Uncertainties for the Common User

Abstract
Uncertainties for the Common User is a white paper based on a short presentation and discussion on the reporting of measurement uncertainties by calibration laboratories. It will cover measurement uncertainties, how to apply them and why they are important. Realistic examples using electrical and dimensional applications will be used to illustrate the topics covered.

Introduction

There has been a lot of discussion in the calibration, metrology, and related accreditation communities about "uncertainties" over the past decade. Historically, the measurement uncertainty information was a primary concern for metrology laboratories and calibration laboratories but, due to the globalization of manufacturing, the ever tightening of manufacturing tolerances and the advancement of measurement technology, measurement uncertainty information is reaching the shop floor and the end user by necessity. Often these discussions revolve around concepts described in excruciating detail and are filled with technical terminology and references to statistics. Admittedly, there really is no way around it; calibration and metrology are complex subjects. In light of that, I will attempt to distill the basic idea of measurement uncertainty within the context of what the common end user may see and in terms which are more familiar.

What

The heart of the discussion centers on this simple statement, "… the [measurement] result is complete only when accompanied by a quantitative statement of its uncertainty."[1] Applying this logic, the following measurement results are considered incomplete: this power supply reads 9.625 Volts; that block is 2.000" in length. Whereas the following results are more complete: this power supply reads 9.625 V ± 0.005 V; that block is 2.000 000" ± 0.000 026" in length. Technically, even these statements are considered to be incomplete because they do not identify a coverage factor or a confidence interval, which is all part of that detail that I have purposely excluded from this paper. But for your information, the coverage factor and confidence interval can typically be found in the tiny print or text of a calibration certificate. So what exactly are these additional plus and minus (±) numbers? We first have to agree that there are no perfect instruments and there are no perfect measurements, so there is always something "unknown" about every measurement. This "unknown" is defined by

Authored By: Phil Mistretta, Transcat Inc.

calibration accredited laboratories as follows: "Measurement uncertainty is the quantitative evaluation of the reasonable values that are associated with a measurement result. It is a probabilistic expression of the doubt in a particular measurement value."[2] Now in plain terms this means these additional numbers are the calibration laboratory's best estimation, in realistic numbers, using scientific and statistical methods. These "unknowns" are formally termed "measurement uncertainties".

Please note I have yet to use the terms accuracy or error. Although uncertainty, accuracy and error are related terms, they have different meanings in this context and cannot be used interchangeably. Error is the difference [offset or deviation] between the measured value and the 'true value' of the thing being measured (also known as the measurand).[3] For example, a gage block may be marked as 2", but the calibration lab test report states the actual size is 2.0001", therefore the error of this block is +0.0001". Whenever possible we try to correct for any known errors.[4] Accuracy describes the closeness of the degree of agreement between the measurement result and the "true value". (Accuracy is a qualitative term only).[5] For our gage block example, the manufacture states they make the gage block to an accuracy of ± 0.0005", meaning the actual size of the block is expected to fall somewhere between 1.9995" and 2.0005", which in this case, it does. The accuracy statement describes the expected quality of the block and helps identify the type of measurements it is suited to perform in general. For a complete measurement result for our gage block, the report must include the measurement uncertainty: 2.0001 ± 0.000 004 1". We now have some quantitative knowledge of our gage block's actual length

To understand an accredited laboratory's calibration and measurement capability (CMC) (i.e., their best measurement uncertainty) you should examine their published Scope of Accreditation. A typical scope of accreditation will look similar to this:

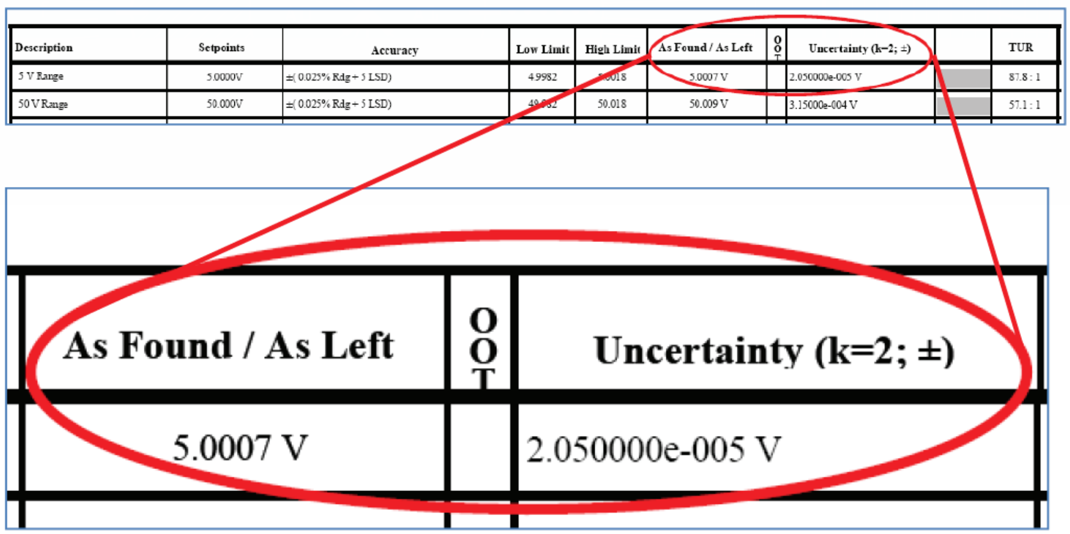
CALIBRATION AND MEASUREMENT CAPABILITIES (CMC)[Notes 1,2]

Measured Parameter or Device Calibrated	Range	Uncertainty (k=2) [Note 3]	Remarks
Digital & Dial Indicators Field calibrations available [Note 4]	0 in to 6 in	1.1 µin + 7.5L µin	Gage Blocks with Surface Plate

Figure 1

Appendix A has 3 full-page examples of different Scopes of Accreditation. These documents quantify the laboratory's best or smallest uncertainty achievable. The 'scope' (as we informally call them) is published so customers can determine whether the laboratory has the ability to perform the calibration activity suitable for their equipment. As a side note, the uncertainty published on the scope of accreditation may not match the uncertainty on your calibration report for your measurement equipment; you may get a larger measurement uncertainty because the "best" uncertainty a lab can achieve is often overkill for most equipment. This doesn't mean you received a "bad" calibration, in all likelihood the lab still followed Good Metrology Practices (GMetP) and followed the infamous 4-to-1 rule (meaning their calibration process is 4 times better than your test equipment) which is accepted industry wide as the minimum target of calibration.

When you send in your units for calibration, what you will actually receive will look something like the data report excerpt shown in Figure 2. These are the actual uncertainty values for the specific measurement reported by the calibration lab. This is the information you will need when you conduct your uncertainty assessment. In this example the measurement taken was 5.0007 Volts, and the laboratory has a ± 0.000 020 5 Volt margin of uncertainty around that specific value.



Description	Setpoints	Accuracy	Low Limit	High Limit	As Found / As Left	OOT	Uncertainty (k=2; ±)		TUR
5 V Range	5.0000V	±(0.025% Rdg + 5 LSD)	4.9982	[illegible]	5.0007 V		2.050000e-005 V		87.8 : 1
50 V Range	50.000V	±(0.025% Rdg + 5 LSD)	[illegible]	50.018	50.009 V		3.15000e-004 V		57.1 : 1

Figure 1

Why

You should be familiar with measurement uncertainties if you a performing any type of calibration on any devices that will in turn be used to perform other process measurements. This can be thought of as the domino effect: any uncorrected errors and all uncertainties in the calibration measurement process will be passed down to all the measurements made by the calibrated device. This is a critical component of metrological traceability. Another case where uncertainties can be important is during an acceptance/ rejection process. If the uncertainties in the testing instrument and the measurement process are large enough, there can be serious economic impact with falsely accepting bad product or falsely rejecting good product, not to mention the potential safety impact this can have. These implications increase significantly as potential nonconforming parts move through the assembly process, into the final product and to the end customer.

