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Meter-Scale Coordinate Measuring Machine Interlaboratory Comparison

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Abstract

The dimensional metrology committee at NCSLI organized an interlaboratory comparison (ILC) for laboratories with coordinate measuring machines (CMMs). The committee limited participation to equipment capable of handling meter-length artifacts, but with capability for MPE_E less than 1 micrometer. The ILC started in November 2009. As of May 2011, 12 labs have participated, and reported either partial or complete results. The available results will be presented at the August 2011 NCSL International Workshop and Symposium. This extended abstract presents results available to the analysis lab as of May 2011.

Learning Objectives

Attendees will see the results (thus far) of the Dimensional Metrology Committee meter-scale CMM interlaboratory comparison. In this particular paper, the attendees will see some of the details necessary in analyzing the results of an ILC. The attendees will discuss possible sources of errors in CMM measurements, and some of the challenges with CMMs working at the submicrometer level.

Introduction

Interlaboratory comparisons (ILC or ILCs) are typically conducted to obtain insight into measurement systems and processes. According to NCSLI RP-15[1], "Laboratories measuring the same material or standard should obtain the same result to within the experimental uncertainty." Thus, conducting an ILC is a valuable exercise for laboratories which measure the same object or class of objects, but which may have different equipment and methods. ISO standard 17043:2010[2] provides a standard for providers of proficiency tests, which are a type of ILC.

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[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Coordinate Measuring Machines (CMMs) are complex dimensional metrology systems. While a CMM is essentially a machine that measures the location of points in a Cartesian coordinate system, it will include motion stages, position and environment transducers, and computer software (both to control the machine, and to interpret the point locations to geometrical features)[3]. This makes for a very complex metrological measurement system. Assessing the performance of a laboratory operating a CMM through interlaboratory comparisons would be useful.

A number of ILCs have been conducted on CMMs. In the 1990s, CIRP (International Center for Production Research), in coordination with the Western European Calibration Cooperation (now EAL, the European Accreditation Cooperation), organized an ILC for CMMs using a ball plate as the comparison artifact [4] and an ILC for form testers and CMMs[5]. Other ILCs have been conducted with National Metrological Institutes (NMIs) as participants, using step bars (also known as step gages)[6].

In 2008, Ed Pritchard proposed to the NCSLI Dimensional Metrology Committee (then, Committee 148; now Committee 175) the idea of doing an ILC for labs with high end commercial CMMs. Part of the motivation was to demonstrate the capability of commercial CMMs as operated by end user laboratories. At the 2009 NCSLI conference, the Dimensional Metrology Committee decided to conduct a CMM ILC. Hy Tran at Sandia National Laboratories volunteered to act as ILC coordinator, and Jim Salsbury at Mitutoyo USA volunteered to find an artifact. The artifact chosen was a Mitutoyo Ceramic "Check Master" step gage. Members of the committee volunteered to participate, or contacted colleagues and asked them to participate in the ILC. In general, participants were in measurement and calibration laboratories, with CMMs in routine use. Participants' CMMs were capable of measuring items up to 1 meter in length. Participants' CMMs typically had specified maximum permissible error MPE_E (per ISO 10360-1:2000 and ISO 10360-2:2000[7]), expressed as $MPE_E=(x + Ly)$ µm, where x was sub-micrometer. Specific interest was for owners of recent high end CMMs, where brochure specifications might state $MPE_E=(0.4 + L)$ µm (L being the measured distance in m).

Participants who volunteered (in alphabetical order by lab, with location of lab (state or province) in parentheses were:

Air Force Primary Standards Lab (Ohio)
Boeing Commercial Airplane Metrology (Washington)
Cummins Corporate Standards (Indiana)
Hexagon Metrology (Rhode Island)
Honeywell FM&T (Missouri)
Mitutoyo Canada (Ontario)
Mitutoyo USA (Illinois)
Navy Primary Standards Lab (California)
NIST (Maryland)
Sandia National Laboratories (New Mexico)
UNC Charlotte (North Carolina)
Y12 Metrology (Tennessee)

Equipment represented include a mix of commercial CMMs and highly customized and/or retrofitted CMMs. Not all participants are accredited calibration laboratories, nor, if accredited, include CMM capability within their accredited scope. Participants included commercial metrology labs (supporting manufacturing), government calibration laboratories, and equipment manufacturers.

The ILC started in November 2009. As of press time for the *Proceedings* in May 2011, not all the volunteers have reported measurements. The results presented in this *Proceedings* are preliminary, pending a repeat measurement or cycle of repeat measurements to establish the stability of the artifact and an estimate of the reference values. Final repeat measurements will be incorporated in the final results, which will be submitted to *NCSLI Measure*.

ILC Structure and Design

The ILC was organized much as recommended by NCSLI RP-15. Mitutoyo USA[2] provided the actual artifact (Ceramic Checkmaster Model Number 515-763, Serial Number 037002, ID Label MM031). While no formal charter document was created, the ILC was organized following NCSLI RP-15 guidance. The organization and informal charter is listed in Table 1 below. A photograph showing part of a Checkmaster is shown in Figure 1.

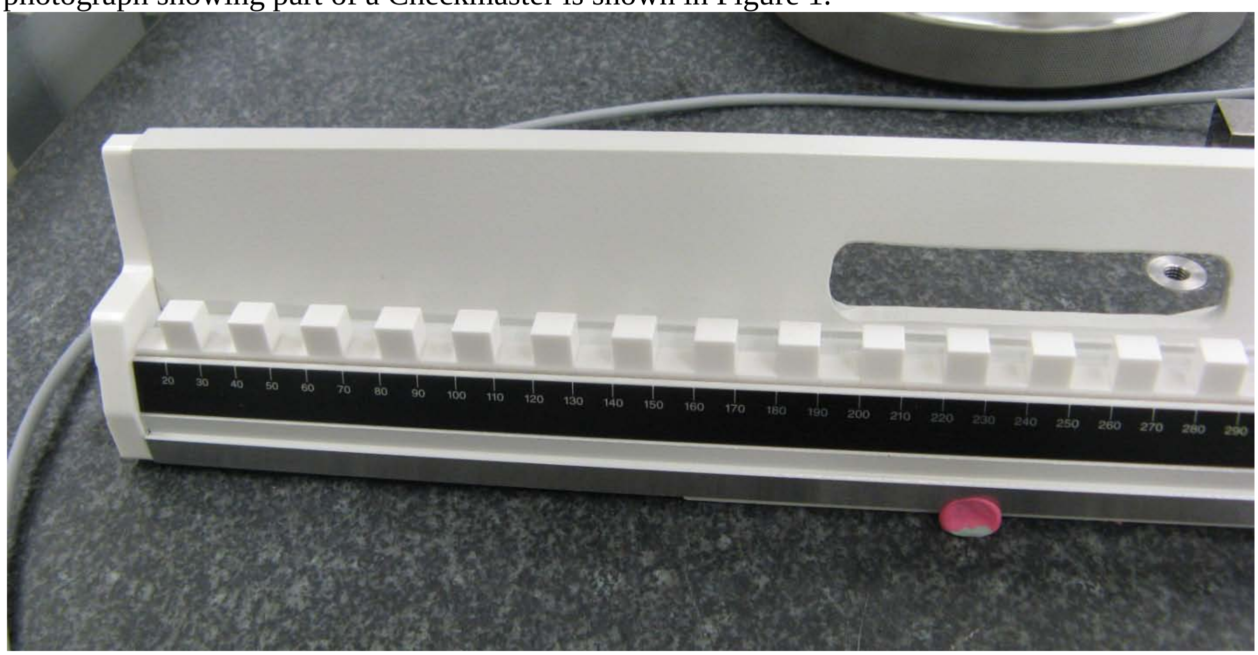

Figure 1. Photograph showing a portion of a typical Mitutoyo Ceramic Checkmaster. This photograph shows the first 290 mm of a step gage which is nominally 1010 mm long.

The major technical objectives were:

- Test CMMs with 1 meter or more on a major axis, and with potential sub-micrometer performance

[2] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the authors, Sandia National Laboratories, or NCSL International, nor does it imply that the materials or equipment identified are the only or best available for the purpose

- Allow individual labs to use their own judgment and methods, within the constraints of sufficiently defining the geometry to meet "Laboratories measuring the same material or standard should obtain the same result to within the experimental uncertainty."
- Publish the results, first, to the NCSLI Dimensional Metrology community at a NCSLI conference, then, in the *NCSLI Measure* journal.

Table 1. Informal charter for the Dimensional Metrology Committee meter-scale CMM ILC (2009-2011)

Participants	NCSLI Dimensional community
Coordinator	Hy Tran, Sandia National Laboratories
Pivot	TBD
Parameter measured	Distance between adjacent steps on a 1-meter long step bar (up to 1010 mm measuring)
Procedure	Circular pattern (Fig. 3 RP-15); single traveling artifact. General measurement guidance given, but each lab uses their own method.
Confidentiality	Hy Tran/SNL receives all data. Published data is scrubbed to remove lab name & equipment name
Goals	(a) Present results in 2010 NCSLI workshop in Providence RI (b) Publish final results in *NCSLI MEASURE* (c) Show capability of COTS/cal lab CMMs & NCSLI dimensional community (d) Look at NCSLI dimensional community measurement methods with CMMs
Target uncertainties	$MPE_E < (x + yL)$ μm (L is measured distance in mm), where x is < 1 μm and y is order of 0.001 (target x < 0.5 μm)
Finances	Done at own cost of volunteers
Publication	See goal (a) and (b)

The artifact selected (Mitutoyo Checkmaster MM031 as described above) is made of Zirconia ceramic gage blocks, permanently wrung together, then, placed in a steel frame. It was selected because it met the needs for a single traveling artifact:

- It was available (not in active use at Mitutoyo USA, so does not impact the owner)
- It had history from Mitutoyo USA demonstrating travel stability and temporal stability (used in the past as a field service standard)
- There was a custom shipping container (wood box with wing-nut screws to fasten the step bar to the box, then, the wood box is inside a foam-padded case)

Mitutoyo USA provided the geometry description. Based on that, the ILC measurement instructions were written[8]. After iterations to improve the ILC measurement instructions, the ILC was started.

Because no formal agreement had been made regarding confidentiality prior to the start of the ILC, the data coordinator (Sandia National Laboratories) treated the ILC as level 2 confidentiality (all published data is anonymous, but each participant knows their own data) per RP-15[1].

In order to establish anonymity, the data coordinator assigned code names to all the participating laboratories. The code names were selected from a list of Boy Scouts of America patrol names[3], and assigned to participating laboratories using a MS-Excel random number generator.

Alligators
Antelopes
Badgers
Bats
Bears
Beavers
Buffalos
Cobras
Dragons
Eagles
Frogs
Moose
Owls
Rams

There are more code names than participating laboratories. This is because some laboratories have multiple CMMs, and chose to enter multiple machines in the ILC. The machines used included both commercial CMMs and modified commercial CMMs. Equipment used included commercial Leitz CMMs, Mitutoyo CMMs, Zeiss CMMs, and modified Moores, Sheltons, and SIPs.

A measurement procedure was developed. This procedure reflects the calibration procedure used at Mitutoyo to measure and use these step gages. Based on Mitutoyo's experience with the stability and shipping robustness of the Checkmaster gage, the Dimensional Metrology Committee chair and co-chair initially decided to structure of the ILC as a circular pattern ILC. Each participant was expected to write their own CMM program based on the written measurement procedure, which included extensive illustrations[8].

