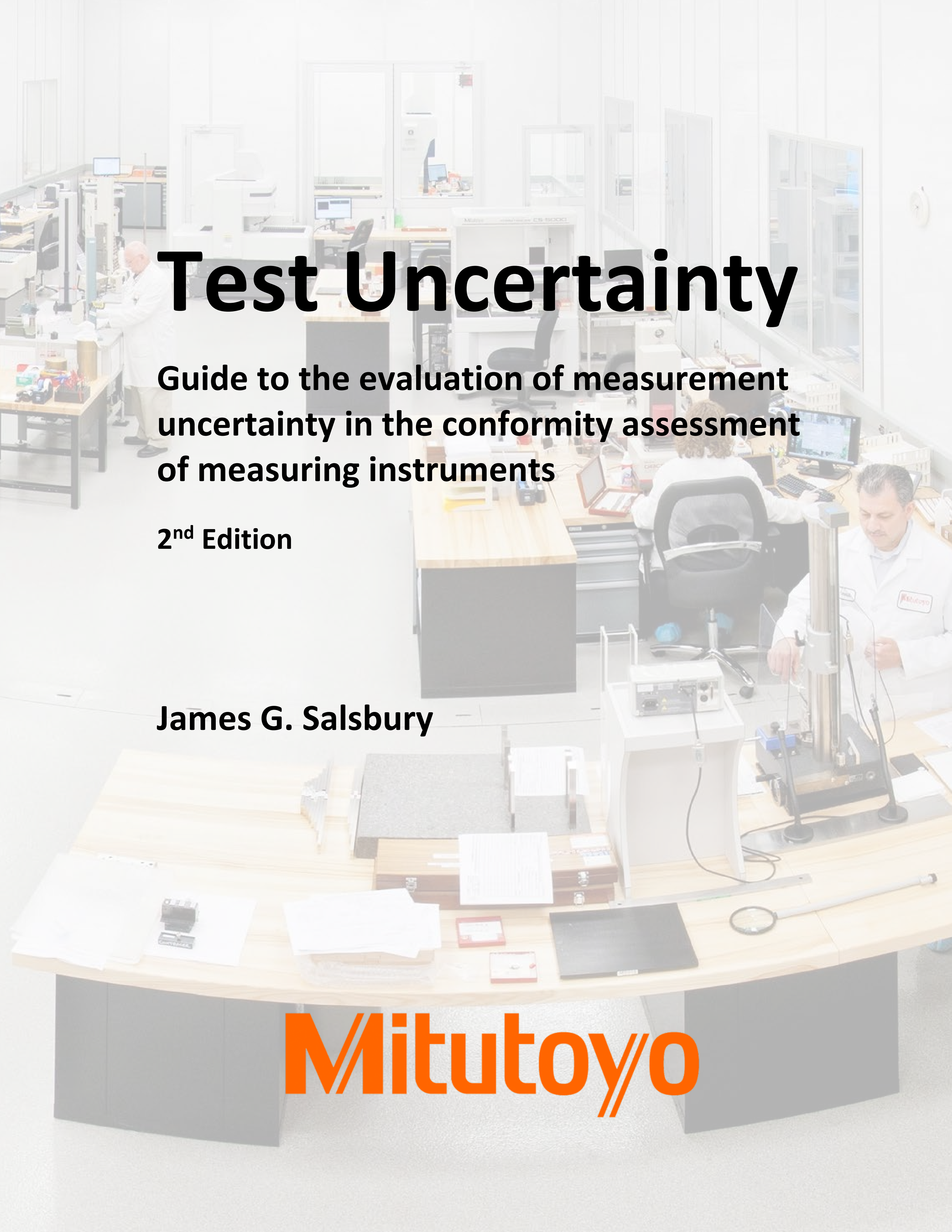

Test Uncertainty

Guide to the evaluation of measurement uncertainty in the conformity assessment of measuring instruments

2nd Edition

James G. Salsbury

Mitutoyo

eLearning

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About Mitutoyo America Corporation

Mitutoyo Corporation was founded in 1934 with just one product – the outside micrometer. Over the years, Mitutoyo has grown to become the world's leading dimensional metrology company offering a huge range of products from calipers and gauge blocks to hardness testers, vision measuring systems and coordinate measuring machines. Mitutoyo America Corporation was formed in 1963 and is headquartered in Aurora, Illinois, USA.

Mitutoyo Corporation is committed to quality and calibration and has built a global network of ISO/IEC 17025 accredited calibration laboratories. Mitutoyo America offers US based repair and accredited calibration service of all Mitutoyo products. The Mitutoyo America Calibration Laboratory in Illinois has been accredited by A2LA (0750.01) since 1998 and is recognized as one of the premier dimensional calibration laboratories in North America. The Mitutoyo America Calibration Laboratory can calibrate both Mitutoyo and non-Mitutoyo products and offers some of the highest precision calibrations that can be found in any commercial calibration laboratory. Mitutoyo America Corporation also offers field installation, repair, and accredited calibrations of all major Mitutoyo products.

Test Uncertainty: Guide to the evaluation of measurement uncertainty in the conformity assessment of measuring instruments

Mitutoyo America Corporation part number: EDU-510-20

2nd Edition; May 20, 2022

About this book

The purpose of this book is to introduce the concept of test uncertainty – the measurement uncertainty associated with test values used in the conformity assessment of measuring instruments – and to provide practical guidance on implementation. Test uncertainty has been the topic of several American and International standards from the dimensional metrology community, and the goal of this book is to bring more awareness of these standards and the critical concepts they contain. The primary intended audience of this book is calibration laboratories, in particular those laboratories accredited to the ISO/IEC 17025 standard.

There is much confusion about test uncertainty, and while the standards provide principles and rules, they often do not frame the rules in a way that promotes understanding and acceptance of new ideas. This book provides useful background and examples that will hopefully lead to greater use of the powerful test uncertainty concepts. This book assumes the reader is familiar with the basic concepts of measurement uncertainty.

All the examples in this book come from the dimensional metrology field, which is the area of expertise of the author. Test uncertainty was initially developed in Technical Committee 213 of the International Organization for Standardization (ISO/TC 213) and was then brought to the U.S. dimensional metrology standards committee, the B89 committee within the American Society of Mechanical Engineers (ASME B89). Test uncertainty concepts are applicable to all areas of metrology that involve the conformity assessment of measuring instruments, but the focus of this book is dimensional metrology.

Mitutoyo America is committed to advancing the science of metrology. Comments or questions regarding the material in this book are welcome. Please contact the education and training department of Mitutoyo America via **www.mitutoyo.com/education** or **training@mitutoyo.com**.

About the title of this book

There are many different types of tests, but this book is only concerned with one. The term *test value uncertainty*, and its synonym *test uncertainty*, comes from the international standard ISO 14253-5:2015, which is concerned with assessing, or testing, the conformity of measuring instruments to specified accuracy requirements. This type of testing is common in the calibration of measuring instruments.

Conformity assessment? Test? Verification? Acceptance testing? Performance evaluation? Verification test? Reverification test? Calibration test? Tolerance-test? Tolerance-test type calibration? Calibration?

All these terms and more are used in a variety of national and international standards and guidance documents to describe the specific activity of demonstrating whether measuring instruments do or do not conform to specified limits of measurement error. The most general of these terms – conformity assessment – was chosen for use in the title of this book. Conformity assessment is defined in ISO 17000:2020, and this term is recognized by ISO/IEC 17025:2017 accredited calibration laboratories.

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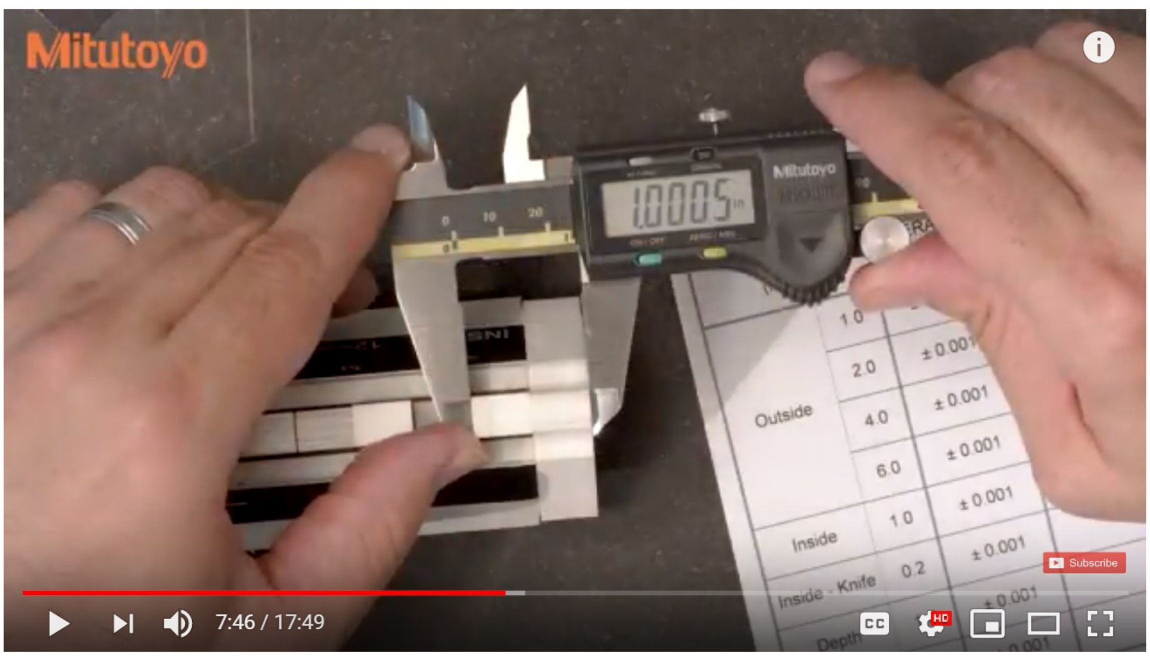
In addition to offering the most complete line of dimensional measuring instruments and solutions, as well as the highest-level commercial calibration, inspection, and repair services in the US, Mitutoyo America Corporation also offers educational courses, customized on-site seminars, and online educational resources. Find out more online at www.mitutoyo.com/education, email training@mitutoyo.com, or call 888-MITUTOYO.

Acknowledgements

Many subject matter experts in the ISO/TC 213 and ASME B89 standards committees have contributed to the evolution of the understanding of measurement uncertainty. The author wants to specifically acknowledge the contribution from the experts in ISO/TC 213 WG 4 on Uncertainty of Measurement and Decision Rules, and in particular, Dr. Alessandro Balsamo (INRIM, Italy), Dr. Edward Morse (UNC Charlotte, USA), Dr. Craig Shakarji (NIST, USA) and the late Dr. Steven Phillips (NIST, USA).



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Caliper Calibration - How to Calibrate a Caliper

Developed by top experts from Mitutoyo America and many available online for free, Mitutoyo America's calibration training videos are helping thousands of customers to standardize methods and improve technique.

The test value uncertainty for indicating measuring instruments is not conceptually trivial to evaluate.

— From the introduction to ISO 14253-5:2015

Contents

Author biography

Dr. James G. Salsbury is the General Manager of Corporate Metrology at Mitutoyo America Corporation. Dr. Salsbury has been working in the measurement field for over 30 years and has been with Mitutoyo since 2000. He has previously worked at Cummins Engine Company, the National Institute of Standards and Technology (NIST), and as a calibration assessor for the American Association for Laboratory Accreditation (A2LA). Dr. Salsbury received his doctoral degree from the Center for Precision Metrology at the University of North Carolina at Charlotte (UNC Charlotte).

Dr. Salsbury is an award-winning author in the area of measurement uncertainty, a frequent speaker and instructor, and was the recipient of the NCSL International 2021 Education and Training Award for his outstanding contribution to the field of measurement science education and training.

The collaborative research of Dr. Salsbury with Dr. Edward Morse from UNC Charlotte led to the publication of the following peer-reviewed journal paper in test uncertainty:

- J. G. Salsbury and E. P. Morse, Measurement uncertainty in the performance verification of indicating measuring instruments, *Precision Engineering*, 36(2012):218-222.

Throughout his career, Dr. Salsbury has been an active contributor to national and international standards efforts in dimensional metrology. Some of the highlights of his activities include:

- ASME B89 Dimensional Metrology, vice chair.
- ASME B89 Division 1 Length, chair.
- ASME B89.1.13 Micrometers, chair.
- ASME B89.7.1 Uncertainty Guidelines, chair.
- NCSL International, Dimensional Committee, chair.
- NCSL International, Board of Directors, VP Standards and Practices.
- ISO/TC 213 WG 4 Uncertainty of measurement and decision rules, U.S. subject matter expert.
- ISO/TC 213 WG 6 General requirements for geometrical product specification (GPS) measuring equipment, U.S. subject matter expert.
- ISO/TC 213 WG 10 Coordinate Measuring Machines, U.S. subject matter expert.

Dr. Salsbury was the chair, task force leader, or lead author for the following published standards:

- ISO 10360-7:2011 Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 7: CMMs equipped with imaging probing systems.
- ISO 13225:2012 Geometrical product specifications (GPS) – Dimensional measuring equipment; Height gauges – Design and metrological characteristics.
- ISO/TS 15530-1:2013 Geometrical product specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement – Part 1: Overview and metrological characteristics.
- ASME B89.1.13-2013 Micrometers.
- ASME B89.7.1-2016 Guidelines for Addressing Measurement Uncertainty in the Development and Application of ASME B89 Standards.

- ISO 14978:2018 Geometrical product specifications (GPS) – General concepts and requirements for GPS measuring equipment.
- ISO 13385-1:2019 Geometrical product specifications (GPS) – Dimensional measuring equipment – Part 1: Design and metrological characteristics of callipers.

The author in the Mitutoyo America Calibration Laboratory by his favorite ultra-high accuracy Mitutoyo Legex coordinate measuring machine holding the ultimate length standard – a Mitutoyo Zero CERA gauge block.

Important references

The concepts in this book are based on existing ASME and ISO standards. All the ASME and ISO standards discussed in this book follow from the principles, terms, and definitions in JCGM 100 and JCGM 200, also known respectively as the GUM and VIM:

- JCGM 100:2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM).
- JCGM 200:2012, International vocabulary of metrology – Basic and general concepts and associated terms (VIM).

The reader of this book should be familiar with the GUM and VIM and the fundamental concepts of evaluating measurement uncertainty. The GUM and VIM are freely available from the website of the Bureau International des Poids et Mesures (BIPM) and are also published as ISO/IEC Guide 98-3 and ISO/IEC Guide 99.

The following ASME and ISO standards specifically address test uncertainty, along with the associated concepts of calibration and verification, as discussed in this book:

- ISO 14253-5:2015, Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 5: Uncertainty in verification testing of indicating measuring instruments.
- ISO 14978:2018, Geometrical product specifications (GPS) — General concepts and requirements for GPS measuring equipment.
- ASME B89.7.1-2016, Guidelines for Addressing Measurement Uncertainty in the Development and Application of ASME B89 Standards.
- ASME B89.7.6-2019, Guidelines for the Evaluation of Uncertainty of Test Values Associated with the Verification of Dimensional Measuring Instruments to Their Performance Specifications.

The following ASME and ISO standards include examples of test uncertainty, as applied to specific types of measuring instruments and associated test methods:

- ISO/TS 23165:2006, Geometrical product specifications (GPS) — Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty.
- ISO/TS 17865:2016, Geometrical product specifications (GPS) -- Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty for CMMs using single and multiple stylus contacting probing systems.
- ISO 13385-1:2019, Geometrical product specifications (GPS) — Dimensional measuring equipment — Part 1: Design and metrological characteristics of callipers.
- ASME B89.1.13-2013, Micrometers.
- ASME B89.1.14-2018, Calipers.

1

Test uncertainty history from the author

I was first introduced to the concepts of test uncertainty when I started following and attending the meetings of ISO/TC 213 WG 10 on coordinate measuring machines (CMMs) in the early 2000s. I reacted like most measurement professionals do when they first hear of these concepts – I thought the subject matter experts in the meetings were crazy. I sat there listening to distinguished measurement scientists, like Dr. Alessandro Balsamo (INRIM, Italy) and Dr. Steven Phillips (NIST, USA), discussing some new and strange type of measurement uncertainty, and the ideas were shocking to me.

I recall the ongoing debate regarding the repeatability of test results when performing verification tests of CMMs to the ISO 10360-2 standard. The working group experts had reached the conclusion that the repeatability of the test results was not to be included in this new type of measurement uncertainty, which they were calling the test uncertainty. I was proud of my knowledge of measurement uncertainty, and I thought these experts were wrong; however, I was too new to the working group to object, so I quietly listened, learned, and studied this thing called test uncertainty.

It took me several years to understand and appreciate the brilliance of test uncertainty, and I decided that the concepts needed to be expanded outside of the CMM community. In particular, I realized that applying test uncertainty concepts to the calibration of micrometers and calipers would bring about a dramatic and positive change to so many Mitutoyo customers – a change that would promote better understanding and good metrology practice – and I wanted to be part of bringing about that change.

My own history with uncertainty

Estimating measurement uncertainty and its application in decision rules has been one constant in my professional career. While still in graduate school, in the summers of 1990 and 1991, I had the opportunity to work at NIST and learn about accuracy and testing of machine tools and measuring instruments from people like Ralph Veale, Dr. Ted Dioron, Dr. Steven Phillips, and Dr. Alkan Donmez. We talked about understanding and managing errors. In those days, we used the term error budgeting, but what we were really talking about was measurement uncertainty; however, that term was not commonly used yet.

I started working as a metrology engineer at Cummins Engine Company in Columbus, Indiana in 1991, and I had the great honor of working with some amazing metrology experts, such as Dr. Bill Grant, Dr. Henrik Nielsen, Dr. Mark Malburg, and Dr. Wayne Eckerle. Dr. Nielsen had recently come from Denmark and had connections to European metrology research. He had early copies of the

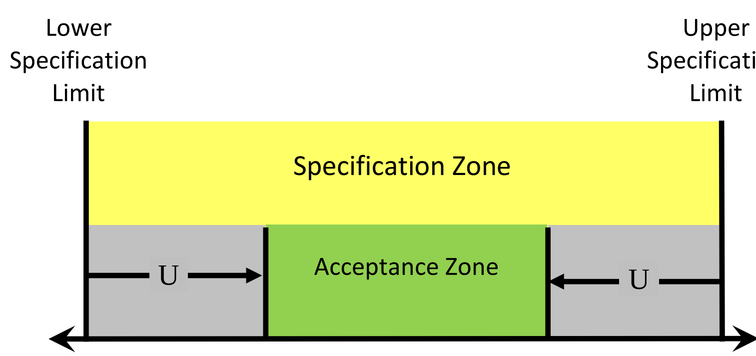
Guide to the expression of uncertainty in measurement (GUM), and I quickly became fascinated with the topic. In 1995, Dr. Nielsen and I wrote a handbook together – the *Cummins Measurement Systems Handbook* – where we tried to blend traditional measurement systems analysis methods, like gauge repeatability and reproducibility studies, with measurement uncertainty concepts. I was young and naive enough that I thought every shop floor would be doing this uncertainty stuff soon. Over twenty-five years later, I have learned that some change takes time.

I loved my job at Cummins, but my passion in metrology led me to return to school and finish my doctoral degree at the Center for Precision Metrology at the University of North Carolina at Charlotte. While at UNC Charlotte, I had the opportunity to further explore the performance evaluation of measuring instruments and work with brilliant leaders in the field, like Dr. Robert Hocken, Dr. Jay Raja, Dr. Edward Morse, and Dr. Robert Wilhelm.

On May 1, 2000, measurement uncertainty brought me to Mitutoyo America Corporation. ISO/IEC 17025 accreditation was taking off in the United States, and Mitutoyo America wanted to build a premier accredited service business, both in the laboratory and in the field. Measurement uncertainty is one of the biggest technical hurdles to accreditation, and I was looking forward to the challenge. By the time I arrived at Mitutoyo, I was already involved with ASME B89 dimensional metrology standards. In my role at Mitutoyo, I had the opportunity to expand my involvement in ASME B89 as well as get involved with ISO/TC 213. And that led me to hear about test uncertainty for the first time.

Motivation for test uncertainty

The deep thinking about test uncertainty came about due to the application of decision rules – a rule that describes how measurement uncertainty is accounted for in the conformity assessment of measuring instruments. In the early 2000s, the subject matter experts in ISO/TC 213 working group 10 on CMMs were struggling with the application of another ISO/TC 213 standard, the recently published ISO 14253-1:1998. This highly controversial standard introduced a default decision rule of stringent acceptance that required guard banding 100% of the measurement uncertainty when making statements of conformity to specified limits of error. A stringent acceptance decision rule requires that the measurement uncertainty be added or subtracted in conformity assessment thereby potentially having a massive impact on the ability to state conformity.



The result of a stringent acceptance decision rule is that manufacturers of measuring instruments would potentially have to increase their specifications by an amount equal to the measurement uncertainty. As ISO 14253-1:1998 was being pushed onto the CMM community, and with the realization that measurement uncertainty would have significant economic consequences, the CMM experts in WG 10 decided to deeply look at measurement uncertainty in the conformity assessment of CMMs.

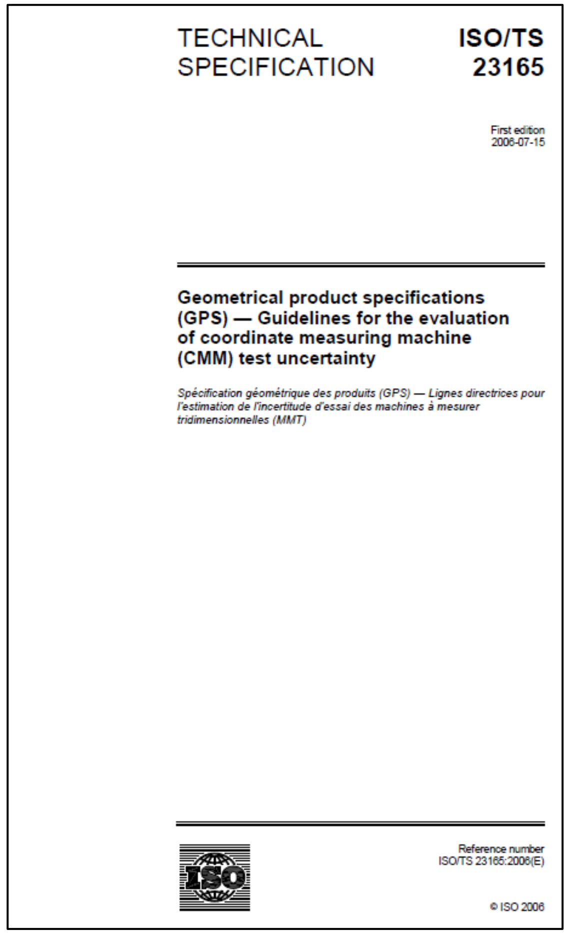
Conventional wisdom back in 2000 was to include all potential variation in measured values into the estimate of uncertainty. For CMMs, which are installed and tested on-site at the customer's location, this meant that errors in the CMM, whether due to the CMM itself or due to the environment in which it was installed, were being estimated and included in the measurement uncertainty. All the variation in the CMM test results – including the influence of the CMM errors – when included in the measurement uncertainty, led to large estimates of uncertainty. These large estimates, in addition to making the application of stringent acceptance decision rules problematic, did not feel right to the CMM experts in WG 10. Manufacturers of CMMs would develop tolerances to express the limits of errors, but if those same errors were also included into the uncertainty, and stringent acceptance decision rules were applied, then errors were "double-counted" and the tolerances for the measuring instrument would have to be increased to a value close to twice the expected errors.