As mentioned earlier, there are no perfect measuring instruments, which also apply to instruments used in the manufacturing process. Taking actual measurements is also a process in and of itself, there is more to the process than just the quantity to be measured and the measuring instrument. There are many sources of potential error which, even a quick error assessment can identify. A few of sources of error to consider are the measurement device and its calibration, test leads, connectors, cables, leads and switches. One should also consider the measurement environment: ambient temperature, pressure and humidity can all be sources of error. A few less obvious environmental errors can be associated with air quality, particulate contamination and lighting conditions, and believe it or not, altitude and gravity. Then you should consider some less obvious sources such as software programs and their resolution limitations, signal conditioning, signal digitization and unit of measurement conversion factors. And finally consideration must be given to the operator. Some measurement techniques require highly skilled operators and require the operator to make interpretations, interpolations or make judgment decisions. This is especially true with dimensional measurements where Gage R&R studies are often completed to quantify and hopefully compensate or correct for these potential errors. Commonly, many of these potential sources of error will have an affect your measurement process. It depends upon your process requirements, what you are measuring, how accurate you need to know the measurement, and other factors. The bottom line is: get to know your measurement process! Any error whose value we do not know [the 'unknown'] is a source of uncertainty.[6] For example, we have an old 2" Gage Bock that was sent for calibration and the calibration data report states it to have an actual length of 1.978 122" ± 0.000 008" at 68°F ± 1°F. What we don't know is the actual length after 6 months of heavy use on your shop floor which is 75°F ± 10°F when sitting on a surface plate being used as a reference during a height transfer technique that also uses an indicator head, a gage amplifier and a height gage. There are at least 10 sources of potential measurement errors in that last sentence; can you identify them all? If you miss any, what impact will it have on your product's safety or cost? If you're not currently taking into account any sources of error, then you might approach this another way: what are some of the common production problems your company is experiencing? Are any of them related to potential sources of error that have not been taken into consideration? Transcat offers consultation that reveals sources of error in the measurements you take with your instruments and can help you to understand how this impacts quality decisions in your production process.

How

In the calibration lab we follow some very detailed and specific procedures when conducting error analysis and developing uncertainty budgets, such as the Guide to Uncertainties of Measurement (GUM) and NIST Technical Note 1297. These analyses can be very time consuming and require a very high level of expertise in the appropriate field of knowledge. The end result of these guides is what we call an Uncertainty Budget (see appendix B for examples). I am not going to explain these in any detail; they are only presented for informational purposes and we offer other white papers and training that go into those details. If you are curious about further detail, I have included a list documents for further reading. I highly recommend Stephanie Bell's "A Beginners Guide to Uncertainty of Measurement", available free on-line through the National Physicals Laboratory (NPL) which is the United Kingdom's equivalent of NIST.

If you look over the sample Electrical Uncertainty Budget, there are only 3 major components: the unit's specifications, the measurement uncertainty associated with the calibration of the unit, and the repeatability of the measurement process. There are 2 minor components covered in the note at the bottom: a minimum noise floor and thermal EMF due to the test leads. Overall it is pretty straight forward as far as the components are concerned. I have completely glossed over the statistics and the method of combining the components used to generate the final uncertainty value. Again, this is an introduction and not meant to cover those details.