The measurand on a step gage is the distance from the step (or face) to the index step. In fact, a step bar has more than 1 measurand. This model of step bar has 101 measurands, with nominal values at 10 mm, 20 mm, …, 1010 mm. The nominal values are the minimum distance between nominally parallel planes (the index face is a plane, as is each step). For convenience, we label each face with a number, such that face 1 is at 10 mm, face 2 at 20 mm, etc. This is shown in Figure 2. A critical consideration was to provide unambiguous instructions for determining the coordinate system and the origin (on the index face). Figure 3 shows an illustration from the measurement instructions.

[3] The ILC data coordinator chose patrol animal mascots as code names, avoiding non-animal patrol s such as "arrows" or "lightning."

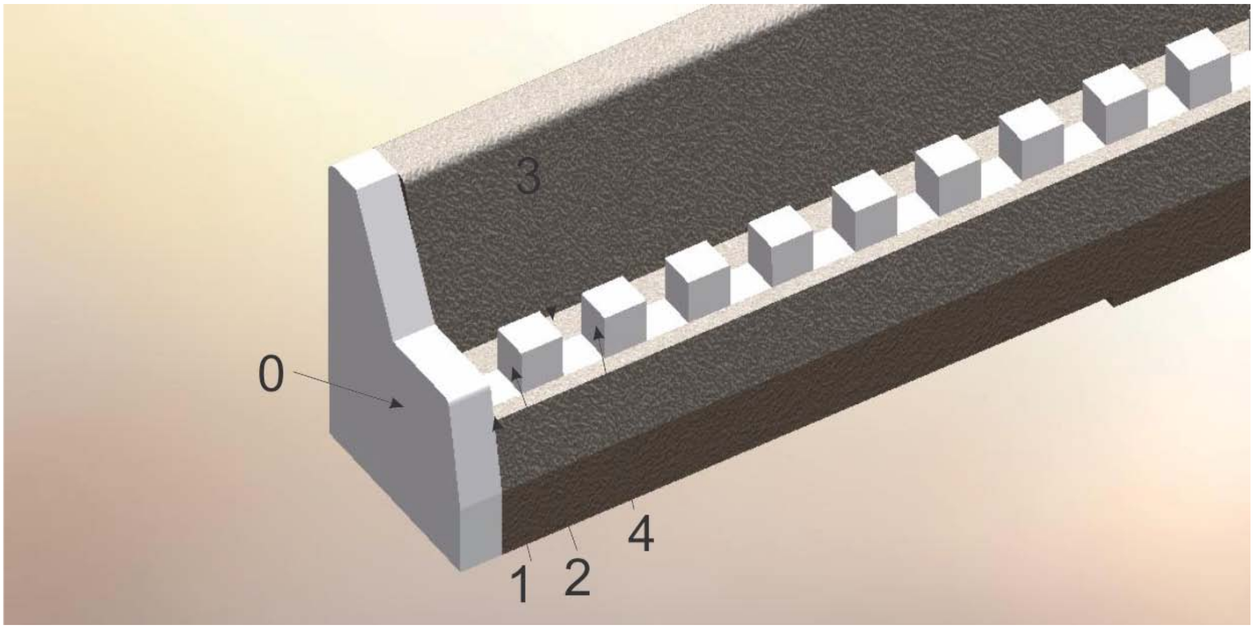

Figure 2. Solid model of a Ceramic Checkmaster, showing numbering of faces for convenience. The nominal step distance is just 10mm×the step number. From [8]

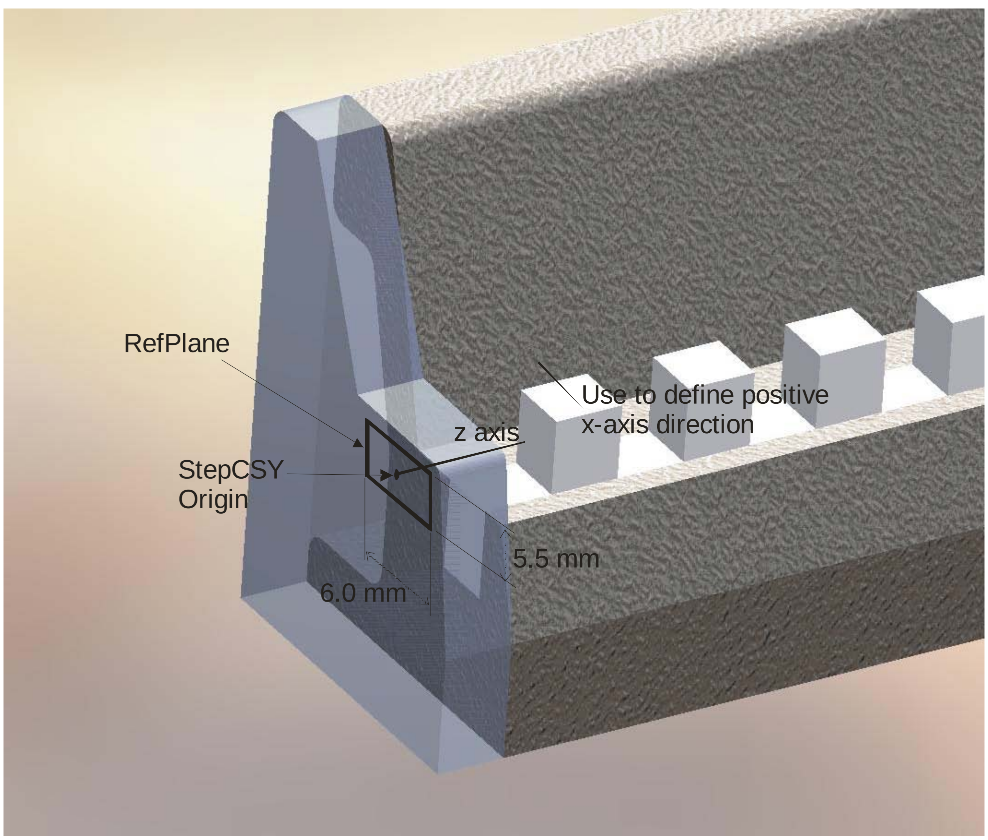

Figure 3. Illustration from the instructions on obtaining a coordinate system for measuring distances of the faces. From[8]

Each participant was asked to report the following:

(1) What is the equipment used?

a. Brand, model, make?
b. Software?
c. Workspace size?

(2) What is the traceability path? (for example, external calibration by field service vendor? Gage blocks used periodically in internal check standards? Gage blocks or other end-standards used in a comparative measurement? Temperature standards? etc.)

(3) Excel spreadsheet, containing the data shown in Table 2 below at a minimum: (Note that the numbers shown here are strictly for illustration purposes).

(4) Temperature during your measurements. At minimum, a temperature and range (20.0±0.5 ° C, for example). At best, a time plot of temperature during measurement. The coefficient of thermal expansion for the step gage was given as 9.3 x10^{-6}/K. The uncertainty of this number has been estimated by the manufacturer at 0.5x10^{-6}/K (k=2).

Table 2. Illustration for desired reported data.

Step ID	L (mm) from 0	U (k=2) (µm)
1	10.00413	0.45
2	19.92323	0.40
3	30.07233	0.55
4	40.00543	0.50
…	…	…

The data coordinator then transformed the data to show the deviations of each step from the nominal. This was done for convenience in tabulating and plotting results. Using the sample data shown in Table 2, the reported data would be as shown in Table 3:

Table 3. Illustration of data as reported by data coordinator.

Step ID	Deviation from nominal position in µm	U (k=2) (µm)
1	4.13	0.45
2	-76.77	0.40
3	72.33	0.55
4	5.43	0.50
…	…	…

Preliminary Results

The reported results (as available at end of May 2011) are shown in Table 4. Data from the same code name (for example, Beaver-A and Beaver-B) are different measurement reports from the same laboratory (e.g. measurements made at different times).

Table 4. Available data from all participants. "NR" indicates "Not Reported yet."

	Alligator Data	Alligator U	Antelope	Antelope U	Badger	Badger U	Bat	Bat U	Bear	Bear U
Step ID	(dev in μm)	(k=2 in μm)	(dev in μm)	(k=2 in μm)	(dev in μm)	(k=2 in μm)	(dev in μm)	(k=2 in μm)	(dev in μm)	(k=2 in μm)
1	-0.40	0.71	-0.28	0.32	NR	NR	-0.19	0.40	0.47	1.02
2	-0.39	0.72	-0.09	0.33	NR	NR	-0.23	0.48	0.04	1.04
3	-0.28	0.72	0.03	0.33	NR	NR	-0.23	0.39	0.61	1.06
4	-0.55	0.73	-0.12	0.34	NR	NR	-0.17	0.53	0.13	1.08
5	-0.54	0.74	0.13	0.34	NR	NR	-0.01	0.35	0.48	1.10
6	-0.59	0.75	-0.07	0.35	NR	NR	-0.13	0.46	0.36	1.12
7	-0.71	0.76	0.14	0.36	NR	NR	0.12	0.37	0.35	1.14
8	-0.68	0.76	0.09	0.36	NR	NR	0.07	0.45	0.42	1.16
9	-0.55	0.77	0.25	0.37	NR	NR	0.07	0.50	0.45	1.18
10	-0.57	0.78	0.14	0.37	NR	NR	0.16	0.56	0.34	1.20
11	-0.55	0.79	0.33	0.38	NR	NR	0.38	0.47	0.39	1.22
12	-0.45	0.80	0.28	0.38	NR	NR	0.28	0.39	0.40	1.24
13	-0.34	0.80	0.35	0.39	NR	NR	0.52	0.36	0.38	1.26
14	-0.29	0.81	0.32	0.39	NR	NR	0.45	0.54	0.49	1.28
15	-0.30	0.82	0.38	0.40	NR	NR	0.50	0.61	0.45	1.30
16	0.01	0.83	0.35	0.41	NR	NR	0.36	0.72	0.62	1.32
17	-0.08	0.84	0.45	0.41	NR	NR	0.48	0.72	0.55	1.34
18	0.09	0.84	0.48	0.42	NR	NR	0.60	0.66	0.81	1.36
19	-0.12	0.85	0.56	0.42	NR	NR	0.57	0.69	0.75	1.38
20	-0.11	0.86	0.56	0.43	NR	NR	0.67	0.73	0.91	1.40
21	-0.17	0.87	0.61	0.43	NR	NR	0.58	0.59	0.67	1.42
22	-0.13	0.88	0.57	0.44	NR	NR	0.33	0.83	0.94	1.44
23	-0.17	0.88	1.33	0.45	NR	NR	0.39	0.62	1.41	1.46
24	-0.17	0.89	0.60	0.45	NR	NR	0.43	0.64	1.21	1.48
25	-0.09	0.90	0.63	0.46	NR	NR	0.45	0.69	0.74	1.50
26	-0.24	0.91	0.66	0.46	NR	NR	0.57	0.80	1.16	1.52

