Performance Testing and Error Hiding

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Introduction

The purpose of this article is to show that it is possible to hide some types of machine errors by correcting unrelated errors. The two standards used to demonstrate this are ISO/IEC 10360-2:2009 and ASME B89.4.1:1997. This article doesn't address the measurement details of either standard outside of the parts that affect the data in this article.

Error hiding is a new concept and was something never considered in the past. It appears to be a problem that only affects CMM calibration using secondary measurement methods and not a direct measurement of the axis parameters. A good example of this might be the use of a ballbar and a select pattern of measurements to update the axis roll instead of using a direct measurement of the axis roll. The measurement from indirect sources is not invalid but may contain contributions from other error sources that bias the end result. Direct measurements of machine specific errors are always preferred for this reason as it is difficult to factor in the impact from other measurement error sources.

Unlike equipment that has a dedicated measurement function a CMM is a universal measurement tool therefore the measurements used to test the machine are not the same as the customers use of the equipment for inspection purposes. Proving the machine can measure X does not guarantee the capability to measure Y. When errors are hidden it is more obvious that showing the machine is capable of measuring X in no way guarantees it can correctly measure Y.

Overview Of Standards

The two common methods used for performance testing of CMM's are quite different. The ASME B89.4.1:1997 ballbar standard uses an artifact with an uncalibrated length focusing on the length repeatability throughout the measurement volume of the CMM. The ISO/IEC 10360-2:2009 standard is the measurement of a calibrated length throughout the volume of the machine using both a zero offset tool and a nominal offset tool of 150 mm.

ASME B89.4.1:1997 Performance Test

The ballbar is the primary equipment used to test the volume of the machine following the ASME B89.4.1:1997 standard. The length of the ballbar is unknown with length repeatability throughout the volume of the machine the item of interest.

The axis scales are calibrated using a separate test (Linear Displacement Accuracy) with a calibrated artifact such as a step gauge or laser. Once the axis scales have been set to measure properly the ballbar is used as a kind of transfer standard to ensure the measurement of length parallel to any axis will repeat when measuring anywhere in the volume of the coordinate measuring machine.

The specification for the ASME B89.4.1:1997 ballbar test is the maximum range of results from all measurements. The specification is usually shown as a single value with an associated nominal ballbar length as shown in the following example but a full length dependent formula has been used in some cases.

$E_{limit} = 0.007/1000$

The longest ballbar length that can be practically used must be slightly shorter than the shortest axis of the CMM (typically 100 mm shorter than the shortest axis). To address this limitation different patterns of ballbar tests are used for different configurations of the CMM axis dimensions.

Performance testing of a CMM using only an uncalibrated ballbar, without testing the axis scales using a certified artifact, does not follow the intent of the ASME B89.4.1:1997 standard and should always be avoided.

ISO/IEC 10360-2:2009 Performance Test

The ISO/IEC 10360-2:2009 performance test involves measuring five lengths along nine specified measurement lines (seven measurement lines for E0 and two measurement lines for E150). There are five measurement lengths along each measurement line repeated three times for a total of 15 unique results. The largest error from the 15 measurement lengths is the reported measurement value for that particular measurement line. For the nine measurement positions a total of 135 length measurements are collected (105 measurements for E0 and 30 measurements for E150).

The specifications for the ISO/IEC 10360-2:2009 test are length dependent and usually expressed as a formula. An example of a typical ISO/IEC 10360-2:2009 specification is shown below:

$E_l MPE = 0.003 + 0.004\,L$ where L is length in meters.

The specifications is a +/- tolerance. Using the example specification from above the tolerance would be +/- 0.007 mm for a measurement length of one meter.

Error Hiding

A feature unique to a CMM class of machine is that there a table of corrections that describe all the known errors in the machine volume. The error correction software can read the correction table and dynamically adjust the reported position of the machine using the information contained in the correction table. In theory, the end result is a perfect machine even if the machine has an imperfect frame.

Error hiding is a realistic problem on a CMM when the effects of one type of error can be fully or partially obscured by the use of other error correction parameters. For a standard error correction table there are 6 correction parameters per axis consisting of 3 linear and 3 angular parameters (18 correction parameters for all axis) and 3 angular correction parameters for squareness. The goal when calibrating a machine is to reduce the reported measuring error to zero so, if updates are done to parameters that do not describe the real machine errors but end up reducing the overall error when running the performance test then some of the errors are hidden.

Technically no error can be hidden. The problem is more from a point of view where a specific set of tests does not reveal specific kinds of machine errors. If the standard used for

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performance testing does not test for specific errors those errors may exist.

This kind of problem highlights why proving the machine can measure X does not guarantee the capability to measure Y.

Evaluation CMM

The simulated CMM used for the error hiding example is a typical sized CMM of 1200, 2200, and 1000 mm. The machine has a large, uncorrected, Y Axis roll of 1 mm/m (1,000 um/m). The configuration of the machine is shown in illustration 1. With the exception of the large Y axis roll error no other errors exist in the simulated CMM.