Now please look over the sample Dimensional Uncertainty Budget. It has a few more components, but did you pick up on the largest source of uncertainty? It is (L Temp 68°F 3°F) which is the temperature variation in the room; it swings a maximum of 3°F. This budget is for the calibration of micrometers, imagine what the uncertainties would be if you calibrated a micrometer on a shop floor with temperature controls swinging 5°F or 10°F! Now it isn't necessary to go to all of the detail as shown in the example budgets to get started. As the old saying goes, how do you walk 1,000 miles…. one step at a time. What is presented here can be thought of as a rough-order-of-magnitude error assessment. At this point all you want to do is identify the realistic sources of potential error. I have found one of the best tools is to draw a picture of the measurement process and then step back and look it over for potential sources of error. For example, let say our process says to check the power supply and it must read 9.00 Volts ± 2.00 Volts, meaning the power supply has to read between 7.00 and 11.00 Volts. You are simply using a Digital Multimeter and a set of test leads. You list the sources of possible error in a chart and simply add up the measurement effect.

Uncertainty	Cause	Effect	Note
1	Meter Accuracy	± 0.00725 V	0.025% of Reading +5 LSD
2	Meter Calibration @ 9 Volts	± 0.000314 V	From Cal Certificate
3	4" Test leads	± 0.000 V	Experiment
		± 0.007564	

As you can see from the chart the largest source of uncertainty is from the Accuracy specification of the multi-meter, while the calibration uncertainty is about 25 times smaller, and the test leads really have no impact at all. From this assessment you may conclude that the process is suitable for making the 9.00 ± 2.00 Volt measurement since the multi-meter can reasonably read to ± 0.008 Volts (due to the resolution of the meter and rounding). However, you can also see that if your test results turn out to be 6.99, 7.00, 7.01 (near the lower process limit) or 10.99, 11.00, or 11.01 (near the upper process limit) your measurement process may not be telling you the correct value due to the analysis you conducted. You may be falsely accepting bad product or falsely rejecting good product if the meter indicates values near these limits. At this point it is a business decision as to what happens next. Are these questionable readings posing an acceptable business risk? How many units actually have readings in these areas of uncertainty? There are many such non-measurement related factors that should be considered in business risk decisions. If the business risk is unacceptable, then you may need to take the next step and learn how to complete an uncertainty analysis following acceptable practices, or take some other process improvement steps in order to remove the unacceptable risk.

The simple example above is far from a true uncertainty budget like the examples in the appendix of this paper, but it does introduce the use of the Calibration Uncertainty into the context of the manufacturing process and provides a method to generate sound information on which to base business decisions intended to remove doubt.

Summary

Don't take unnecessary risks; understand the limitations posed by unknown sources of error and take action to remove them or reduce them to an acceptable level. Ask for help if you need to, but don't leave it alone and hope it goes away.

References

ASME Division 7. "Measurement Uncertainty: Understanding and Economic Benefits." ASME B89.7. New York, NY 10016 5990: ASME Division 7.

Bell, Stephanie. "A Beginner's Guide to Uncertainty of Measurement." Measurement Good Practice Guide #11 (Issue 2). Teddington, Middlesex, United Kingdom, TW11 0LW: Centre for Basic, Thermal and Length Metrology, National Physical Laboratory, August 1992.

Taylor, Barry N. and Chris E. Kuyatt. NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. Technical Note. Gaithersburg, MD 20899 0001: Physics Laboratory NIST, U.S. Dept of Commerce, 1994.

[1] (Taylor and Kuyatt)
[2] (ASME Division 7)
[3] (Bell)
[4] (Bell)
[5] (Bell)
[6] (Bell)

Further Reading:

- http://www.npl.co.uk/publications/guides/ (many free guides available for download)
- ASME B89.7 (free brochure available on-line)
- ASME B89.7.2 Dimensional Measurement Planning
- ASME B89.7.3.1 Guidelines for Decision Rules: Considering Measurement Uncertainty, Determining Conformance to Specifications
- ASME B89.7.3.2 Guidelines for the Evaluation of Dimensional Measurement Uncertainty
- ASME B89.7.3.3 Guidelines for Assessing the Reliability of Dimensional Measurement Uncertainty Statements
- ASME B89.7.4.1 Measurement Uncertainty and Conformance Testing : Risk Analysis
- ASME B89.7.5.1 Metrological Traceability of Dimensional Measurements to the SI unit of Length

Although the B89.7 series of documents are written specifically for Dimensional measurements, some of them have information that is applicable to almost all areas of measurement. I particularly like the B89.7.3.1 which covers Decision Rules which can cause many disagreements between customers and different measurement service providers. It is intended to clarify the Decision Rule terms as well as ownership of a Decision Rule.