27	-0.08	0.92	0.80	0.47	NR	NR	0.55	0.79	0.92	1.54
28	0.01	0.92	0.74	0.47	NR	NR	0.67	0.85	1.44	1.56
29	0.01	0.93	0.81	0.48	NR	NR	0.73	0.80	1.12	1.58
30	-0.10	0.94	0.81	0.49	NR	NR	0.75	1.09	1.49	1.60
31	0.23	0.95	0.93	0.49	NR	NR	0.64	0.82	1.36	1.62
32	0.17	0.96	0.91	0.50	NR	NR	0.71	1.01	1.68	1.64
33	0.13	0.96	0.94	0.50	NR	NR	0.73	0.87	1.33	1.66
34	0.39	0.97	0.96	0.51	NR	NR	0.82	0.99	1.74	1.68
35	0.13	0.98	0.95	0.51	NR	NR	0.62	0.84	1.54	1.70
36	0.25	0.99	1.01	0.52	NR	NR	0.78	0.95	1.66	1.72
37	0.09	1.00	1.01	0.52	NR	NR	0.76	1.15	1.66	1.74
38	0.35	1.00	1.06	0.53	NR	NR	0.88	0.83	2.06	1.76
39	0.44	1.01	1.11	0.54	NR	NR	0.88	0.97	1.80	1.78
40	0.69	1.02	1.15	0.54	NR	NR	1.04	1.15	2.19	1.80
41	0.53	1.03	1.14	0.55	NR	NR	0.81	0.93	2.15	1.82
42	0.54	1.04	1.16	0.55	NR	NR	0.90	1.13	2.35	1.84
43	0.75	1.04	1.31	0.56	NR	NR	1.01	1.00	2.31	1.86
44	0.70	1.05	1.28	0.56	NR	NR	1.08	0.93	2.47	1.88
45	0.79	1.06	1.36	0.57	NR	NR	1.01	0.93	2.59	1.90
46	0.91	1.07	1.40	0.58	NR	NR	1.02	1.04	2.60	1.92
47	1.02	1.08	1.47	0.58	NR	NR	1.09	1.14	2.67	1.94
48	1.07	1.08	1.48	0.59	NR	NR	1.17	0.96	2.69	1.96
49	0.96	1.09	1.51	0.59	NR	NR	1.12	1.08	2.70	1.98
50	1.18	1.10	1.51	0.60	NR	NR	1.22	1.15	2.94	2.00
51	1.12	1.11	1.54	0.60	NR	NR	1.20	1.11	2.90	2.02
52	1.34	1.12	1.53	0.61	NR	NR	1.20	1.11	3.15	2.04
53	1.18	1.12	1.62	0.61	NR	NR	1.31	1.05	2.99	2.06
54	1.40	1.13	1.51	0.62	NR	NR	1.30	1.20	2.91	2.08
55	1.19	1.14	1.59	0.63	NR	NR	1.36	1.10	3.02	2.10
56	1.35	1.15	1.48	0.63	NR	NR	1.15	1.35	2.93	2.12

57	1.09	1.16	1.47	0.64	NR	NR	1.10	1.38	2.94	2.14
58	1.34	1.16	1.45	0.64	NR	NR	1.14	1.16	2.87	2.16
59	1.13	1.17	1.51	0.65	NR	NR	1.17	1.23	2.69	2.18
60	1.34	1.18	1.45	0.65	NR	NR	1.22	1.22	2.69	2.20
61	1.24	1.19	1.43	0.66	NR	NR	1.12	1.31	2.79	2.22
62	1.57	1.20	1.47	0.67	NR	NR	1.19	1.18	2.74	2.24
63	1.51	1.20	1.55	0.67	NR	NR	1.22	1.22	2.81	2.26
64	1.70	1.21	1.60	0.68	NR	NR	1.27	1.43	2.77	2.28
65	1.91	1.22	1.69	0.68	NR	NR	1.36	1.22	2.64	2.30
66	1.95	1.23	1.74	0.69	NR	NR	1.44	1.37	2.94	2.32
67	1.99	1.24	1.80	0.69	NR	NR	1.71	1.32	2.72	2.34
68	2.04	1.24	1.74	0.70	NR	NR	1.71	1.49	2.77	2.36
69	1.91	1.25	1.81	0.71	NR	NR	1.49	1.41	2.39	2.38
70	1.94	1.26	1.82	0.71	NR	NR	1.67	1.40	2.72	2.40
71	1.92	1.27	1.92	0.72	NR	NR	1.68	1.49	2.70	2.42
72	2.19	1.28	1.87	0.72	NR	NR	1.76	1.65	2.80	2.44
73	1.89	1.28	1.89	0.73	NR	NR	1.84	1.49	2.54	2.46
74	2.14	1.29	1.91	0.73	NR	NR	1.91	1.35	2.98	2.48
75	2.06	1.30	1.94	0.74	NR	NR	2.06	1.37	2.51	2.50
76	2.32	1.31	1.91	0.74	NR	NR	2.03	1.55	2.50	2.52
77	2.17	1.32	1.98	0.75	NR	NR	1.92	1.51	2.32	2.54
78	2.29	1.32	1.99	0.76	NR	NR	2.06	1.57	2.78	2.56
79	2.21	1.33	2.13	0.76	NR	NR	1.94	1.58	2.39	2.58
80	2.43	1.34	2.04	0.77	NR	NR	2.07	1.48	2.63	2.60
81	2.32	1.35	2.08	0.77	NR	NR	2.19	1.57	2.48	2.62
82	2.42	1.36	2.02	0.78	NR	NR	2.26	1.61	2.61	2.64
83	2.30	1.36	2.06	0.78	NR	NR	2.14	1.75	2.24	2.66
84	2.51	1.37	2.04	0.79	NR	NR	2.26	1.55	2.61	2.68
85	2.48	1.38	2.13	0.80	NR	NR	2.32	1.67	2.46	2.70
86	2.47	1.39	2.03	0.80	NR	NR	2.21	1.85	2.68	2.72

87	2.61	1.40	2.14	0.81	NR	NR	2.24	1.65	2.44	2.74
88	2.53	1.40	2.06	0.81	NR	NR	2.27	1.80	2.60	2.76
89	2.63	1.41	2.22	0.82	NR	NR	2.48	1.83	2.39	2.78
90	2.58	1.42	2.14	0.82	NR	NR	2.39	1.87	2.20	2.80
91	2.85	1.43	2.21	0.83	NR	NR	2.58	1.78	2.29	2.82
92	2.75	1.44	2.17	0.84	NR	NR	2.54	1.97	2.31	2.84
93	2.70	1.44	2.17	0.84	NR	NR	2.51	1.75	2.03	2.86
94	2.90	1.45	2.23	0.85	NR	NR	2.58	1.90	2.47	2.88
95	2.87	1.46	2.25	0.85	NR	NR	2.67	1.83	2.02	2.90
96	2.79	1.47	2.20	0.86	NR	NR	2.42	1.84	2.28	2.92
97	2.81	1.48	2.19	0.86	NR	NR	2.60	1.97	1.77	2.94
98	2.80	1.48	2.19	0.87	NR	NR	2.58	1.82	1.89	2.96
99	2.81	1.49	2.12	0.87	NR	NR	2.52	2.06	1.56	2.98
100	3.17	1.50	2.36	0.88	NR	NR	2.82	1.92	1.84	3.00
101	3.26	1.51	2.40	0.89	NR	NR				

Step ID	Beaver-A (dev in μm)	Beaver U (k=2 in μm)	Beaver-B (dev in μm)	Beaver U (k=2 in μm)	Buffalo (dev in μm)	Buffalo U (k=2 in μm)	Cobra-A (dev in μm)	Cobra U (k=2 in μm)	Cobra-B (dev in μm)	Cobra U (k=2 in μm)
1	-0.14	0.26	-0.35	0.26	-0.28	0.11	-0.32	0.21	-0.49	0.21
2	-0.22	0.26	-0.50	0.26	-0.24	0.12	-0.34	0.22	-0.55	0.22
3	0.05	0.27	-0.43	0.27	-0.05	0.12	-0.04	0.22	-0.49	0.22
4	-0.24	0.28	-0.70	0.28	-0.21	0.12	-0.35	0.23	-0.67	0.23
5	0.10	0.29	-0.58	0.29	-0.03	0.12	0.00	0.24	-0.66	0.24
6	-0.14	0.29	-0.79	0.29	-0.13	0.13	-0.29	0.25	-0.71	0.25
7	0.22	0.30	-0.60	0.30	0.06	0.13	0.02	0.25	-0.71	0.25
8	0.00	0.31	-0.79	0.31	-0.05	0.13	-0.28	0.26	-0.78	0.26
9	0.35	0.31	-0.63	0.31	0.12	0.13	0.11	0.27	-0.75	0.27
10	0.12	0.32	-0.78	0.32	0.02	0.14	-0.12	0.28	-0.80	0.28
11	0.42	0.33	-0.61	0.33	0.19	0.14	0.15	0.28	-0.81	0.28
12	0.13	0.33	-0.80	0.33	0.08	0.14	-0.11	0.29	-0.87	0.29
13	0.40	0.34	-0.70	0.34	0.23	0.14	0.21	0.30	-0.85	0.30
14	0.11	0.35	-0.84	0.35	0.11	0.15	-0.09	0.31	-0.84	0.31
15	0.40	0.36	-0.73	0.36	0.25	0.15	0.16	0.31	-0.89	0.31
16	0.14	0.36	-0.84	0.36	0.19	0.15	-0.06	0.32	-0.82	0.32
17	0.37	0.37	-0.75	0.37	0.34	0.15	0.25	0.33	-0.86	0.33
18	0.15	0.38	-0.81	0.38	0.27	0.16	0.03	0.34	-0.79	0.34
19	0.43	0.38	-0.69	0.38	0.42	0.16	0.28	0.34	-0.84	0.34
20	0.17	0.39	-0.78	0.39	0.29	0.16	0.03	0.35	-0.79	0.35
21	0.47	0.40	-0.65	0.40	0.45	0.16	0.35	0.36	-0.85	0.36
22	0.17	0.40	-0.76	0.40	0.33	0.17	0.00	0.37	-0.81	0.37
23	0.45	0.41	-0.65	0.41	0.50	0.17	0.31	0.37	-0.84	0.37
24	0.19	0.42	-0.71	0.42	0.36	0.17	0.01	0.38	-0.77	0.38
25	0.46	0.43	-0.59	0.43	0.55	0.18	0.36	0.39	-0.78	0.39
26	0.22	0.43	-0.57	0.43	0.43	0.18	0.06	0.40	-0.72	0.40
27	0.56	0.44	-0.40	0.44	0.61	0.18	0.44	0.41	-0.69	0.41
28	0.31	0.45	-0.36	0.45	0.50	0.18	0.16	0.41	-0.53	0.41