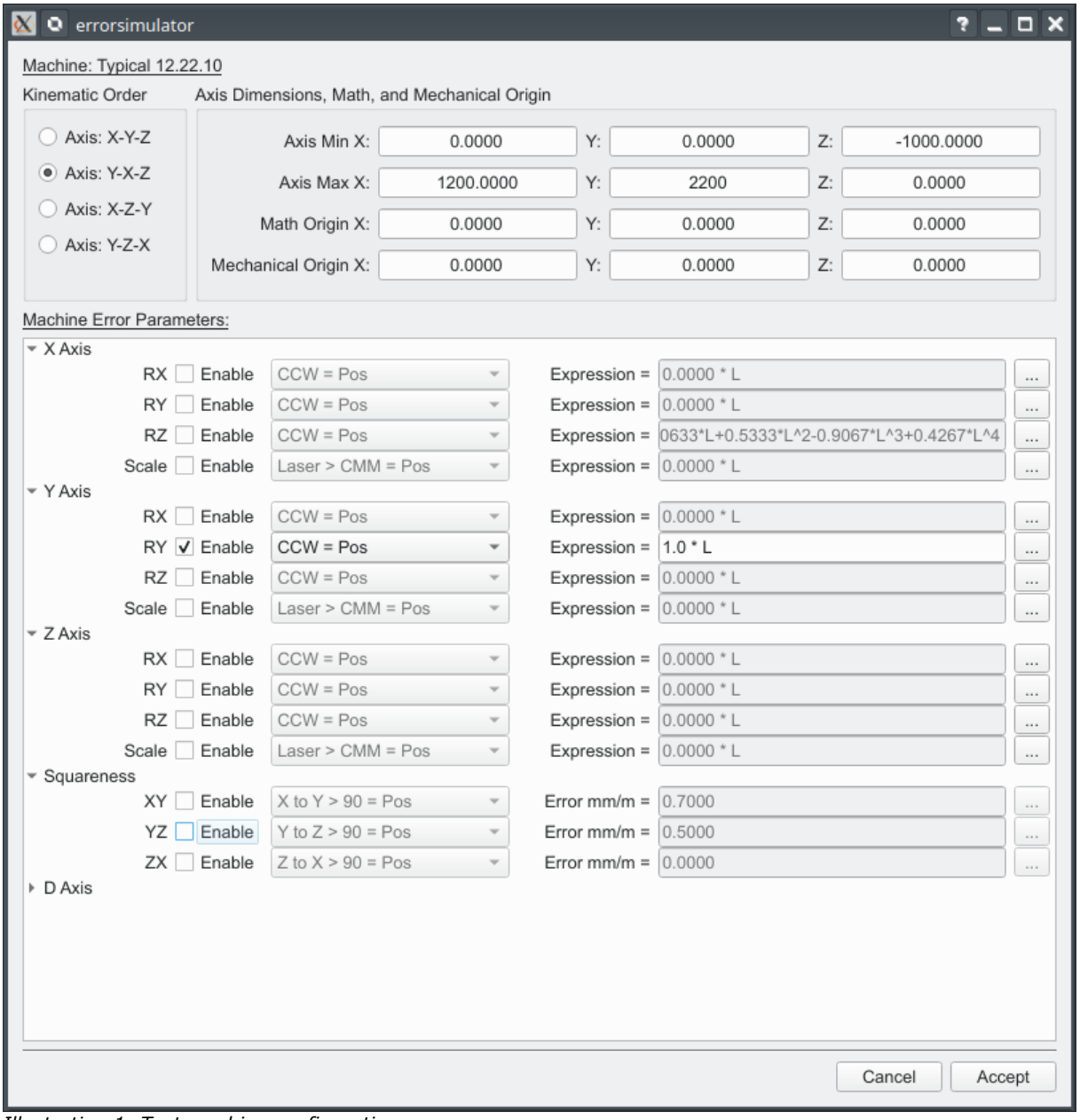

Illustration 1: Test machine configuration.

Measurement Results B89.4.1:1997 BallBar

The recommended measurement pattern for this machine with a single long axis (2.1.1 pattern) is shown in the following illustrations:

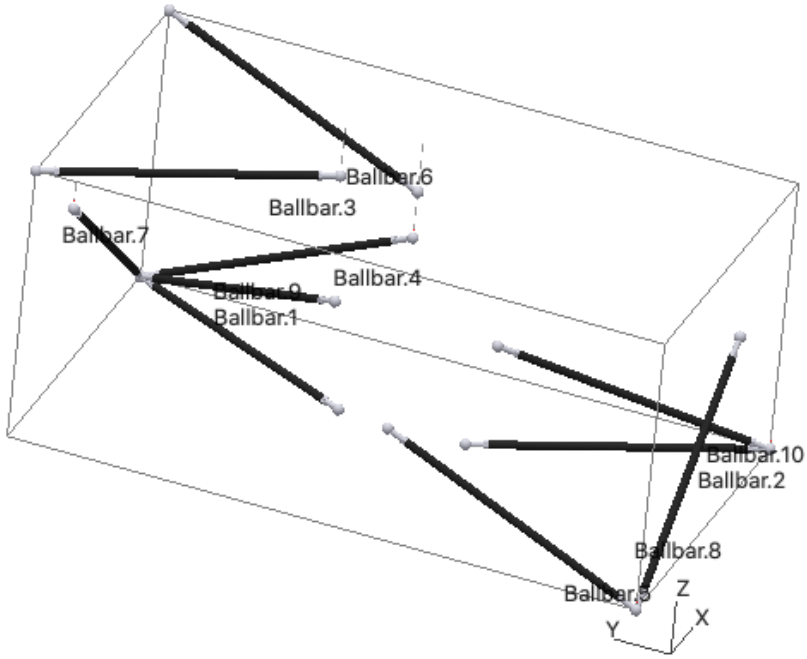

Illustration 2: Ballbar positions 1-10.

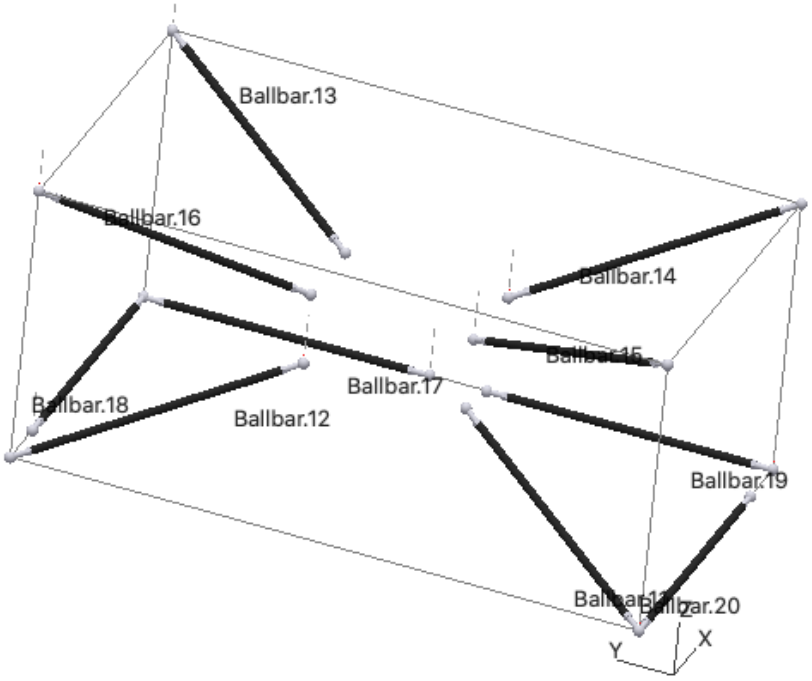

Illustration 3: Ballbar positions 11-20.

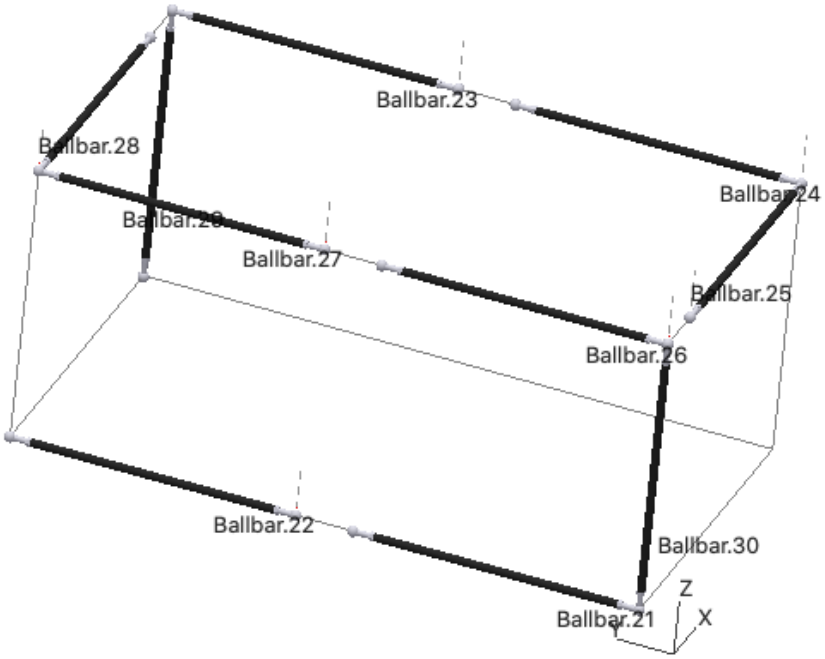

Illustration 4: Ballbar positions 21-30.