The Mitutoyo America Calibration Laboratory in Aurora, Illinois, is one of the premier dimensional calibration and inspection laboratories in North America. The laboratory specializes in all types of length calibrations, gauge blocks, 3D specialty gauges, form, and vision measurements.

Beginnings of test uncertainty

One of the fundamental questions to consider with test uncertainty is whether or not the errors that are being tested – the purpose of the test itself – are also to be included in the measurement uncertainty. For example, consider a simple test that is designed to test only the repeatability of a measuring instrument under specific conditions. If the purpose of the test is to test the repeatability, does it make any sense to also attempt to estimate the repeatability and include that in the uncertainty of the test values?

Manufacturers specify CMMs to perform within stated accuracy limits across rated temperature conditions. The CMM performance is expected to vary across the allowed range of temperatures, but only within the stated accuracy limits. During testing, the temperature is allowed to change, and the CMM must still perform to within its stated accuracy. The measured errors during testing, the test values, may vary due to the inaccuracy of the CMM and its slowly changing state over time or over its rated operational temperature limits. Tests within ISO 10360-2, the primary CMM standard, are specifically designed to test this variation, and so if the performance of the CMM across the permitted environment is subject to test, does it make any sense to also estimate the influence of temperature on the CMM results and include that in the uncertainty of the test values?


TECHNICAL SPECIFICATION

ISO/TS 23165

First edition
2006-07-15

Geometrical product specifications (GPS) — Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty

Spécification géométrique des produits (GPS) — Lignes directrices pour l'estimation de l'incertitude d'essai des machines à mesurer tridimensionnelles (MMT)

Reference number
ISO/TS 23165:2006(E)

© ISO 2006

After much discussion and debate, WG 10 completed the standard that introduced the initial concept of test uncertainty, ISO/TS 23165:2006, for use with CMM testing. As defined in this standard, test uncertainty is the measurement uncertainty to be used when applying decision rules in conformity assessments of measuring instruments. This new test uncertainty specifically did not include any instrumental errors introduced by the CMM, and instead was an expression of only the elements of variation that were the responsibility of the person performing the test. Based on how CMM testing is performed, test uncertainty in this standard was defined relative to just the testing equipment and its use.

Back in 2006, I accepted the concepts of ISO/TS 23165:2006, but I felt the solution was too tailored to CMM testing and did not provide a general enough model of measurement uncertainty that allowed the approach to be applied to all conformity assessment situations. As I tried to extend the concepts to testing micrometers and calipers, for example, I felt something was missing, particularly as micrometers and calipers were specified and tested under very different conditions then CMMs.

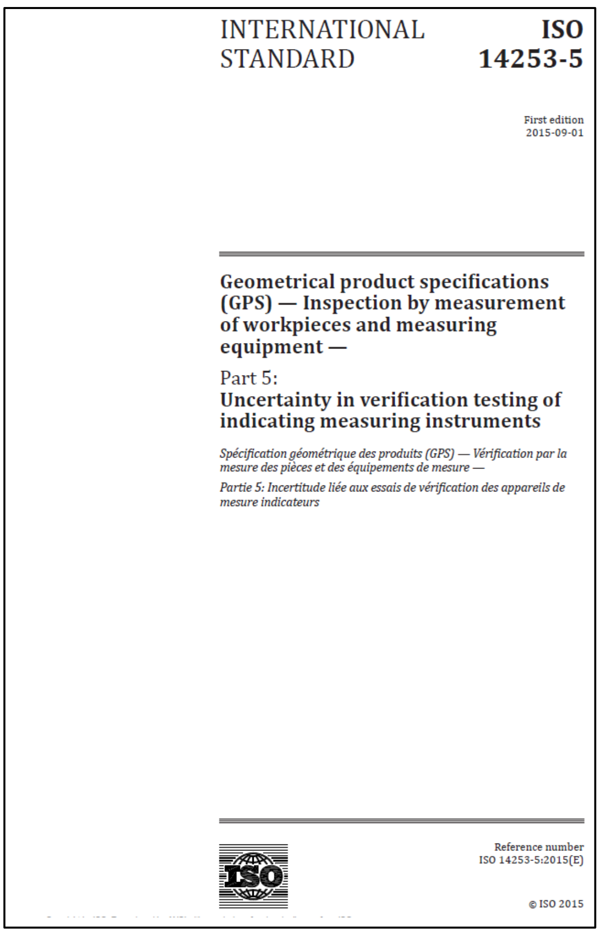
Test measurand

I started working the test uncertainty problem with a colleague from UNC Charlotte, Dr. Edward Morse. ISO/TC 213 had already decided to start work on a general standard for test uncertainty within WG 4 Uncertainty of measurement and decision rules, and Dr. Morse and myself joined the working group effort. The project was led by Dr. Balsamo, who had also led the ISO/TS 23165:2006 effort within WG 10.

At the time, I felt like test uncertainty was not being framed correctly. I kept considering other testing scenarios for different types of measuring instruments, and the current model for test uncertainty was not working well for them. I was frustrated, and I asked Dr. Morse if he would come to Mitutoyo America's headquarters in Aurora, Illinois, for a brainstorming session. It was during that long session that we realized that we were missing a key piece to measurement uncertainty, and that the solution was sitting right in front of us, in the definition of the term.

Measurement uncertainty, as defined in the International Vocabulary of Metrology (VIM), is associated with "values being attributed to a measurand". I think many people skip over the idea of the measurand – the quantity intended to be measured – and instead focus on the measured values coming from a specific measurement procedure. In the GUM, it says a measurement "begins with an appropriate specification of the measurand", but when estimating measurement uncertainty, we often assume the definition of the measurand is self-evident, and we move on.

Dr. Morse and I realized that the definition of the measurand when testing measuring instruments is not self-evident but is instead rather complex. When the purpose of the measurement is to assign a value to some feature, such as the diameter of a bore in a manufactured engine component or the calibrated size of a length standard, the measurand is pretty well defined and understood. But if I'm testing the errors of indication of a measuring instrument, solely to determine conformity, bound by the rules in the test standard, then what exactly is the quantity intended to be measured – what is the measurand?


INTERNATIONAL STANDARD

ISO 14253-5

First edition
2015-09-01

Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment —

Part 5:
Uncertainty in verification testing of indicating measuring instruments

Spécification géométrique des produits (GPS) — Vérification par la mesure des pièces et des équipements de mesure —

Partie 5: Incertitude liée aux essais de vérification des appareils de mesure indicateurs

Reference number
ISO 14253-5:2015(E)

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The answer to this question is complicated and is addressed later in this book; however, a key concept is that the measurand associated with testing conformity is fundamentally different from the measurand associated with assigning values. Once the measurand is understood, the concepts of test uncertainty are straightforward and logical.

Within WG 4, the unique case of the measurand in assessing conformity was given its own term – the test measurand. The concept of this test measurand was fully developed within WG 4, along with a number of other key concepts to test uncertainty. When ISO 14253-5:2015 was published, it became the first national or international standard, in any field of metrology, to directly address the specific case of the evaluation of measurement uncertainty in the conformity assessment of measuring instruments.

Test versus calibration

Test uncertainty was initially framed as some other type of uncertainty. We now realize test uncertainty is just the measurement uncertainty associated with a particularly interesting measurand. But what is a test, and how does a test differ from a calibration? According to the VIM, metrological traceability requires an “unbroken chain of *calibrations*” not *tests*. The deep thinking of test uncertainty led to further consideration of the meaning of, and difference between, test and calibration, and these new concepts were captured in ISO 14978:2018 and ASME B89.7.1-2016.

The VIM definition of calibration highlights the importance of using the “information” from the calibration when making subsequent measurements with the calibrated measuring instrument. For many measuring instruments, the information that is needed and used from the calibration is the conformity assessment to specifications. Users want and need to know their micrometer is within tolerance, their coordinate measuring machine (CMM) is with tolerance, or their caliper is within tolerance. ISO 14978:2018 and ASME B89.7.1-2016 present the critical concept that conformity assessment is not something that follows from calibration. Instead, the conformity assessment of measuring instruments – including obtaining test values, evaluating the test uncertainty, and assessing conformity to specified limits of error with an appropriate decision rule – is the calibration.

The calibration of a micrometer is the conformity assessment of the micrometer to specified maximum permissible measurement errors.

2

Test uncertainty myths vs. facts

This chapter summarizes some key facts about test uncertainty and attempts to dispel some commonly held myths:

- The official term is *test value uncertainty*, as defined in ISO 14253-5:2015. The term *test uncertainty* was first introduced in ISO/TS 23165:2006 and is still an official synonym, per ISO 14253-5:2015, for test value uncertainty.
- Test uncertainty is fully compliant with the concepts of the GUM and the definitions in the VIM. Test uncertainty is measurement uncertainty. In practice, such as on calibration certificates, test uncertainty should be reported as the measurement uncertainty.
- Test uncertainty applies in the conformity assessment – or verification testing – of measuring instruments to specified maximum permissible measurement errors (often called accuracy specifications or tolerances). The primary application of test uncertainty is in decision rules when stating conformity with a specified requirement.
- Test uncertainty does not ignore contributions to uncertainty from the device being calibrated (also known as the unit under test, UUT); however, test uncertainty does raise critical questions about whether the variation attributed to the UUT is a contributor to measurement uncertainty or is subject to test.
- Assessment of conformity requires a well-defined and agreed upon test protocol. Test protocols are ideally developed by subject matter experts and codified in national or international standards.
- If a test is properly executed, following an agreed upon test protocol, there is no contribution to test uncertainty associated with the thoroughness of the test protocol to completely test the measuring instrument. It is not the role of test uncertainty to guess, or estimate, the variation in test values that might occur under different permissible test instances.
- Calibration involves either measuring and assigning a calibrated value, which is intended to be used as a reference value, or measuring test values for the assessment of conformity, and sometimes both.
- Test uncertainty does not apply when assigning a calibrated value to a measuring instrument, such as the calibrated value of a material measure.
- The reporting of measurement results should be clear as to the purpose – whether a test value for conformity assessment or an assigned calibrated value for use as a reference value.
- While statements of conformity are generally optional when reporting measurement results, it must be clear when the results are test values, with an associated test uncertainty, intended to be used for assessing conformity.

- A measured value used to assign a calibrated value to a measuring instrument is not necessarily useful to assess conformity.
- Measurement uncertainty characterizes dispersion of values being attributed to a measurand. Measurement, and measurement uncertainty, begins with an appropriate specification of the measurand.
- Test uncertainty is not a different type of uncertainty – test uncertainty is just the measurement uncertainty associated with the test values attributed to a specific type of measurand – the test measurand.
- The measurement uncertainty or test uncertainty associated with calibrating measuring instruments should never be confused with the measurement uncertainty associated with using the calibrated measuring instrument to measure other items.
- In general, the reference standard used in testing is always a contributor to test uncertainty.
- In general, any variation associated with the quality of the measuring instrument being tested, including the resolution and the perceived repeatability, is not a contributor to test uncertainty.
- In general, any variation associated with the performance of a measuring instrument changing within permitted and rated operating conditions is not a contributor to test uncertainty.
- For some manually operated measuring instruments, the user may influence the test values; however, this does not necessarily mean this variation is a contributor to the test uncertainty.

Mitutoyo America Corporation offers hands-on educational courses in the calibration and use of dimensional measuring instruments.

3

General concept of testing and test uncertainty

The purpose of this chapter is to introduce the concepts of testing and test uncertainty without many technical details. All the details will be developed and discussed in later chapters of this book.

Measurement uncertainty applies to all measurements, and in the conformity assessment of measuring instruments the goal is to evaluate the measurement uncertainty of the test values measured in a test. The term test uncertainty simply refers to the measurement uncertainty of the test values. The test values and the test uncertainty are used in conformity assessment to determine whether a measuring instrument meets some stated maximum permissible measurement error. Test uncertainty applies in any situation where a test is done and where test values are measured for use in assessing conformity, such as in calibration.

To understand and estimate test uncertainty correctly, it is critical to understand the purpose of a test. In the conformity assessment of a measuring instrument, the purpose of a test is to efficiently find and measure errors following a test protocol that is sufficient to assess conformity. The errors of the measuring instrument are subject to testing and are not to be estimated and included in the test uncertainty. It is critical that the test be allowed to stand on its own and not be second guessed via the measurement uncertainty. Test uncertainty is not a measure of the accuracy or uncertainty of a measuring instrument – that is the purpose of the instrument specifications, test values, and conformity assessment. A common mistake that is made when evaluating the measurement uncertainty of test values is to forget that the measurement is a test. In a test, the goal is to search for errors, and the very errors being tested are not also to be included in the uncertainty.

Repeatability

Consider a scenario where two different measurements are made with the measured values being 20.051 and 20.163. For this example, the units of measurement and what is being measured is not important at this time. Further consider that these two measured values are obtained only a few seconds apart with no changes to the measuring system. A button is pressed, and 20.051 is the measured value. The same button is pressed again, and the measured value is 20.163.

Is the difference between these two measured values – the difference of 0.112 – something that must be somehow accounted for in the measurement uncertainty? Is the repeatability of the measured values a contributor to the measurement uncertainty? The answer to these questions is critical to understanding test uncertainty as well as the very nature of testing and the conformity assessment of measuring instruments.

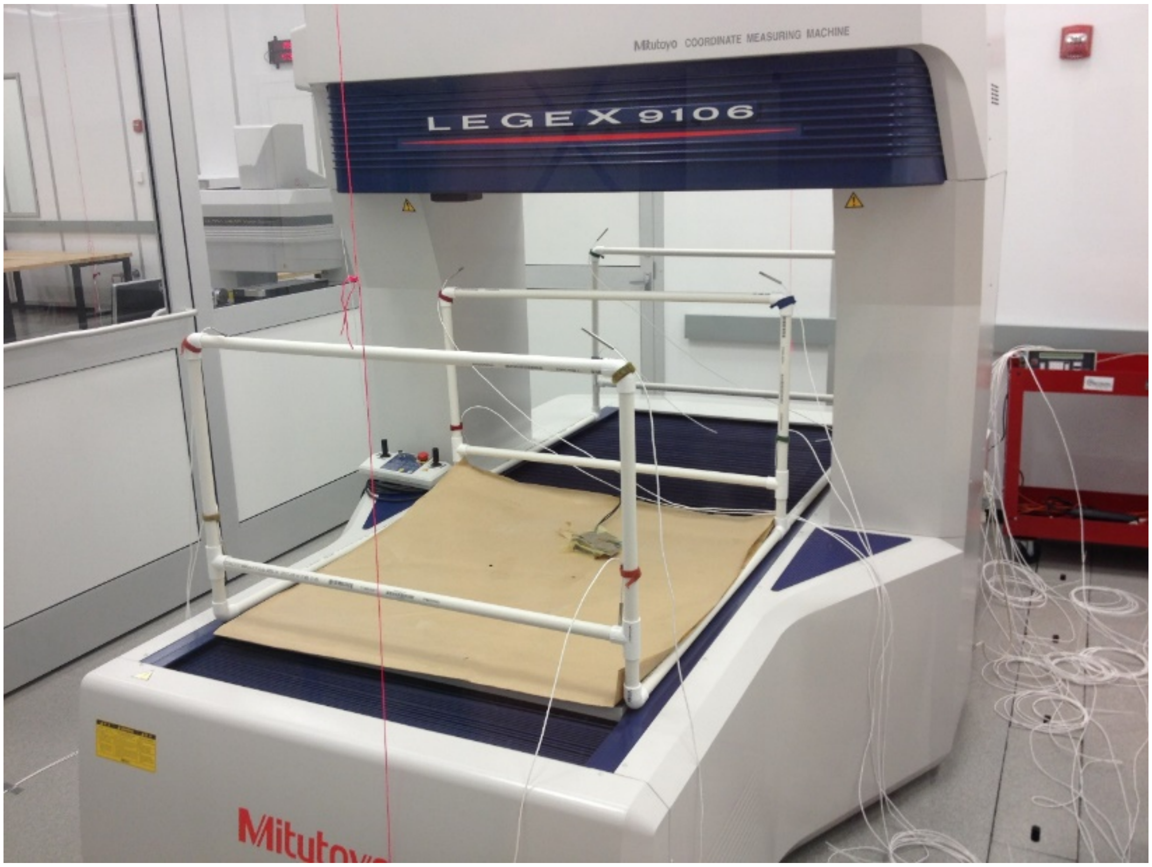
20.051 20.163

In some historical measurement uncertainty practices, the goal often seems to be to account for all variation in the measured values in the uncertainty evaluation. Terms like repeatability and reproducibility are often used to describe statistical studies that capture this variation and include it in the measurement uncertainty. While this practice may be perfectly valid for some measurements, it needs to be considered very carefully in the conformity assessment of measuring instruments. The very purpose of testing measuring instruments – the search for measurement errors – is often to uncover this variation in the process of assessing conformity. Finding variation is often the purpose of the test, and this variation is not a source of uncertainty.

Going back to the two measured values of 20.051 and 20.163, what if these two measured values are test values being used to assess the conformity of the temperature of a room to a specified requirement. Say a temperature-controlled room is being built to house a new high accuracy coordinate measuring machine, and the specifications for any point in the room is 20 °C ± 0.25 °C. In this scenario 20.051 °C and 20.163 °C are two measured values being used to assess conformity. These are test values associated with two different test points and are not repeat measurements of the same test point. Test points are commonly defined over the measuring range of a measuring instrument, but they can vary in time as well. The variation of the temperature of the room over time is subject to test and the difference between the two test values – the 0.112 °C – is part of the test and not a part of the measurement uncertainty. The repeatability of the unit under test, which is the room being tested, is not to be included in the evaluation of the uncertainty of the test values.

It needs to be mentioned that the variation of 0.112 °C between the two values could also be coming from whatever temperature measuring system is being used – the reference standard in this case. This example assumes the uncertainty associated with the reference standard is otherwise addressed in the evaluation of the uncertainty. This possibility does not change the message of this example, but it does highlight the need for careful consideration of these issues.

Test Point	Nominal Temperature (°C)	Measured Temperature (°C)	Measured Error (°C)	Tolerance (°C)	Pass/Fail Judgement
Time 1	20	20.051	+ 0.051	± 0.250	Pass
Time 2	20	20.163	+ 0.163	± 0.250	Pass



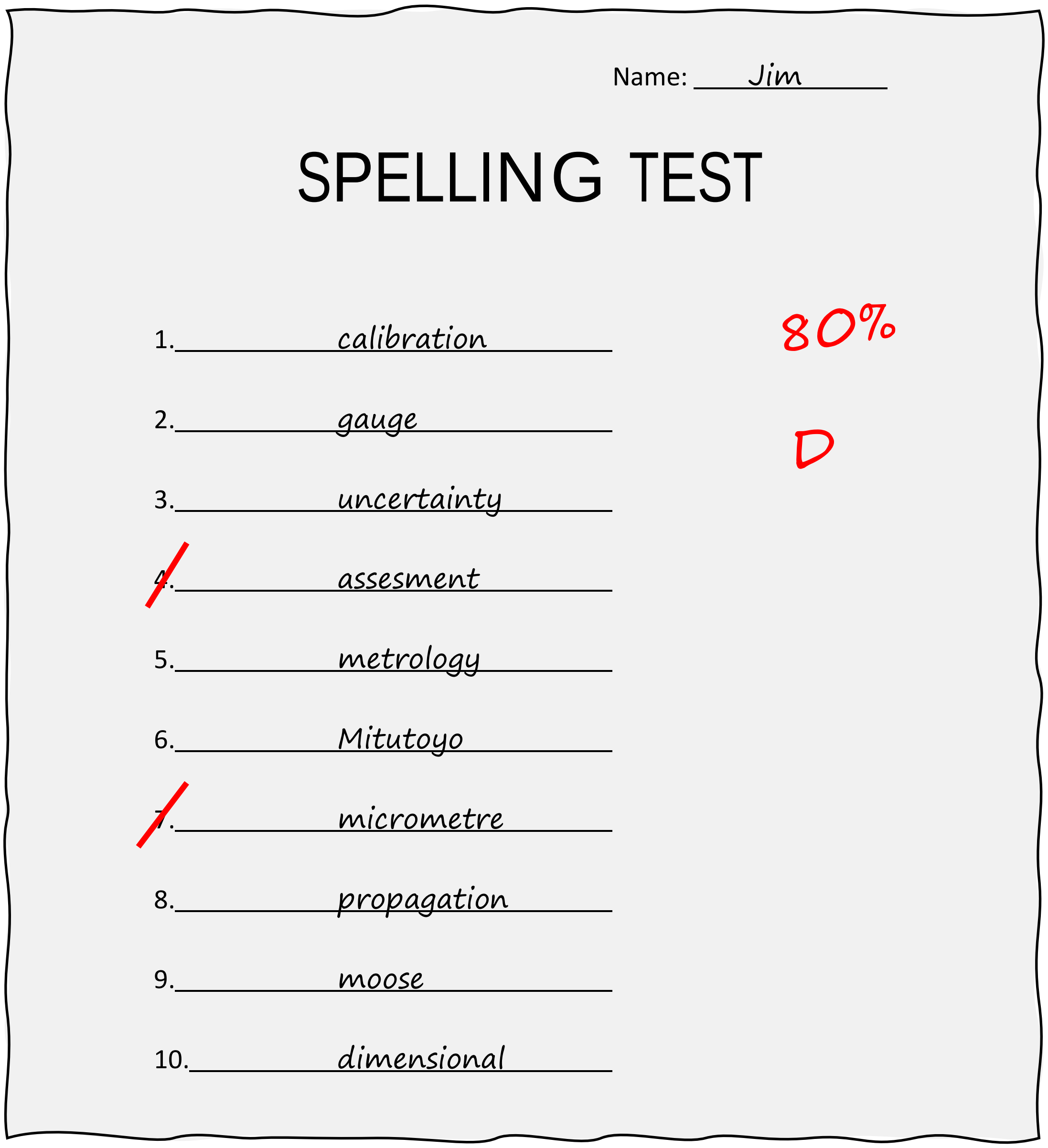
Testing the temperature within the measuring volume of a high accuracy CMM at Mitutoyo America.

Spelling Test

A conformity assessment test is one type of test. It may be useful to frame the discussion of testing around a very different type of test – a spelling test from school. Consider a classroom of students taking a spelling test that has ten questions. Each question is worth one point, and a straight grading scale is used – 90% for an A, 80% for a B, 70% for a C, 60% for a D, and less than 60% is an F. Consider a student, named Jim, who took the test and got two questions wrong, 80%, and therefore should receive a grade of B. The teacher, however, started second guessing the test result.

Consider that Jim has a history of inconsistent results on spelling tests. Spelling is just not Jim's strength and sometimes he does poorly on the tests; however, Jim studies hard and sometimes he "gets lucky" with the words on the spelling test. The teacher has a record of Jim's history of spelling tests, and the teacher decides that the repeatability of Jim's prior test results must be accounted for in the grading of this latest test result. Because of Jim's erratic repeatability in spelling tests, there is the possibility that if he took the latest test again, he might get very different results. Due to the repeatability of the unit under test, or UUT (which is Jim in this example), the teacher calculates that Jim's result of 80% is actually somewhere between 65% to 95%. The teacher happens to be strict about grading and since Jim's "actual" test score *might be* less than 70%, Jim can only earn a grade of D on this spelling test.

This example might seem preposterous, but this is exactly what is happening when the errors of the UUT are included in the uncertainty of a test to find the errors of the UUT. In a good test, the quality of a measuring instrument is detected and reported through the test values. When evaluating the uncertainty of the test values, estimated errors of the UUT must not be included. In a test, it is not the role of uncertainty to try to estimate or guess the measurement errors of the UUT when finding those errors is the purpose of the test. The errors of the UUT cannot be second guessed in a test.



An absurd spelling test result where the test value, the 80%, is second guessed by the teacher. Instead of getting a grade of B, the teacher gives the student a D since the teacher estimated there is a possibility that the student might do worse if the test was repeated.