29	0.66	0.45	-0.19	0.45	0.67	0.19	0.49	0.42	-0.58	0.42
30	0.40	0.46	-0.19	0.46	0.55	0.19	0.23	0.43	-0.45	0.43
31	0.73	0.47	-0.07	0.47	0.73	0.19	0.55	0.44	-0.46	0.44
32	0.43	0.47	-0.05	0.47	0.60	0.19	0.28	0.44	-0.31	0.44
33	0.63	0.48	0.02	0.48	0.69	0.20	0.51	0.45	-0.37	0.45
34	0.41	0.49	0.14	0.49	0.62	0.20	0.26	0.46	-0.16	0.46
35	0.63	0.50	0.18	0.50	0.68	0.20	0.47	0.47	-0.29	0.47
36	0.40	0.50	0.31	0.50	0.62	0.20	0.30	0.47	-0.08	0.47
37	0.61	0.51	0.32	0.51	0.70	0.21	0.51	0.48	-0.18	0.48
38	0.37	0.52	0.41	0.52	0.65	0.21	0.33	0.49	0.04	0.49
39	0.60	0.52	0.48	0.52	0.77	0.21	0.59	0.50	-0.02	0.50
40	0.37	0.53	0.61	0.53	0.71	0.21	0.39	0.50	0.25	0.50
41	0.64	0.54	0.75	0.54	0.82	0.22	0.66	0.51	0.19	0.51
42	0.45	0.54	0.88	0.54	0.78	0.22	0.50	0.52	0.42	0.52
43	0.71	0.55	1.00	0.55	0.95	0.22	0.78	0.53	0.46	0.53
44	0.44	0.56	1.04	0.56	0.84	0.22	0.54	0.53	0.64	0.53
45	0.68	0.57	1.15	0.57	0.97	0.23	0.85	0.54	0.54	0.54
46	0.44	0.57	1.18	0.57	0.89	0.23	0.67	0.55	0.76	0.55
47	0.67	0.58	1.28	0.58	1.01	0.23	0.98	0.56	0.76	0.56
48	0.41	0.59	1.30	0.59	0.95	0.23	0.76	0.56	0.94	0.56
49	0.69	0.59	1.40	0.59	1.05	0.24	1.00	0.57	0.86	0.57
50	0.47	0.60	1.49	0.60	1.02	0.24	0.81	0.58	1.05	0.58
51	0.77	0.61	1.62	0.61	1.10	0.24	1.06	0.59	0.97	0.59
52	0.48	0.61	1.58	0.61	0.99	0.25	0.82	0.60	1.10	0.60
53	0.77	0.62	1.70	0.62	1.13	0.25	1.12	0.60	1.03	0.60
54	0.43	0.63	1.65	0.63	1.00	0.25	0.81	0.61	1.12	0.61
55	0.69	0.64	1.68	0.64	1.09	0.25	1.04	0.62	1.02	0.62
56	0.34	0.64	1.64	0.64	0.95	0.26	0.73	0.63	1.06	0.63
57	0.54	0.65	1.65	0.65	1.01	0.26	1.01	0.63	0.94	0.63
58	0.21	0.66	1.58	0.66	0.90	0.26	0.71	0.64	1.02	0.64

59	0.44	0.66	1.62	0.66	0.96	0.26	0.95	0.65	0.92	0.65
60	0.15	0.67	1.60	0.67	0.82	0.27	0.63	0.66	0.98	0.66
61	0.35	0.68	1.59	0.68	0.88	0.27	0.89	0.66	0.87	0.66
62	0.11	0.68	1.61	0.68	0.83	0.27	0.65	0.67	0.99	0.67
63	0.50	0.69	1.78	0.69	0.99	0.27	1.02	0.68	0.98	0.68
64	0.26	0.70	1.76	0.70	0.91	0.28	0.74	0.69	1.04	0.69
65	0.58	0.71	1.86	0.71	1.07	0.28	1.13	0.69	1.01	0.69
66	0.37	0.71	1.88	0.71	1.04	0.28	0.93	0.70	1.10	0.70
67	0.65	0.72	1.95	0.72	1.21	0.28	1.26	0.71	1.10	0.71
68	0.29	0.73	1.80	0.73	1.05	0.29	0.95	0.72	1.08	0.72
69	0.52	0.73	1.83	0.73	1.24	0.29	1.27	0.72	1.09	0.72
70	0.20	0.74	1.74	0.74	1.15	0.29	0.99	0.73	1.14	0.73
71	0.54	0.75	1.85	0.75	1.31	0.29	1.34	0.74	1.10	0.74
72	0.21	0.75	1.78	0.75	1.19	0.30	1.03	0.75	1.17	0.75
73	0.57	0.76	1.94	0.76	1.34	0.30	1.30	0.75	1.10	0.75
74	0.26	0.77	1.89	0.77	1.25	0.30	1.09	0.76	1.24	0.76
75	0.53	0.78	1.96	0.78	1.38	0.31	1.40	0.77	1.17	0.77
76	0.13	0.78	1.84	0.78	1.22	0.31	1.10	0.78	1.21	0.78
77	0.48	0.79	1.99	0.79	1.38	0.31	1.41	0.79	1.15	0.79
78	0.11	0.80	1.91	0.80	1.26	0.31	1.15	0.79	1.29	0.79
79	0.46	0.80	2.06	0.80	1.43	0.32	1.50	0.80	1.29	0.80
80	0.10	0.81	2.02	0.81	1.25	0.32	1.22	0.81	1.39	0.81
81	0.49	0.82	2.19	0.82	1.43	0.32	1.53	0.82	1.39	0.82
82	0.10	0.82	2.15	0.82	1.29	0.32	1.21	0.82	1.47	0.82
83	0.34	0.83	2.17	0.83	1.47	0.33	1.56	0.83	1.39	0.83
84	-0.08	0.84	2.12	0.84	1.33	0.33	1.25	0.84	1.55	0.84
85	0.24	0.85	2.27	0.85	1.50	0.33	1.56	0.85	1.53	0.85
86	-0.16	0.85	2.23	0.85	1.33	0.33	1.23	0.85	1.69	0.85
87	0.08	0.86	2.30	0.86	1.51	0.34	1.55	0.86	1.67	0.86
88	-0.33	0.87	2.23	0.87	1.34	0.34	1.24	0.87	1.73	0.87

89	0.02	0.87	2.37	0.87	1.53	0.34	1.64	0.88	1.71	0.88
90	-0.34	0.88	2.33	0.88	1.40	0.34	1.39	0.88	1.81	0.88
91	-0.06	0.89	2.38	0.89	1.55	0.35	1.64	0.89	1.80	0.89
92	-0.44	0.89	2.29	0.89	1.37	0.35	1.41	0.90	1.88	0.90
93	-0.14	0.90	2.38	0.90	1.46	0.35	1.56	0.91	1.82	0.91
94	-0.31	0.91	2.45	0.91	1.44	0.35	1.39	0.91	2.02	0.91
95	-0.03	0.91	2.47	0.91	1.54	0.36	1.61	0.92	1.87	0.92
96	-0.41	0.92	2.33	0.92	1.40	0.36	1.29	0.93	1.92	0.93
97	-0.18	0.93	2.31	0.93	1.48	0.36	1.56	0.94	1.75	0.94
98	-0.45	0.94	2.29	0.94	1.38	0.36	1.30	0.94	1.86	0.94
99	-0.17	0.94	2.32	0.94	1.48	0.37	1.53	0.95	1.73	0.95
100	-0.23	0.95	2.48	0.95	1.61	0.37	1.53	0.96	2.07	0.96
101					1.74	0.37	1.78	0.97	2.02	0.97

Step ID	Cobra-C (dev in μm)	Cobra U (k=2 in μm)	Cobra-D (dev in μm)	Cobra U (k=2 in μm)	Dragon (dev in μm)	Dragon U (k=2 in μm)	Eagle (dev in μm)	Eagle U (k=2 in μm)	Frog (dev in μm)	Frog U (k=2 in μm)
1	-0.75	0.21	-0.49	0.21	-0.40	0.40	-0.44	0.21	-0.26	0.46
2	-0.37	0.22	-0.33	0.22	-0.22	0.42	-0.55	0.21	-0.55	0.47
3	-0.61	0.22	-0.34	0.22	-0.09	0.43	-0.67	0.22	-0.24	0.47
4	-0.42	0.23	-0.38	0.23	-0.37	0.45	-0.72	0.23	-0.68	0.48
5	-0.65	0.24	-0.39	0.24	-0.10	0.46	-0.75	0.23	-0.40	0.49
6	-0.38	0.25	-0.41	0.25	-0.19	0.47	-0.72	0.24	-0.69	0.50
7	-0.62	0.25	-0.38	0.25	-0.17	0.49	-0.90	0.25	-0.40	0.51
8	-0.34	0.26	-0.38	0.26	-0.34	0.50	-0.82	0.25	-0.77	0.51
9	-0.60	0.27	-0.42	0.27	-0.15	0.52	-0.97	0.26	-0.44	0.52
10	-0.33	0.28	-0.39	0.28	-0.26	0.53	-0.84	0.27	-0.73	0.53
11	-0.58	0.28	-0.36	0.28	-0.03	0.54	-1.02	0.27	-0.42	0.54
12	-0.30	0.29	-0.31	0.29	-0.16	0.56	-0.85	0.28	-0.75	0.55
13	-0.59	0.30	-0.35	0.30	-0.19	0.57	-0.99	0.29	-0.52	0.55
14	-0.29	0.31	-0.28	0.31	-0.18	0.59	-0.87	0.29	-0.76	0.56
15	-0.54	0.31	-0.34	0.31	-0.05	0.60	-1.03	0.30	-0.52	0.57
16	-0.23	0.32	-0.27	0.32	-0.09	0.61	-0.83	0.31	-0.69	0.58
17	-0.53	0.33	-0.34	0.33	-0.01	0.63	-0.96	0.31	-0.40	0.59
18	-0.21	0.34	-0.20	0.34	-0.05	0.64	-0.72	0.32	-0.56	0.59
19	-0.50	0.34	-0.27	0.34	0.13	0.66	-0.90	0.33	-0.30	0.60
20	-0.20	0.35	-0.20	0.35	-0.16	0.67	-0.68	0.33	-0.49	0.61
21	-0.47	0.36	-0.24	0.36	0.03	0.68	-0.86	0.34	-0.23	0.62
22	-0.22	0.37	-0.18	0.37	-0.18	0.70	-0.65	0.35	-0.41	0.63
23	-0.49	0.37	-0.23	0.37	0.01	0.71	-0.77	0.35	-0.17	0.63
24	-0.19	0.38	-0.15	0.38	-0.21	0.73	-0.58	0.36	-0.37	0.64
25	-0.42	0.39	-0.14	0.39	0.06	0.74	-0.72	0.37	-0.07	0.65
26	-0.13	0.40	0.00	0.40	-0.11	0.75	-0.40	0.37	-0.20	0.66
27	-0.33	0.41	-0.09	0.41	0.09	0.77	-0.61	0.38	0.14	0.67
28	-0.05	0.41	0.05	0.41	-0.22	0.78	-0.28	0.39	0.07	0.67