ASME B89.4.1:1997 Measurement Results

ASME B89 Ballbar Measurement

Length Min: 999.5173
Length Max: 1000.4842
Length Mean: 1000.0025
Length Range: 0.9669

Name	Length	Sph1.X	Sph1.Y	Sph1.Z	Sph2.X	Sph2.Y	Sph2.Z	Probe X	Probe Y	Probe Z
Ballbar.1	999.517	1197.467	2200.000	-1152.637	719.627	1322.104	-1150.952	0.000	0.000	-150.000
Ballbar.10	1000.055	1200.000	0.000	-1150.000	754.615	815.374	-779.991	0.000	0.000	-150.000
Ballbar.11	999.583	0.000	0.000	-1150.000	444.114	815.374	-779.738	0.000	0.000	-150.000
Ballbar.12	1000.417	443.670	1384.626	-779.990	-2.530	2200.000	-1149.997	0.000	0.000	-150.000
Ballbar.13	999.583	1199.667	2200.000	-152.640	754.529	1384.626	-521.670	0.000	0.000	-150.000
Ballbar.14	1000.417	754.826	815.374	-521.240	1200.000	0.000	-150.000	0.000	0.000	-150.000
Ballbar.15	999.946	444.325	815.374	-520.987	0.000	0.000	-150.000	0.000	0.000	-150.000
Ballbar.16	1000.054	-0.330	2200.000	-150.000	444.028	1384.626	-521.240	0.000	0.000	-150.000
Ballbar.17	1000.001	1198.619	1200.000	-1151.439	1197.467	2200.000	-1152.637	0.000	0.000	-150.000
Ballbar.18	1000.000	197.470	2200.000	-1150.437	1197.467	2200.000	-1152.637	0.000	0.000	-150.000
Ballbar.19	1000.001	1200.000	0.000	-1150.000	1198.849	1000.000	-1151.199	0.000	0.000	-150.000
Ballbar.2	1000.484	1200.000	0.000	-1150.000	720.138	877.896	-1150.633	0.000	0.000	-150.000
Ballbar.20	1000.000	0.000	0.000	-1150.000	1000.000	0.000	-1150.000	0.000	0.000	-150.000
Ballbar.21	1000.001	0.000	0.000	-1150.000	-1.150	1000.000	-1149.999	0.000	0.000	-150.000
Ballbar.22	1000.001	-1.380	1200.000	-1149.999	-2.530	2200.000	-1149.997	0.000	0.000	-150.000
Ballbar.23	1000.001	1199.819	1200.000	-151.440	1199.667	2200.000	-152.640	0.000	0.000	-150.000
Ballbar.24	1000.001	1200.000	0.000	-150.000	1199.849	1000.000	-151.200	0.000	0.000	-150.000
Ballbar.25	1000.000	200.000	0.000	-150.000	1200.000	0.000	-150.000	0.000	0.000	-150.000
Ballbar.26	1000.000	0.000	0.000	-150.000	-0.150	1000.000	-150.000	0.000	0.000	-150.000
Ballbar.27	1000.000	-0.180	1200.000	-150.000	-0.330	2200.000	-150.000	0.000	0.000	-150.000
Ballbar.28	1000.000	-0.330	2200.000	-150.000	999.668	2200.000	-152.200	0.000	0.000	-150.000
Ballbar.29	1000.000	1197.467	2200.000	-1152.637	1199.667	2200.000	-152.640	0.000	0.000	-150.000
Ballbar.3	1000.063	478.653	1322.104	-150.633	-0.330	2200.000	-150.000	0.000	0.000	-150.000

```
Ballbar.30 1000.000 0.000 0.000 -1150.000 0.000 0.000 -150.000 0.000 0.000 -150.000
Ballbar.4 1000.453 1199.050 1289.634 -737.744 1197.467 2200.000 -1152.637 0.000 0.000 -150.000
Ballbar.5 1000.000 0.000 0.000 -1150.000 -0.670 910.367 -736.197 0.000 0.000 -150.000
Ballbar.6 999.549 1199.272 1289.634 -565.350 1199.667 2200.000 -152.640 0.000 0.000 -150.000
Ballbar.7 1000.000 430.656 2200.000 -510.764 1197.467 2200.000 -1152.637 0.000 0.000 -150.000
Ballbar.8 1000.000 0.000 0.000 -1150.000 768.221 0.000 -509.816 0.000 0.000 -150.000
Ballbar.9 999.946 1197.467 2200.000 -1152.637 754.171 1384.626 -780.420 0.000 0.000 -150.000
```

Measurement Results ISO/IEC 10360-2:2009

The measurement pattern used for the 10360-2 is shown in the following illustrations:

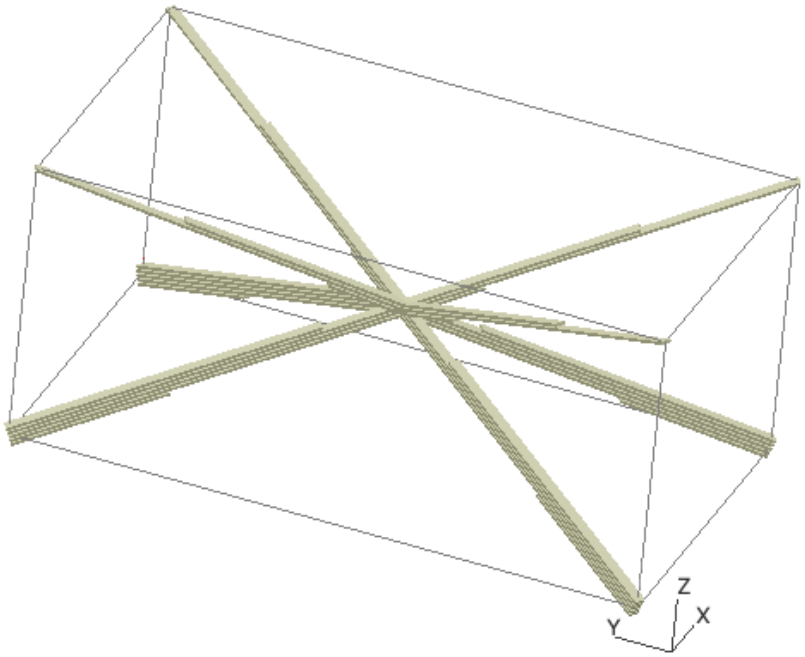

Illustration 5: 10360-2 positions 1-4.

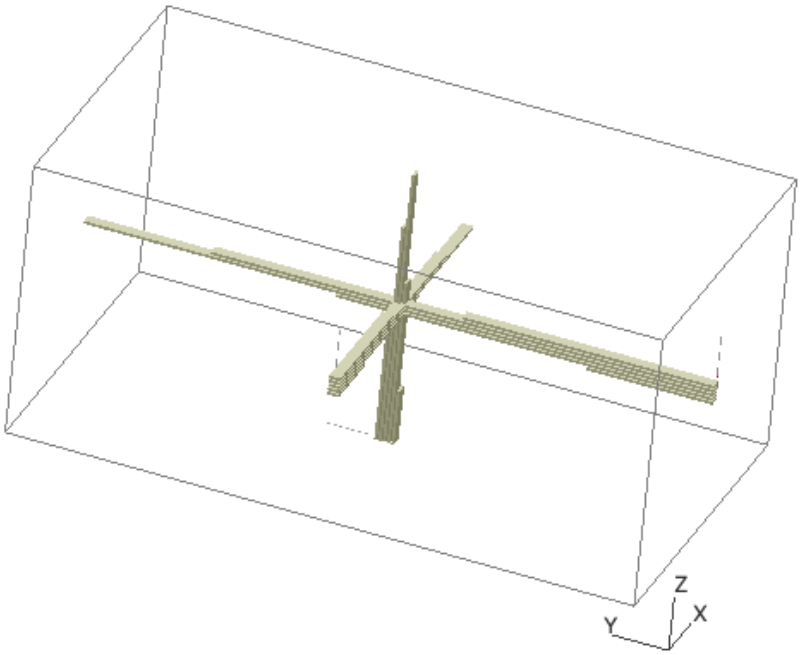

Illustration 6: 10360-2 positions 5-7.