Reproducibility

Consider a slightly different scenario where the two measured values, the 20.051 °C and 20.163 °C, are measured values obtained at two different sides of the room under test. The tolerance of the room temperature, 20 °C ± 0.25 °C, applies across the volume of the room, and these two test values are used in the conformity assessment of the room. In this case, the location of the testing has been specifically changed, and the VIM uses the term reproducibility to describe variation associated with changing something specific. In this case, these test values are now associated with the reproducibility of the temperature across the volume of the room.

Like the discussion on repeatability, is this reproducibility of the unit under test – the reproducibility of the temperature across the room – something that should be included in the measurement uncertainty of this test? And once again, searching for this variation – this reproducibility – is specifically part of the purpose of the test. The two measured values are once again two different test values associated with two different test points at different locations in the measuring volume. This variation is subject to test and not a contributor to the test uncertainty.

Test Point	Nominal Temperature (°C)	Measured Temperature (°C)	Measured Error (°C)	Tolerance (°C)	Pass/Fail Judgement
Position 1	20	20.051	+ 0.051	± 0.250	Pass
Position 2	20	20.163	+ 0.163	± 0.250	Pass

Resolution of the UUT

In some historical measurement uncertainty practices, it has been common to see the resolution of the item being calibrated, the resolution of the unit under test (UUT), included in the measurement uncertainty. When the calibration is a test of conformity, is this practice correct? Is the resolution of the UUT a contributor to test uncertainty or is it a contributor to the errors of the micrometer that are subject to test?

In the conformity assessment of a measuring instrument, the purpose of the test is to find and measure errors; the purpose is not to estimate errors nor include them in the uncertainty. When the goal is to search for measurement errors, the resolution of the UUT is just another part of the measuring instrument that is subject to test. The observed measurement errors in the test are influenced by the resolution, along with all the other components of the measuring instrument; however, it is not the purpose of testing to try to estimate what the measurement errors might be but rather test and determine what the errors are.

Consider the calibration of a 0-25 mm digital outside micrometer using gauge blocks. The digital resolution of 0.001 mm impacts the measured values from the micrometer; however, this does not mean that this should be included in the test uncertainty. The measured values from the micrometer are also influenced by other characteristics of the micrometer, such as the accuracy of the micrometer encoder, the stiffness of the micrometer frame, and the flatness and parallelism of the measuring faces. The quality of these characteristics, including the resolution, are critical in establishing the accuracy of the micrometer. The manufacturer then specifies the accuracy of the micrometer based on all these characteristics. It is the purpose of calibration to then test and verify if a particular micrometer does indeed achieve the specified quality. Limitations and imperfections in the characteristics of the micrometer create errors that must be experimentally found in calibration. These limitations and imperfections are not to be estimated and included in the uncertainty of the test, but rather assessing them is the entire purpose of the test.

When contemplating the influence of the resolution of the UUT in the measurement uncertainty, it is useful to remember what is being measured. In the micrometer example, proper calibration involves using the micrometer to measure the gauge block. In the calibration, the micrometer is operated in a manner similar to typical use. While this measurement looks and feels like the micrometer is measuring the gauge blocks, what is actually happening is that the gauge blocks are measuring the micrometer. The gauge blocks are the reference standard that are used to measure and evaluate the errors of the micrometer. Being the reference standard, any uncertainty associated with the repeatability, reproducibility, or resolution of the gauge blocks, not the micrometer, would need to be accounted for in the uncertainty. For the micrometer calibration, however, it is uncommon to see these contributors in the evaluation of uncertainty as they are typically negligible compared to other sources of uncertainty.

Calibration of a 0-25 mm digital outside micrometer using gauge blocks. The micrometer is the UUT, and the gauge blocks are measuring the micrometer in the test. The digital resolution of 0.001 mm influences the accuracy of the micrometer as stated by the manufacturer. The limitations built into the design of the micrometer, as well as its imperfections during manufacturing and over time, create errors. The purpose of calibration is to experimentally find these errors and assess conformity to the stated accuracy.

Not including the resolution of the UUT in the test uncertainty does not mean that the resolution is not important. Resolution is a critical factor impacting the accuracy of measuring instruments. Consider the calibration of a high accuracy outside micrometer, such as the Mitutoyo MDH-25. The typical digital 0-25 mm outside micrometer has a resolution of 0.001 mm and an accuracy specification of ±0.001 mm to ±0.002 mm. The high accuracy MDH-25 micrometer has an improved resolution of 0.0001 mm and a tighter accuracy specification of ±0.0005 mm. The improved accuracy of this micrometer is achieved by a number of changes in the micrometer design, including a heavy duty and stiff frame, a more accurate screw mechanism and encoder, a removable heat shield to reduce thermal expansion for hand-held measurements, and the improved digital resolution. The resolution of a measuring instrument is part of the instrument design to help achieve the stated accuracy. A different resolution might improve or reduce the accuracy of a measuring instrument, and the manufacturer must consider this when stating the accuracy specifications; however, the resolution of the UUT has no impact on the uncertainty when testing conformity to those specifications.

Calibration of a high accuracy outside micrometer using gauge blocks. The resolution is 0.1 µm compared to 1 µm for a typical micrometer. The improved resolution helps the micrometer achieve an improved accuracy, but the resolution has no impact on the uncertainty of the test values in calibration.

UUT Contributors

When evaluating measurement uncertainty, it is common practice to consider the contributions from the unit under test. The concepts of test uncertainty do not change this practice. However, it is critical to keep separate the variation that is being tested from the variation coming from uncertainty contributors. This topic will be discussed in more detail later in this book.

Measurand in testing

In the VIM, measurement uncertainty is not defined just as "the dispersion of the quantity values" but rather as "the dispersion of the quantity values *being attributed to a measurand*". As will be discussed in detail in later chapters in this book, understanding the measurand – that quantity intended to be measured – is a critical piece to properly evaluate the measurement uncertainty. In calibrations that involve conformity assessment, each test value at each test point is associated with a different measurand. As such, the variation between the test values is not included in the measurement uncertainty.

In some historical measurement uncertainty practices, the term *measurement process* can be found, and in particular the concept that measurement uncertainty is supposed to evaluate the uncertainty of the measurement process. This language and approach are problematic. The use of this term seems to put an over-emphasis on the entire process, which tends to incorrectly imply that all variation of the measured values coming from this "measurement process," including the errors of the UUT, should be included in the evaluation of the measurement uncertainty. In addition, the term measurement process is a bit questionable as measurement is already defined as a process in the VIM.

As already discussed, in calibrations that involve conformity assessment, the purpose of the calibration is to search for measurement error, and variation in the test values is expected. This variation coming from the "measurement process" is part of the test and not part of the measurement uncertainty. The measurand in testing needs to be carefully understood to avoid including the wrong contributors and inflating the measurement uncertainty. This is a critical topic that is discussed in ISO 14253-5:2015 and throughput this book. Measurement is a process, but measurement is a process associated with a specific measurand. Measurement, and measurement uncertainty, must start with a careful consideration of the measurand. If the measurand is not well defined and understood, then the evaluation of the measurement uncertainty will lack integrity, and any use of that measurement uncertainty, including in decision rules, will be completely and utterly meaningless.

Conclusions

The purpose of this chapter was to discuss the concept of testing and introduce test uncertainty, the measurement uncertainty associated with test values. The next chapter will show the implementation of test uncertainty using a worked example. This example will also demonstrate how testing for conformity assessment is different than other types of calibrations. Further chapters will more formally present a test uncertainty model and include some examples.

Acknowledgement

The temperature example in this chapter was inspired by the excellent paper from Dr. Craig Shakarji and Dr. Steven Phillips, "Should the repeatability of the instrument under test be included in the test uncertainty," that was presented at the *2017 NCSL International Annual Workshop and Symposium*.

4

Case study in test uncertainty

In this chapter a case study is used to further develop the concepts of test uncertainty. Test uncertainty will be more formally introduced in the next chapter, but this case study allows the concepts of test uncertainty to be shown is a straightforward manner to highlight some of the key issues.

This case study considers the calibration of a height gauge, the Mitutoyo LH-600 Linear Height, which is a high-accuracy model with advanced functions that allows many of the test uncertainty concepts to be presented. The metrological characteristic that is considered in this case study is the length (or height) measuring accuracy of the instrument. For brevity in this example, some details were changed or not included, and as such, this example should not be considered as an example of best practices in the calibration of this height gauge.

Calibration procedure

A typical calibration procedure for the Mitutoyo LH-600 includes the following basic steps:

- As-found, or as-received, test results to test for conformity to the stated accuracy specifications.
- Cleaning and other maintenance and service.
- Correction or adjustment of the measuring instrument, as needed, including mechanical or software adjustments.
- As-left test results to test for conformity to the stated accuracy specifications prior to return shipment to the customer.

The general calibration method is straightforward for a height gauge. The unit and the reference standard, a type of step gauge – in this case a Mitutoyo Check Master – are placed next to each other on a granite surface plate. A series of height measurements are made on the reference standard relative to the surface plate. The manufacturer stated accuracy specification is ± (1.1+L/1000) µm, where L is the length or height from the surface plate (in mm). ISO 13225 Height Gauges is the normative standard for the testing.

As-found test results

Prior to any service, including cleaning or adjustments, the LH-600 is tested for conformity to specification. These test results are typically called the as-found, or as-received, test results. The as-found test results are critical in determining the historical condition of the unit and in determining future calibration intervals.

Testing for conformity usually goes quickly on the LH-600. The unit is motorized, and the technician simply places the Check Master – the reference standard – in the correct place and hits a button to take a measurement. The technician just needs a basic level of training on the operation of the unit to do the testing.

Below are example as-found test results. The measured errors are the test values used to determine conformity of the LH-600 to the stated accuracy specifications (tolerance) prior to any cleaning, service, or adjustment. These results are reported on the calibration certificate.

Example as-found test results for the Mitutoyo LH-600:

Nominal Height (mm)	Calibrated Check Master Length (mm)	Measured Height (mm)	Measured Error (µm)	LH-600 Tolerance (µm)	Pass/Fail Judgement
10	10.0005	10.0003	– 0.2	± 1.1	Pass
100	100.0001	100.0005	+ 0.4	± 1.2	Pass
200	199.9996	200.0006	+ 1.0	± 1.3	Pass
300	299.9998	300.0014	+ 1.6	± 1.4	Fail
400	399.9993	400.0012	+ 1.9	± 1.5	Fail
500	500.0003	500.0009	+ 0.6	± 1.6	Pass
600	600.0010	600.0026	+ 1.6	± 1.7	Pass

For example purposes, these test results show that the LH-600 is not within tolerance at all test points. These results indicate that some service or adjustments might be necessary to bring this unit back to within the manufacturer stated accuracy. However, the unit must first be cleaned and inspected carefully.

Maintenance and service

After the as-found results are completed, the unit is typically inspected carefully. Cleaning of the main column is often needed, and sometimes additional service is required. Typical service includes items like removing rust and debris from the base and adjusting the spacers on the vertical slider.

After maintenance and service, the accuracy of the unit needs to be checked again. If the results are acceptable, then those test results could be used as the as-left results. For this example, it is assumed that the unit needs further corrections or adjustments.

Adjustment of the measuring instrument

After maintenance and service, the accuracy of the unit may need to be adjusted or corrected to be within the stated accuracy specifications. The Check Master is once again used as the reference standard, and a series of height measurements are again made with the unit. For these measurements, unlike the as-found results, there is no tolerance or judgement of pass or fail. The objective of the measurement is to find the best correction value for any particular height. The values are then uploaded to the LH-600 where they are directly used to correct future measurements.

Example adjustment measurement results for the LH-600:

Nominal Height (mm)	Calibrated Check Master Length (mm)	Measured Height (mm)	Measured Error (µm)	LH-600 Tolerance (µm)	Pass/Fail Judgement
10	10.0005	10.0004	– 0.1	Correction values only. There is no tolerance or pass/fail judgement.	
50	50.0003	50.0005	+ 0.2		
100	100.0001	100.0007	+ 0.6		
150	150.0002	150.0005	+ 0.3		
200	199.9996	199.9999	+ 0.3		
250	249.9996	250.0003	+ 0.7		
300	299.9998	300.0012	+ 1.4		
350	349.9994	350.0010	+ 1.6		
400	399.9993	400.0015	+ 2.2		
450	449.9995	450.0020	+ 2.5		
500	500.0003	500.0023	+ 2.0		
550	550.0000	550.0028	+ 2.8		
600	600.0010	600.0037	+ 2.7		

In this case, the measured error is an estimate of the systematic length measurement error of the LH-600 at a particular height. The results are not used as test values to determine conformity, and these results are not reported on the calibration certificate. More measurements are taken than for assessing conformity – about every 50 mm versus 100 mm. This is done following the manufacturer recommendations to ensure the correction data is dense enough to yield the desired results. (Note: in actual practice, more measurements are used, but for brevity, the number was reduced in this example.)

As-left test results

The final as-left measurements are made following the same procedure as the as-found results. The measured errors are the test values used to determine conformity of the LH-600 to the stated accuracy specifications after cleaning, service, and any adjustments. These results are reported on the calibration certificate.

Example as-left test results for this LH-600:

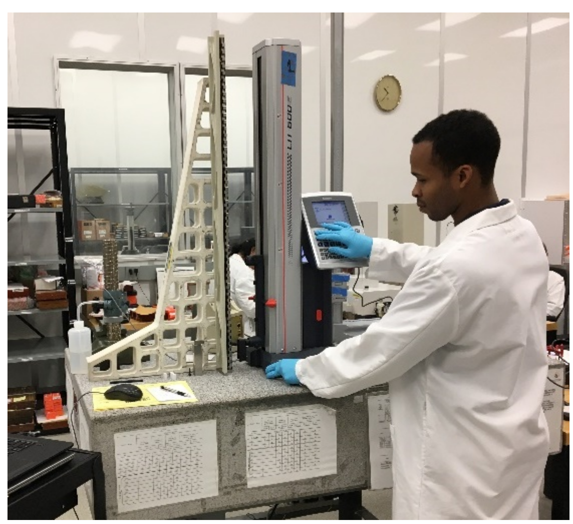
Nominal Height (mm)	Calibrated Check Master Length (mm)	Measured Height (mm)	Measured Error (µm)	LH-600 Tolerance (µm)	Pass/Fail Judgement
10	10.0005	10.0006	+ 0.1	± 1.1	Pass
100	100.0001	100.0003	+ 0.2	± 1.2	Pass
200	199.9996	200.0001	+ 0.5	± 1.3	Pass
300	299.9998	299.9993	– 0.5	± 1.4	Pass
400	399.9993	400.0000	+ 0.7	± 1.5	Pass
500	500.0003	500.0001	– 0.2	± 1.6	Pass
600	600.0010	600.0004	– 0.6	± 1.7	Pass

Conformity assessment vs. adjustments

To the casual observer, the measurement for conformity assessment, including both the as-found and as-left results, may appear to be identical to the measurement to determine the correction values. But they are not identical, and it is critical to understand the difference between these two measurements – and the two measurands – in order to properly evaluate the measurement uncertainty.

For the technician calibrating the LH-600, the measurements for conformity assessment versus determining corrections are nowhere near identical. Even though the same general measurement is being made in both cases, the as-found and as-left measurements feel completely different – much less stressful – than the measurements for correction values. The conformity assessment measurements can be done fairly quickly by a technician with minimal training. The unit and the reference standard are moved into place, a single button is pressed, and the measurement occurs automatically. If the results are acceptable, the technician moves on without further thought. In general, conformity assessment results can be obtained without much knowledge about the LH-600 beyond basic operation.

When making measurements for correction purposes, there is a much more serious feeling. The measurements are going to be used to change the accuracy of the LH-600, and any mistake will be passed along to all subsequent measurements made using the measuring instrument. There is no pass or fail result or any immediate feedback; there is only a measured value. The technician doing this measurement needs greater skills, more experience, and the ability to objectively assess the situation to avoid problems and to possibly modify the procedure. For example, the technician may decide to repeat several measurements to increase confidence in the correction values.



Two different measurands

Carefully specifying the measurand – the quantity intended to be measured – is necessary for any measurement and is critical to properly evaluate the measurement uncertainty. Too often in measurement uncertainty practice, a mistake is made by starting the uncertainty evaluation with the measurement procedure without first understanding and stating the measurand. An assumption is made, often incorrectly, that the measurand is self-evident.

For the LH-600, the measurements made to determine the correction values feel so different than the test values for conformity assessment because the measurand is so different. The measurement procedures are almost identical, but the measurand and the purpose of the measurement are completely different, and this greatly impacts the contributors to the measurement uncertainty.

In ISO 14253-5:2015, the measurand associated with conformity assessment is defined as the test measurand. Measurement uncertainty, as stated by the GUM, is attributed to a measurand, so the measurand must be clearly specified and understood to properly evaluate the uncertainty. Different measurands will have different contributors to uncertainty. For this LH-600 example, this means that the measurement uncertainty for the conformity assessment measurements, the test uncertainty, will likely have a different estimate than the measurement uncertainty associated with determining the correction values. For the LH-600, the two different measurement procedures are almost identical, and for other measuring instruments they may be identical, but the measurand is different and therefore the measurement uncertainty may be different. The measurand associated with conformity assessment versus determining correction values is summarized below.

Two different quantities intended to be measured for the LH-600:

Measurement purpose	Measurand	Measured value
Conformity assessment	The length measurement error, *E*, as defined by ISO 13225, based on a single permissible test instance. Note: this includes operating the unit per manufacturer stated recommendations by someone of reasonable skill and operating within, or correcting to, the stated rated operating conditions.	Test value – for use in conformity assessment
Determine correction values	Best estimate of the systematic length measurement error, at a specific height, at 20 °C. Note: this measurement is not bound to the rules of ISO 13225 or any other test protocol, as it is not a conformity assessment test, but instead the measurement method is developed based on best metrology practices to achieve the desired results.	Calibrated value – for use in adjustments or corrections, or as an assigned reference value

Note: see the Glossary at the end of this book for a discussion of the term *calibrated value*.

Uncertainty contributors

Measurement uncertainty needs to be evaluated relative to the measurand, and not just the measurement procedure. When measurement uncertainty is evaluated only from the perspective of the measurement procedure, it is typical to include any and all sources of variation in the measured values into the estimate of the measurement uncertainty. To properly evaluate measurement uncertainty, any contributions to variation must be examined from the perspective of the measurand. Using this LH-600 case study, the difference between evaluating the measurement procedure and the measurand is shown in the table below.

Uncertainty contributors associated with different measurands. In this table, the ✓ indicates the item is measured, and the *U* indicates it is a contributor to measurement uncertainty:

Source of variation	Conformity Assessment	Determine Correction Values
LH-600 linear encoder (scale) errors and traceability	✓	✓
LH-600 column geometry and mechanical motion	✓	✓
Resolution of the LH-600	✓	U
Repeatability of the LH-600	✓	U
Condition of LH-600 base, including flatness	✓	U
Reference standard – calibrated values of the Check Master	U	U
Deviation from 20 °C – impact on the Check Master	U	U
Deviation from 20 °C – impact on the LH-600	U	U
Surface plate flatness	U	U

When determining correction values for the LH-600, the objective of the measurement is a best estimate of the systematic instrument error at a specific location, which is mostly associated with the scale errors of the LH-600, the mounting in the column, and possibly the influence of the geometry of the column. The measured value is an estimate of that error, and any other variation contributes to the measurement uncertainty. The reference standard, the surface plate, and the environment contribute to the measurement uncertainty. The condition of the LH-600, including the lack of repeatability or the resolution of the instrument, also impact the ability to obtain good correction values, and are therefore also contributors to measurement uncertainty.

For conformity assessment, the test uncertainty is associated with a very different measurand. When determining the correction values, the measurement procedure is based on recommendations from the manufacturer and taking into account the experience of the technician who may need to assess and modify the standard procedure based on the condition of the unit. In conformity assessment, the measurement procedure is set by the test protocol defined in the ISO 13225:2012 standard, and no deviations from this protocol are allowed.

For example, when doing the conformity assessment, the number of test points, and any data treatment, such as averaging of multiple measurements, must follow the test protocol. Ideally, all details of the test protocol are defined in the governing standard or in the rated operating conditions (either in the standard or stated by the manufacturer). For some specifications, further requirements for the test protocol are included with the stated accuracy specifications. Further details may also be found in any operational recommendations from the manufacturer.

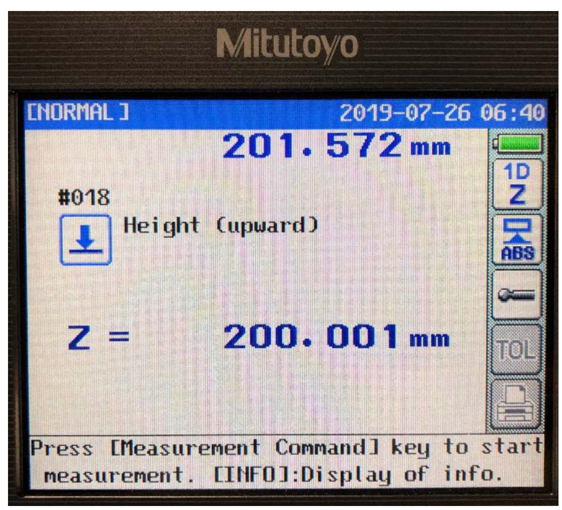
The conformity assessment test used in this example is for the length measurement error, *E*, in accordance with ISO 13325:2012. By design of the ISO committee, this error is directly influenced by all the errors in the unit, including the scale, geometry, base, repeatability, and resolution. The purpose of the test is to assess this variation to determine conformity, and this variation is not a contributor to the test uncertainty.

Resolution of the UUT

Measurement uncertainty is always influenced by the item being calibrated, or the unit under test (UUT). How the UUT contributes to measurement uncertainty depends on many factors, including the specification of the measurand. This issue will be discussed in detail in a later chapter of this book; however, this LH-600 case study provides a good opportunity to examine one specific issue – the impact of the resolution of the UUT on the measurement uncertainty.

When determining correction values, the resolution of the UUT limits the resolution of the correction values, which limits the ability to determine the best estimate of the error, and therefore the resolution of the UUT is a contributor to the measurement uncertainty.

In conformity assessment, the resolution of the UUT is just another source of error in the LH-600 that is subject to test. The objective of the test is not to find some sort of best test value, but simply to observe the test value and assess conformity. The resolution will impact the error, which may impact the conformity to specification, but the resolution is not also a contributor to the test uncertainty.



The Mitutoyo LH-600 has resolution that is selectable by the user of the measuring instrument. Changing the resolution of the LH-600 may change the measured value. Using the example measured values shown earlier in this chapter, the impact of changing the resolution is shown in the tables below.

Sample of the original as-found LH-600 test results:

Nominal Height (mm)	Calibrated Check Master Length (mm)	Measured Height (mm)	Measured Error (µm)	LH-600 Tolerance (µm)	Pass/Fail Judgement
200	199.9996	200.0006	+ 1.0	± 1.3	Pass
300	299.9998	300.0014	+ 1.6	± 1.4	Fail
600	600.0010	600.0026	+ 1.6	± 1.7	Pass

The LH-600 offers selectable resolution, and the accuracy specification is valid when the resolution is set to 0.0001 mm. If the resolution was changed to 0.001 mm, the test values may change.

As-found test results with resolution changed to 0.001 mm:

Nominal Height (mm)	Calibrated Check Master Length (mm)	Measured Height (mm)	Measured Error (µm)	LH-600 Tolerance (µm)	Pass/Fail Judgement
200	199.9996	200.001	+ 1.4	± 1.3	Fail
300	299.9998	300.001	+ 1.2	± 1.4	Pass
600	600.0010	600.003	+ 2.0	± 1.7	Fail

In these results, the change in the resolution of the LH-600 changed the measured height, which changed the measured error, which changed the pass or fail condition at that test point. For conformity assessment measurement, the resolution is just another source of error that is subject to test and that the manufacturer must consider when stating accuracy specifications. For this reason, the resolution of 0.0001 mm is a rated operating condition for testing the accuracy of the LH-600.