About the Author:

Philip Mistretta is a Metrology Manager for Transcat Inc. He has over 25 years experience in the Metrology field including Managing an ISO-17025 Accredited Laboratory. Phil currently holds an ASQ-CCT certificate.

Phil was a Lean Manufacturing Engineer for Viatran Corporation in Grand Island, NY where he earned his 6-Sigma Green Belt, received his Lean Enterprise training and experience and managed the company's Calibration Program.

Phil also completed his AAS in Communication Electronics Technology from Central Texas College and his ISCET Associate CET while serving his 9 years of active duty in U.S. Army. He received his Metrology training at Lowry Air Force Base in Denver, Colorado in 1987, and was an Honor Graduate of the U.S. Army Secondary Reference Laboratory course covering DC & Low Frequency, Physical & Dimensional, and RF & Microwave Measurements in 1993 also at Lowry AFB.

He currently is in his 3rd year of college, pursuing a Bachelor of Science Degree in Engineering Physics from the State University of New York at Buffalo.

You may contact Phil Mistretta at phil.mistretta@transcat.com

Transcat sells and markets test and measurement instrumentation as well as trusted and convenient Metrology services (including accredited calibration, repair, accredited reference standards services, managed services, 3D Metrology, managed operations and consulting/training) to a variety of industries including medical device manufacturers, pharmaceutical, biotech engineering, petroleum refining, chemical manufacturing, and public utility. Transcat celebrates its 48th year in business in 2012. For more information, go to www.transcat.com.

TRANSCAT®
Better by every measure

35 Vantage Point Drive
Rochester, NY 14624

800.828.1470
Transcat.com

National Voluntary Laboratory Accreditation Program

CALIBRATION LABORATORIES **NVLAP LAB CODE 200914-0**

SCOPE OF ACCREDITATION TO ISO/IEC 17025:2005

Transcat - Rochester 35 Vantage Point Drive Rochester, NY 14264 Mr. Chris Herrmann Phone: 585-352-9720 Fax: 800-395-0543 E-mail: cherrmann@transcat.com URL: www.transcat.com	**Parameter(s) of Accreditation** Dimensional Electromagnetics – DC/Low Frequency Time and Frequency Mechanical Electromagnetics – RF/Microwave Thermodynamic This laboratory is compliant to ANSI/NCSL Z540-1-1994; Part 1. (NVLAP Code: 20/A01)

CALIBRATION AND MEASUREMENT CAPABILITIES (CMC) [Notes 1,2]

Measured Parameter or Device Calibrated	Range	Uncertainty (k=2) [Note 3]	Remarks
DIMENSIONAL			
NVLAP Code: 20/D01 **ANGULAR**	0 ° to 75 ° 90 °	5.4 arc seconds 1.1 arc seconds	Angle Blocks Granite Square
NVLAP Code: 20/D05 **LENGTH & DIAMETER; STEP GAGES** Micrometers & Calipers – Outside, Inside, Depth Field calibrations available [Note 4]	0 in to 8 in 8 in to 24 in	12 µin + 7L µin 7 µin + 7.5L µin	Comparison to Gage Blocks Where L is length in inches of the device under test.
Surface Flatness Field calibrations available [Note 4]	0 in to ~~1~~ 4 in	6.6 µin	Optical Flats
Anvil Parallelism Field calibrations available [Note 4]	0 in to 1 in	6.6 µin	Optical Flats