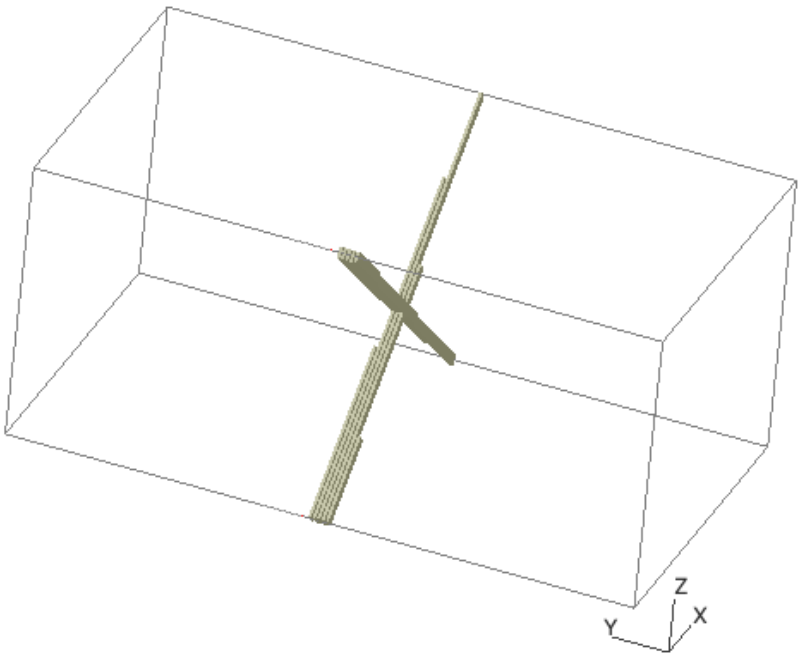

Illustration 7: 10360-2 positions D1 and D2.

ISO/IEC 10360-2:2009 Measurement Results

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 540.0295 0.0295
1080.0000 1080.0591 0.0591
1620.0000 1620.0886 0.0886
2160.0000 2160.1179 0.1179
2700.0000 2700.1470 0.1470

Max Error: 0.1470
Min Error: 0.0295

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 539.9707 -0.0293
1080.0000 1079.9416 -0.0584
1620.0000 1619.9123 -0.0877
2160.0000 2159.8829 -0.1171
2700.0000 2699.8533 -0.1467

Max Error: -0.0293
Min Error: -0.1467

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 540.2251 0.2251
1080.0000 1080.4503 0.4503
1620.0000 1620.6756 0.6756
2160.0000 2160.9008 0.9008
2700.0000 2701.1259 1.1259

Max Error: 1.1259
Min Error: 0.2251

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 539.7747 -0.2253
1080.0000 1079.5495 -0.4505

1620.0000 1619.3244 -0.6756
2160.0000 2159.0992 -0.9008
2700.0000 2698.8739 -1.1261

Max Error: -0.2253
Min Error: -1.1261

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 240.0000 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: 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 440.0002 0.0002
880.0000 880.0003 0.0003
1320.0000 1320.0005 0.0005
1760.0000 1760.0007 0.0007
2200.0000 2200.0009 0.0009

Max Error: 0.0009
Min Error: 0.0002

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 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: 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 312.0000 -0.0000
624.0000 624.0000 -0.0000
936.0000 936.0000 -0.0000
1248.0000 1248.0000 -0.0000
1560.0000 1560.0000 -0.0000

Max Error: -0.0000
Min Error: -0.0000

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 312.0000 -0.0000
624.0000 624.0000 -0.0000
936.0000 936.0000 -0.0000
1248.0000 1248.0000 -0.0000
1560.0000 1560.0000 0.0000

Max Error: 0.0000
Min Error: -0.0000
```

ASME B89.4.1:1997 Measurement Results With Squareness Corrections

Using only squareness corrections the following results were achievable using the same two test methods. The Y axis roll error still exists but it has been partially hidden by the squareness corrections. The measurement pattern has not changed from the initial pattern used.

Compensation Map with Squareness Corrections:

Map compensation data with Y axis roll error and squareness corrections:

```
Selected Machine: Typical 12.22.10

Squareness
-------------------------------------------------------------------------------
YZ: 0.6730 mm/m
XY: 0.7070 mm/m
ZX: 0.0000 mm/m

X Axis Data.  Linear units are mm, angular units are mm/m.
-------------------------------------------------------------------------------
     Pos          Lx          Ly          Lz          Rx          Ry          Rz
-------------------------------------------------------------------------------
       0.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     100.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     200.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     300.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     400.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     500.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     600.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     700.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     800.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
     900.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
    1000.0      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
```

1100.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1200.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Y Axis Data. Linear units are mm, angular units are mm/m.

Pos	Lx	Ly	Lz	Rx	Ry	Rz
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0	0.0000	0.0000	0.0000	0.0000	0.1000	0.0000
200.0	0.0000	0.0000	0.0000	0.0000	0.2000	0.0000
300.0	0.0000	0.0000	0.0000	0.0000	0.3000	0.0000
400.0	0.0000	0.0000	0.0000	0.0000	0.4000	0.0000
500.0	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000
600.0	0.0000	0.0000	0.0000	0.0000	0.6000	0.0000
700.0	0.0000	0.0000	0.0000	0.0000	0.7000	0.0000
800.0	0.0000	0.0000	0.0000	0.0000	0.8000	0.0000
900.0	0.0000	0.0000	0.0000	0.0000	0.9000	0.0000
1000.0	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
1100.0	0.0000	0.0000	0.0000	0.0000	1.1000	0.0000
1200.0	0.0000	0.0000	0.0000	0.0000	1.2000	0.0000
1300.0	0.0000	0.0000	0.0000	0.0000	1.3000	0.0000
1400.0	0.0000	0.0000	0.0000	0.0000	1.4000	0.0000
1500.0	0.0000	0.0000	0.0000	0.0000	1.5000	0.0000
1600.0	0.0000	0.0000	0.0000	0.0000	1.6000	0.0000
1700.0	0.0000	0.0000	0.0000	0.0000	1.7000	0.0000
1800.0	0.0000	0.0000	0.0000	0.0000	1.8000	0.0000
1900.0	0.0000	0.0000	0.0000	0.0000	1.9000	0.0000
2000.0	0.0000	0.0000	0.0000	0.0000	2.0000	0.0000
2100.0	0.0000	0.0000	0.0000	0.0000	2.1000	0.0000
2200.0	0.0000	0.0000	0.0000	0.0000	2.2000	0.0000

Z Axis Data. Linear units are mm, angular units are mm/m.

Pos	Lx	Ly	Lz	Rx	Ry	Rz
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-100.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-200.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-300.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-400.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-500.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-600.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-700.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-800.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-900.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-1000.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Measurement Results with Y Roll Error and Squareness Corrections:

ASME B89 Ballbar Measurement

Length Min: 999.7659
Length Max: 1000.2539
Length Mean: 1000.0011
Length Range: 0.4880

Name	Length	Sph1.X	Sph1.Y	Sph1.Z	Sph2.X	Sph2.Y	Sph2.Z	Probe X	Probe Y	Probe Z
Ballbar.1	999.815	1197.467	2200.175	-1152.637	719.627	1321.941	-1150.952	0.000	0.000	-150.000
Ballbar.10	1000.002	1200.000	0.175	-1150.000	754.615	815.485	-779.991	0.000	0.000	-150.000
Ballbar.11	1000.043	0.000	-0.673	-1150.000	444.114	815.265	-779.738	0.000	0.000	-150.000
Ballbar.12	999.958	443.670	1384.517	-779.990	-2.530	2199.327	-1149.997	0.000	0.000	-150.000
Ballbar.13	1000.043	1199.667	2200.848	-152.640	754.529	1384.910	-521.670	0.000	0.000	-150.000
Ballbar.14	999.958	754.826	815.659	-521.240	1200.000	0.848	-150.000	0.000	0.000	-150.000
Ballbar.15	999.999	444.325	815.439	-520.987	0.000	0.000	-150.000	0.000	0.000	-150.000
Ballbar.16	1000.001	-0.330	2200.000	-150.000	444.028	1384.691	-521.240	0.000	0.000	-150.000