Test versus calibration

At the beginning of this example, it was stated that this was a case study of the calibration of a height gauge; however, none of the measurements have yet to be called the calibration results. Measurements were made to assess conformity – the as-found results and the as-left results – and measurements were made to determine the correction values for adjustment purposes. But are any of these measurements "the calibration"?

This is unfortunately a rather complicated question that is well-addressed in ISO 14978:2018 and ASME B89.7.1-2016. In the end, all the measurements discussed in this case study meet the VIM definition of calibration. The information that should be reported on a certificate of calibration depends on the needs of the customer. In this case, as is the case in many calibrations, the as-found and as-left test results, including a statement of conformity, are the results needed by the customer. Even if a statement of conformity is not included, the customer needs the test results to make a decision on conformity. In contrast, the measured correction values on the LH-600 are only used by the technician doing the calibration and have no direct use by the customer.

Mitutoyo

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ilac-MRA

A2LA ACCREDITED
CERTIFICATE #0750.01

Certificate of Calibration

Company:	Metrology Training Lab	Calibration control no:	123456
Address:	965 Corporate Blvd	Calibration date:	1-Apr-2019
	Aurora, IL 60502	Date of issue:	1-Apr-2019

Description:	Linear Height	Main unit serial no:	600591708	Probe model no:	12AAF634
Model name:	LH-600E	QMDATA serial no:	600591708		
Code number:	518-351A-21				

Specification	Tolerance	As-Left	Pass/Fail	As-Found	Pass/Fail
Length Accuracy	±(1.1+0.6L/600) µm	See below	Pass	See below	Fail
Repeatability	0.4 µm	0.18	Pass	0.27	Pass
Perpendicularity	5 µm	1.9	Pass	2.3	Pass
Straightness	4 µm	2.2	Pass	2.4	Pass

Length L	As-Left Error	As-Found Error	Length L	As-Left Error	As-Found Error	Length L	As-Left Error	As-Found Error	Length L	As-Left Error	As-Found Error
0.0	0.00	0.00	140.0	-0.22	0.08	300.0	0.03	0.93	460.0	-0.40	1.60 *
10.0	-0.25	-0.35	170.0	0.08	0.58	330.0	0.70	1.40	490.0	-0.18	1.22
20.0	-0.15	-0.15	180.0	-0.05	0.55	340.0	0.59	1.19	500.0	-0.46	0.94
50.0	-0.54	-0.44	210.0	0.22	0.52	370.0	0.08	1.48 *	530.0	-0.55	1.05
60.0	0.14	0.24	220.0	0.22	0.62	380.0	0.48	1.38	540.0	-0.27	0.83
90.0	0.40	0.20	250.0	0.27	1.07	410.0	0.53	1.53 *	570.0	-0.01	0.89
100.0	0.28	0.48	260.0	0.19	0.89	420.0	0.60	1.60 *	580.0	-0.03	1.07
130.0	0.31	0.91	290.0	0.53	1.13	450.0	0.14	1.24	610.0	-0.36	1.24

Measured errors in micrometers (µm). L in mm. Shaded values are upward measurements. * out of tolerance

Statements of conformity are based on the test values and the original manufacturer tolerances and when accounting for the measurement uncertainty using a simple 1:1 acceptance decision rule in accordance to ASME B89.7.3.1. Uncertainty: Length Accuracy: ± (0.50 + 0.9L/1000) µm, Perpendicularity: ± (0.77 + 1.5L/1000) µm, Straightness: ± 1.4 µm. The uncertainty represents an expanded uncertainty expressed at approximately a 95% confidence level using a coverage factor of k=2. The uncertainty applies to this calibration only and not the measurement of customer parts. The errors shown above are test values for verification purposes only. Traceability is through the National Institute of Standards and Technology - see listed Mitutoyo reference standards below. NIST No. 683/285684-14. This calibration was performed at the Mitutoyo Calibration Laboratory. Customer visits and tours are welcome. Procedure: CLTM-83 Rev. B. Temperature: 20°C ± 0.25°C. This is an endorsed accredited calibration certificate (A2LA 0750.01) in accordance to ISO/IEC 17025:2005 and ANSI/NCSL Z540-1-1994. This one-page certificate shall not be reproduced except in full without the written permission of Mitutoyo America Corporation.

Reference Standards	MM128, 1000 mm Checkmaster, s/n 810105	Cal Date: 9-Jan-2019	Cal Due Date: Jan-2020
	MM004, Surface plate, s/n 348-9	Cal Date: 4-Dec-2018	Cal Due Date: Dec-2019
	MM029, Ceramic Square, s/n 95059	Cal Date: 4-Jan-2019	Cal Due Date: Jan-2020
	MM096, Mu-Checker, s/n 160006	Cal Date: 1-May-2018	Cal Due Date: May-2019

COMMENTS

This sample certificate is for demonstration purposes only.

Calibration completed and authorized by: Jim Salsbury, Calibration Technician

Example LH-600 calibration certificate showing the assessment of conformity to manufacturer stated specifications.

For ISO/IEC 17025 accredited laboratories, the as-found and as-left results are generally expected to be on calibration certificates, while any additional measurements used for service and adjustments are not. As the purpose of the LH-600 calibration, in this example, is an assessment of conformity to the manufacturer's stated specifications, the as-found and as-left test values are reported on the calibration certificate along with the test uncertainty. The test uncertainty is the only appropriate statement of measurement uncertainty in this case.

Test uncertainty is used in the decision rule that applies when stating conformity, in this case a simple 1:1 acceptance decision rule in accordance with ASME B89.7.3.1-2001. This decision rule requires the measurement uncertainty to be less than the tolerance being verified. Many decision rules are based on the ratio of the tolerance to the measurement uncertainty. ANSI/NCSL Z540.3-2006 uses the term *test uncertainty ratio*, TUR, and JCGM 106:2012 uses me*asurement capability index*, C_m. For this LH-600, the tolerance, or sometimes called the maximum permissible error (MPE), is ±(1.1+L/1000) µm, and the test uncertainty shown on the calibration certificate is ±(0.5+0.9L/1000) µm. As an example, the C_m or TUR at L = 200 mm is determined by the following:

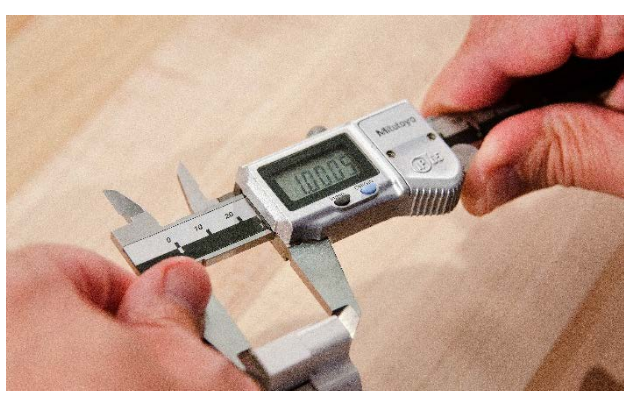
$$C_{\mathrm{m}} = \mathrm{TUR} = \frac{\pm\,\mathrm{MPE}}{\pm\,\mathrm{U}} = \frac{1.3}{0.7} = 1.9$$

TUR < 1

In this LH-600 example, the TUR is greater than one, and therefore the requirements of the decision rule in this case are satisfied and conformity can be assessed. If the principles of test uncertainty were not followed, and instead the measurement uncertainty included all the variation caused by the measuring instrument under test, then it is likely the TUR would be less than one and conformity could not be properly assessed.

As mentioned earlier in this book, the development of test uncertainty was motivated by the need to satisfy requirements of decision rules. Common practice in the calibration business often mandates decision rules that require either a high TUR, such as a TUR ≥ 4, or some uncertainty-based guard band or other method to control measurement decision risk. Without the understanding of the test measurand, uncertainty estimates become inflated and the application of decision rules almost meaningless.

Case Study Epilogue



The LH-600 was specifically chosen for this case study as it provided an example where it is common to have measurements for the assessment of the as-found and as-left conformity as well as measurements to determine correction values. There are many cases where one or the other is not the case.

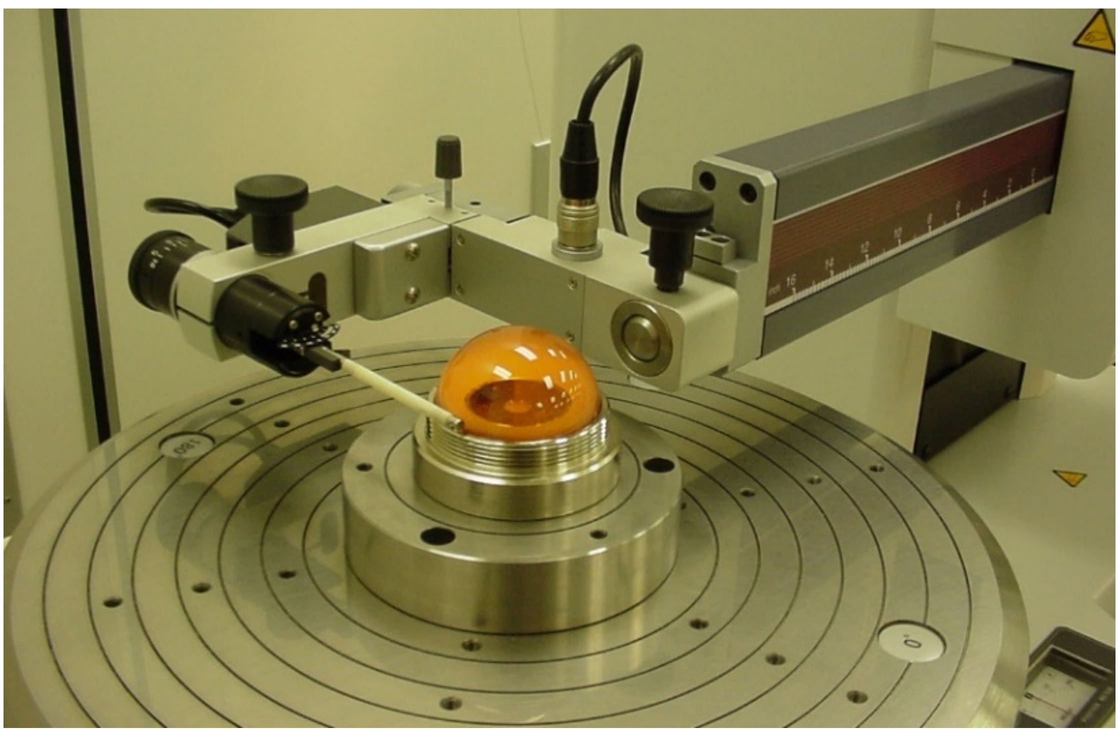
Some measuring instruments do not provide for any means to adjust the accuracy, except cleaning and repair. In dimensional metrology, examples of these types of measuring instruments would be calipers and micrometers. In these cases, general calibration practice is only conformity assessment, and there is never an attempt to determine correction values.

In other measuring instruments, particularly physical artifacts (i.e., *material measures*), calibration may never involve assessment of conformity but only the determination and assignment of values that are then used as the reference value of the measuring instrument. For example, on the Check Master that was used to calibrate the LH-600, the nominal values are generally not used, and the calibration of the Check Master does not include conformity assessment. Instead, the purpose of the calibration is to determine the actual length for each step, which is then reported on the calibration certificate. For the calibration of the Check Master, therefore, the concepts of test uncertainty do not apply. In the data tables shown earlier, the column for the "Calibrated Check Master Length" shows these previously calibrated reference values, which were taken from the latest certificate of calibration.

In later chapters of this book, additional examples will be used to demonstrate the importance of understanding the calibration needs of different types of measuring instruments. This understanding leads to understanding the measurand and thus the appropriate approach to measurement uncertainty.

The reference standard used to calibrate the Mitutoyo LH-600 Linear Height Gauge is a Mitutoyo step gauge called the Check Master. In the Mitutoyo America Calibration Laboratory, an ultra-high accuracy CMM, the Mitutoyo Legex 910, is used to calibrate Check Masters and other length standards with a measurement uncertainty as low as 0.25 µm (10 µin).

The LH-600 Linear Height gauge is a great measuring instrument to use in teaching a variety of concepts in dimensional inspection and calibration. Shown here are participants in the Hands-On Calibration class in the Metrology Training Lab at the headquarters of Mitutoyo America Corporation in Aurora, Illinois.



Using a reversal method to measure roundness to 5 nanometers (0.2 µin) in the Mitutoyo America Calibration Laboratory. Mitutoyo built a premier calibration facility to provide the support needed by Mitutoyo field service for the calibration of customer's measuring instruments.

5

Test uncertainty model

The test uncertainty concepts of ISO 14253-5:2015 are summarized in this chapter. A practical model, based on this standard, is introduced to provide direction on the implementation of test uncertainty. In addition, some worked examples can be found in later chapters.

ISO 14253-5:2015 is the first national or international standard to carefully examine the quantity intended to be measured, the measurand, when performing verification tests of indicating measuring instruments – tests that are used in conformity assessment to stated specifications. The full title of this standard is:

> ISO 14253-5:2015, Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 5: Uncertainty in verification testing of indicating measuring instruments

This standard was developed by ISO/TC 213, Dimensional and geometrical product specifications (GPS) and verification, and therefore directly impacts the dimensional metrology field. While this standard was developed for use in dimensional metrology, the general concepts apply to all fields of metrology, and the concepts need to be deeply considered by anybody involved with conformity assessment of any type of measuring instrument to specified requirements.

ISO 14253-5:2015 introduces the concepts of the *test measurand* and the *test value uncertainty*, or test uncertainty, which is the measurement uncertainty of *test values* associated with the test measurand. The measurand associated with verification testing is different from the measurand associated with calibrations that assign calibrated values. The test measurand is not trivial to specify; however, once understood, the uncertainty contributors to consider in the measurement uncertainty become more straightforward.

The scope of ISO 14253-5:2015 is limited in application to indicating measuring instruments and does not address the conformity assessment of material measures (physical artifacts). This chapter will focus on the scope of ISO 14253-5:2015. In a later chapter of this book, the test uncertainty concepts will be extended beyond the scope of the ISO 14253-5:2015, and it will be demonstrated how the test measurand also applies in the conformity assessment of material measures.

ISO 14253-5:2015 does not discuss the relationship between conformity assessment and calibration. As was discussed in Chapter 1 of this book, when the user of a measuring instrument needs to know their instrument is within tolerance, then the conformity assessment of the measuring instrument to that tolerance is the calibration. Conformity assessment does not follow from calibration; conformity assessment is the calibration.

Test

ISO 14253-5:2015 uses the term *test* interchangeably with *verification test*. According to ISO 14253-5:2015, a test is defined as a

> *sequence of preparatory, measurement, mathematical and decisional actions according to a test protocol*

and is often used to verify the specifications of indicating measuring instruments. In ISO 14978:2018, another standard from ISO/TC 213, the term *verification test* is defined with the term *test* as a synonym, and the two terms are connected to conformity assessment (see Glossary in this book). The verification test is the action – the operational part – in the conformity assessment of measuring instruments to specified requirements. The specified requirements of measuring instruments are the so-called accuracy tolerances or specifications, and which are more formally called the limits of measurement error or maximum permissible errors (MPE).

An important concept of a test is the *test protocol*, which provides the detailed specification of the test and defines the test measurand, the required test conditions, and a decision rule. The test protocol is best defined by subject matter experts and published in national or international standards, and the supplier and customer must agree on the test protocol prior to testing.

The importance of the test protocol must be considered deeply by practitioners in metrology. In accordance with ISO 14253-5:2015, the party that is performing the verification testing of an indicating measuring instrument is not at liberty to unilaterally decide the test protocol, but rather must rely on direction from available standards and reach agreement with the customer prior to testing. The test protocol should define necessary items to ensure the testing method is not left to the discretion of the party performing the verification test. For example, the test protocol should define the number and location of test points that are sufficient to assess conformity.

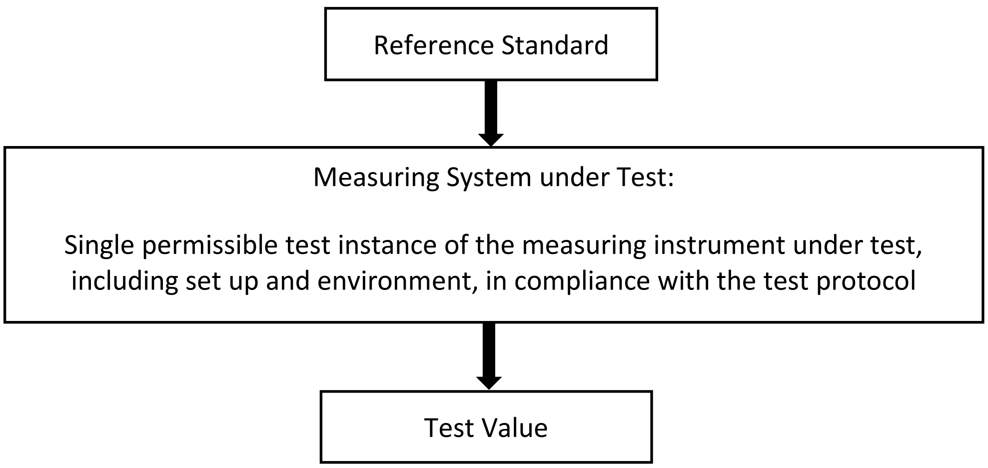
In ISO 14253-5:2015, the value measured in a test is a test value. The measurement uncertainty associated with a test value is the test value uncertainty, or just test uncertainty. Test value and test value uncertainty are just special cases of measured value and measurement uncertainty, as defined in the VIM and GUM. The terms test value and test value uncertainty are somewhat superfluous, but they are useful in providing clarity when the measurand of interest happens to be the test measurand.

Test measurand

The most important concept of ISO 14253-5:2015, and possibly of this entire book, is the test measurand. The test measurand is defined as a:

> *metrological characteristic of an indicating measuring instrument intended to be verified in a test, based on a single permissible test instance, defined by a test protocol*

The concept of a single *permissible test instance* may be one of the most important yet challenging new concepts to understand. A *test instance* is any single combination of the measuring instrument under test, the test equipment, the setup, the environmental conditions, etc. which yields a measured test value. A test instance captures not just the measuring instrument, but the entire measuring system, at a single point in time. For any test instance, the instantaneous state of the measuring instrument under test may be different. In addition, any other devices that are part of the measuring system, along with the environment, may be different from any one test instance to another.



From the theoretical population of infinite test instances, there are select permissible test instances where conformity assessment applies. ISO 14253-5:2015 defines a permissible test instance as a test instance that complies with the rules of the test protocol. The test measurand, as defined, is then based on any single permissible test instance.

A critical concept of the definition of the test measurand is that the test measurand, and its value (the true value), is uniquely defined for each single permissible test instance. As such, the test measurand is different for each permissible test instance. The test measurand is not defined as the complete population of test values from all possible permissible test instances, and as such, variation of test values due to the changing state of the measuring instrument, including across its rated operating conditions, are not contributors to the test uncertainty. For example, multiple test values at the same location, if permitted by the test protocol, are not multiple measurements of the same measurand but are instead single measurements of multiple test measurands. In this case, the variation between the multiple test values must not be seen as measurement uncertainty but rather the variation in the measuring system that is being subjected to test. In fact, it is often the explicit purpose of the test to look for this type of variation.

Of course, any variation in the test values is important, and the general purpose of a verification test is to detect the quality of a measuring instrument. The concept of ISO 14253-5:2015 is that this quality is detected and reported through the test values and not through the measurement uncertainty. Test uncertainty is a measure of the accuracy of the test values and not a measure of the accuracy of the measuring instrument. A proper verification test of a measuring instrument should involve testing the performance of the instrument and not attempting to estimate the performance via measurement uncertainty.

This concept of the test measurand relies on a rigorous test protocol. A test protocol is always a careful balance between thoroughness and practical issues like time and cost. The ideal test protocol would result in complete knowledge of the performance of an indicating measuring instrument with the minimal number of measurements.

In practice, one goal of the test protocol is to ensure the results of any one test would be sufficiently similar to the results of another. The burden of responsibility of defining the test protocol is best left to the subject matter experts developing the standards for the specific measuring instrument. As the adequacy of the test protocol to sufficiently test the measuring instrument is not a source of test uncertainty, it is critical that experts are involved with the development of the test protocol. In practice, this concept is often welcomed by practitioners, as they do not usually want or need to be concerned with the development of the test protocol, only with its proper execution, and as such, they can focus on good implementation.

Rated operating conditions

The maximum permissible errors of measuring instruments are always prescribed within specific operating conditions – the rated operating conditions. Conformity assessment of measuring instruments is done relative to the rated operating conditions, whether stated by the manufacturer or included in some governing standard. Many rated operating conditions define an interval, and the accuracy of the measuring instrument is guaranteed over the interval. Testing can, and should, be done anywhere within the stated interval. The test protocol must consider how testing across the rated operating condition will be done. Testing is not permitted outside of the rated interval.

Some rated operating conditions are prescribed at an exact value, and in these cases, the accuracy of the measuring instrument is only guaranteed at that condition. In some cases, like for instrument settings or choice of accessories, it is straightforward to realize an exact value rated operating condition. In other cases, it may be impossible to use the measuring instrument at the exact value during testing. In these cases, corrections to measured values are expected, and are typically required by the test protocol. In dimensional metrology, the most common example of this is when the specified accuracy of a measuring instrument is only valid at exactly 20 °C.

Test value uncertainty

To implement the test uncertainty concepts in ISO 14253-5:2015, it is useful to consider that a measuring instrument to be tested is always part of an entire measuring system. It is the measuring system that generates measured values – the test values. The measuring system includes the measuring instrument, operating within specified rated operating conditions and in accordance with all recommendations from the manufacturer, e.g. from a supplied operating manual. The purpose of the verification test is to test the performance of the measuring system following a defined test protocol. Test values are produced by the measuring system, and it is critical to identify the measurand and the contributors to the test uncertainty.

In conformity assessment of measuring instruments, there are three primary inputs to the measuring system under test that contribute to the test uncertainty:

- Any reference standards used in the testing.
- Any user-provided inputs necessary to operate the measuring instrument and obtain measured values.
- Any corrections to measured values associated with operating the measuring instrument outside of rated operating conditions.

All the contributors to test uncertainty fall within these three broad categories. These will be described in this chapter, and the examples in later chapters will provide further clarity.

Reference standard

The measurement uncertainty associated with the reference standard includes the measurement uncertainty associated with its calibrated and traceable reference value, u_x, such as that obtained from a calibration certificate, plus any additional uncertainty associated with its use in the test, u_a. The additional measurement uncertainty associated with the reference value may come from something such as handling, preparing, and fixturing of the reference standard.