2011-10-01 through 2012-09-30
Effective dates

For the National Institute of Standards and Technology

Sample

ANSI-ASQ National Accreditation Board/ACLASS

SCOPE OF ACCREDITATION TO ISO/IEC 17025:2005 & ANSI/NCSL Z540-1-1994

Transcat – Phoenix

6150 W. Chandler Blvd Suite 38 Chandler, AZ 85226
POC: Ryan Gohl Phone: 480-820-1500

CALIBRATION

Valid to: March 16, 2013 Certificate Number: AC-1381

I. Electromagnetic - DC/Low Frequency

PARAMETER / EQUIPMENT	RANGE	CALIBRATION & MEASUREMENT CAPABILITY [EXPRESSED AS UNCERTAINTY(±)]	REFERENCE STANDARD OR EQUIPMENT	METHOD(S)
AC Current - Measure	**Up to 100 µA**		Agilent 3458A	OEM or GIDEP-Sourced, or Customer Specific Procedures
	(10 to 20) Hz	3.8 mA/A + 29 nA		
	(20 to 45) Hz	1.4 mA/A + 29 nA		
	(45 to 100) Hz	590 µA/A + 29 nA		
	100 Hz to 1 kHz	590 µA/A + 29 nA		
	100 µA to 1 mA			
	(10 to 20) Hz	3.8 mA/A + 190 nA		
	(20 to 45) Hz	1.4 mA/A + 190 nA		
	(45 to 100) Hz	590 µA/A + 190 nA		
	100 Hz to 5 kHz	330 µA/A + 190 nA		
	(1 to 10) mA			
	(10 to 20) Hz	3.8 mA/A + 1.9 µA		
	(20 to 45) Hz	1.4 mA/A + 1.9 µA		
	(45 to 100) Hz	590 µA/A + 1.9 µA		
	100 Hz to 5 kHz	330 µA/A + 1.9 µA		
	(10 to 100) mA			
	(10 to 20) Hz	3.8 mA/A + 19 µA		
	(20 to 45) Hz	1.4 mA/A + 19 µA		
	(45 to 100) Hz	590 µA/A + 19 µA		
	100 Hz to 5 kHz	330 µA/A + 19 µA		
	100 mA to 1 A			
	(10 to 20) Hz	3.8 mA/A + 190 µA		
	(20 to 45) Hz	1.5 mA/A + 190 µA		
	(45 to 100) Hz	770 µA/A + 190 µA		
	100 Hz to 5 kHz	960 µA/A + 190 µA		
	(1 to 3) A			
	(3 to 5) Hz	10 mA/A + 1.7 mA	Agilent 34401A	
	(5 to 10) Hz	3.4 mA/A + 1.7 mA		
	10 Hz to 5 kHz	1.6 mA/A + 1.7 mA		

Appendix A

Sample

NVLAP®

National Voluntary Laboratory Accreditation Program

SCOPE OF ACCREDITATION TO ISO/IEC 17025:2005

Transcat – Charlotte
8334 Arrowridge Blvd., Suite B
Charlotte, NC 28273
Mr. Brian Samuelson
Phone: 704-529-6154 Fax: 704-529-3590
E-mail: bsamuelson@transcat.com
URL: www.transcat.com

CALIBRATION LABORATORIES **NVLAP LAB CODE 200903-0**

NVLAP Code: 20/A01 ANSI/NCSL Z540-1-1994; Part 1 Compliant

DIMENSIONAL

NVLAP Code: 20/D01
Angular

Range	*Best Uncertainty* (±) note 1	*Remarks*
(0 to 75) °	5.3 arc seconds	Angle Blocks
90 °	1.3 arc seconds	Master Square

NVLAP Code: 20/D03
Gage Blocks

Range	*Best Uncertainty* (±) note 1, 2	*Remarks*
(0.05 to 1) in	$(1.3 + 1.4L)$ µin	Comparator and Grade 1 Blocks
(1 to 4) in	$(0.3 + 1.9L)$ µin	Comparator and Grade 1 Blocks

NVLAP Code: 20/D05
Length and Diameter

Micrometers & Calipers – Outside, Inside, Depth Note 3

Range	*Best Uncertainty* (±) note 1, 2	*Remarks*
(8 to 48) in	$(13 + 7L)$ µin	Comparison to Gage Blocks
(0 to 8) in	$(9 + 7L)$ µin	Comparison to Gage Blocks