```
Ballbar.17 1000.001 1198.619 1200.175 -1151.439 1197.467 2200.175 -1152.637 0.000 0.000 -150.000
Ballbar.18 1000.000 197.470 2199.468 -1150.437 1197.467 2200.175 -1152.637 0.000 0.000 -150.000
Ballbar.19 1000.001 1200.000 0.175 -1150.000 1198.849 1000.175 -1151.199 0.000 0.000 -150.000
Ballbar.2 1000.187 1200.000 0.175 -1150.000 720.138 877.732 -1150.633 0.000 0.000 -150.000
Ballbar.20 1000.000 0.000 -0.673 -1150.000 1000.000 0.034 -1150.000 0.000 0.000 -150.000
Ballbar.21 1000.001 0.000 -0.673 -1150.000 -1.150 999.327 -1149.999 0.000 0.000 -150.000
Ballbar.22 1000.001 -1.380 1199.327 -1149.999 -2.530 2199.327 -1149.997 0.000 0.000 -150.000
Ballbar.23 1000.001 1199.819 1200.848 -151.440 1199.667 2200.848 -152.640 0.000 0.000 -150.000
Ballbar.24 1000.001 1200.000 0.848 -150.000 1199.849 1000.848 -151.200 0.000 0.000 -150.000
Ballbar.25 1000.000 200.000 0.141 -150.000 1200.000 0.848 -150.000 0.000 0.000 -150.000
Ballbar.26 1000.000 0.000 0.000 -150.000 -0.150 1000.000 -150.000 0.000 0.000 -150.000
Ballbar.27 1000.000 -0.180 1200.000 -150.000 -0.330 2200.000 -150.000 0.000 0.000 -150.000
Ballbar.28 1000.000 -0.330 2200.000 -150.000 999.668 2200.707 -152.200 0.000 0.000 -150.000
Ballbar.29 1000.000 1197.467 2200.175 -1152.637 1199.667 2200.848 -152.640 0.000 0.000 -150.000
Ballbar.3 999.766 478.653 1322.443 -150.633 -0.330 2200.000 -150.000 0.000 0.000 -150.000
Ballbar.30 1000.000 0.000 -0.673 -1150.000 0.000 0.000 -150.000 0.000 0.000 -150.000
Ballbar.4 1000.200 1199.050 1290.087 -737.744 1197.467 2200.175 -1152.637 0.000 0.000 -150.000
Ballbar.5 1000.254 0.000 -0.673 -1150.000 -0.670 909.972 -736.197 0.000 0.000 -150.000
Ballbar.6 999.802 1199.272 1290.203 -565.350 1199.667 2200.848 -152.640 0.000 0.000 -150.000
Ballbar.7 1000.000 430.656 2200.063 -510.764 1197.467 2200.175 -1152.637 0.000 0.000 -150.000
Ballbar.8 1000.001 0.000 -0.673 -1150.000 768.221 0.301 -509.816 0.000 0.000 -150.000
Ballbar.9 999.999 1197.467 2200.175 -1152.637 754.171 1384.736 -780.420 0.000 0.000 -150.000
```

ISO/IEC 10360-2 Measurement Results With Squareness Corrections

Using only squareness corrections the following results were achievable. The Y axis roll error still exists but it has been partially hidden by the squareness corrections. The measurement pattern has not changed from the initial pattern used.

Squareness Corrections:

Map compensation data with Y axis roll error and squareness corrections:

```
Selected Machine: Typical 12.22.10

Squareness
------------------------------------------------------------------------------
YZ: 0.5990 mm/m
XY: 0.6510 mm/m
ZX: 0.0000 mm/m

X Axis Data.  Linear units are mm, angular units are mm/m.
------------------------------------------------------------------------------
     Pos         Lx         Ly         Lz         Rx         Ry         Rz
------------------------------------------------------------------------------
       0.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     100.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     200.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     300.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     400.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     500.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     600.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     700.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     800.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     900.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
    1000.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
    1100.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
    1200.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000