29	-0.28	0.42	0.05	0.42	-0.25	0.80	-0.44	0.39	0.39	0.68
30	0.01	0.43	0.22	0.43	-0.51	0.81	-0.19	0.40	0.31	0.69
31	-0.14	0.44	0.23	0.44	-0.14	0.82	-0.33	0.41	0.48	0.70
32	0.13	0.44	0.36	0.44	-0.33	0.84	0.05	0.41	0.40	0.71
33	-0.16	0.45	0.24	0.45	-0.29	0.85	-0.28	0.42	0.58	0.71
34	0.20	0.46	0.44	0.46	-0.45	0.87	0.10	0.43	0.57	0.72
35	-0.16	0.47	0.29	0.47	-0.37	0.88	-0.24	0.43	0.76	0.73
36	0.22	0.47	0.48	0.47	-0.60	0.89	0.16	0.44	0.77	0.74
37	-0.11	0.48	0.36	0.48	-0.40	0.91	0.00	0.45	0.95	0.75
38	0.27	0.49	0.60	0.49	-0.57	0.92	0.50	0.45	0.97	0.75
39	0.03	0.50	0.50	0.50	-0.40	0.94	0.34	0.46	1.25	0.76
40	0.34	0.50	0.76	0.50	-0.57	0.95	0.76	0.47	1.28	0.77
41	0.14	0.51	0.75	0.51	-0.57	0.96	0.59	0.47	1.51	0.78
42	0.51	0.52	0.97	0.52	-0.55	0.98	0.98	0.48	1.52	0.79
43	0.31	0.53	0.95	0.53	-0.49	0.99	0.81	0.49	1.79	0.79
44	0.61	0.53	1.14	0.53	-0.64	1.01	1.09	0.49	1.80	0.80
45	0.44	0.54	1.12	0.54	-0.53	1.02	0.89	0.50	2.03	0.81
46	0.77	0.55	1.31	0.55	-0.70	1.03	1.26	0.51	1.95	0.82
47	0.55	0.56	1.30	0.56	-0.42	1.05	1.10	0.51	2.23	0.83
48	0.90	0.56	1.51	0.56	-0.57	1.06	1.44	0.52	2.10	0.83
49	0.67	0.57	1.41	0.57	-0.39	1.08	1.28	0.53	2.27	0.84
50	1.02	0.58	1.65	0.58	-0.49	1.09	1.60	0.53	2.29	0.85
51	0.74	0.59	1.51	0.59	-0.39	1.10	1.45	0.54	2.50	0.86
52	1.03	0.60	1.69	0.60	-0.61	1.12	1.73	0.55	2.39	0.87
53	0.85	0.60	1.68	0.60	-0.33	1.13	1.52	0.55	2.56	0.87
54	1.15	0.61	1.81	0.61	-0.58	1.15	1.77	0.56	2.38	0.88
55	0.86	0.62	1.75	0.62	-0.43	1.16	1.52	0.57	2.52	0.89
56	1.15	0.63	1.95	0.63	-0.55	1.17	1.65	0.57	2.29	0.90
57	0.96	0.63	1.84	0.63	-0.58	1.19	1.48	0.58	2.49	0.91
58	1.26	0.64	1.99	0.64	-0.59	1.20	1.56	0.59	2.30	0.91

59	0.95	0.65	1.89	0.65	-0.51	1.22	1.41	0.59	2.45	0.92
60	1.28	0.66	2.00	0.66	-0.63	1.23	1.63	0.60	2.24	0.93
61	0.95	0.66	1.89	0.66	-0.64	1.24	1.34	0.61	2.39	0.94
62	1.34	0.67	2.12	0.67	-0.51	1.26	1.57	0.61	2.27	0.95
63	1.10	0.68	2.06	0.68	-0.35	1.27	1.47	0.62	2.52	0.95
64	1.42	0.69	2.25	0.69	-0.36	1.29	1.66	0.63	2.40	0.96
65	1.16	0.69	2.27	0.69	-0.18	1.30	1.53	0.63	2.68	0.97
66	1.56	0.70	2.47	0.70	-0.05	1.31	1.76	0.64	2.51	0.98
67	1.37	0.71	2.46	0.71	-0.14	1.33	1.61	0.65	2.83	0.99
68	1.60	0.72	2.52	0.72	-0.23	1.34	1.65	0.65	2.59	0.99
69	1.37	0.72	2.47	0.72	-0.10	1.36	1.58	0.66	2.81	1.00
70	1.70	0.73	2.62	0.73	-0.17	1.37	1.76	0.67	2.65	1.01
71	1.43	0.74	2.58	0.74	-0.08	1.38	1.63	0.67	2.90	1.02
72	1.75	0.75	2.71	0.75	-0.17	1.40	1.80	0.68	2.69	1.03
73	1.52	0.75	2.61	0.75	0.00	1.41	1.60	0.69	2.91	1.03
74	1.81	0.76	2.77	0.76	0.00	1.43	1.78	0.69	2.70	1.04
75	1.49	0.77	2.69	0.77	0.14	1.44	1.67	0.70	3.00	1.05
76	1.73	0.78	2.74	0.78	-0.16	1.45	1.79	0.71	2.79	1.06
77	1.51	0.79	2.72	0.79	0.05	1.47	1.65	0.71	3.00	1.07
78	1.79	0.79	2.84	0.79	-0.13	1.48	1.87	0.72	2.83	1.07
79	1.57	0.80	2.84	0.80	0.15	1.50	1.75	0.73	3.07	1.08
80	1.80	0.81	2.86	0.81	-0.06	1.51	1.89	0.73	2.89	1.09
81	1.52	0.82	2.85	0.82	0.05	1.52	1.82	0.74	3.05	1.10
82	1.74	0.82	2.93	0.82	-0.20	1.54	1.94	0.75	2.92	1.11
83	1.47	0.83	2.84	0.83	0.07	1.55	1.84	0.75	3.10	1.11
84	1.74	0.84	2.97	0.84	-0.23	1.57	2.01	0.76	2.99	1.12
85	1.49	0.85	2.93	0.85	-0.01	1.58	1.88	0.77	3.18	1.13
86	1.66	0.85	2.93	0.85	-0.37	1.59	2.07	0.77	3.04	1.14
87	1.43	0.86	2.91	0.86	-0.18	1.61	2.00	0.78	3.25	1.15
88	1.61	0.87	2.95	0.87	-0.45	1.62	2.18	0.79	3.14	1.15

89	1.43	0.88	2.96	0.88	-0.24	1.64	1.97	0.79	3.28	1.16
90	1.67	0.88	3.06	0.88	-0.52	1.65	2.22	0.80	3.18	1.17
91	1.49	0.89	3.09	0.89	-0.33	1.66	2.09	0.81	3.39	1.18
92	1.72	0.90	3.15	0.90	-0.51	1.68	2.30	0.81	3.24	1.19
93	1.40	0.91	3.04	0.91	-0.45	1.69	2.04	0.82	3.35	1.19
94	1.78	0.91	3.20	0.91	-0.62	1.71	2.28	0.83	3.35	1.20
95	1.46	0.92	3.11	0.92	-0.43	1.72	2.05	0.83	3.46	1.21
96	1.68	0.93	3.10	0.93	-0.56	1.73	2.25	0.84	3.32	1.22
97	1.36	0.94	2.99	0.94	-0.53	1.75	2.00	0.85	3.38	1.23
98	1.64	0.94	3.05	0.94	-0.74	1.76	2.23	0.85	3.26	1.23
99	1.41	0.95	3.04	0.95	-0.81	1.78	1.99	0.86	3.39	1.24
100	1.91	0.96	3.34	0.96	-0.78	1.79	2.48	0.87	3.49	1.25
101	1.68	0.97	3.28	0.97	-0.59	1.80	2.26	0.87	3.61	1.26

Step ID	Moose (dev in μm)	Moose U (k=2 in μm)	Owl (dev in μm)	Owl U (k=2 in μm)	Ram (dev in μm)	Ram U (k=2 in μm)
1	-0.20	0.73	-0.52	0.63	-0.33	NR
2	-0.68	0.75	-0.68	0.65	-0.20	NR
3	-0.30	0.78	-0.57	0.68	-0.18	NR
4	-0.78	0.80	-0.88	0.70	-0.30	NR
5	-0.32	0.83	-0.70	0.73	-0.23	NR
6	-0.78	0.85	-0.72	0.75	-0.31	NR
7	-0.38	0.88	-0.59	0.78	-0.19	NR
8	-0.79	0.90	-0.84	0.80	-0.25	NR
9	-0.33	0.93	-0.73	0.83	-0.15	NR
10	-0.71	0.95	-0.89	0.85	-0.17	NR
11	-0.11	0.98	-0.84	0.88	-0.14	NR
12	-0.43	1.00	-1.00	0.90	-0.11	NR
13	-0.21	1.03	-0.80	0.93	-0.07	NR
14	-0.53	1.05	-0.83	0.95	-0.08	NR
15	-0.18	1.08	-0.63	0.98	0.00	NR
16	-0.37	1.10	-0.64	1.00	0.05	NR
17	-0.04	1.13	-0.44	1.03	0.10	NR
18	-0.25	1.15	-0.44	1.05	0.15	NR
19	-0.12	1.18	-0.76	1.08	0.13	NR
20	-0.33	1.20	-0.83	1.10	0.13	NR
21	0.02	1.23	-0.49	1.13	0.22	NR
22	-0.20	1.25	-0.35	1.15	0.19	NR
23	0.16	1.28	-0.28	1.18	0.21	NR
24	-0.02	1.30	-0.24	1.20	0.29	NR
25	0.21	1.33	-0.21	1.23	0.24	NR
26	0.08	1.35	-0.13	1.25	0.26	NR
27	0.41	1.38	-0.03	1.28	0.35	NR
28	0.32	1.40	0.04	1.30	0.38	NR

29	0.68	1.43	0.15	1.33	0.53	NR
30	0.54	1.45	0.32	1.35	0.52	NR
31	0.80	1.48	0.51	1.38	0.59	NR
32	0.75	1.50	0.61	1.40	0.62	NR
33	0.94	1.53	0.57	1.43	0.61	NR
34	0.95	1.55	0.68	1.45	0.71	NR
35	1.12	1.58	0.73	1.48	0.67	NR
36	1.12	1.60	0.90	1.50	0.84	NR
37	1.49	1.63	0.85	1.53	0.80	NR
38	1.55	1.65	1.04	1.55	0.89	NR
39	1.76	1.68	1.12	1.58	0.85	NR
40	1.78	1.70	1.24	1.60	0.99	NR
41	1.99	1.73	1.33	1.63	0.97	NR
42	1.96	1.75	1.57	1.65	1.10	NR
43	2.35	1.78	1.65	1.68	1.17	NR
44	2.24	1.80	1.82	1.70	1.23	NR
45	2.62	1.83	2.05	1.73	1.28	NR
46	2.52	1.85	2.18	1.75	1.42	NR
47	2.74	1.88	2.07	1.78	1.44	NR
48	2.61	1.90	2.12	1.80	1.57	NR
49	3.02	1.93	2.27	1.83	1.48	NR
50	2.89	1.95	2.40	1.85	1.66	NR
51	3.14	1.98	2.57	1.88	1.61	NR
52	2.98	2.00	2.59	1.90	1.72	NR
53	3.48	2.03	2.77	1.93	1.74	NR
54	3.24	2.05	2.74	1.95	1.81	NR
55	3.41	2.08	2.63	1.98	1.81	NR
56	3.17	2.10	2.54	2.00	1.83	NR
57	3.40	2.13	2.78	2.03	1.78	NR
58	3.16	2.15	2.80	2.05	1.88	NR

59	3.49	2.18	2.79	2.08	1.91	NR
60	3.22	2.20	2.70	2.10	1.93	NR
61	3.37	2.23	2.72	2.13	1.86	NR
62	3.14	2.25	2.80	2.15	2.06	NR
63	3.53	2.28	2.99	2.18	2.15	NR
64	3.32	2.30	2.89	2.20	2.34	NR
65	3.55	2.33	2.91	2.23	2.44	NR
66	3.34	2.35	2.88	2.25	2.62	NR
67	3.62	2.38	3.04	2.28	2.68	NR
68	3.28	2.40	2.84	2.30	2.67	NR
69	3.64	2.43	3.15	2.33	2.80	NR
70	3.40	2.45	3.12	2.35	2.89	NR
71	3.72	2.48	3.29	2.38	2.93	NR
72	3.44	2.50	3.27	2.40	3.01	NR
73	3.63	2.53	3.54	2.43	3.07	NR
74	3.47	2.55	3.48	2.45	3.12	NR
75	3.71	2.58	3.55	2.48	3.22	NR
76	3.43	2.60	3.43	2.50	3.19	NR
77	3.75	2.63	3.63	2.53	3.19	NR
78	3.56	2.65	3.62	2.55	3.25	NR
79	3.88	2.68	3.62	2.58	3.31	NR
80	3.63	2.70	3.44	2.60	3.26	NR
81	3.90	2.73	3.73	2.63	3.48	NR
82	3.69	2.75	3.68	2.65	3.40	NR
83	4.05	2.78	3.63	2.68	3.43	NR
84	3.89	2.80	3.64	2.70	3.45	NR
85	4.00	2.83	3.80	2.73	3.40	NR
86	3.83	2.85	3.76	2.75	3.38	NR
87	4.03	2.88	3.69	2.78	3.46	NR
88	3.83	2.90	3.57	2.80	3.41	NR

89	4.14	2.93	3.67	2.83	3.55	NR
90	3.95	2.95	3.72	2.85	3.50	NR
91	4.21	2.98	3.92	2.88	3.63	NR
92	3.99	3.00	3.97	2.90	3.57	NR
93	4.24	3.03	3.92	2.93	3.59	NR
94	4.10	3.05	3.94	2.95	3.71	NR
95	4.38	3.08	4.07	2.98	3.67	NR
96	4.13	3.10	4.05	3.00	3.65	NR
97	4.32	3.13	3.93	3.03	3.55	NR
98	4.13	3.15	3.94	3.05	3.56	NR
99	4.28	3.18	3.97	3.08	3.62	NR
100	4.29	3.20	4.23	3.10	3.86	NR
101	4.59	3.23	4.19	3.13	3.90	NR

We plot the data (without the measurement uncertainties) in temporal sort order in Figure 4.