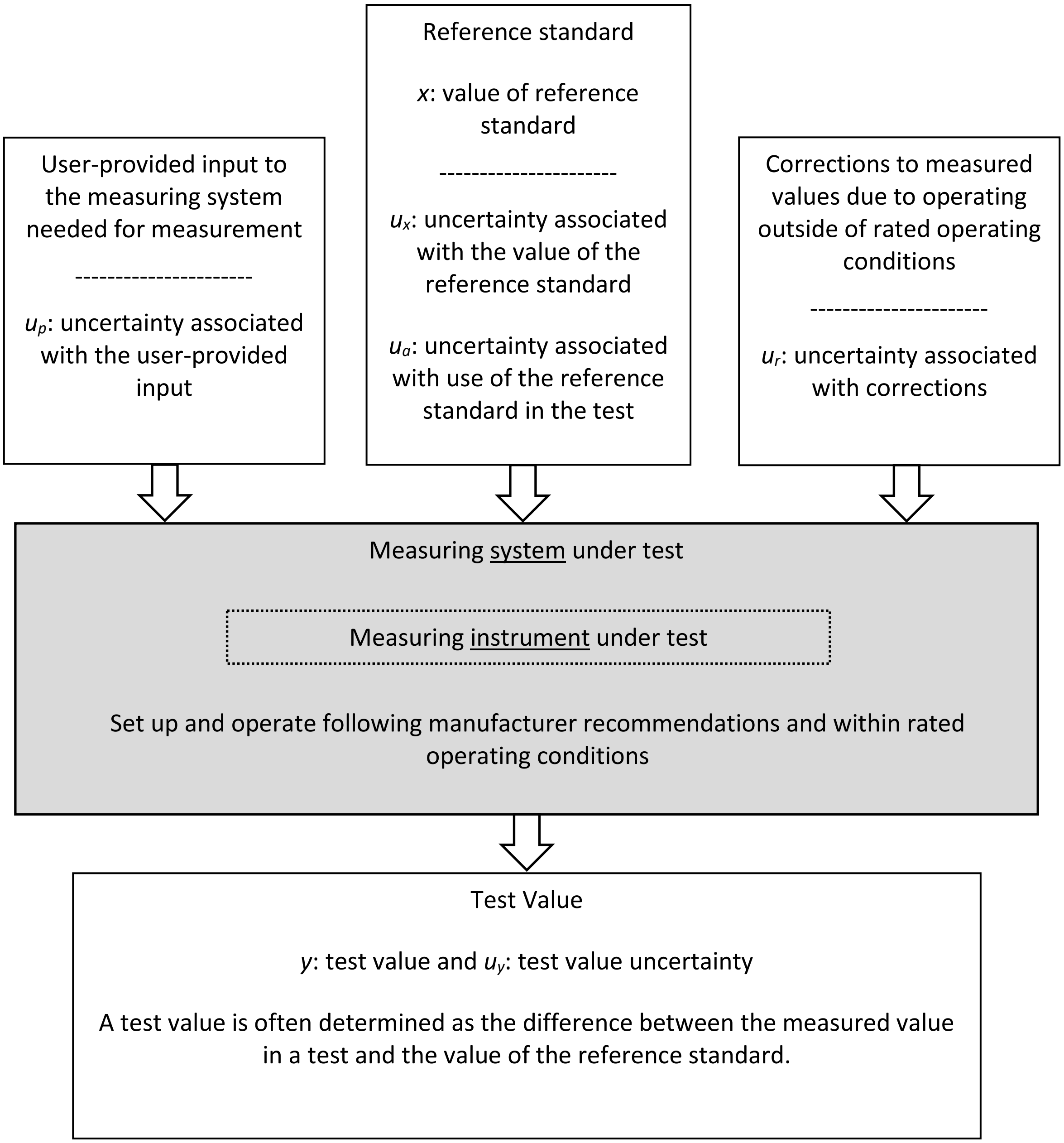
The measurement uncertainty associated with the reference standard may be quite simple, such as the measurement uncertainty associated with the calibrated reference value of a gauge block, or it could be quite complex, for example when a laser interferometer is used as the reference standard. The reference standard is the most commonly seen contributor to measurement uncertainty in uncertainty budgets.

User-provided inputs

The measurement uncertainty associated with user-provided inputs, u_p, depends on the test protocol and does not exist in all tests. The proper use of some measuring instruments requires the user to provide additional information to the measuring system, and this information may introduce additional measurement uncertainty.

In dimensional metrology, the one common case of this is for measuring instruments with built-in temperature compensation, where the user must provide the measuring instrument with the coefficient of thermal expansion (CTE) of the item being measured. In this case, the testing may require the CTE of the reference standard to be input to the measuring instrument and therefore any uncertainty in the value of the CTE is a contributor to the measurement uncertainty.

When the measuring instrument requires user-provided inputs, and when the user-provided information impacts measured values from the measuring instrument, then this must be considered in the evaluation of the test uncertainty.



General concept of test value uncertainty based on ISO 14253-5:2015.

Corrections to measured values

Ideally, all measuring instruments would have stated intervals of rated operating conditions for all of the conditions of measurement, but unfortunately that is often not practical. When a rated operating condition is defined over an interval, then the testing is required to be done within those conditions. For example, a large measuring instrument that is installed at a customer site might have a rated operating condition for temperature of 18 °C to 22 °C. In that case, permissible test instances are only within that temperature range.

The performance of a measuring instrument can change as the actual testing conditions vary across the rated operating conditions. Variation in test values is expected, and in some cases, the test protocol is designed to expose sensitivities in measuring instrument performance to changing operating conditions. To protect the customer, the test may be designed to test the measuring instrument across some portion of the rated operating conditions. The variation in test values associated with the changing performance of a measuring instrument is specifically part of the test and is not a contributor to the test uncertainty. This variation is sometimes labelled as the "repeatability of the unit under test" and is incorrectly included into the uncertainty. When testing measuring instruments, this practice is dangerous and is usually going to lead to incorrect and inflated evaluations of uncertainty.

Some measuring instruments have rated operating conditions defined at an exact value. In dimensional metrology, the most common example of this is for the many small measuring instruments with the accuracy defined at exactly 20 °C. When rated operating conditions are defined at an exact value, and corrections to measured values are permitted or required by the test protocol, then the measurement uncertainty associated with these corrections, u_r, must be considered in the test uncertainty. In dimensional metrology, common cases are corrections for temperature or deformation. When permitted by the test protocol, these corrections are usually done by the user during measurement and may require additional measurements and assumptions, all of which contribute to the test uncertainty.

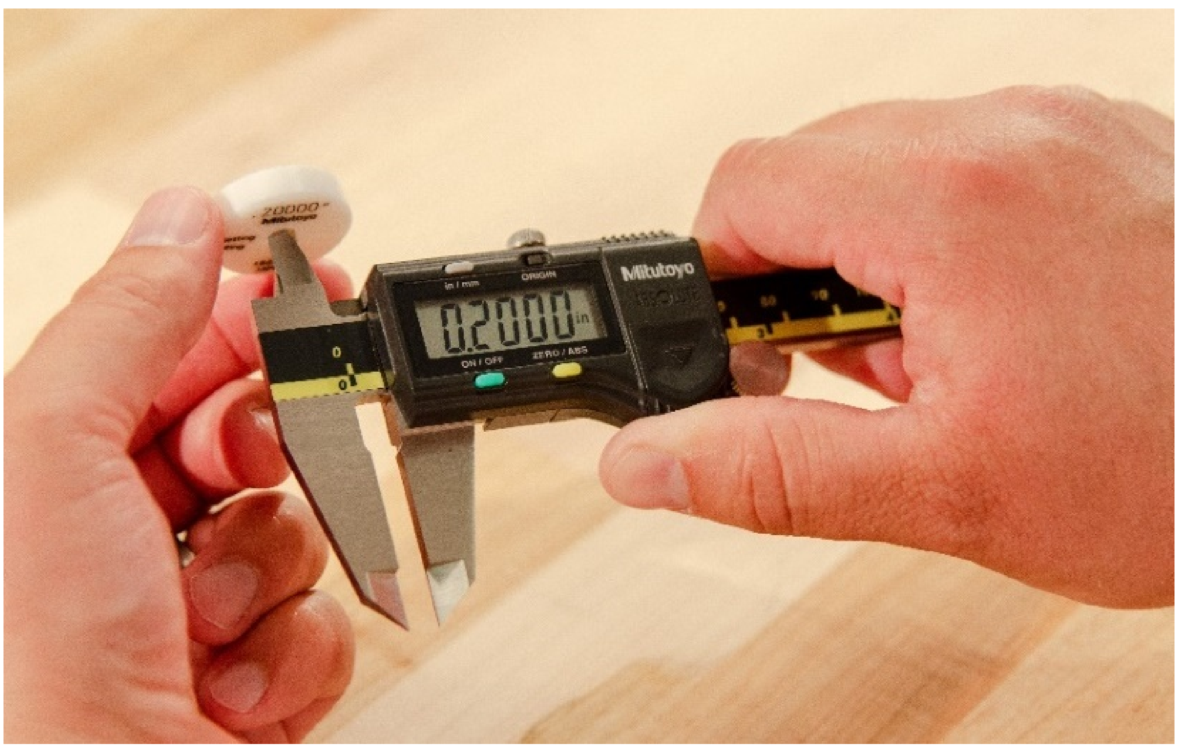
Documentary standards

This chapter discussed the test measurand and the importance of the test protocol. The goal of any test protocol is to test the measuring instrument in a manner that is both sufficient and efficient. Testing takes time and costs money, yet insufficient testing could create dangerous quality risks.

As the concepts of test uncertainty grew within the dimensional metrology standards community, a new focus emerged on the content in the documentary metrology standards. The impact of test uncertainty raises the burden on the developers of national and international standards to ensure that standards are sufficiently complete to allow the test protocol to be defined without ambiguity yet efficient and economical to perform.

Many older standards, or standards in other metrology fields, may create some issues with implementation of test uncertainty ideas. It is expected and hoped that work on standards will continue to move forward and embrace test uncertainty concepts, and by doing so, reduce ambiguity and improve quality in calibration.

To reduce the uncertainty of their use in less-than-ideal environments, Mitutoyo offers gauge blocks with the Coefficient of Thermal Expansion (CTE) calibrated.



The American standard for calipers, ASME B89.1.14-2018, requires testing the inside measuring function of certain styles of calipers using a ring gauge with a nominal size of 0.2 inch (5 mm). A single reading at this test point, with no averaging of multiple readings, is required. This type of specificity in the test protocol is critical.

6

Applying the test uncertainty model to a CMM

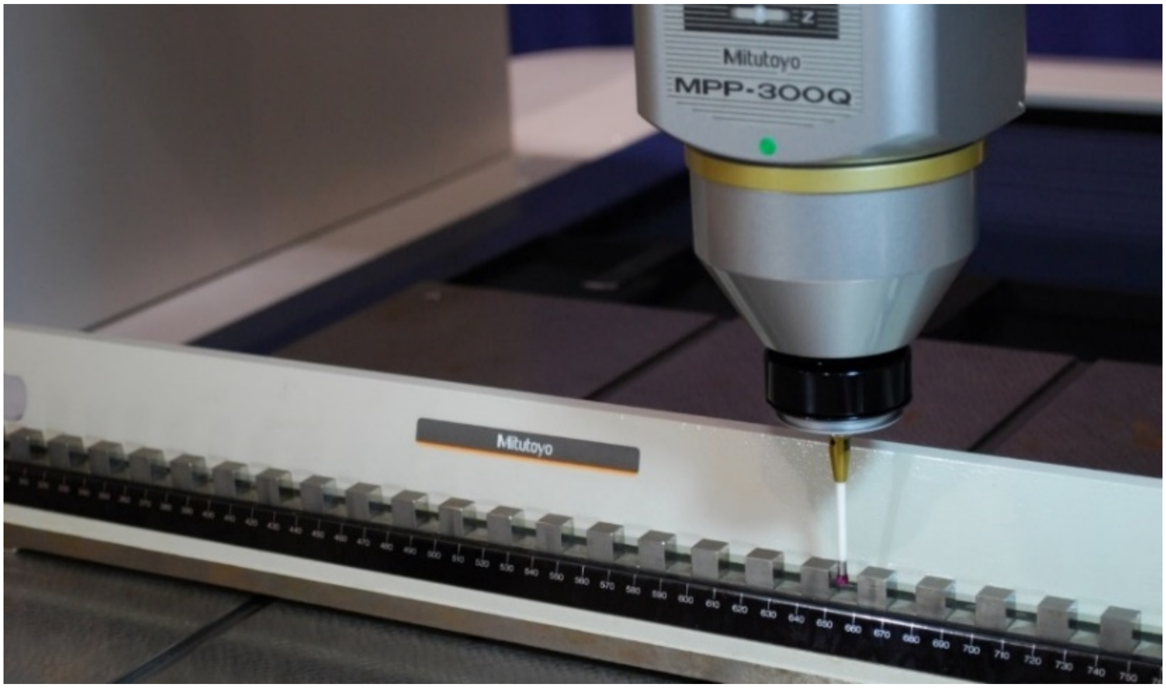
The concept of test uncertainty originated in ISO/TC 213/WG 10 on coordinate measuring machines (CMMs) in response to the need to better understand measurement uncertainty for use in the application of decision rules in conformity assessment. WG 10 developed the first standard on test uncertainty, ISO/TS 23165:2006, as a guide to test uncertainty evaluation for use when testing CMMs in accordance with the most important CMM testing standard at the time, ISO 10360-2:2001. The current version of this standard is ISO 10360-2:2009.

ISO 10360-2:2009 is an example of a standard that has a well-developed test protocol. Testing a complex, three-dimensional, indicating measuring instrument is challenging, and many experts from around the world have been involved with defining and refining standardized CMM test methods for many decades. The primary length test in ISO 10360-2:2009, known as the E_0 test, has proven itself since 1994 as the preferred verification test for CMMs. All global CMM manufacturers state specifications in accordance with this standard, and most accredited calibration laboratories around the world perform the E_0 test from ISO 10360-2:2009 when testing CMMs.

ISO 10360-2:2009 includes many specific details for a verification test of the stated specification for E_0, the maximum permissible error $E_{0,\mathrm{MPE}}$. The details are rather specific, and although possibly confusing to those not familiar with CMMs, the extent of specificity should be apparent even for those who do not work in dimensional metrology. The following are some of the standardized requirements associated with testing for conformity to $E_{0,\mathrm{MPE}}$:

- 105 test values with seven measurement lines and five lengths repeated three times across each measurement line.
- Minimum coverage of 66% of the measurement range per measurement line.
- Single-point to single-point definition of an indication for each test point.
- Requirement for opposing point, bidirectional, measurement for each test value.
- Guidelines for the sequencing of the test points.
- Range of permitted coefficient of thermal expansion (CTE) for the material of the reference standard.
- Technique for handling non-conforming data with rules for repeat measurements.
- Defined conformity assessment decision rule.
- Requirement for specification of rated operating conditions, e.g. limits for temperature.

The level of detail in ISO 10360-2:2009 results in a test protocol with little to no ambiguity and is straightforward to follow in practice. A technician testing a CMM applies the same test protocol to all types of CMMs and trusts that the subject matter experts who developed the standard have developed an efficient test method that sufficiently tests the CMM.



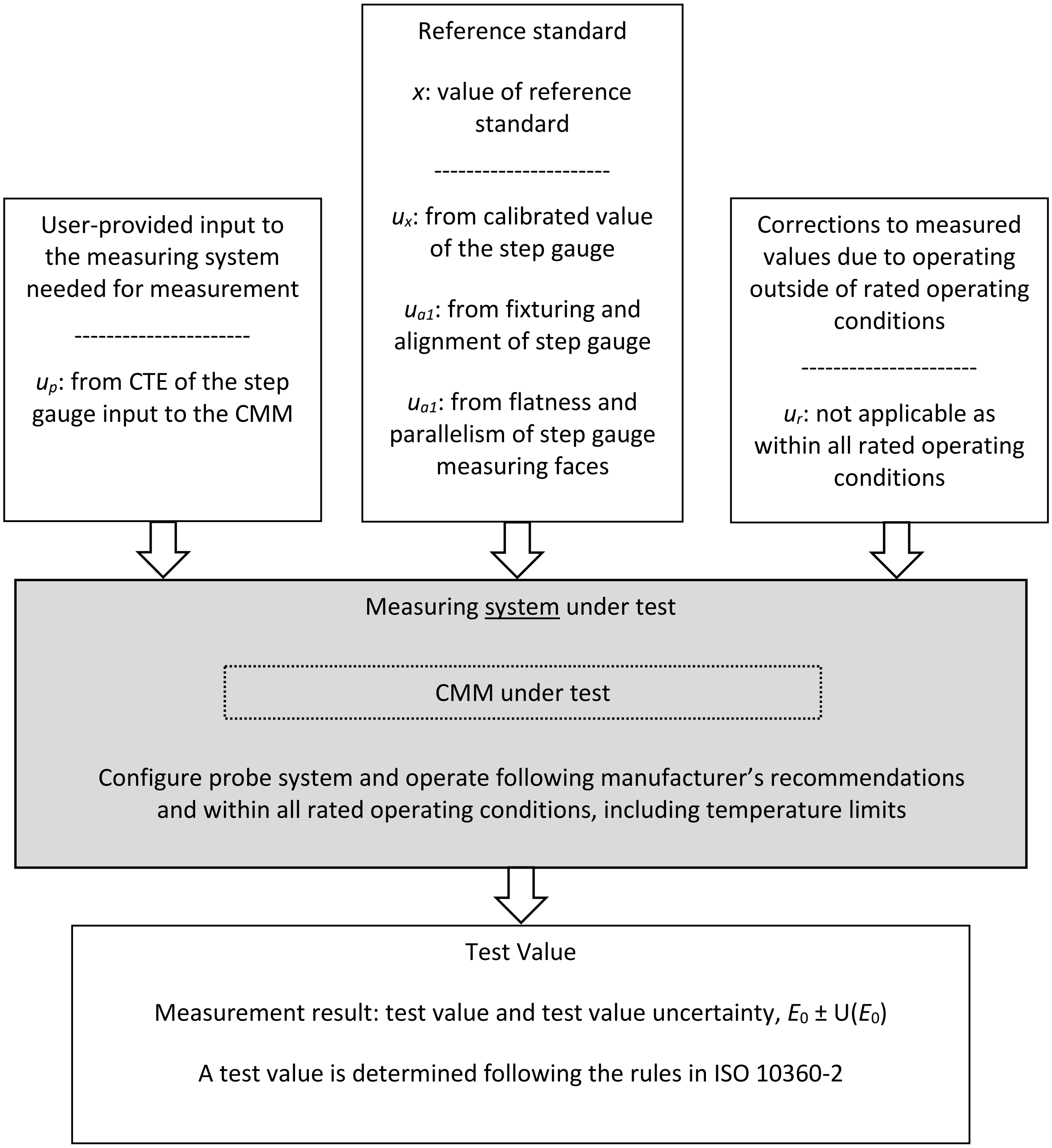
Using a step gauge to test the conformity assessment of a CMM to $E_{0,MPE}$ from ISO 10360-2:2009.

Case study

For this example, an automated computer numerically controlled (CNC) CMM is considered. The CMM also has built-in temperature compensation, which is standard on many CMMs. A step gauge is the reference standard used in testing. The step gauge is a Mitutoyo Check Master like discussed in Chapter 4 for the LH-600 height gauge case study. The CMM is tested in the field at the customer's site where the CMM has been installed. The environmental conditions around the CMM have been confirmed to meet the rated operating conditions. The CMM is operated following all manufacturer recommendations and in accordance with all rated operating conditions.

The test uncertainty model for this example is shown on the next page. The test uncertainty, in accordance with this model, ISO/TS 23165:2006, and ISO 14253-5:2015, is summarized in the table below. This example assumes that a CMM with built-in temperature compensation is being operated following manufacturer recommendations and in accordance with rated operating conditions, including rated environmental limits.

The two non-negligible uncertainty contributors are the calibrated reference value of the step gauge and the uncertainty in the step gauge CTE input into the CMM. This type of uncertainty budget has been common practice in ISO/IEC 17025 accredited CMM testing since ISO/TS 23165:2006 was first released.



Test uncertainty model applied to this CMM example.

Contributors to test uncertainty when testing a CMM to $E_{0,MPE}$ according to ISO 10360-2.

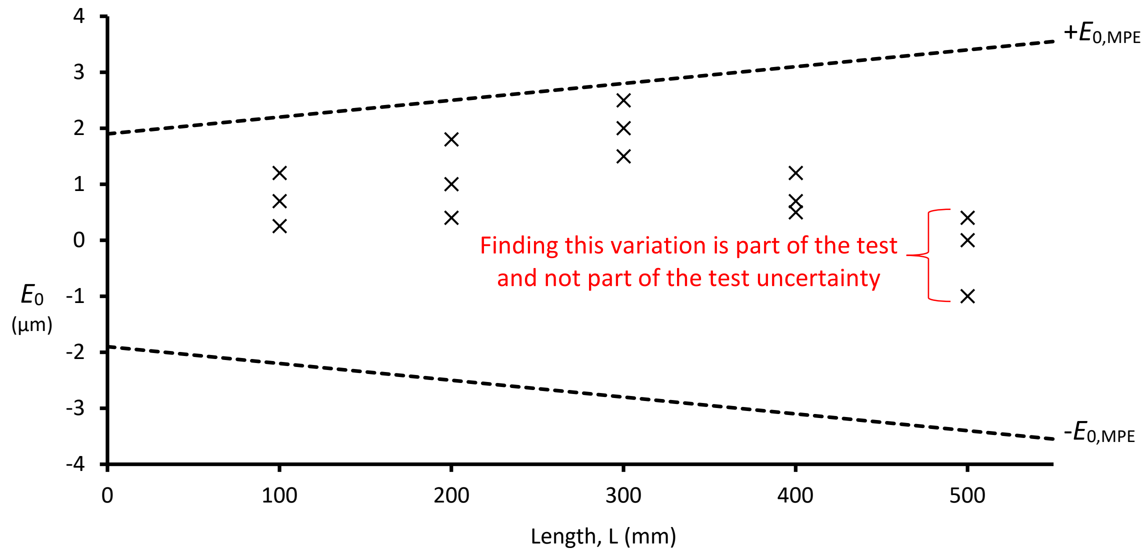
Uncertainty Contributor	Symbol	Comment
Uncertainty in the calibrated reference value of the step gauge	u_x	Usually a Type B evaluation based on the calibration certificate for the reference standard
Uncertainty in the CTE of the step gauge	u_p	Usually a Type B evaluation based on manufacturer data or calibration of the CTE
Impact of fixturing and alignment of the step gauge	u_{a1}	To be considered, but potentially negligible
Impact of flatness and parallelism of the surfaces on the step gauge	u_{a2}	To be considered, but potentially negligible

Repeatability

In accordance with ISO/TS 23165:2006 and ISO 14253-5:2015, there are no other sources of test uncertainty to consider in this CMM example other than those shown in the table above. The lack of a source of uncertainty called repeatability is of particular note and importance. There are numerous measurement uncertainty examples in the published literature that suggest that most uncertainty budgets should include a contributor to uncertainty called repeatability. This is a particularly confusing issue with verification testing of measuring instruments.

In accordance with ISO 14253-5:2015, based on the definition of the test measurand, errors of the measuring instrument, including repeatability, are subject to test and not included in the test uncertainty. The repeatability of the measuring instrument under test is not included in the test uncertainty when the purpose of the test is to assess, in part, the repeatability of the measuring instrument. Poor repeatability will generally make it more likely the measuring instrument will not conform to specification, but it will not also increase the test uncertainty.

It is important to note that ISO 14253-5:2015 is not saying that repeatability is not important or ignored, only that the repeatability of the measuring instrument under test is generally not included in the test uncertainty for verification tests. If there is a possibility that the reference standard is not stable, thereby causing the test values to not be repeatable, then that repeatability would need to be considered as a contributor to the test uncertainty. This might be the case for certain measurement standards, particularly those that are indicating measuring instruments, but this is not the case for the step gauge in this example. In addition, for this example, it is assumed the CMM is operated following manufacturer recommendations and therefore there are no additional contributions to test uncertainty from repeatability.



Example of testing a CMM in accordance with ISO 10360-2. The fifteen test values for one of the seven required measurement lines are shown in comparison to the tolerance of $E_{0,MPE} = 1.9+3L/1000$ µm. Three test values are reported at each of five lengths. The variation between the three values is part of the test and not a contributor to the test uncertainty.