Y Axis Data.  Linear units are mm, angular units are mm/m.
------------------------------------------------------------------------------
     Pos         Lx         Ly         Lz         Rx         Ry         Rz
------------------------------------------------------------------------------
       0.0     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
```

100.0	0.0000	0.0000	0.0000	0.0000	0.1000	0.0000
200.0	0.0000	0.0000	0.0000	0.0000	0.2000	0.0000
300.0	0.0000	0.0000	0.0000	0.0000	0.3000	0.0000
400.0	0.0000	0.0000	0.0000	0.0000	0.4000	0.0000
500.0	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000
600.0	0.0000	0.0000	0.0000	0.0000	0.6000	0.0000
700.0	0.0000	0.0000	0.0000	0.0000	0.7000	0.0000
800.0	0.0000	0.0000	0.0000	0.0000	0.8000	0.0000
900.0	0.0000	0.0000	0.0000	0.0000	0.9000	0.0000
1000.0	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
1100.0	0.0000	0.0000	0.0000	0.0000	1.1000	0.0000
1200.0	0.0000	0.0000	0.0000	0.0000	1.2000	0.0000
1300.0	0.0000	0.0000	0.0000	0.0000	1.3000	0.0000
1400.0	0.0000	0.0000	0.0000	0.0000	1.4000	0.0000
1500.0	0.0000	0.0000	0.0000	0.0000	1.5000	0.0000
1600.0	0.0000	0.0000	0.0000	0.0000	1.6000	0.0000
1700.0	0.0000	0.0000	0.0000	0.0000	1.7000	0.0000
1800.0	0.0000	0.0000	0.0000	0.0000	1.8000	0.0000
1900.0	0.0000	0.0000	0.0000	0.0000	1.9000	0.0000
2000.0	0.0000	0.0000	0.0000	0.0000	2.0000	0.0000
2100.0	0.0000	0.0000	0.0000	0.0000	2.1000	0.0000
2200.0	0.0000	0.0000	0.0000	0.0000	2.2000	0.0000

Z Axis Data. Linear units are mm, angular units are mm/m.

Pos	Lx	Ly	Lz	Rx	Ry	Rz
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-100.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-200.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-300.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-400.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-500.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-600.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-700.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-800.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-900.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-1000.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Measurement Results with Y Roll Error and Squareness Corrections:

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	539.9998	-0.0002
1080.0000	1079.9996	-0.0004
1620.0000	1619.9994	-0.0006
2160.0000	2159.9990	-0.0010
2700.0000	2699.9984	-0.0016

Max Error: -0.0002
Min Error: -0.0016

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   540.0005     0.0005
 1080.0000  1080.0010     0.0010
 1620.0000  1620.0015     0.0015
 2160.0000  2160.0019     0.0019
 2700.0000  2700.0020     0.0020

Max Error:  0.0020
Min Error:  0.0005

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   540.0000    -0.0000
 1080.0000  1080.0001     0.0001
 1620.0000  1620.0002     0.0002
 2160.0000  2160.0004     0.0004
 2700.0000  2700.0003     0.0003

Max Error:  0.0004
Min Error: -0.0000

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   540.0000     0.0000
 1080.0000  1080.0002     0.0002
 1620.0000  1620.0004     0.0004
 2160.0000  2160.0006     0.0006
 2700.0000  2700.0007     0.0007

Max Error:  0.0007
Min Error:  0.0000

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   240.0001     0.0001
  480.0000   480.0001     0.0001
  720.0000   720.0002     0.0002
  960.0000   960.0002     0.0002
 1200.0000  1200.0003     0.0003

Max Error:  0.0003
Min Error:  0.0001

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	440.0002	0.0002
880.0000	880.0003	0.0003
1320.0000	1320.0005	0.0005
1760.0000	1760.0007	0.0007
2200.0000	2200.0009	0.0009

Max Error: 0.0009
Min Error: 0.0002

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	200.0000	0.0000
400.0000	400.0001	0.0001
600.0000	600.0001	0.0001
800.0000	800.0001	0.0001
1000.0000	1000.0002	0.0002

Max Error: 0.0002
Min Error: 0.0000

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	312.0001	0.0001
624.0000	624.0002	0.0002
936.0000	936.0004	0.0004
1248.0000	1248.0005	0.0005
1560.0000	1560.0006	0.0006

Max Error: 0.0006
Min Error: 0.0001

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	312.0000	0.0000
624.0000	624.0000	0.0000
936.0000	936.0000	0.0000
1248.0000	1248.0000	0.0000
1560.0000	1560.0000	0.0000

Max Error: 0.0000
Min Error: 0.0000

Analysis Of Performance Testing

The following summarizes what was found from hiding the Y axis roll error with squareness corrections:

Performance Standard	*Results From Only the Machine Error*	*Results From Machine Error With Squareness Correction*
ASME B89.4.1:1997	0.9669 mm	0.4880 mm
ISO/IEC 10360-2:2009	1.1261 mm	0.0020 mm

Using only squareness corrections it was possible to reduce the reported error to 50% of the original error for the ASME B89.4.1:1997 ballbar tests and to 0.2% of the original error for the ISO/IEC 10360-2 tests. The symmetrical nature of the 10360-2 tests makes it easier to reduce the measured errors to near zero as compared to the ASME B89.4.1:1997 ballbar tests.

Calculation of Ideal Squareness Corrections

The ideal squareness corrections can be calculated a variety of ways. Using the ballbar measurements as an example the following ideal squareness corrections were found with the *Squareness Calculator* utility as shown in illustration 8. The range of the initial data was 0.9669 (0.4817 to -0.4852) where the final estimated range was 0.4872 (0.2530 to -0.2342) with squareness corrections of 0.7067 mm/m in the XY, 0.6730 mm/m in the YZ, and -0.0003 mm/m in the ZX.

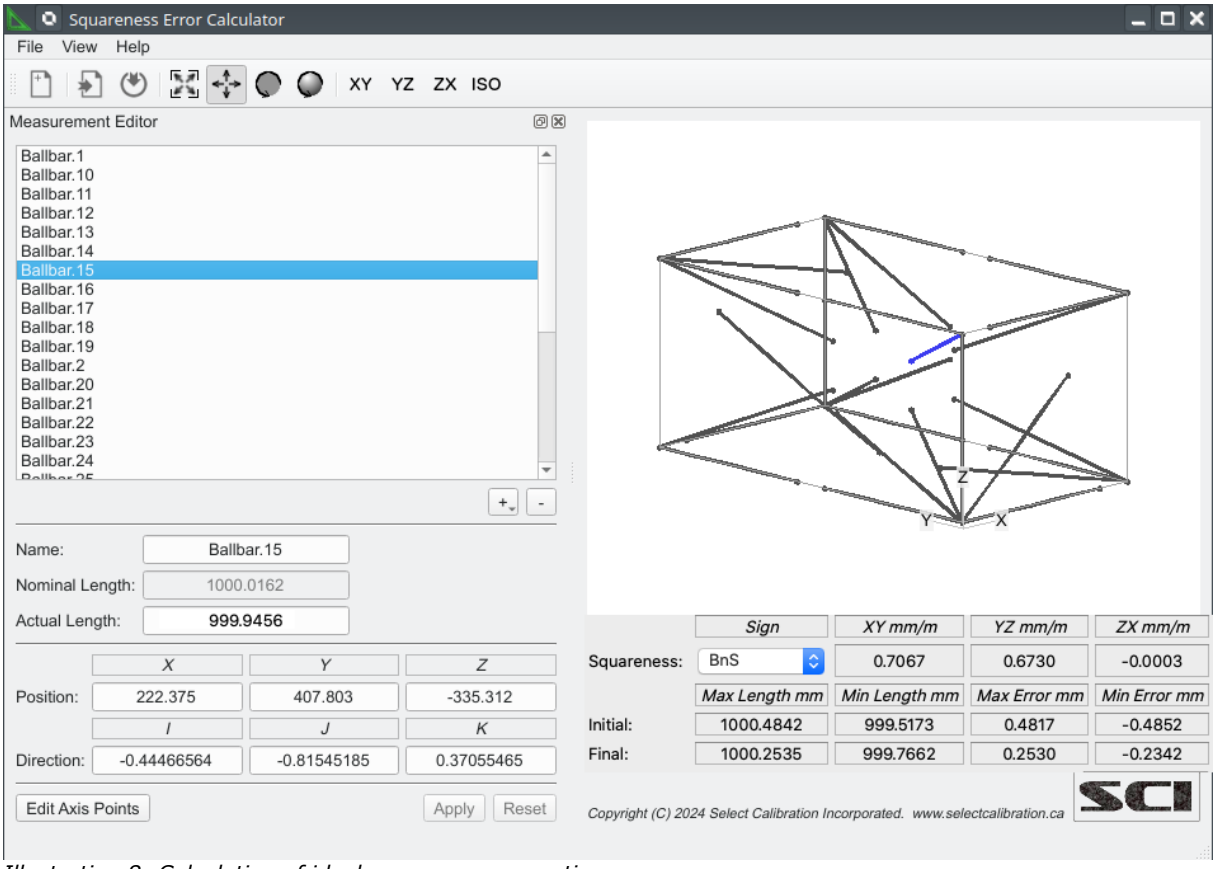

Illustration 8: Calculation of ideal squareness corrections.

Other Scenarios

It is suspected that there are other examples of error hiding that could be shown. The example described in this article is for the Y axis roll but this problem was brought to light from observations of the X axis data on a CMM. By repeating some of the tests using only an X axis roll of 1 mm/m instead of a Y axis roll of 1 mm/m the following measurements are expected:

```
ASME B89 Ballbar Measurement
-----------------------------------------------------------------------------------------------------
Length Min:       999.3546
Length Max:      1000.6451
Length Mean:      999.9979
Length Range:       1.2905
```

It was possible to reduce the errors to the following values when using an error map with the following corrections to squareness and various other parameters:

```
ASME B89 Ballbar Measurement
-----------------------------------------------------------------------------------------------------
Length Min:       999.7524
Length Max:      1000.3152
Length Mean:     1000.0604
Length Range:       0.5628
```

Performance Testing and Error Hiding

Map compensation data with X axis roll and various parameter updated to hide the error:

Selected Machine: Typical 12.22.10

Squareness

YZ: 0.6610 mm/m
XY: -0.7680 mm/m
ZX: 0.0170 mm/m

X Axis Data. Linear units are mm, angular units are mm/m.

Pos	Lx	Ly	Lz	Rx	Ry	Rz
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0	0.0020	0.0000	-0.0011	0.1000	-0.0030	0.0000
200.0	0.0040	0.0000	-0.0018	0.2000	-0.0060	0.0000
300.0	0.0060	0.0000	-0.0023	0.3000	-0.0090	0.0000
400.0	0.0080	0.0000	-0.0024	0.4000	-0.0120	0.0000
500.0	0.0100	0.0000	-0.0023	0.5000	-0.0150	0.0000
600.0	0.0120	0.0000	-0.0019	0.6000	-0.0180	0.0000
700.0	0.0140	0.0000	-0.0011	0.7000	-0.0210	0.0000
800.0	0.0160	0.0000	-0.0001	0.8000	-0.0240	0.0000
900.0	0.0180	0.0000	0.0012	0.9000	-0.0270	0.0000
1000.0	0.0200	0.0000	0.0029	1.0000	-0.0300	0.0000
1100.0	0.0220	0.0000	0.0048	1.1000	-0.0330	0.0000
1200.0	0.0240	0.0000	0.0071	1.2000	-0.0360	0.0000

Y Axis Data. Linear units are mm, angular units are mm/m.

Pos	Lx	Ly	Lz	Rx	Ry	Rz
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0	0.0034	0.0040	0.0017	-0.0024	0.0000	0.0050
200.0	0.0064	0.0080	0.0031	-0.0048	0.0000	0.0100
300.0	0.0089	0.0120	0.0042	-0.0072	0.0000	0.0150
400.0	0.0108	0.0160	0.0052	-0.0096	0.0000	0.0200
500.0	0.0123	0.0200	0.0059	-0.0120	0.0000	0.0250
600.0	0.0132	0.0240	0.0063	-0.0144	0.0000	0.0300
700.0	0.0137	0.0280	0.0066	-0.0168	0.0000	0.0350
800.0	0.0136	0.0320	0.0065	-0.0192	0.0000	0.0400
900.0	0.0131	0.0360	0.0063	-0.0216	0.0000	0.0450
1000.0	0.0120	0.0400	0.0058	-0.0240	0.0000	0.0500
1100.0	0.0105	0.0440	0.0050	-0.0264	0.0000	0.0550
1200.0	0.0084	0.0480	0.0040	-0.0288	0.0000	0.0600
1300.0	0.0059	0.0520	0.0028	-0.0312	0.0000	0.0650
1400.0	0.0028	0.0560	0.0014	-0.0336	0.0000	0.0700
1500.0	-0.0007	0.0600	-0.0003	-0.0360	0.0000	0.0750
1600.0	-0.0048	0.0640	-0.0023	-0.0384	0.0000	0.0800
1700.0	-0.0093	0.0680	-0.0045	-0.0408	0.0000	0.0850
1800.0	-0.0143	0.0720	-0.0069	-0.0432	0.0000	0.0900
1900.0	-0.0199	0.0760	-0.0095	-0.0456	0.0000	0.0950
2000.0	-0.0259	0.0800	-0.0125	-0.0480	0.0000	0.1000
2100.0	-0.0325	0.0840	-0.0156	-0.0504	0.0000	0.1050
2200.0	-0.0395	0.0880	-0.0190	-0.0528	0.0000	0.1100

Z Axis Data. Linear units are mm, angular units are mm/m.

Pos	Lx	Ly	Lz	Rx	Ry	Rz
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-100.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-200.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-300.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-400.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-500.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-600.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

-700.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-800.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-900.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-1000.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

The roll error of 1.0 mm/m in the X axis was not changed but a variety of other parameters and squarenesses were adjusted to minimize the range of the ballbar measurement results.

Performance Standard	*Results From Machine Error*	*Results From Machine Error With Various Corrections*
ASME B89.4.1:1997	1.2905 mm	0.5628 mm

The improvement from improperly correcting the machine reduced the error to 44% from the original value when using the ASME B89.4.1:1997 ballbar standard. The amount of improvement is actually better than the squareness only version with a Y axis roll of 1 mm/m.

Summary and Comments

The following is a list of observations, comments, and opinions about the testing:

- It appears that some machine errors can be almost completely hidden when performing ISO/IEC 10360-2 tests and partially hidden when running ASME B89.4.1:1997 ballbar tests. The amount of symmetry in the performance testing measurement patterns may be a key problem.
- All performance testing strategies may have this potential problem. The example used for this data is from one specific kind of error but there are other potential errors that could contribute to this kind of problem. No standard likely addresses every possible scenario that could exist.
- Using the Y axis roll highlights other problems as this particular error does not have a big impact on the axis scale parameters. Roll errors are the least likely items that are checked or updated when calibrating a CMM simply because they have the least impact on the scale errors.
- Although the Y axis roll was used as an example the impact of hiding errors was first observed with the X axis. There are other examples of this problem that can probably be created.
- Calibration technicians often have trouble testing for roll errors along a specific axis when not using devices designed to measure roll (using a ballbar instead of electronic levels for example). In the scenario described in this article it is possible to use something like a ballbar to estimate the residual roll errors but it is involved and may not be well understood by the calibration technician.
- When measuring axis parameters using indirect methods such as a ballbar it is important to do a secondary measurement that will help identify the error sources. The best results are not necessary the correct results when fitting indirect measurement data such as a

ballbar.

- Direct measurements of machine parameters are always preferred. It is simply too easy to substitute one error for another.

Calculation of X and Y Axis Roll With Ballbar Data

Due to the nature of the test data it is relevant to describe how the roll errors for the X and Y axis can be estimated using only ballbar measurements. Illustration 9 shows an example of the minimum measurement pattern needed to detect X and Y axis roll errors.

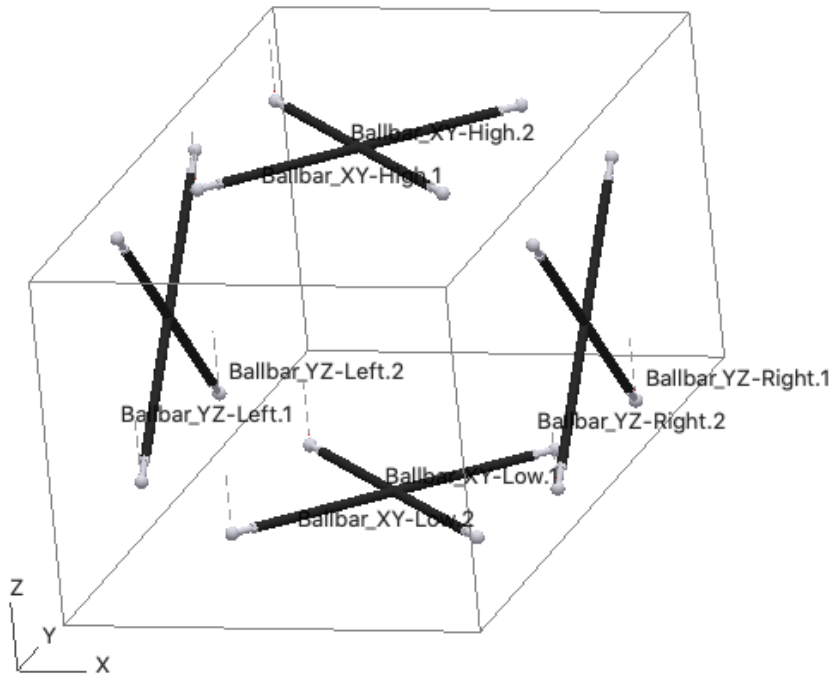

Illustration 9: Ballbar pattern to evaluate X and Y axis roll.

The two sets of XY and YZ ballbar measurements contains the sum and difference of the X and Y roll errors so therefore it can be separated into individual errors by removing one from the other.

