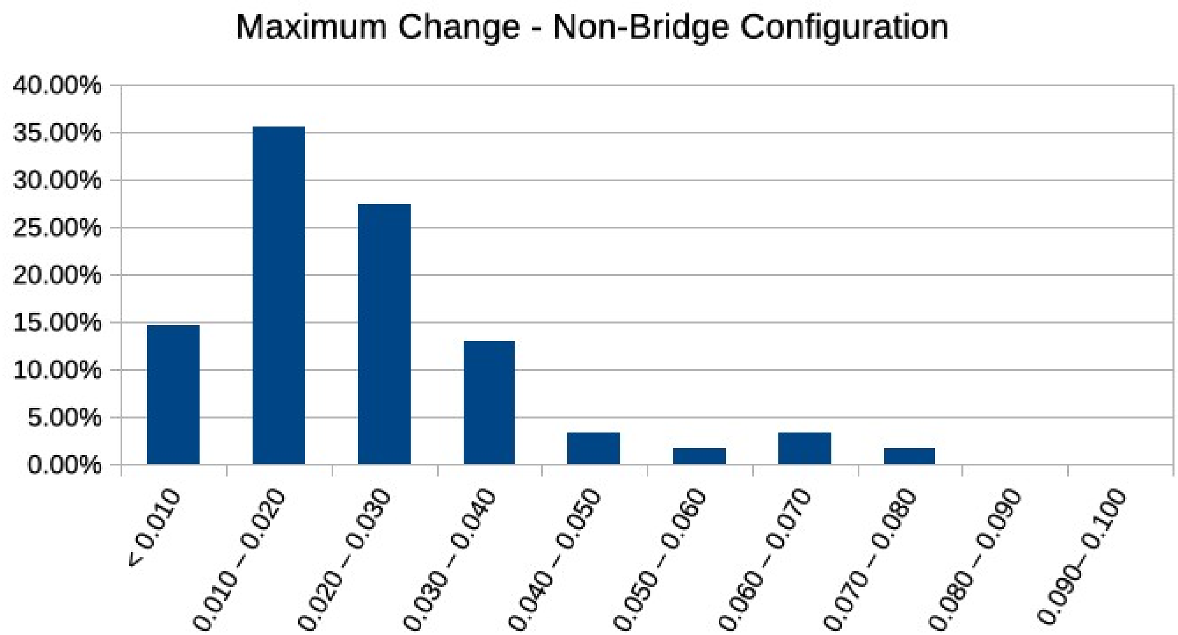

Illustration 7: Maximum change distribution for non-bridge CMM's.

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.

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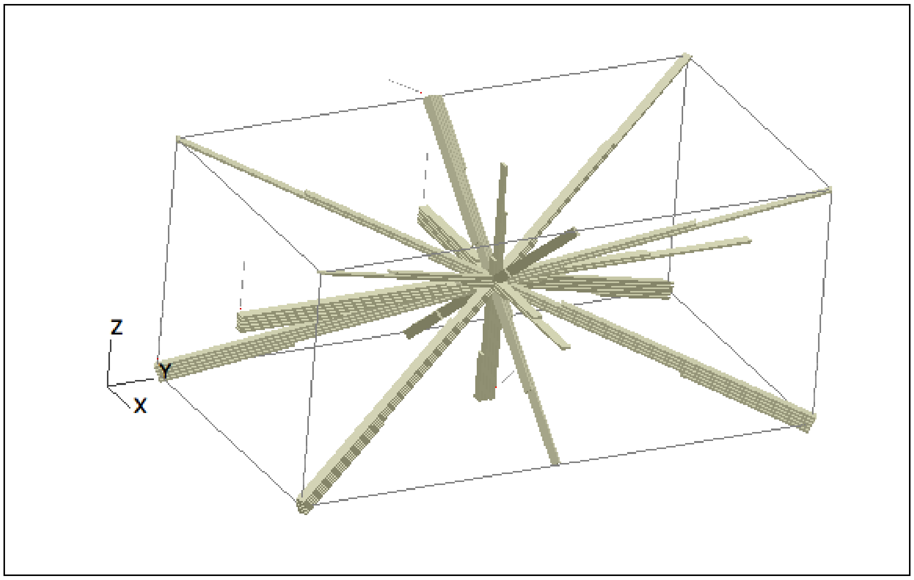

Illustration 8: Performance test measurement pattern following 10360-2.