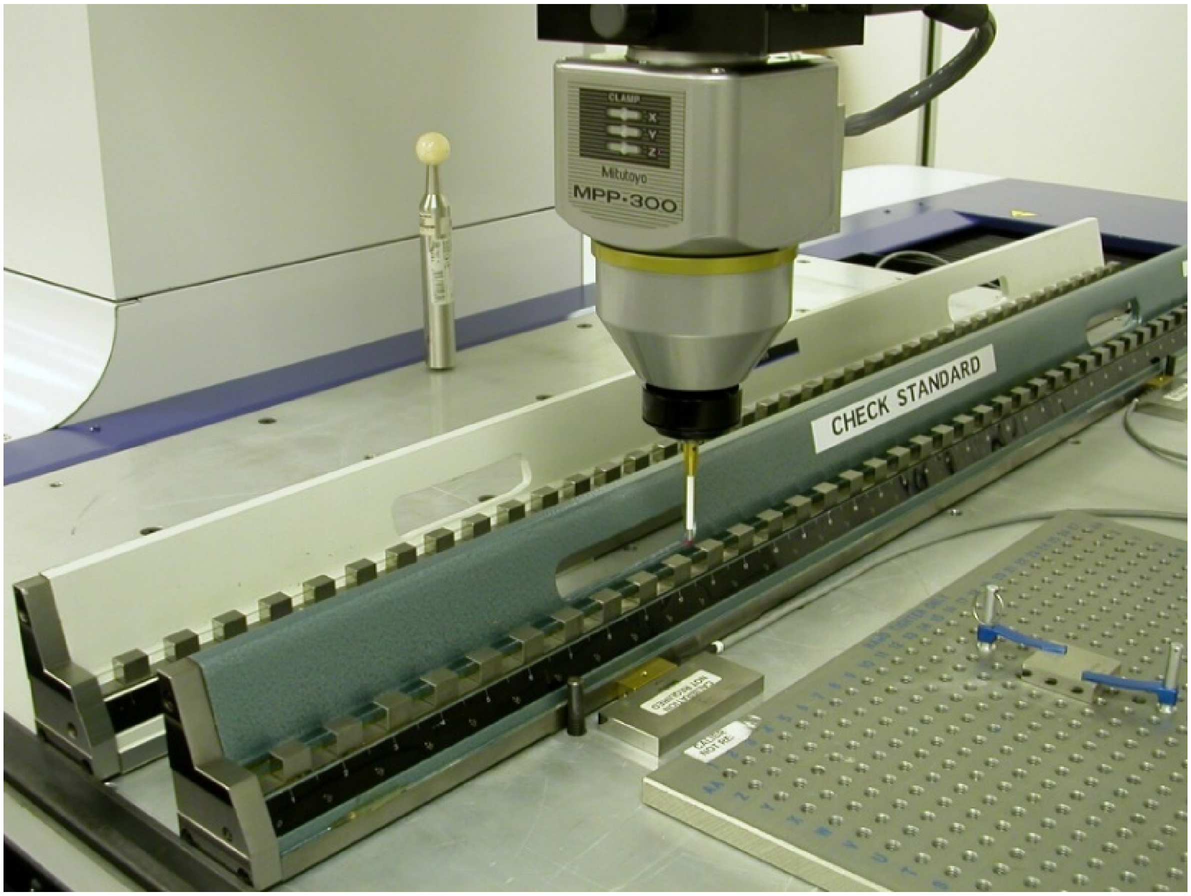
Test Protocol

According to ISO 14253-5:2015,

> *a good test protocol will cover a high fraction of the indicating measuring instrument performance with a limited effort and cost*

Developers of test protocols are concerned with the adequacy of the test protocol – is there a possibility that a test protocol will not provide a sufficient test and will "miss something". The most common example of this is a larger error somewhere in the measuring range that is simply not tested.

Examples like this may encourage metrology practitioners to consider increasing the test uncertainty to account for the potential untested errors between test points; however, any such attempt will be quite questionable, as there is no reliable or practical source of information to estimate such uncertainty. Good metrology standards will yield good test protocols that will properly mitigate this risk. Once developed and agreed upon, the test protocol is trusted, and the adequacy of the test protocol is not included in the test uncertainty.



A Mitutoyo Check Master being calibrated on a Mitutoyo Legex 910 CMM in the Mitutoyo America Calibration Laboratory. In the calibration of the Check Master, the purpose of calibration is to measure and report a calibrated length for each step of the gauge. There is no conformity assessment, as the Check Master is not typically used in that manner.

Learning proper calibration technique for the Mitutoyo LH-600 linear height gauge in the Mitutoyo America training laboratory.

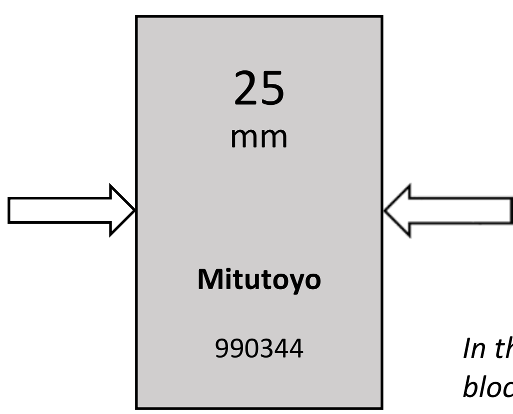
7

Material measures

In the VIM, physical artifacts with assigned values, such as gauge blocks, standard weights, and line scales, are known as material measures. Indicating measuring instruments and material measures are two different types of measuring instruments. The scope of ISO 14253-5:2015 is limited to indicating measuring instruments; however, in this chapter, the test uncertainty concepts will be extended and applied to material measures.

The test uncertainty concepts are demonstrated here using an example that is common in dimensional metrology – the calibration of a gauge block. Gauge blocks are well standardized, including in American standards, ASME B89.1.9-2002, and internationally, ISO 3650:1998. There are also many good examples of measurement uncertainty budgets for the calibration of gauge blocks in the literature, for example in EA-4/02 M:2013.

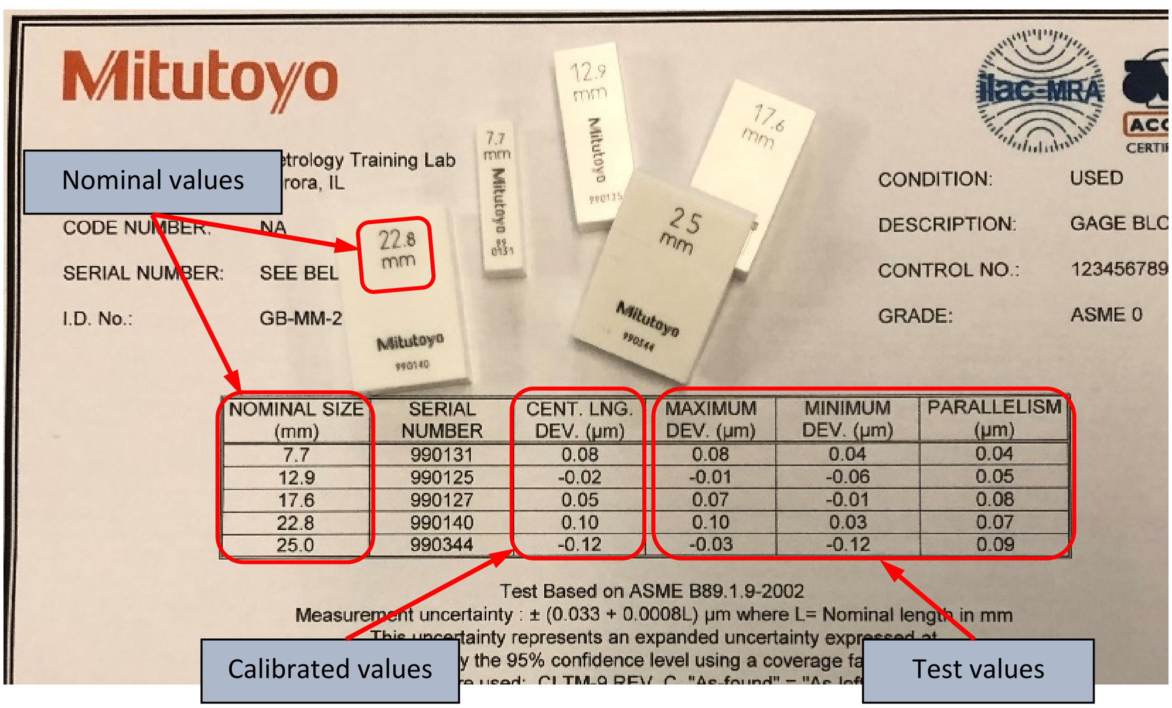
In practice, gauge blocks can be used in two different manners. In general purpose use, the nominal value shown on the gauge block is often used as the reference value. This value is managed in calibration to ensure the actual size of the gauge block is within specified tolerances over time. The documentary standards for gauge blocks include defined tolerance grades, e.g. Grade 0. When improved accuracy is needed, the alternative use of the gauge block is to use the measured (in calibration) and assigned central length of the block, l_c, per ISO 3650:1998 (this is called the gauge length, l_g, in ASME B89.1.9-2002). The calibrated length is generally more accurate than the nominal value and is independent of the tolerance grade. The use of the calibrated value requires looking up the value from the calibration certificate, which may be undesirable in some cases. The use of the nominal value is therefore easier but less accurate.



Example:
Calibrated central length
l_c = 24.99988 mm

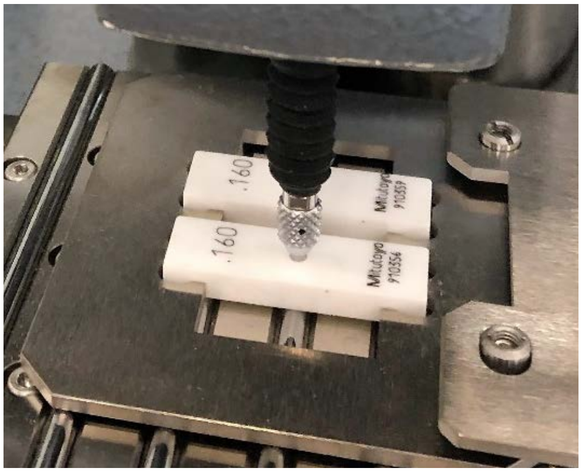
In this example, the reference value for the gauge block could be either 25 mm or 24.99988 mm.

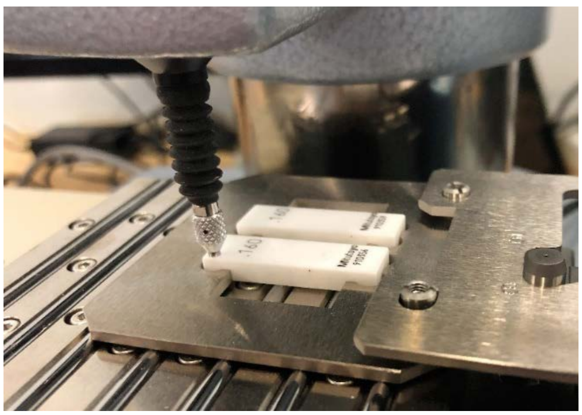
Comments	Nominal Value	Calibrated Value
Reference value	Nominal value l_n marked on gage block (e.g. 25 mm)	Calibrated central length l_c from the calibrated certificate (e.g. 24.99988 mm)
Uncertainty in reference value	Based on tolerance grade in the standards ($\pm\ t_e$)	Uncertainty of calibrated value from calibration certificate, $U(l_c)$
Advantages and Disadvantages	(1) Easy to use – just read value marked on gauge block. (2) Applies across the entire measuring face.	(1) More accurate as calibrated value not limited by tolerance. (2) Must look-up value from calibration certificate. (3) Only applies at a single defined point on the measuring face.
Calibration	Verification test at five points: the central length and near the four corners	Calibrated and assigned value at one specific point



NOMINAL SIZE (mm)	SERIAL NUMBER	CENT. LNG. DEV. (µm)	MAXIMUM DEV. (µm)	MINIMUM DEV. (µm)	PARALLELISM (µm)
7.7	990131	0.08	0.08	0.04	0.04
12.9	990125	-0.02	-0.01	-0.06	0.05
17.6	990127	0.05	0.07	-0.01	0.08
22.8	990140	0.10	0.10	0.03	0.07
25.0	990344	-0.12	-0.03	-0.12	0.09

The calibration certificate says the 25 mm gauge block is 24.99988 mm at the central gauge point. Additional measured values are also provided to determine conformity to specification. Depending on how it is used, the reference value of the gauge block could be either 25 mm or 24.99988 mm. This single calibration certificate provides the necessary information for either use of the gauge block.





The use of a gauge block is important when understanding how to manage the calibration of a gauge block. When using the nominal value, changes over time in the length of a gauge block may not matter much if the gauge block remains within tolerance; however, if the calibrated value is used, then small changes in the gauge block length may impact measurement quality. Commercial and in-house calibration laboratories will frequently report the central (gauge) length as well as assess conformity to the grade tolerance. Many national metrology institutes (NMI) will only report the central (gauge) length, as gauge blocks sent to them are typically going to be used as masters in the calibration of other gauge blocks.

To assess conformity of a gauge block to its tolerance grade, both ISO 3650 and ASME B89.1.9 prescribe measuring the gauge block length at the center and near the four corners of the measuring faces.

Measurement uncertainty in gauge block calibration

For this case study, the uncertainty budget for the calibration of the central gauge length of a 50 mm gauge block that is found in EA-4/02 M:2013 is used. This example is similar to other uncertainty examples found in the literature for calibrating gauge blocks and contains many of the same uncertainty contributors that are common in dimensional metrology examples.

The uncertainty budget from EA-4/02 M:2013 is shown on the next page, and of interest is the source of uncertainty based on the influence of the geometry of the gauge block measuring faces. The central gauge length is defined at a specific point – the exact center of the measuring faces for rectangular gauge blocks. This exact location is part of the definition of the measurand. The measurand is more than just length at 20 °C – it also includes being the length at a defined point at 20 °C. The measurement; however, might not be done at exactly the center of the measurement faces. This is the reason why this uncertainty contributor is included in the uncertainty budget.

The flatness and parallelism of the gauge block measuring faces influence how much variation is expected due to not measuring at the exact center of the measuring faces. The evaluation of the measurement uncertainty must also include an estimate of how close the measurement might be to the center point. In this example, EA-4/02 M:2013 used an assumption of the measured point being with a 1 mm diameter around the actual center point. Between the two assumptions, a standard uncertainty associated with this uncertainty contributor can be calculated.

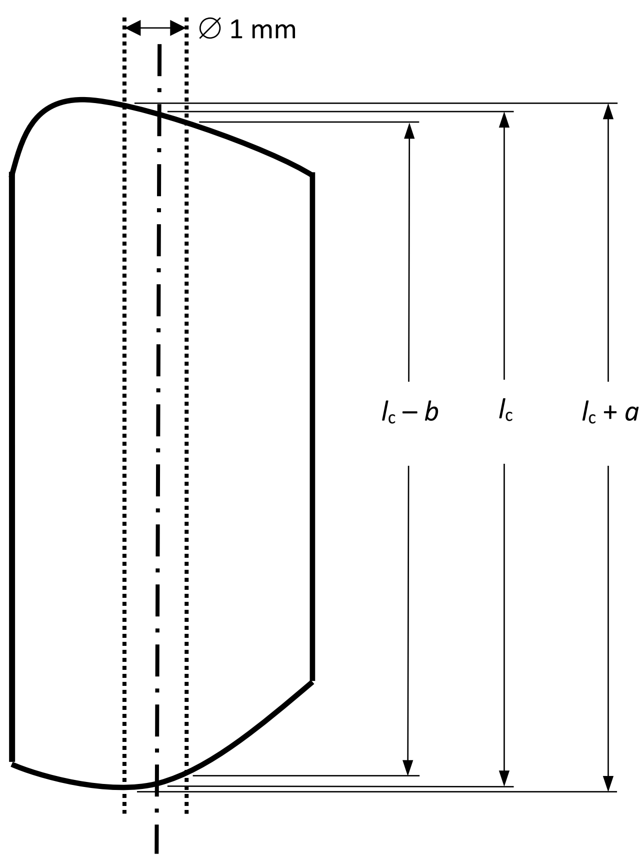
Uncertainty budget from EA-4/02 M:2013 for the calibration of the central gauge length of a 50 mm gauge block.

Uncertainty Contributor	Standard Uncertainty (nm)
Master gauge block	15.0
Drift of master gauge block	17.3
Repeatability	5.4
Mechanical comparator	18.5
Temperature – difference between master and test block	16.6
Temperature – differences in CTE and deviation from 20°C	11.8
Geometry of gauge block measuring faces	**3.9**
Combined uncertainty	36.4

This highly exaggerated two-dimensional drawing shows the flatness and parallelism of the gauge block measuring faces. When trying to measure the length at a specific point, any error in measuring at that point will result in length errors due to the geometric influence of the flatness and parallelism of gauge block faces. The geometry of these faces therefore impacts the uncertainty when measuring the length at a defined point.

In this example, the assumption is that the actual measured point is located within a circular radius of 0.5 mm around the defined measured point (the central gauge length). The error in length measurement is shown here as (l_c+a) and (l_c-b).

The estimated uncertainty in this example, as shown in the table above, is quite small, only 3.9 nm; however, the concept of including this contributor to uncertainty is important.



Gauge block test uncertainty

The uncertainty budget from EA-4/02 M:2013 for gauge block calibration is an example where the measurand is the length at a defined point on a gauge block, the central length l_c as defined in ISO 3650. The measured value, along with this uncertainty, is typically reported on a calibration certificate and is used as the assigned reference value of the gauge block when the gauge block is used. This is the measurement result needed when, as discussed earlier, the calibrated value of the gauge block is intended to be used in subsequent measurements.

Nominal value

The alternative use a gauge block – the nominal value marked on the gauge block – requires that the gauge block calibration include an assessment of the conformity of the gauge block to the specified tolerance grade. For the overall length tolerance, the gauge block standards define the tolerance, $\pm\, t_e$, as the "deviation of the length at any point from nominal length". Continuing the example of the 50 mm gauge block, if specified as Grade 0 per ISO 3650, then the tolerance would be 50 mm $\pm$ 0.2 μm. It is critical to note that this tolerance applies at any point across the measuring faces and not just the central length. The calibration results previously discussed for the central length would therefore provide insufficient information for conformity assessment of the gauge block to this tolerance.

Test protocol

According to the gauge block standards, five measurement points is sufficient to determine conformity to tolerance. The test points are the central length and one point near each of the four corners. Using the language of ISO 14253-5:2015, these five points are part of the test protocol that needs to be accepted between supplier and customer. The tolerance still applies at any point across the measuring faces, and the gauge block can be rejected as non-conforming if any point is found to be exceeding the tolerance limits. The gauge block subject matter experts who crafted the standards determined that five points provides a good balance of thoroughness and cost to sufficiently and efficiently assess conformity for gauge blocks.

Test uncertainty

All the general concepts from ISO 14253-5:2015 apply in this gauge block conformity assessment example, with each of the five test points being single permissible test instances under the definition of the test measurand. With the measurand changing from being a defined length at a specific position to being a test measurand defined by a test protocol, the previous measurement uncertainty budget needs to be examined carefully:

- Reference standard. Each of the five measurements are made in the exact same manner as the central length, and therefore all the uncertainty contributors related to the reference standard and its use would not change.
- Rated operating conditions. A rated operating condition for gauge block tolerances is that the tolerances apply at exactly 20 °C. During calibration, the influence of any deviations from 20 °C would need to be corrected and accounted for in the measurement uncertainty.

- Geometry of measuring faces. The flatness and parallelism of the measuring faces introduced uncertainty in the ability to measure the length at a defined point. When assessing the conformity of the gauge block, however, the test points are just approximately located. The measured values are test values and are not intended to be used as assigned calibrated values of the gauge block. This source of uncertainty therefore does not apply.

When different “calibration information” is used, the measurand may change, which may change the measurement uncertainty. In this example, when using the assigned calibrated value of the gauge block, there is some uncertainty contribution from the ability to measure the exact defined point. However, when using the nominal value of the gauge block, there is no longer a defined measured point, and therefore there is no longer a contributor to uncertainty due to the geometry of the measuring faces. The final uncertainty budget for the test values is shown below.

The overall difference is numerically small in this particular example, but the concept is important. Measuring the length at a defined point is a different measurand and therefore has different uncertainty contributors to consider than measuring the length at an approximate point to assess conformity. The concepts of test uncertainty apply to all measuring instruments, both indicating measuring instruments and material measures.

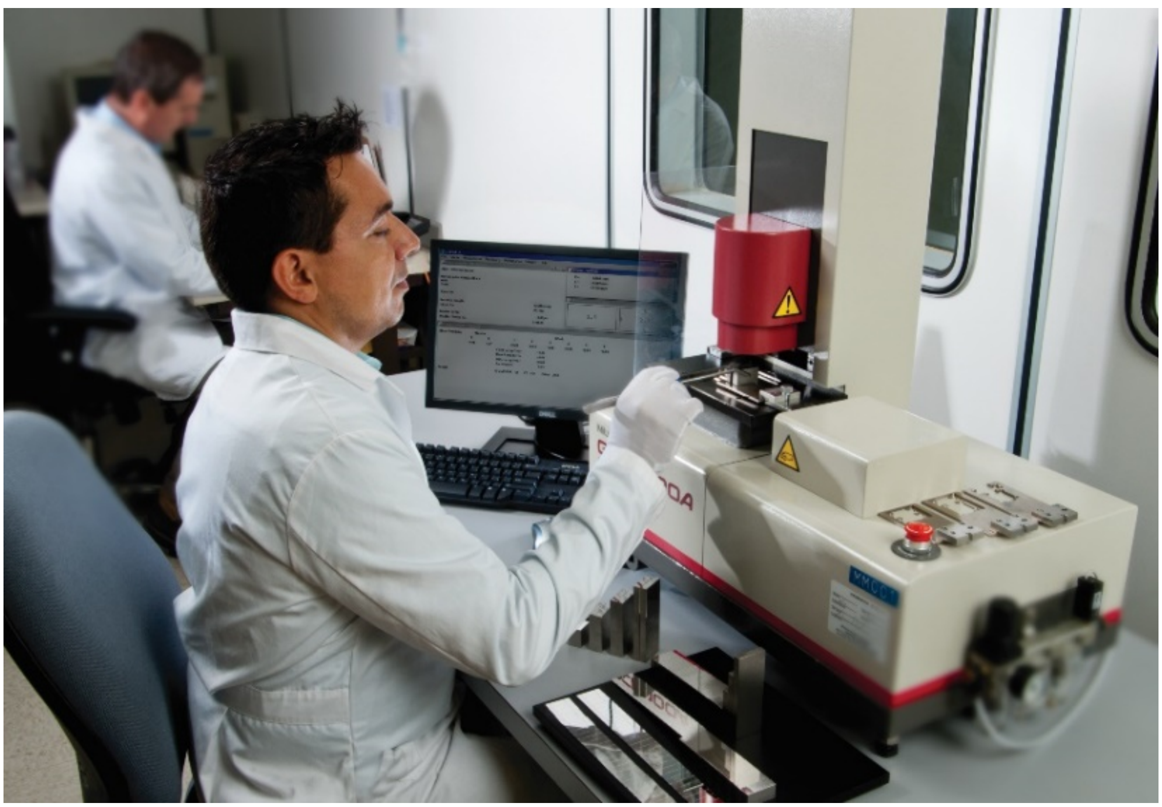
Uncertainty budget for calibration of any length of a 50 mm gauge block, modified from EA-4/02 M:2013, and implementing test uncertainty concepts:

Category of Test Uncertainty	Uncertainty Contributor	Standard Uncertainty (nm)
Reference standard (u_{x1})	Master gauge block	15.0
	Drift of master gauge block	17.3
Reference standard (u_{x2})	Repeatability	5.4
	Mechanical comparator	18.5
Corrections to measured values (u_r)	Temperature – difference between master and test block	16.6
	Temperature – differences in CTE and deviation from 20°C	11.8
	Combined uncertainty	**36.2**

Two measurands in calibration

In extending the concepts of ISO 14253-5:2015 to material measures, it becomes apparent that there are two different measurands encountered in calibration that are often not recognized. In some situations, like the central length of the gauge block – which is used as both an assigned calibrated value and a test value – these two measurands coexist for the same measured value. However, for even such a relatively simple material measure, when assigning a value to a particular point on a gauge block for subsequent use, the measurement uncertainty is different than when assessing conformity.