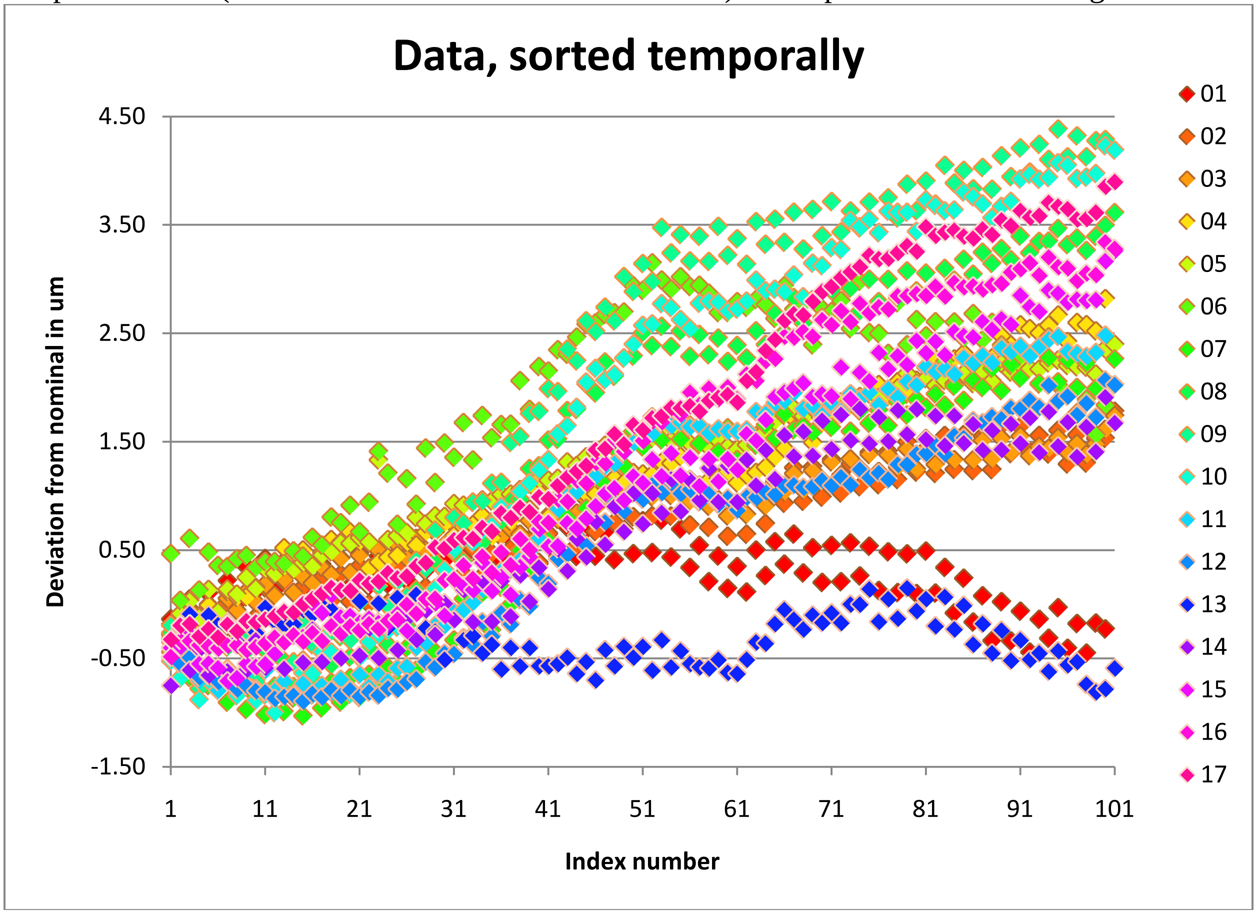

Figure 4. Summary of all reported data, without uncertainties. The data are graphed in temporal order, with earliest data in red, to orange, yellow, etc. and most recent data in violet/magenta.

From looking at the data, it can be seen that there is a lot of measurement scatter. In addition, there appear to be a temporal correlation with the data. If you ignore the '01' and '13' data, '02' thru '05' look well correlated. '06' thru '12' also look well correlated. Finally, '11', '12', '14', look correlated, as do '15', '16', and '17'.

Discussion

Because this is an interlaboratory comparison rather than a proficiency test, the determination of the "reference value" poses interesting questions[4]. A number of laboratories (Antelopes, Beavers, Buffalos, Cobras, and Eagles) report significantly lower uncertainties than other labs (Bats, Bears). However, the data reported within the group with lower uncertainties diverge. Nielsen[9] lists a number of methods for determining the consensus "reference value." Nielsen proposes identifying reliable measurements, based on a maximum likelihood type of evaluation ("Value Voted Most Likely to be Correct"), then, taking a weighted average of reliable measurements.

[4] The ILC coordinator greatly appreciates discussion and assistance from Mr. John Stoup at NIST for practices with CMM ILCs and from Dr. Harold Parks, Sandia Primary Electrical Standards, for help with the mathematics.

Without examining each individual data point (potentially 101 data points from each participant), the ILC data coordinator noted that in the first 4 data sets, one lab (‘01’) reported data substantially different (when considering measurement uncertainties using E_n calculation as described in ISO 17043 [2] and ISO 13528[10]. Using Nielsen’s method for “value voted most likely,” the coordinator removed data set ‘01’ in calculating a reference value.

The data coordinator then calculated a weighted average using data sets ‘02’ thru ‘05’.

In order to obtain a weighted average, we assume that a laboratory with a lower reported uncertainty has a higher likelihood of reporting a number near the reference value. We use the weighted average and estimated uncertainties as described in Taylor[11]. A weighted average is:

$$\bar{x} = \sum_i w_i x_i \tag{1}$$

where $\bar{x}$ is the weighted average, x_i is the individual laboratory measurement, and w_i is the weight for that value (note that the sum of the weights should be 1). From Taylor, assuming Gaussian distribution and uncorrelated errors,

$$w_i \propto \frac{1}{\sigma_i^2} \tag{2}$$

We need to find a normalizing constant c. From the condition that the sum of weights must be 1,

$$\begin{aligned} w_i &= c\frac{1}{\sigma_i^2} \\ c &= \left(\sum_i \frac{1}{\sigma_i^2}\right)^{-1} \end{aligned} \tag{3}$$

This shows that a lab with a smaller uncertainty has a higher weight on the weighted average. We note that one can use U instead of σ in Equation (3), and still have a valid result.

We therefore calculated the weighted average, using measurements made in the period November 2009 to March 2010 as an initial reference value. The weighted average of each deviation from the nominal step length was calculated using Equations (1) and (3). The expanded uncertainty U of each weighted average at a step is[5]:

$$U_{step} = k \cdot \sqrt{\left(\sum_i \frac{1}{\sigma_i^2}\right)^{-1}} \tag{4}$$

where k is the coverage factor, and σ_i the estimated standard deviation for an individual laboratory[6].

Similar calculations were made using the measurements from the period April 2010-June 2010; June 2010-December 2010, and December 2010-March 2011.

[5] Note the correction to the equation in the 2010 NCSLI Proceedings.
[6] Note that if you are consistent, you can use U’s instead of σ and omit k in Equation (4).

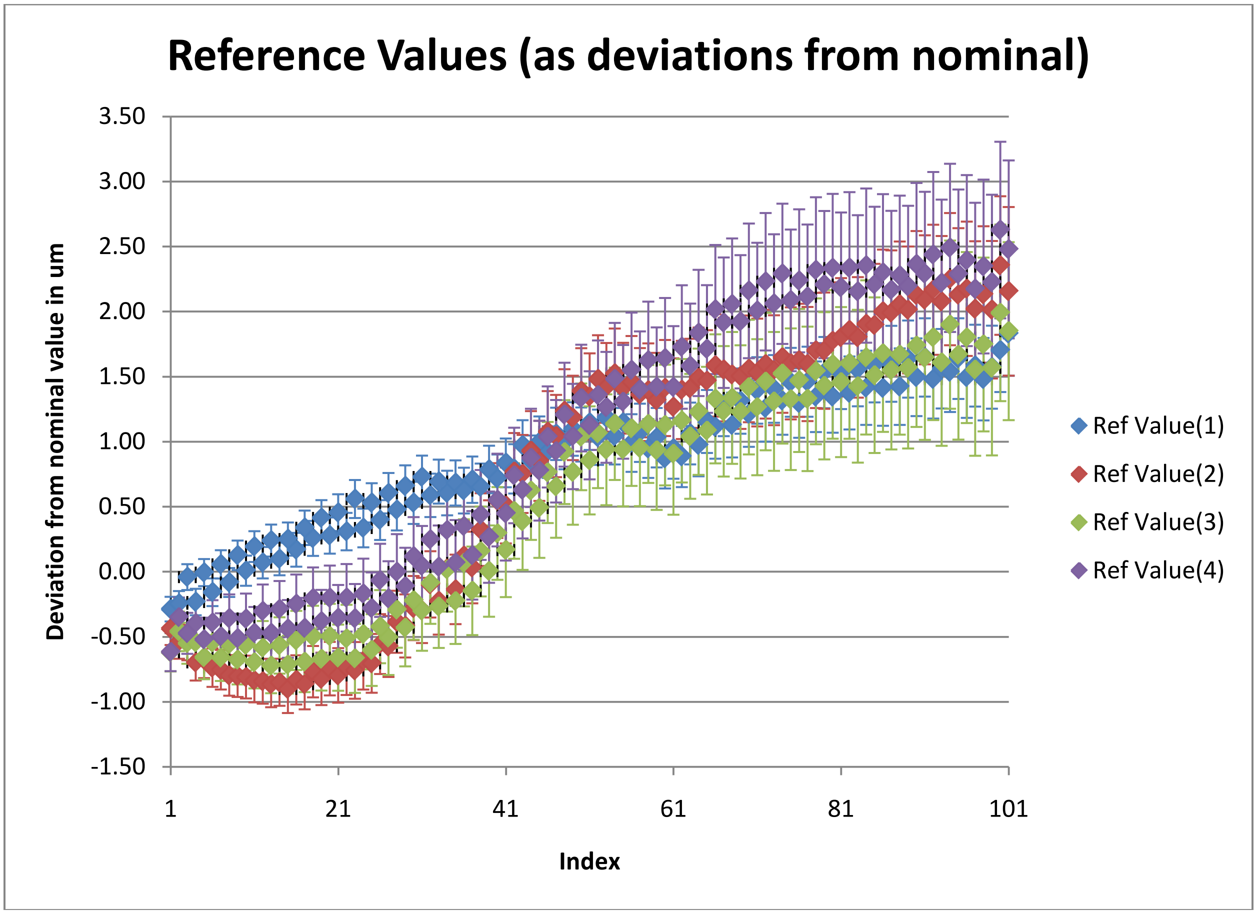

Figure 5. Calculations of 4 different sets of reference values, based on different time periods during the ILC.