2011-07-01 through 2012-06-30
Effective dates

For the National Institute of Standards and Technology

Transcat - Sample Electrical Uncertainty Budget

Name:	Measure
Parameter:	DC Voltage
Range or Nominal:	(1 to 10) V
Primary Equipment:	H.P. 3458A Opt. 002
Personnel:	Philip Mistretta, Metrology Manager
Date:	6/15/2012

Ancillary Equipment

None

Type A Uncertainty	Uncert	Units	Cor	Sens	Dist	Deg	Div	Std Uncert
Repeatability	4.50E-01	µV/V	N/A	1	Norm	>100	1.000	4.5000E-01
							1.000	0.0000E+00
							1.000	0.0000E+00

Type B Uncertainty	Uncert	Units	Cor	Sens	Dist	Deg	Div	Std Uncert
Mfg. Specifications	4.00	µV/V	N/A	1	Rect	>100	1.732	2.3095E+00
Calibration Uncert.	2.00	µV/V	N/A	1	Norm	>100	2.000	1.0000E+00
							1.000	0.0000E+00
							1.000	0.0000E+00
							1.000	0.0000E+00
							1.000	0.0000E+00

Results	Uncertainty	Std Uncertainty	Variance
Type A	4.5000E-01	4.5000E-01	2.0250E-01
Type B	4.4721E+00	2.5167E+00	6.3336E+00
Combined	4.4947E+00	2.5566E+00	6.5361E+00
Effective Degrees of Freedom		Not Computed	
Coverage Factor (k)		2.000	
Expanded Uncertainty		**5.1132E+00**	

Remarks

Expanded uncertainty expressed in µV/V

0.5 µV to be added to cover floor spec and Thermal EMF

Appendix B

Transcat - Sample Dimensional Uncertainty Budget

Name: Measuring Equipment
Parameter: Length
Range or Nominal: 0.4 to 1.0 inches
Primary Equipment: Gage Block Set, Grade 2
Personnel: Phil Mistretta, Metrology Manager
Date: June 14, 2012

Ancillary Equipment

None

Type A Uncertainty	Uncert	Units	Cor	Sens	Dist	Deg	Div	Std Uncert
Repeatability	3.30E-01	µin	N/A	1	1U	100	1.000	3.3000E-01
							1.000	0.0000E+00
							1.000	0.0000E+00
							1.000	0.0000E+00

Type B Uncertainty	Uncert	Units	Cor	Sens	Dist	Deg	Div	Std Uncert
Grade 2 Specification	6.00	µin	N/A	1	Rect	>100	1.732	3.4642E+00
ΔL Temp 68°F Δ3°F	19.20	µin	N/A	1	Rect	>100	1.732	1.1085E+01
ΔL ΔTemp MU	0.32	µin	N/A	1	Rect	>100	1.732	1.8476E-01
Cal Unc (Starrett)	2.60	µin	N/A	1	Norm	>100	2.000	1.3000E+00
						>100	1.000	0.0000E+00

Results	Uncertainty	Std Uncertainty	Variance
Type A	3.3000E-01	3.3000E-01	1.0890E-01
Type B	2.0286E+01	1.1688E+01	1.3661E+02
Combined	2.0288E+01	1.1693E+01	1.3672E+02

Effective Degrees of Freedom Not Computed
Coverage Factor (k) 2.000
Expanded Uncertainty **2.3386E+01** µin

Remarks

ΔL Temp 68°F Δ(3°F) - A temp difference from 68° (Cal Temp) is 3°F worse case. 3 x 6.4 (Exp Coef of Steel) x length.

ΔL Δtemp MU - Temp difference from Master vs. UUT, Δα ≈10% (0.64 µ"/"), ΔT 0.5 °F (G103-A2LA 19Dec2008)