The difference in the measurement uncertainty between calibrated values and test values may often be negligible for material measures. This may be the reason why the difference between these two measurands often goes ignored. However, the situation is very different with indicating measuring instruments where the test uncertainty can be dramatically smaller.



Calibrating one of the over 50,000 gauge blocks that come through the Mitutoyo America Calibration Laboratory every year. Mitutoyo America calibrates all types and makes of gauge blocks and supports many of the other calibration laboratories in the US by calibrating their master gauge blocks. The gauge block comparator shown is the automatic gauge block comparator Mitutoyo GBCD-100A.

Certification in Dimensional Calibration

Mitutoyo Institute of Metrology

Mitutoyo CALIBRATION SERVICES

This is to certify that

Jane Doe

has been formally evaluated for demonstrated knowledge and hands-on skill in dimensional calibration and has successfully completed the requirements prescribed by the Institute of Metrology at Mitutoyo America Corporation to earn the following credential:

CREDENTIAL: Dimensional Calibration – General Concepts, Micrometers, and Calipers – Level 1 Theory
DATE OF ISSUE: June 15, 2018
CERTIFICATE NUMBER: 18-0007

Mitutoyo

James G. Salsbury, PhD
General Manager, Corporate Metrology
Mitutoyo America Corporation

For additional information visit:
www.mitutoyo.com/education

Mitutoyo America offers a certification program in dimensional calibration that combines written theory tests plus hands-on skills performance tests. Shown here are participants testing their skills in micrometer and caliper calibration

8

Uncertainty contributions from the user

One of the key principles of ISO 14253-5:2015 is that the quality of a measuring instrument is evaluated through test and not through the test uncertainty. The purpose of a test is to assess the accuracy of a measuring instrument, and the purpose of test uncertainty is to evaluate the accuracy of test values. In addition, a test never evaluates just a measuring instrument, but rather a test assesses an entire measuring system – the measuring instrument, its set up and operation, and all within its rated operating conditions.

The test measurand relies upon a rigorous test protocol that provides a sufficient, yet efficient, amount of testing to have confidence in the test results. To this end, the rated operating conditions are critical. Many rated operating conditions define an operational interval over which the accuracy of the measuring instrument is guaranteed. Variation in the measuring instrument accuracy across the rated operating conditions is expected, and the test protocol must address how the testing of this variation is handled.

The sufficiency of the test protocol is critical in testing. For this reason, the ideal test protocol comes from national or international standards developed by subject matter experts. In this manner, the users of the standard can focus on doing the test correctly and not worry about the sufficiency of the test protocol.

In the test protocol, typical approaches to testing across rated operating conditions would include:

- Testing at required test points across the rated operating conditions. This is the most rigorous and usually most costly approach.
- Stating minimum requirements and conditions for the testing but allowing some amount of flexibility and choice for the person performing the test.
- Allowing the customer to select the conditions at time of test, particularly for measuring instruments calibrated at the customer's location. This is less rigorous but protects the customer, as the conditions are not known in advance.
- Allowing natural variation to occur during testing. This approach works for conditions that are expected to naturally vary during testing but might otherwise be difficult to set.

Manually operated measuring instruments

Some measuring instruments are operated manually, and in some cases, the user of the measuring instrument may greatly influence the performance of the measuring instrument. In cases where there is known variation caused by the user, how is this variation handled? Is this variation part of the measuring system under test, such that the test protocol should intentionally and sufficiently test it, or is this variation a contributor to test uncertainty?

The ASME B89 and ISO/TC 213 standards committees struggled with this question. In addition, any rated operating conditions regarding the skills or contributions to the performance of the measuring instrument from the user are rarely explicitly stated. In the end, at least for measuring instruments in the dimensional metrology field, the standards committees decided that the specifications for manually operated measuring instruments must apply under normal expected use, including being operated by somebody with a certain level of skill in the use of the measuring instrument. Without this expectation, the specifications have little meaning, as the measuring system will always involve both the measuring instrument and the user.

For example, what if a robotic system, instead of a person, was used to test the performance of a measuring instrument that is sensitive to the skills of the operator? If the robotic system had better control of the measuring force, for example, then the performance of the measuring instrument might appear to be much better than is possible under normal conditions of use. A specification based on this type of test protocol would be misleading and not useful for the user.

In ISO 14253-5:2015, the "sufficient skill" of the user is considered like any other rated operating condition, even though it is not typical to explicitly state it. Instead, this rated operating condition is implicit in the specifications of manually operating measuring instruments. Proper testing to assess conformity therefore requires a user of sufficient skill, and if not, the testing is not valid.

The principles of test uncertainty say that any variation in the performance of measuring instruments across any rated operating conditions is the purpose of test and not included in the test uncertainty. When the testing is done by a user of sufficient skill, the testing is done within the rated operating conditions, and therefore there is no contributor to test uncertainty due to the skill of the user.

With this approach, the next big question is what is meant by the "sufficient skill" of the user? ISO 14253-5:2015 avoids this question a bit but does state that possibly some type of certification of skills is necessary. To specifically address this need, a type of proficiency test was developed at Mitutoyo America Corporation to test calibration skills and that offers the ability to earn certified credentials in dimensional calibration.

A caliper is a hand-held, manually operated, measuring instrument. The accuracy specifications need to be valid for a user of sufficient skill and the caliper needs to be tested under that condition. Variation from the user is expected and is part of what is being tested. Variation from the user is not also a contributor to the test uncertainty.

9

Uncertainty contributions from the UUT

In any measurement, the uncertainty of the measurement includes contributions from the entire measuring system. This includes contributions from the measuring instrument being used in the measurement as well as the object being measured. In calibration, it is common to consider what is sometimes called the contribution from the unit under test (UUT). In the conformity assessment of measuring instruments, the contribution from the UUT in the uncertainty of the test values can be difficult to identify.

In conformity assessment, the contribution from the UUT does not mean to consider all the errors in the UUT that are also subject to test. As discussed earlier in this book, errors in the UUT, like the resolution or repeatability of the UUT are generally not to be included in the test uncertainty. These sources of variation contribute to the errors of the UUT that are being tested and are not also to be included as contributors to the test uncertainty. However, the influence of the UUT must still be considered in the evaluation of test uncertainty. In this chapter, some examples of including the contribution of the UUT in the test uncertainty are discussed.

Temperature influences

All dimensional measuring instruments have a rated operating condition for temperature. In some cases, the rated condition is an interval, such as 18 °C to 20 °C. In other cases, the specifications are defined at exactly 20 °C. In the latter case, temperature must always be considered in the test protocol and the test uncertainty as it is impossible to do any test at exactly 20 °C.

When the rated operating condition is exactly 20 °C, then the test values should be corrected as if the test was actually being done at exactly 20 °C. In this case, there will be a contributor to uncertainty associated with that correction. In many cases, the calibration laboratory performing the test may not wish to perform the calculation, e.g. due to the time and cost involved. In those cases, the test uncertainty must consider the impact of not making the correction. In either case, there will be some contributors to the test uncertainty associated with not being at 20 °C exactly.

To evaluate the uncertainty associated with temperature, how the temperature influences the reference standard and the UUT must be considered. In particular, for dimensional measuring instruments that measure length, the effective coefficient of thermal expansion (CTE) associated with the UUT versus the measurement standard must be considered in the test uncertainty. It is typical to include some contribution to uncertainty called something like “difference in the CTE” with a value that changes as the CTE of the UUT changes or as the deviation from 20 °C changes in the test environment.

Geometry

Earlier in this book, an example was shown for evaluating the test uncertainty associated with testing a coordinate measuring machine (CMM) to $E_{0,MPE}$ in accordance with ISO 10360-2:2009. In that example, a step gauge, the Mitutoyo Check Master, was used, and it was mentioned that the impact of the flatness and parallelism of the measured surfaces of the Check Master had a negligible contribution to the test uncertainty. The CMM is the UUT, and in that example a fully automated, computer numerically controlled (CNC) CMM was considered. The flatness and parallelism of the Check Master measuring faces introduce negligible uncertainty since the CNC CMM precisely controls the measuring point. If the UUT were different, say a manually driven CMM, the test uncertainty would need to be reconsidered.

On a manually operated CMM, the operator of the CMM controls the location of the measurement points. Due to this, it is much more difficult to measure at a specific point. The calibrated lengths of the Check Master are defined in the middle of the measuring faces for each step of the Check Master. If the measurement is not done exactly at the central calibrated point, then additional uncertainty is possible due to the flatness and parallelism of the step gauge.

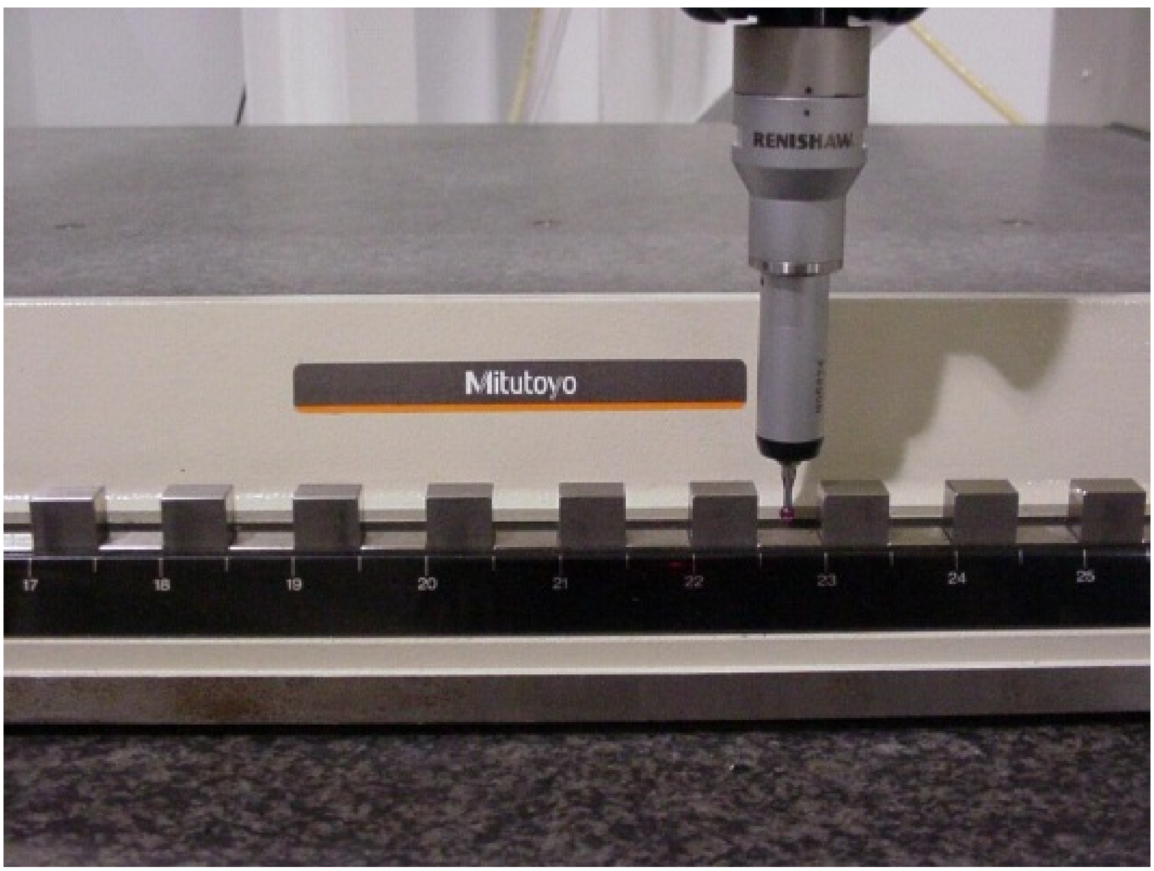
In the CMM example, the test uncertainty associated with testing the manual CMM will likely be larger than the test uncertainty when testing a CNC CMM even when the testing conditions are otherwise identical. The UUT – the manual CMM – contributes to the test uncertainty differently than the CNC CMM and this contribution must be evaluated. It is important to recognize that it is not the errors of the CMM contributing to the uncertainty; instead, the uncertainty contributed from the reference standard, the step gauge, needs to be reconsidered given the different UUT.

Contributors to test uncertainty when testing a CNC versus manual CMM for conformity assessment to $E_{0,MPE}$ according to ISO 10360-2:

Uncertainty Contributor	Symbol	CNC CMM	Manual CMM
Uncertainty in the calibrated reference value of the step gauge	u_x	Yes	Yes
Uncertainty in the CTE of the step gauge	u_p	Yes	Yes
Impact of flatness and parallelism of the measured surfaces on the step gauge	u_a	Negligible	Yes

Side note on repeatability

In general, repeatability of the UUT is not a contributor to test uncertainty. However, in a more general sense, repeatability is one of the most misunderstood concepts in measurement uncertainty, not just in test uncertainty, but also in the measurement uncertainty of anything. By definition, measurement uncertainty characterizes dispersion, and any non-repeatability in measured values may seem to directly lead to some type of Type A statistical test and the calculation of something called repeatability. In many uncertainty budgets, it is common to see *repeatability* listed. However, it must be remembered that Type A studies, often called repeatability studies, are methods to evaluate specific contributors to uncertainty. Repeatability is not really a contributor to uncertainty; instead, repeatability is the property of an experimental study that is designed to evaluate the uncertainty of something specific. In dimensional metrology, it is common to use repeatability studies to evaluate uncertainty associated with temperature, or fixturing, or operator influences. Those are the contributors to uncertainty and the Type A repeatability study is just one method to evaluate those contributors. It is often equally valid to use Type B estimates of uncertainty for those contributors. The one use of repeatability as an uncertainty contributor is as a catch-all when the real sources of measurement uncertainty are not known well. It is perfectly valid, and arguably better practice, to never have repeatability listed as a contributor in an uncertainty budget.



When testing a manual CMM, the location of the measured point on the reference standard – in this case a Mitutoyo Check Master – will be less accurate. In this case, there is additional test uncertainty, associated with the flatness and parallelism of the measuring faces, due to this contribution from the specific unit under test (UUT).

Small dimensional measuring instruments like micrometers and calipers have rated operating conditions defined at 20 °C. In these situations, there will always be uncertainty due to temperature in the calibration. The material of the micrometer or caliper, the specific unit under test (UUT), needs to be considered in the uncertainty evaluation.

The thermal diffusivity of ceramic gauge blocks makes them an ideal measurement standard for calibrations that require handling of small measurement standards, like in the calibration of outside micrometers. However, the coefficient of thermal expansion (CTE) of the gauge blocks compared to the CTE of the unit of test, the micrometer, must be considered. This contributor to uncertainty may vary from micrometer to micrometer, and the contribution to the test uncertainty due to the UUT must be considered.

10

Calibration certificates

Deep thinking about measurement uncertainty led to the critical concept of the test measurand and the measurement uncertainty associated with test values – the test uncertainty. The concepts in ISO 14253-5:2015 are just the beginning of understanding and implementing these concepts in calibration, particularly in ISO/IEC 17025 accredited calibration laboratories. Further work in ISO 14978:2018 and ASME B89.7.1-2016 applied the test measurand concept to the general question of calibration and identified that two different measurands have coexisted in the past that need to be better recognized.

When looking at calibration certificates, or scopes of accreditation, or when calibration providers are discussing work with customers, there needs to be better awareness of whether an assigned calibrated value or conformity assessment, or both, applies. When a calibration certificate contains something called measured errors and no statement of conformity, regardless of the type of measuring instrument, the application of the calibration certificate may be ambiguous. Are the measured errors supposed to be used as correction values or are they test values intended for assessing conformity (whether or not conformity is stated)? And if conformity is not stated, are the provided test values the necessary information for the customer to assess conformity, or are there additional tests and test values needed?

Calibration of an outside micrometer showing the measured test values. With no statement of conformity, it is unclear if the measured errors are intended for use as an assigned calibrated value or a test value for assessing conformity.

Nominal Length (mm)	Measured Value (mm)	Measured Error (µm)
7.7	7.701	+ 1
12.9	12.900	0
17.6	17.599	− 1
22.8	22.800	0
25.0	25.000	0

There currently is not a standardized approach for handling the two different measurands used in calibration in either scopes of accreditation or in calibration certificates. Accreditation bodies have been managing CMM verification testing and test uncertainty according to ISO/TS 23165 since 2006, and this may provide some insight into how the concepts of the test measurand could be generalized and applied to the accredited calibration of all measuring instruments. In some regions of the world, the term *performance verification* is used on scopes of accreditation to help clarify what kind of measurement will be done. As the test measurand concepts spread to all dimensional measuring instruments, and likely to other metrology disciplines, an improved and standardized approach will be needed.

Modified version of the calibration report for an outside micrometer showing the measured test values, tolerance, and pass/fail judgement. Applying the concepts of test uncertainty allows for a clear decision rule and an assessment of conformity which reduces ambiguity in calibration.

Nominal Length (mm)	Measured Value (mm)	Measured Error (µm)	Tolerance (µm)	Pass/Fail Judgement
7.7	7.701	+ 1	± 1	Pass
12.9	12.900	0	± 1	Pass
17.6	17.599	– 1	± 1	Pass
22.8	22.800	0	± 1	Pass
25.0	25.000	0	± 1	Pass

Measurement uncertainty = ± 0.25 µm (k=2). Statements of conformity based on the test values and the original manufacturer tolerances shown above and when applying a simple 4:1 acceptance decision rule.

Mitutoyo

Certificate of Calibration

ilac-MRA A2LA ACCREDITED CERTIFICATE #0750.01

NAME & ADDRESS: ABC Technologies
Springfield, IL

DESCRIPTION: Digital Caliper, 0-6 inches
CODE NUMBER: 500-196-30
SERIAL NUMBER: ABC1234

CONTROL NO.: 1234567

CALIBRATED BY: Jim Salsbury
Service Tech 1
CALIBRATION DATE: May 20, 2021
DATE OF ISSUE: May 20, 2021

CALIBRATION DUE DATE: May 31, 2022

OUTSIDE	TOLERANCE	ERROR	
		AS-FOUND	AS-LEFT
1	± 0.0010	NEW	0.0000
2	± 0.0010	NEW	0.0000
4	± 0.0010	NEW	0.0000
6	± 0.0010	NEW	0.0000
8	-----	--------	--------
12	-----	--------	--------
18	-----	--------	--------

OUTSIDE		TOLERANCE	ERROR	
			AS-FOUND	AS-LEFT
24		-----	--------	--------
32		-----	--------	--------
40		-----	--------	--------
INSIDE	0.2	± 0.0010	NEW	0.0000
	1	± 0.0010	NEW	0.0000
STEP	0.65	± 0.0010	NEW	0.0000
DEPTH	0.65	± 0.0010	NEW	0.0000

Conformity to manufacturer specifications: As-Found Condition = NEW, As-Left Condition = PASS

All values in inches

Statements of conformity are based on the test values and the original manufacturer tolerances shown above and when accounting for the measurement uncertainty using a simple 1:1 acceptance decision rule in accordance to ASME B89.7.3.1-2001. The measurement uncertainty = ±(100+2L) µin, with L in inches, which achieves better than a 4:1 test uncertainty ratio. The uncertainty represents an expanded uncertainty expressed at approximately a 95% confidence level using a coverage factor of k=2. The errors shown above are test values for verification purposes only. These test values are traceable to the SI unit of length via NIST through the listed Mitutoyo reference standards. Procedure: CLTM-7 REV. E in accordance to ASME B89.1.14-2018. Environment: 20°C ± 0.50°C, RH 40% to 50%. This is an endorsed accredited calibration certificate (A2LA 0750.01) in accordance to ISO/IEC 17025:2017 and ANSI/NCSL Z540-1-1994. This certificate shall not be reproduced except in full without the written permission of Mitutoyo America Corporation.

Reference Standards

ID	Cal Date	Due Date
MM133	6/2/20	6/2021
MM053E	10/26/20	10/2021
RG-114	12/15/20	12/2021

This calibration was performed at the world-class Mitutoyo America Calibration Laboratory. Customer visits are welcome.

Mitutoyo
Control No: 1234567 | By
Serial No: ABC1234 | JS
Cal Date: 5/20/21

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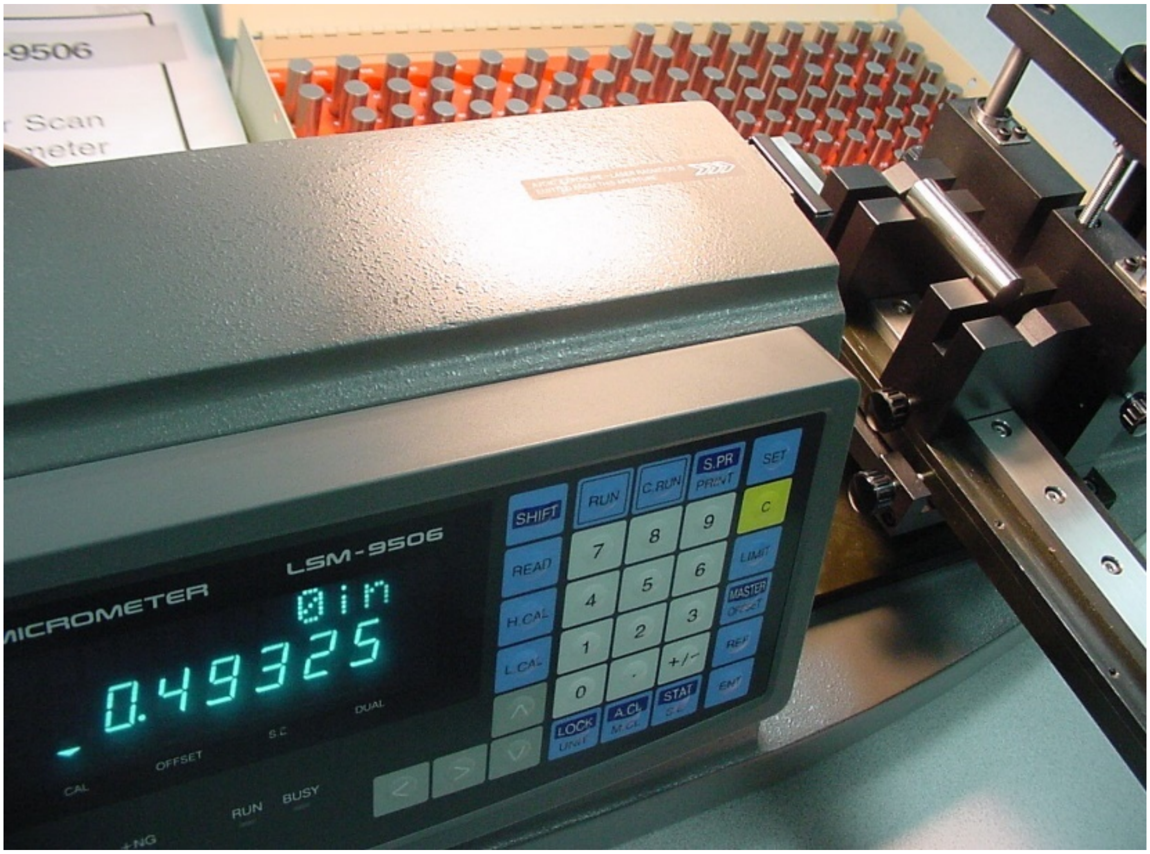
Applying the concepts of test uncertainty in practice, Mitutoyo America launched a new style calibration certificate for calipers in 2016 that incorporated the concepts of ISO 14253-5:2015. Notice that the certificate uses the term measurement uncertainty and not test uncertainty. When conformity assessment is the calibration, then the test uncertainty is the only valid measurement uncertainty and needs to be reported on the calibration certificate as the measurement uncertainty. The term test uncertainty is only used in documents explaining the concepts of test uncertainty. In practice, the term measurement uncertainty should always be used.