RP-15, ISO-17043, and ISO-13528 all provide statistical evaluations for performance of an ILC. One commonly used method is to calculate the normalized error E_n. A common form for E_n is:

$$E_n = \frac{x_{ref} - x_i}{\sqrt{U_{ref}^2 + U_i^2}} \tag{5}$$

where x is the measured quantity, U is the expanded uncertainty with a coverage factor k=2, and the subscripts indicate the laboratory or the reference. In general, $|E_n| < 1$ is considered acceptable performance.

Note that one should also include artifact stability, if possible, in the calculation for U_{ref}, the expanded measurement uncertainty for the reference value. This has not been done in this case. The weighted average expanded uncertainty calculation of Equation (4) does not calculate a drift or stability term. One should use a drift or stability calculation, perhaps as a repeatability of standard deviation data, such as in [12] Chapter 2.3.3.2. We have not done that analysis yet.

Reference values and estimated uncertainties (only based on the reported laboratory uncertainties used in calculating the reference values) are tabulated below.

Table 5. Preliminary tabulation of reference values and uncertainties. The first set is the period November 2009-March 2010; second set is April 2010-July 2010; third set is July 2010-December 2010; fourth set is December 2010-March 2011.

Step ID	RefVal1 (dev in μm)	RefU1 (k=2, μm)	RefVal2 (dev in μm)	RefU2 (k=2, μm)	RefVal3 (dev in μm)	RefU3 (k=2, μm)	RefVal4 (dev in μm)	RefU4 (k=2, μm)
1	-0.29	0.09	-0.44	0.13	-0.62	0.15	-0.62	0.15
2	-0.25	0.10	-0.54	0.13	-0.46	0.15	-0.35	0.15
3	-0.04	0.10	-0.54	0.14	-0.55	0.16	-0.47	0.16
4	-0.23	0.10	-0.70	0.14	-0.54	0.16	-0.40	0.16
5	-0.01	0.10	-0.67	0.14	-0.66	0.17	-0.52	0.17
6	-0.16	0.11	-0.74	0.15	-0.55	0.17	-0.39	0.17
7	0.06	0.11	-0.75	0.15	-0.66	0.18	-0.50	0.18
8	-0.08	0.11	-0.80	0.16	-0.56	0.18	-0.36	0.18
9	0.13	0.11	-0.80	0.16	-0.68	0.19	-0.51	0.19
10	0.01	0.12	-0.81	0.16	-0.56	0.20	-0.36	0.20
11	0.19	0.12	-0.84	0.17	-0.70	0.20	-0.47	0.20
12	0.07	0.12	-0.84	0.17	-0.58	0.21	-0.30	0.21
13	0.24	0.12	-0.86	0.18	-0.72	0.21	-0.47	0.21
14	0.10	0.13	-0.85	0.18	-0.57	0.22	-0.29	0.22
15	0.25	0.13	-0.90	0.19	-0.71	0.22	-0.44	0.22
16	0.17	0.13	-0.83	0.19	-0.53	0.23	-0.25	0.23
17	0.34	0.13	-0.86	0.19	-0.69	0.23	-0.43	0.23
18	0.26	0.13	-0.77	0.20	-0.50	0.24	-0.20	0.24
19	0.41	0.14	-0.82	0.20	-0.67	0.24	-0.38	0.24
20	0.28	0.14	-0.74	0.21	-0.50	0.25	-0.20	0.25
21	0.45	0.14	-0.80	0.21	-0.66	0.25	-0.36	0.25
22	0.31	0.14	-0.73	0.21	-0.51	0.26	-0.20	0.26
23	0.56	0.15	-0.76	0.22	-0.67	0.27	-0.36	0.27
24	0.34	0.15	-0.68	0.22	-0.48	0.27	-0.17	0.27
25	0.53	0.15	-0.70	0.23	-0.60	0.28	-0.28	0.28
26	0.40	0.15	-0.56	0.23	-0.42	0.28	-0.07	0.28
27	0.60	0.16	-0.57	0.23	-0.51	0.29	-0.21	0.29

28	0.48	0.16	-0.38	0.24	-0.29	0.29	0.00	0.29
29	0.66	0.16	-0.42	0.24	-0.43	0.30	-0.11	0.30
30	0.53	0.16	-0.28	0.25	-0.22	0.30	0.12	0.30
31	0.73	0.16	-0.30	0.25	-0.30	0.31	0.04	0.31
32	0.59	0.17	-0.10	0.25	-0.09	0.31	0.25	0.31
33	0.69	0.17	-0.22	0.26	-0.27	0.32	0.04	0.32
34	0.61	0.17	0.03	0.26	0.02	0.32	0.32	0.32
35	0.68	0.17	-0.14	0.27	-0.23	0.33	0.07	0.33
36	0.62	0.18	0.12	0.27	0.07	0.33	0.35	0.33
37	0.71	0.18	0.03	0.28	-0.15	0.34	0.13	0.34
38	0.65	0.18	0.32	0.28	0.16	0.35	0.44	0.35
39	0.79	0.18	0.27	0.28	0.01	0.35	0.27	0.35
40	0.72	0.19	0.55	0.29	0.29	0.36	0.55	0.36
41	0.84	0.19	0.51	0.29	0.17	0.36	0.45	0.36
42	0.79	0.19	0.77	0.30	0.47	0.37	0.74	0.37
43	0.97	0.19	0.75	0.30	0.39	0.37	0.63	0.37
44	0.85	0.19	0.93	0.30	0.62	0.38	0.88	0.38
45	1.00	0.20	0.85	0.31	0.49	0.38	0.78	0.38
46	0.92	0.20	1.08	0.31	0.76	0.39	1.04	0.39
47	1.06	0.20	1.04	0.32	0.66	0.39	0.93	0.39
48	0.99	0.20	1.24	0.32	0.92	0.40	1.21	0.40
49	1.10	0.21	1.18	0.32	0.77	0.40	1.04	0.40
50	1.05	0.21	1.39	0.33	1.04	0.41	1.34	0.41
51	1.15	0.21	1.35	0.33	0.86	0.42	1.13	0.42
52	1.03	0.21	1.48	0.34	1.06	0.42	1.36	0.42
53	1.18	0.21	1.42	0.34	0.94	0.43	1.26	0.43
54	1.04	0.22	1.52	0.34	1.14	0.43	1.48	0.43
55	1.15	0.22	1.41	0.35	0.94	0.44	1.31	0.44
56	0.99	0.22	1.46	0.35	1.10	0.44	1.55	0.44
57	1.07	0.22	1.36	0.36	0.95	0.45	1.40	0.45

58	0.95	0.23	1.39	0.36	1.14	0.45	1.62	0.45
59	1.03	0.23	1.32	0.37	0.93	0.46	1.42	0.46
60	0.87	0.23	1.41	0.37	1.13	0.46	1.64	0.46
61	0.95	0.23	1.27	0.37	0.91	0.47	1.42	0.47
62	0.89	0.24	1.40	0.38	1.16	0.47	1.73	0.47
63	1.06	0.24	1.41	0.38	1.04	0.48	1.58	0.48
64	0.97	0.24	1.49	0.39	1.23	0.49	1.84	0.49
65	1.16	0.24	1.47	0.39	1.08	0.49	1.71	0.49
66	1.11	0.24	1.59	0.39	1.33	0.50	2.02	0.50
67	1.29	0.25	1.55	0.40	1.23	0.50	1.91	0.50
68	1.13	0.25	1.52	0.40	1.34	0.51	2.06	0.51
69	1.31	0.25	1.50	0.41	1.23	0.51	1.92	0.51
70	1.21	0.25	1.56	0.41	1.42	0.52	2.16	0.52
71	1.39	0.26	1.53	0.41	1.27	0.52	2.01	0.52
72	1.26	0.26	1.60	0.42	1.46	0.53	2.23	0.53
73	1.41	0.26	1.55	0.42	1.31	0.53	2.06	0.53
74	1.32	0.26	1.65	0.43	1.52	0.54	2.29	0.54
75	1.46	0.26	1.60	0.43	1.33	0.54	2.09	0.54
76	1.30	0.27	1.63	0.43	1.47	0.55	2.24	0.55
77	1.46	0.27	1.60	0.44	1.33	0.56	2.11	0.56
78	1.35	0.27	1.70	0.44	1.54	0.56	2.32	0.56
79	1.53	0.27	1.70	0.45	1.43	0.57	2.21	0.57
80	1.35	0.28	1.77	0.45	1.59	0.57	2.33	0.57
81	1.53	0.28	1.80	0.46	1.46	0.58	2.19	0.58
82	1.37	0.28	1.86	0.46	1.60	0.58	2.34	0.58
83	1.55	0.28	1.80	0.46	1.43	0.59	2.15	0.59
84	1.41	0.29	1.90	0.47	1.65	0.59	2.35	0.59
85	1.59	0.29	1.90	0.47	1.51	0.60	2.21	0.60
86	1.41	0.29	2.00	0.48	1.68	0.60	2.30	0.60
87	1.60	0.29	1.99	0.48	1.55	0.61	2.17	0.61

88	1.42	0.29	2.06	0.48	1.67	0.61	2.28	0.61
89	1.64	0.30	2.01	0.49	1.57	0.62	2.19	0.62
90	1.50	0.30	2.13	0.49	1.74	0.63	2.36	0.63
91	1.65	0.30	2.09	0.50	1.64	0.63	2.29	0.63
92	1.48	0.30	2.17	0.50	1.80	0.64	2.44	0.64
93	1.56	0.31	2.08	0.50	1.61	0.64	2.22	0.64
94	1.54	0.31	2.25	0.51	1.90	0.65	2.49	0.65
95	1.64	0.31	2.13	0.51	1.67	0.65	2.29	0.65
96	1.50	0.31	2.18	0.52	1.80	0.66	2.39	0.66
97	1.58	0.31	2.02	0.52	1.55	0.66	2.17	0.66
98	1.48	0.32	2.13	0.52	1.75	0.67	2.35	0.67
99	1.57	0.32	2.01	0.53	1.57	0.67	2.23	0.67
100	1.70	0.32	2.35	0.53	1.99	0.68	2.63	0.68
101	1.83	0.32	2.16	0.65	1.85	0.68	2.48	0.68

We believe that the estimated uncertainty for the reference value, as reported in Table 5, is too small, as that estimate does not include a term for stability of the artifact. The plot of Figure 5 shows that the artifact has drifted significantly over time. E_n calculations are therefore not performed at this time.