```
XY_Sum_Roll = (YZSQ_Xp - YZSQ_Xm) / (Distance(Xp - Xm) / 1000.000)
XY_Diff_Roll = (XYSQ_Zp - XYSQ_Zm) / (Distance(Zp - Zm) / 1000.000)
X_Roll = (XY_Sum_Roll + XY_Diff_Roll) / 2
Y_Roll = XY_Sum_Roll - X_Roll

Where:
Xp: Positive X position.
Xm: Negative X position.
Zp: Positive Z position.
Zm: Negative Z position.
```

The recommended ballbar pattern for this size of machine (2.1.1 pattern) as described by ASME B89.4.1:1997 does not include measurement positions that could be used for measurements of the residual X and Y roll errors. It is something the technician performing the calibration would

need to look for if those errors were expected. Using the example from illustration 9 two sets of example measurements were created with expected results.

The calculation is involved so it is expected that it will not be done properly unless a utility or dedicated spreadsheet is used for the calculations based on the map type, sign rules, and other details.

Example 1

The roll errors in this simulated measurement were set to 0.5 mm/m for the X axis and 1.5 mm/m for the Y axis. The results of these errors with this specific measurement pattern are:

```
ASME B89 Ballbar Measurement
-------------------------------------------------------------------------------------------------------
Length Min:      998.8003
Length Max:     1001.2003
Length Mean:    1000.0003
Length Range:      2.4000

Name                    Length
-------------------------------------------------------------------------------------------------------
Ballbar_XY-High.1      999.9251
Ballbar_XY-High.2     1000.0751
Ballbar_XY-Low.1      1000.5758
Ballbar_XY-Low.2       999.4258
Ballbar_YZ-Left.1     1000.0002
Ballbar_YZ-Left.2     1000.0002
Ballbar_YZ-Right.1    1001.2003
Ballbar_YZ-Right.2     998.8003
```

XY_Sum_Roll

```
BallBar_YZ-Left.1     1000.0002
BallBar_YZ-Left.2     1000.0002
BallBar_YZ-Right.1    1001.2003
BallBar_YZ-Right.2     998.8003
YZ Squareness Left:      0.0000 mm/m
YZ Squareness Right:     2.4000 mm/m
Dist_Xp_Xm:           1200.0 mm
XY_Sum_Roll = (YZSQ_Right - YZSQ_Left) / (Dist_Xp_Xm / 1000)
XY_Sum_Roll = (2.4000 - 0.0000) / (1200 / 1000)
XY_Sum_Roll = 2.0000 mm/m
```

XY_Diff_Roll

```
BallBar_XY-High.1      999.9251
BallBar_XY-High.2     1000.0751
BallBar_XY-Low.1      1000.5758
BallBar_XY-Low.2       999.4258
XY Squareness High:      0.1500 mm/m
XY Squareness Low:       1.1500 mm/m
Dist_Zp_Zm:           1000.0 mm
XY_Diff_Roll = (XYSQ_High - XYSQ_Low)) / (Dist_Zp_Zm / 1000)
XY_Diff_Roll = (0.1500 - 1.1500)) / (1000 / 1000)
XY_Diff_Roll = -1.0000 mm/m
```

X Roll

```
X_Roll = (XY_Sum_Roll + XY_Diff_Roll) / 2.0
X_Roll = (2.0000 mm/m + (-1.0000) mm/m) / 2.0
X_Roll = 0.5000 mm/m
```

Y_Roll

```
Y Roll = XY_Sum_Roll - X_Roll
Y Roll = 2.0000 mm/m - 0.5000 mm/m
Y Roll = 1.5000 mm/m
```

Example 2

The roll errors in this simulated measurement were set to -1.5 mm/m for the X axis and 0.5 mm/m for the Y axis. The results of these errors with this specific measurement pattern are:

```
ASME B89 Ballbar Measurement
-------------------------------------------------------------------------------------------------------
Length Min:      998.8502
Length Max:     1001.1502
Length Mean:    1000.0000
Length Range:      2.3000

Name                    Length
-------------------------------------------------------------------------------------------------------
Ballbar_XY-High.1      999.8500
Ballbar_XY-High.2     1000.1500
Ballbar_XY-Low.1      1001.1502
Ballbar_XY-Low.2       998.8502
Ballbar_YZ-Left.1     1000.0000
Ballbar_YZ-Left.2     1000.0000
Ballbar_YZ-Right.1     999.3999
Ballbar_YZ-Right.2    1000.5999
```

XY_Sum_Roll

```
BallBar_YZ-Left.1     1000.0000
BallBar_YZ-Left.2     1000.0000
BallBar_YZ-Right.1     999.3999
BallBar_YZ-Right.2    1000.5999
YZ Squareness Left:      0.0000 mm/m
YZ Squareness Right:    -1.2000 mm/m    ← Squareness sign reversed from previous example
Dist_Xp_Xm:           1200.0 mm
XY_Sum_Roll = (YZSQ_Right - YZSQ_Left) / (Dist_Xp_Xm / 1000)
XY_Sum_Roll = (-1.2000 - 0.0000) / (1200 / 1000)
XY_Sum_Roll = -1.0000 mm/m
```

XY_Diff_Roll

```
BallBar_XY-High.1      999.8500
BallBar_XY-High.2     1000.1500
BallBar_XY-Low.1      1001.1502
BallBar_XY-Low.2       998.8502
XY Squareness High:      0.3000 mm/m
XY Squareness Low:       2.3000 mm/m
Dist_Zp_Zm:           1000.0 mm
XY_Diff_Roll = (XYSQ_High - XYSQ_Low)) / (Dist_Zp_Zm / 1000)
XY_Diff_Roll = (0.3000 - 2.3000) / (1000 / 1000)
XY_Diff_Roll = -2.0000 mm/m
```

X Roll

```
X_Roll = (XY_Sum_Roll + XY_Diff_Roll) / 2.0
X_Roll = (-1.0000 mm/m + (-2.0000) mm/m) / 2.0
X_Roll = -1.5000 mm/m
```

Y_Roll

```
Y Roll = XY_Sum_Roll - X_Roll
Y Roll = -1.0000 mm/m - (-1.5000) mm/m
Y Roll = 0.5000 mm/m
```

Revision History

Date	*Version*	*Changes*
Feb 2, 2025	1	Initial Release
Mar 23, 2025	2	Document update.