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 average errors described in table 2:

```
ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            10360-2.1
Probe Offset:    0.0000, 0.0000, -150.0000
Start Position: 1200.0000, 0.0000, -1150.0000
Test Axis:       -0.444749590, 0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
  540.0000   540.0032     0.0032
 1080.0000  1080.0059     0.0059
 1620.0000  1620.0082     0.0082
 2160.0000  2160.0101     0.0101
 2700.0000  2700.0116     0.0116

Max Error:  0.0116
Min Error:  0.0032

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:            10360-2.2
Probe Offset:    0.0000, 0.0000, -150.0000
Start Position: 1200.0000, 2200.0000, -1150.0000
Test Axis:       -0.444749590, -0.815374248, 0.370624658

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

```
  540.0000   540.0055     0.0055
 1080.0000  1080.0101     0.0101
 1620.0000  1620.0140     0.0140
 2160.0000  2160.0171     0.0171
 2700.0000  2700.0194     0.0194

Max Error:  0.0194
Min Error:  0.0055

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:           10360-2.3
Probe Offset:   0.0000, 0.0000, -150.0000
Start Position: 0.0000, 2200.0000, -1150.0000
Test Axis:      0.444749590, -0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
  540.0000   540.0006     0.0006
 1080.0000  1080.0017     0.0017
 1620.0000  1620.0031     0.0031
 2160.0000  2160.0050     0.0050
 2700.0000  2700.0072     0.0072

Max Error:  0.0072
Min Error:  0.0006

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:           10360-2.4
Probe Offset:   0.0000, 0.0000, -150.0000
Start Position: 0.0000, 0.0000, -1150.0000
Test Axis:      0.444749590, 0.815374248, 0.370624658

   Nominal     Actual      Dev
----------------------------------------------------------------------
  540.0000   540.0073     0.0073
 1080.0000  1080.0144     0.0144
 1620.0000  1620.0216     0.0216
 2160.0000  2160.0286     0.0286
 2700.0000  2700.0355     0.0355

Max Error:  0.0355
Min Error:  0.0073

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:           10360-2.5
Probe Offset:   0.0000, 0.0000, -150.0000
Start Position: 0.0000, 1100.0000, -650.0000
Test Axis:      1.000000000, 0.000000000, 0.000000000

   Nominal     Actual      Dev
```



```
------------------------------------------------------------------------
  240.0000   240.0005     0.0005
  480.0000   480.0009     0.0009
  720.0000   720.0014     0.0014
  960.0000   960.0018     0.0018
 1200.0000  1200.0023     0.0023

Max Error:  0.0023
Min Error:  0.0005

ISO 10360-2 Measurement
------------------------------------------------------------------------
Name:            10360-2.6
Probe Offset:    0.0000, 0.0000, -150.0000
Start Position: 600.0000, 0.0000, -650.0000
Test Axis:       0.000000000, 1.000000000, 0.000000000

   Nominal     Actual      Dev
------------------------------------------------------------------------
  440.0000   440.0043     0.0043
  880.0000   880.0085     0.0085
 1320.0000  1320.0128     0.0128
 1760.0000  1760.0171     0.0171
 2200.0000  2200.0214     0.0214

Max Error:  0.0214
Min Error:  0.0043

ISO 10360-2 Measurement
------------------------------------------------------------------------
Name:            10360-2.7
Probe Offset:    0.0000, -150.0000, 0.0000
Start Position: 600.0000, 950.0000, -1000.0000
Test Axis:       0.000000000, 0.000000000, 1.000000000

   Nominal     Actual      Dev
------------------------------------------------------------------------
  200.0000   199.9998    -0.0002
  400.0000   399.9996    -0.0004
  600.0000   599.9995    -0.0005
  800.0000   799.9993    -0.0007
 1000.0000   999.9991    -0.0009

Max Error: -0.0002
Min Error: -0.0009

ISO 10360-2 Measurement
------------------------------------------------------------------------
Name:            10360-2.D1
Probe Offset:    0.0000, -150.0000, 0.0000
Start Position: 0.0000, 950.0000, -1000.0000
Test Axis:       0.768221280, 0.000000000, 0.640184400
```



```
   Nominal     Actual      Dev
----------------------------------------------------------------------
  312.0000   312.0011     0.0011
  624.0000   624.0025     0.0025
  936.0000   936.0041     0.0041
 1248.0000  1248.0061     0.0061
 1560.0000  1560.0082     0.0082

Max Error:  0.0082
Min Error:  0.0011

ISO 10360-2 Measurement
----------------------------------------------------------------------
Name:           10360-2.D2
Probe Offset:   0.0000, -150.0000, 0.0000
Start Position: 0.0000, 950.0000, 0.0000
Test Axis:      0.768221280, 0.000000000, -0.640184400

   Nominal     Actual      Dev
----------------------------------------------------------------------
  312.0000   311.9990    -0.0010
  624.0000   623.9981    -0.0019
  936.0000   935.9973    -0.0027
 1248.0000  1247.9965    -0.0035
 1560.0000  1559.9958    -0.0042