It is also very possible that in addition to artifact stability, another source of variability is set up. While the instructions were fairly explicit about how to set up the measurement, different laboratories will set up the measurement differently. During the discussion at the oral presentation at the 2010 NCSLI Workshop and Symposium [8], it was noted that some laboratories clamped the step gage, even though the instructions noted that this was not necessary. Stoup [13] reports that the origin of a step gage could vary by as much as "50 μm depending on the surfaces sampled during coordinate system generation." Furthermore, the "long axis direction can easily vary by as much as 0.1 degrees (6 arc-minutes) and results in a length dependent effect of 0.15 μm/m.

The data coordinator performed some finite element analysis[7] to look at gravity-induced deformation of the step bar, and the effect of changing the support points. The bottom of the Checkmaster contains 2 sets of feet, spaced at approximately the Airy points for the length of the bar. However, these feet are relatively wide, and do not support the Checkmaster kinematically, as they approximate a "flat against flat" contact (flat feet against flat surface plate). Figure 6 shows a typical boundary condition, where we varied where the foot would contact the surface plate. Figure 7 shows a typical result from a finite element analysis, showing on the order of 30 nm of horizontal deflection of a step.

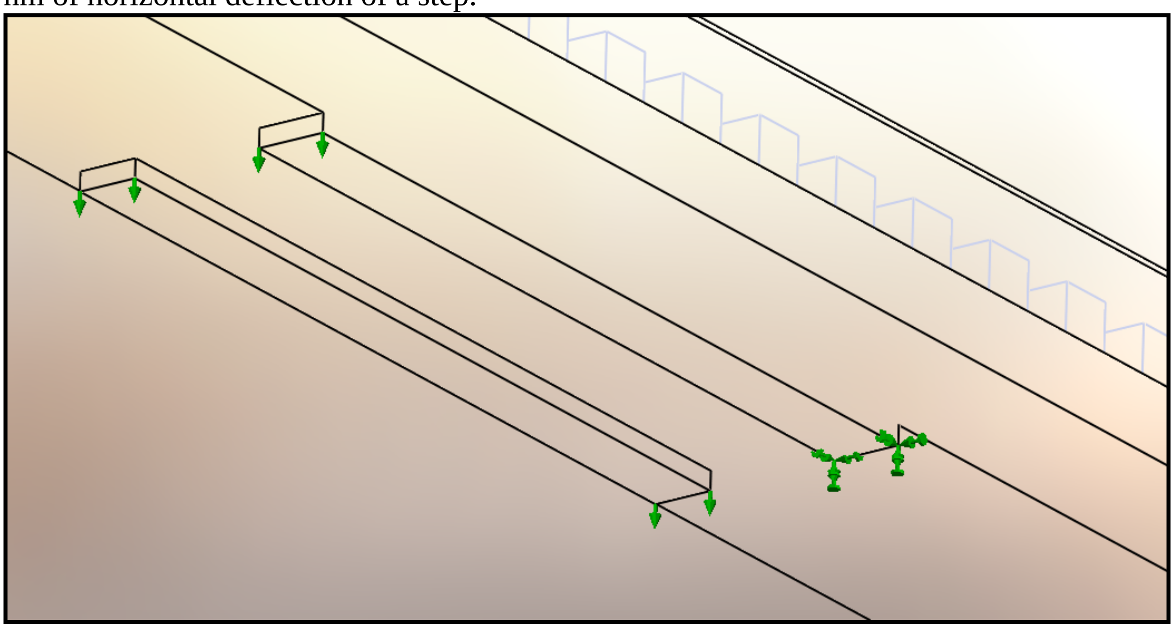

Figure 6. Boundary conditions for the finite element analysis, fixing high points or low points where the foot contacts the CMM surface plate, and allowing the foot to slide

[7] The speaker thanks Aubrey Blair-Pattison, then a student intern at Sandia National Laboratories, for actually running the analyses in the summer of 2010, using SolidWorks Simulation Professional 2009.

The variation in horizontal deflections, based on whether the support contact is closer to the inside edge of the feet or the outside edge of the feet, is at most 50 nm. This variation is insignificant compared to the variations observed over multiple laboratories.

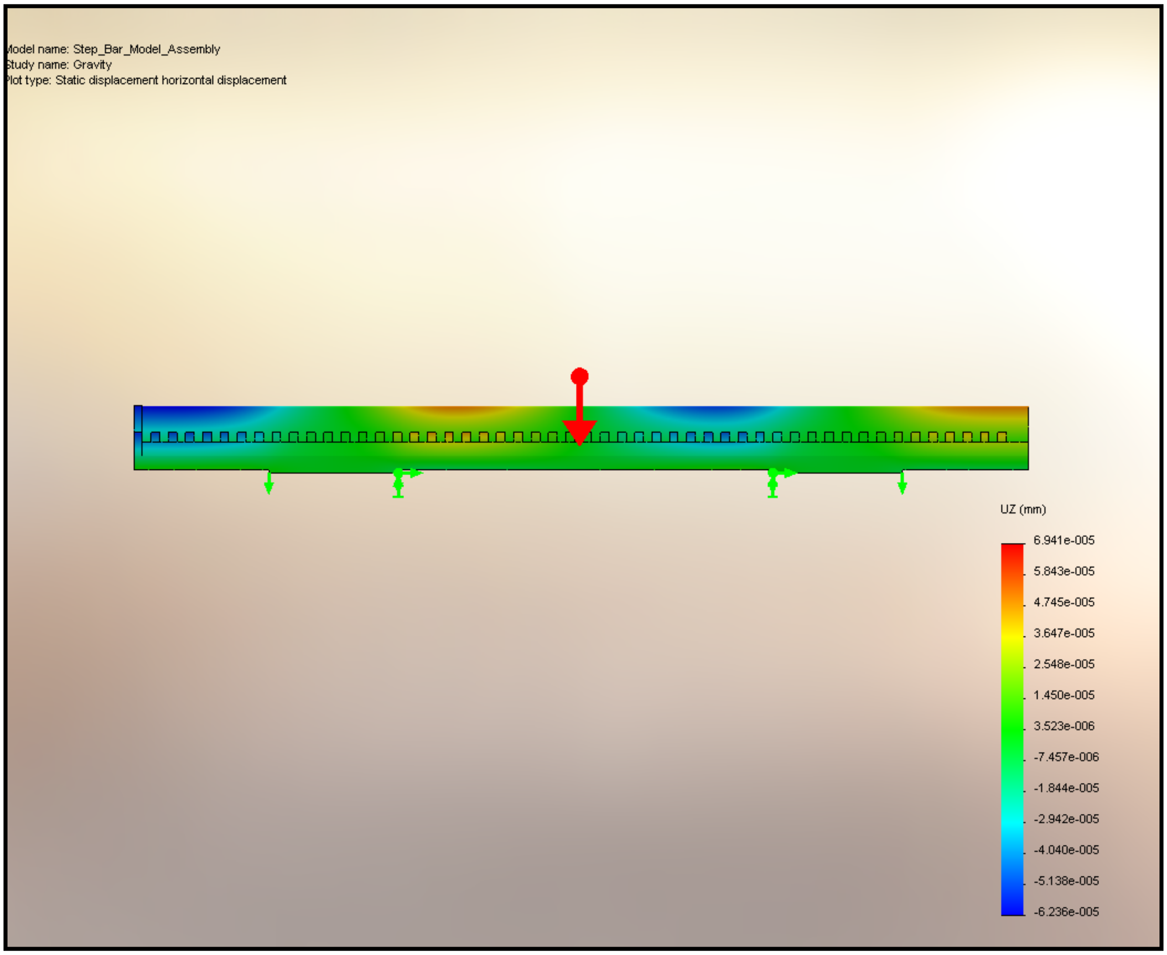

Figure 7. Typical finite element analysis for gravity-induced deflection. The "z" axis is actually along the length of the bar; gravity is along "y" and "x" is normal to the page.

Sandia National Laboratories owns a ceramic Checkmaster similar to the one used for the ILC. Figure 8 shows measurements performed on this gage over the period of several months. These measurements were made with removing the gage from the CMM and putting it into its storage case, then, placing back on the CMM and measuring. The measurements are very consistent. This leads the data coordinator to believe that a portion of the observed variability is due to transportation.

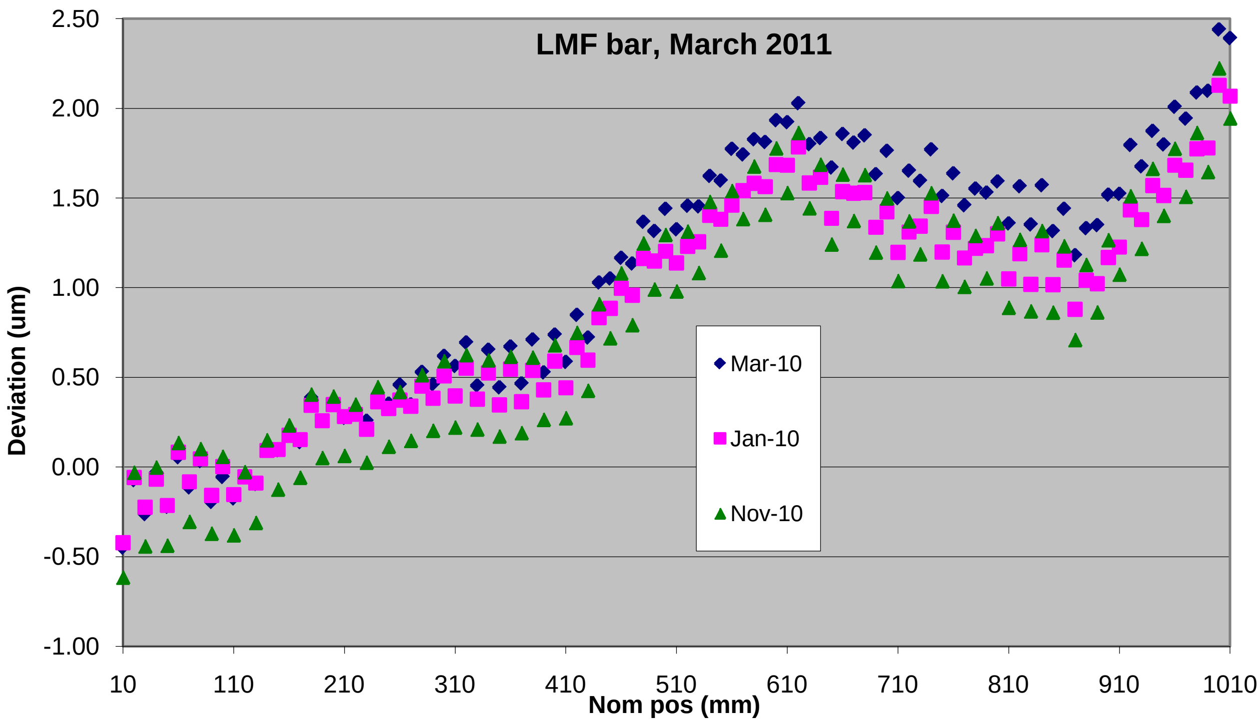

Figure 8. Reproducibility of a Checkmaster which is not shipped.

Conclusions

The analysis is still on-going. 2 participants have not yet reported complete results as of submission date for the proceedings, and 3 repeat measurements are still necessary (Beaver, Buffalo, and Cobra). The data coordinator anticipates providing more complete analysis during the oral presentation.

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