Max Error: -0.0010
Min Error: -0.0042
```

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	240.0004	0.0004
	312	312.001	0.0010
	312	311.9993	-0.0007
	400	399.9997	-0.0003
	440	440.0043	0.0043
	480	480.0008	0.0008
	540	540.0033	0.0033
	540	540.0053	0.0053
	540	540.0006	0.0006
	540	540.0072	0.0072
	600	599.9996	-0.0004
	624	624.0022	0.0022
	624	623.9988	-0.0012
	720	720.0013	0.0013
	800	799.9995	-0.0005
	880	880.0086	0.0086
	936	936.0037	0.0037
	936	935.9982	-0.0018

	960	960.0017	0.0017
	1000	999.9994	-0.0006
	1080	1080.0062	0.0062
	1080	1080.0098	0.0098
	1080	1080.0015	0.0015
	1080	1080.0143	0.0143
	1200	1200.0021	0.0021
	1248	1248.0054	0.0054
	1248	1247.9978	-0.0022
	1320	1320.0129	0.0129
	1560	1560.0075	0.0075
	1560	1559.9974	-0.0026
	1620	1620.0087	0.0087
	1620	1620.0136	0.0136
	1620	1620.0029	0.0029
	1620	1620.0213	0.0213
	1760	1760.0171	0.0171
	2160	2160.0108	0.0108
	2160	2160.0167	0.0167
	2160	2160.0047	0.0047
	2160	2160.0283	0.0283
	2200	2200.0214	0.0214
	2700	2700.0125	0.0125
	2700	2700.019	0.0190
	2700	2700.0069	0.0069
	2700	2700.0353	0.0353
Stats	Min		-0.0026
	Max		0.0353
	Range		0.0379
	Std.Dev		0.0085

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 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   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 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   623.9999    -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	199.9998	-0.0002
	240	240.0005	0.0005
	312	312.0011	0.0011
	312	311.9990	-0.0010
	400	399.9996	-0.0004

	440	440.0043	0.0043
	480	480.0009	0.0009
	540	540.0032	0.0032
	540	540.0055	0.0055
	540	540.0006	0.0006
	540	540.0073	0.0073
	600	599.9995	-0.0005
	624	624.0025	0.0025
	624	623.9981	-0.0019
	720	720.0014	0.0014
	800	799.9993	-0.0007
	880	880.0085	0.0085
	936	936.0041	0.0041
	936	935.9973	-0.0027
	960	960.0018	0.0018
	1000	999.9991	-0.0009
	1080	1080.0059	0.0059
	1080	1080.0101	0.0101
	1080	1080.0017	0.0017
	1080	1080.0144	0.0144
	1200	1200.0023	0.0023
	1248	1248.0061	0.0061
	1248	1247.9965	-0.0035
	1320	1320.0128	0.0128
	1560	1560.0082	0.0082
	1560	1559.9958	-0.0042
	1620	1620.0082	0.0082
	1620	1620.0140	0.0140
	1620	1620.0031	0.0031
	1620	1620.0216	0.0216
	1760	1760.0171	0.0171
	2160	2160.0101	0.0101
	2160	2160.0171	0.0171
	2160	2160.0050	0.0050
	2160	2160.0286	0.0286
	2200	2200.0214	0.0214
	2700	2700.0116	0.0116
	2700	2700.0194	0.0194
	2700	2700.0072	0.0072
	2700	2700.0355	0.0355
Stats	Min		-0.0042
	Max		0.0355
	Range		0.0397
	Std.Dev		0.0087

CMM Performance Stability

Performance Specifications

The specifications for a typical 12.22.10 CMM would be around 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	0.0003	0.0009
540	0.0052		
540	0.0052	0.0021	
600	0.0054		
624	0.0055		
624	0.0055		
720	0.0059		
800	0.0062		
880	0.0065	0.0020	
936	0.0067		
936	0.0067		
960	0.0068		
1000	0.0070		
1080	0.0073		
1080	0.0073	0.0028	0.0039
1080	0.0073		0.0016
1080	0.0073	0.0071	
1200	0.0078		
1248	0.0080		
1248	0.0080		
1320	0.0083	0.0045	0.0009
1560	0.0092		
1560	0.0092		
1620	0.0095		
1620	0.0095	0.0045	0.0060
1620	0.0095		0.0030
1620	0.0095	0.0121	
1760	0.0100	0.0071	0.0023
2160	0.0116		
2160	0.0116	0.0055	0.0072
2160	0.0116		0.0040
2160	0.0116	0.0170	

2200	0.0118	0.0096	0.0036
2700	0.0138		
2700	0.0138	0.0056	0.0075
2700	0.0138		0.0044
2700	0.0138	0.0217	
Stats	Min	0.0003	0.0009
	Max	0.0217	0.0075
	Std.Dev	0.0060	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. Using a traditional laser system and relying on investigative measurements to decide on the update strategy can be very tricky. It may be the 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
2	Sep 28, 2024	Updated results with additional measurement data. Kinematic XYZ transposed to YXZ for better comparisions. Documentation review and update.
3	Sep 29, 2024	Updated measurement results using average errors.
4	Mar 23, 2025	Updated results with additional measurement data.