Calibrating pin gauges with a laser scanning micrometer or high accuracy micrometer can achieve measurement uncertainty around 0.5 µm (20 µin).

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Examples

A series of worked examples, some with numerical values, have been selected that cover the calibration of some common dimensional measuring instruments and also summarize and highlight many of the important aspects of test uncertainty. The examples include:

- Outside micrometer
- Caliper
- Linear height gauge
- CNC CMM with temperature compensation
- Manual CMM without temperature compensation

Temperature

Thermal influences frequently appear in the evaluation of measurement uncertainty for various dimensional measurements. For measuring instruments with a rated operating condition of 20 °C, there are typically four uncertainty contributors related to temperature to consider. These may be combined in different manners and may also be negligible.

<table>
<tr><th>Category of Test Uncertainty</th><th>Uncertainty Contributor</th></tr>
<tr><td rowspan="4">Corrections to measured values (u_r)</td><td>Uncertainty in CTE of the reference standard</td></tr>
<tr><td>Uncertainty in CTE of the UUT</td></tr>
<tr><td>Nominal CTE difference</td></tr>
<tr><td>Temperature difference</td></tr>
</table>

The uncertainty in the coefficient of thermal expansion (CTE) is frequently approximated to be around 10% of the nominal CTE; however, the CTE can also be calibrated.

Outside micrometer

ASME B89.1.13-2013 includes a complete evaluation of test uncertainty following the concepts of ISO 14253-5:2015. That example is summarized here.

The purpose of calibration is the conformity assessment of a digital 0-25 mm outside micrometer. The micrometer is tested for the *length measurement error* following ASME B89.1.13-2013 (or ISO 3611) with the tolerance being ±1 µm. The micrometer specifications apply at 20°C; for this example, the testing conditions are 20 °C ± 2 °C. Grade 0 ceramic gauge blocks are used as the reference standard. The resolution and repeatability of the UUT are not contributors to the test uncertainty. The operator is considered sufficiently skilled and does not contribute to the test uncertainty. ASME B89.1.13-2013 mandates a simple 4:1 acceptance decision rule. In this example, the TUR = 4 and therefore conformity assessment is allowed.

Uncertainty budget for assessing the conformity of a micrometer from ASME B89.1.13-2013:

Category of Test Uncertainty	Uncertainty Contributor	Standard Uncertainty (µm)
Reference standard (u_x)	Gauge block tolerance	0.081
	Calibration uncertainty	0.030
Corrections to measured values (u_r)	Uncertainty in CTE of the reference standard	0.013
	Uncertainty in CTE of the UUT	0.025
	Nominal CTE difference	0.055
	Temperature difference	0.065
Expanded uncertainty (k=2)		0.25

The numbers are for example only but does demonstrate that the subject matter experts who developed ASME B89.1.13 consider a TUR ≥ 4 is achievable in the calibration of an outside micrometer.

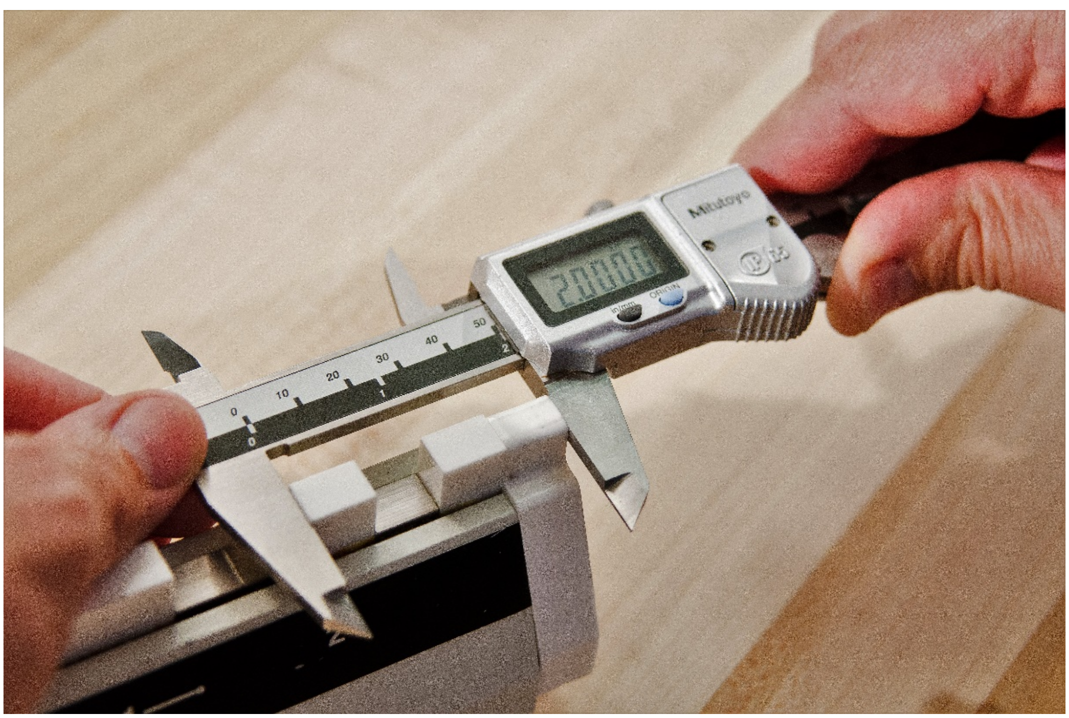
Caliper

A 0-150 mm (0-6 inch) digital caliper is calibrated. The purpose of the calibration is assessment of conformity to the manufacturer specifications following ASME B89.1.14-2018 or ISO 13385-1:2019. This example considers the metrological characteristic called the partial surface contact error, E, which is for measurements made with the outside measuring faces. The specifications are defined at 20 °C exactly. The reference standard is a Mitutoyo caliper checker.

The resolution and repeatability of the UUT are not contributors to the test uncertainty. The operator is considered sufficiently skilled and does not contribute to the test uncertainty.

Uncertainty contributors when assessing a caliper to the partial surface contact error, E_{MPE}, using a caliper checker:

Category of Test Uncertainty	Uncertainty Contributor
Reference standard (u_x)	Caliper checker tolerance
	Calibration uncertainty
Corrections to measured values (u_r)	The four temperature contributors previously described



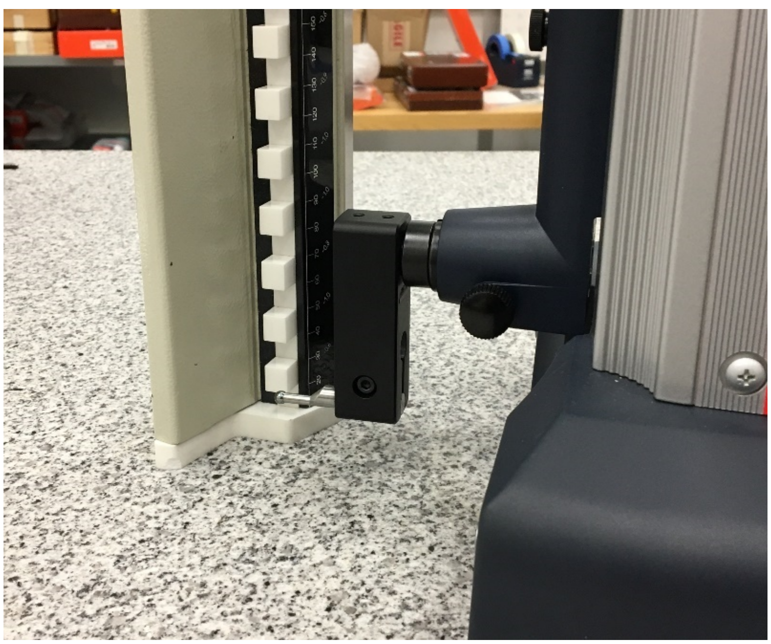
Testing the partial surface contact error, E_{MPE}, with a caliper checker.

Linear height gauge

A Mitutoyo LH-600 linear height gauge is assessed for conformity to the manufacturer stated specification for the length measurement error, E_{MPE}, in accordance with ISO 13225:2012. The specifications are defined at 20 °C exactly. The reference standard is a type of step gauge called a Mitutoyo Check Master. The calibrated values of the Check Master are used; however, being manually operated, the user can not exactly hit the calibrated point, and therefore the flatness and parallelism of the measuring faces contribute additional uncertainty. Operation of the LH-600 requires it be placed on a flat reference surface, e.g. a granite surface plate, which is another reference standard used in the calibration.

Uncertainty contributors when assessing conformity of a height gauge to E_{MPE} in accordance with ISO 13225:2012 using a step gauge:

Category of Test Uncertainty	Uncertainty Contributor
Reference standard (u_{x1})	Uncertainty of the step gauge calibrated value, from the calibration certificate
Use of reference standard in the test (u_{a1})	Flatness and parallelism of the step gauge measuring faces
Reference standard (u_{x2})	Influence of the granite surface plate
Corrections to measured values (u_r)	The four temperature contributors previously described



Testing a Mitutoyo LH-600 Linear Height Gauge with a step gauge (a Mitutoyo Check Master).

Two different coordinate measuring machine (CMM) examples

Two different CMM examples are considered. In both cases, the calibration is the assessment of conformity to $E_{0,MPE}$ in accordance with ISO 10360-2:2009. The CMM rated operating conditions include an interval for temperature, e.g. 18 °C to 22 °C, and therefore temperature issues are handled differently than in prior examples. The CMM is installed and tested at the customer site.

CNC CMM with temperature compensation

This example considers an automated CNC CMM with temperature compensation. The operation of the built-in temperature compensation system requires the user to input the CTE of the measured object, which is the CTE of the reference standard used in testing (the step gauge). Unlike previous examples, there is some uncertainty associated with this user-provided input to the measuring system.

Uncertainty contributors for assessing the conformity of a CNC CMM with temperature compensation to $E_{0,MPE}$ in accordance with ISO 10360-2:2009:

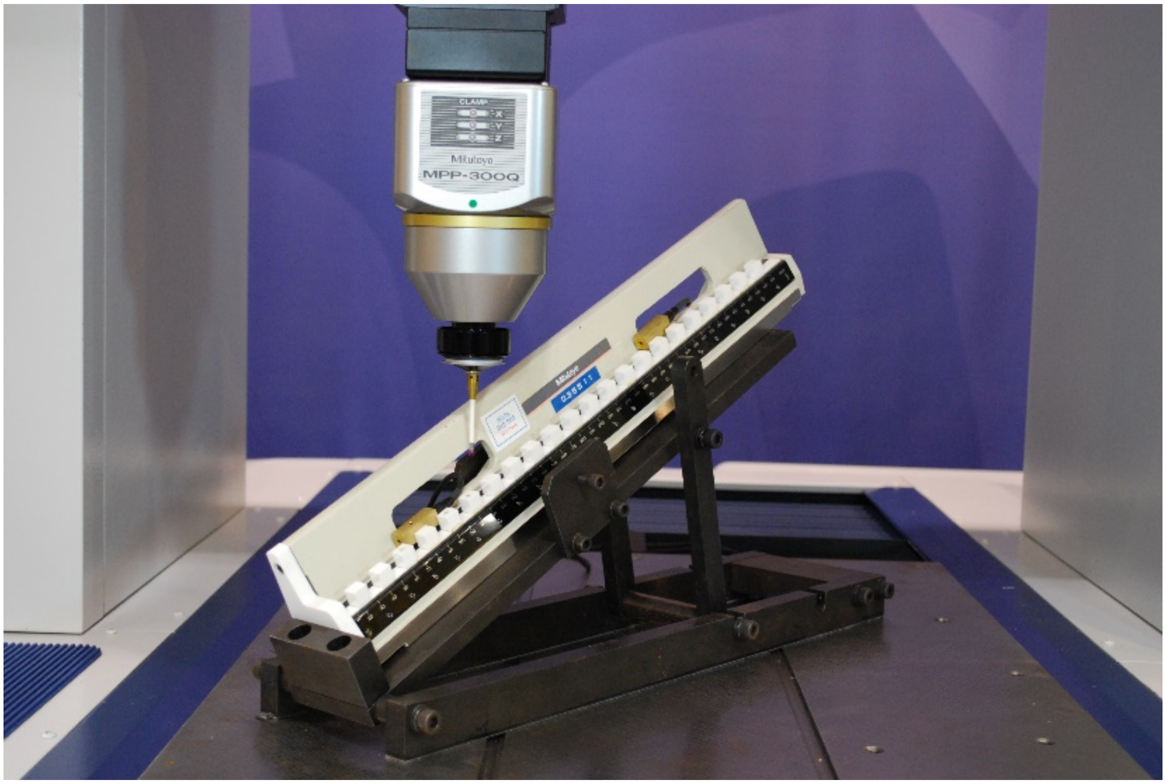
Category of Test Uncertainty	Uncertainty Contributor
Reference standard (u_x)	Uncertainty of the step gauge calibrated value, from the calibration certificate
User-provided input (u_p)	Uncertainty in the input CTE of the reference standard

Manual CMM without temperature compensation

This example is the exact same testing scenario as the prior CMM example but with a different UUT. In this case, a manually operated CMM with no built-in temperature compensation system is considered, and therefore the uncertainty contributor associated with the CTE of the reference standard does not apply. When using a manual CMM, the measured point is less controlled and therefore the geometry of the reference standard must be considered as a contributor to the test uncertainty.

Uncertainty contributors for assessing the conformity of a manual CMM with no temperature compensation to $E_{0,MPE}$ in accordance with ISO 10360-2:2009:

Category of Test Uncertainty	Uncertainty Contributor
Reference standard (u_x)	Uncertainty of the step gauge calibrated value, from the calibration certificate
Use of reference standard in the test (u_{a1})	Flatness and parallelism of the step gauge measuring faces



ISO 10360-2:2009 requires three-dimensional, volumetric, testing. There may be many different calibration methods in practice for CMMs, but there is only one method that is standardized across all national and international standards. In the U.S., ASME B89.4.10360.2-2008 has the same general test methods as ISO 10360-2:2009.

The Metrology Training Lab at Mitutoyo America Corporation.

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Epilogue from the author

My metrology career began in 1990, and I witnessed the beginnings of the formal evaluation of measurement uncertainty. I joined Mitutoyo America Corporation in 2000 as the requirement for the accreditation of commercial calibration laboratories was exploding in the United States. That was also the year that I first encountered the requirement in ISO/IEC 17025:1999 clause 5.10.4.2:

> *When statements of compliance are made, the uncertainty of measurement shall be taken into account.*

There was no general consensus on what this phrase meant, particularly amongst the many accreditation bodies around the world. To some, this phrase was interpreted as simply a requirement to state a clear decision rule. To others, this phrase meant applying a stringent acceptance decision rule, which required reducing or guard banding the specification by 100% of the measurement uncertainty when assessing conformity.

In 2000, measurement uncertainty was new and not well understood. The typical implementation was to include all variation associated with the measured values, regardless of the measurand, which resulted in the inflated uncertainty estimates discussed throughout this book.

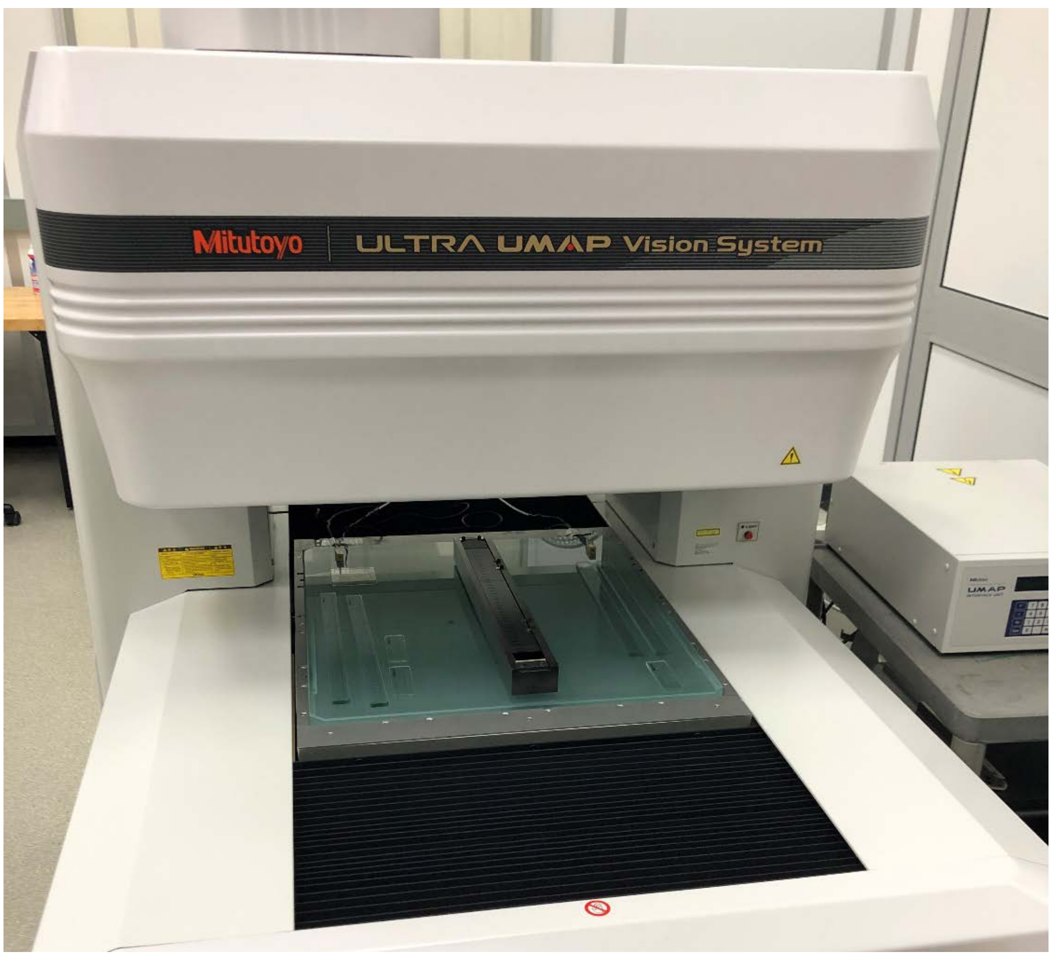
Combining inflated uncertainty estimates with stringent decision rules was a disaster. Those early practices created situations where it was simply not possible to make statements of conformity. Accreditation bodies and assessors start recommending the removal of statements of conformity from calibration certificates, an unfortunate practice that has continued for over 20 years. In addition, and even worse, having uncertainty greater than the tolerance became normal and accepted in calibration. These practices created a generation of damage in the field of calibration that needs to be healed.

When you bring your car to a service center, you are expecting an expert to evaluate your car, provide recommendations, and perform the necessary maintenance. When you have someone calibrate your measuring instrument, you are expecting an expert to perform a similar level of service. Customers need calibration services to do calibrations to the right specifications, to provide clear pass/fail judgements with adequate capability, and to make necessary adjustments. I'm embarrassed for my profession when I hear colleagues say that specifications, test methods, and pass/fail decisions are part of contract review with no baseline of acceptable service that protects customers. Only in rare cases do customers have the level of knowledge to make these kinds of decisions. Would you want your car returned to you from a service center with worn brake pads and low fluids with no mention of any problem simply because you didn't ask that question? This kind of service should also never be acceptable in calibration.

I strongly believe that test uncertainty is the solution craved by calibration practitioners. The application of test uncertainty results in measurement uncertainty values that make sense, that match observed quality, and that can be logically applied in decision rules in conformity assessment. The application of test uncertainty clears the path for including statements of conformity on calibration certificates with proper decision rules.

Test uncertainty also brings focus back to good metrology. The concepts of test uncertainty highlight the importance of following a standard test protocol and not leaving that to the discretion of the calibration provider. And when the errors of the unit under test, such as repeatability and resolution, dominate the measurement uncertainty, then everyone has the same large uncertainty and there is no incentive to improve quality. The true measurement quality is hidden when inflating the uncertainty with the errors of the UUT. If instead, the reference standards and temperature dominate uncertainty, then there will be more transparency is calibration capability, and calibration providers will look to improve their standards and calibration environment.

Test uncertainty is not conceptually trivial, but once understood and applied, the door will be opened to improve calibration practices, make clear statements of conformity, and better serve the customers of calibration services.



The Mitutoyo QV Ultra vision system is used for high accuracy calibration of 1D and 2D glass artifacts in the Mitutoyo America Calibration Laboratory. The measurement uncertainty is as low as 0.25 µm (10 µin).

Glossary

The following terms and definitions apply in the use of this book. This content was pulled from international documents when available with no changes. Notes and examples were removed for brevity.

adjustment of a measuring system (JCGM 200:2012, 3.11)
adjustment

set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured

calibrated quantity value
calibrated value

measured quantity value estimating the magnitude of a measurand and which is intended to be used as an assigned value of a calibrated measuring instrument

NOTE: See further discussion at the end of this glossary

calibration (JCGM 200:2012, 2.39)

operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

conformity assessment (ISO/IEC 17000:2020, 4.1)

demonstration that specified requirements are fulfilled

correction (JCGM 200:2012, 2.53)

compensation for an estimated systematic effect

decision rule (ISO/IEC 17025, 3.7)

rule that describes how measurement uncertainty is accounted for when stating conformity with a specified requirement

indicating measuring instrument (JCGM 200:2012, 3.3)

measuring instrument providing an output signal carrying information about the value of the quantity being measured

indication (JCGM 200:2012, 4.1)

quantity value provided by a measuring instrument or a measuring system

material measure (JCGM 200:2012, 3.6)

measuring instrument reproducing or supplying, in a permanent manner during its use, quantities of one or more given kinds, each with an assigned quantity value

maximum permissible measurement error (JCGM 200:2012, 4.26)
maximum permissible error
limit of error

extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system

measurand (JCGM 200:2012, 2.3)

quantity intended to be measured

measured quantity value (JCGM 200:2012, 2.10)
value of a measured quantity
measured value

quantity value representing a measurement result

measured test indication (ISO 14253-5:2015, 3.6)

result of a measurement performed in a test, which contributes to the test value according to a test operator

measurement (JCGM 200:2012, 2.1)

process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity

measurement capability index (JCGM 106:2012, 3.3.17)
C_m

tolerance divided by a multiple of the standard measurement uncertainty associated with the measured value of a property of an item

measurement error (JCGM 200:2012, 2.16)
error of measurement
error

measured quantity value minus a reference quantity value

measurement method (JCGM 200:2012, 2.5)
method of measurement

generic description of a logical organization of operations used in a measurement

measurement procedure (JCGM 200:2012, 2.6)

detailed description of a measurement according to one or more measurement principles and to a given measurement method, based on a measurement model and including any calculation to obtain a measurement result

measurement repeatability (JCGM 200:2012, 2.21)
repeatability

measurement precision under a set of repeatability conditions of measurement

measurement result (JCGM 200:2012, 2.9)
result of measurement

set of quantity values being attributed to a measurand together with any other available relevant information

measurement standard (JCGM 200:2012, 5.1)
etalon

realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference

measurement uncertainty (JCGM 200:2012, 2.26)
uncertainty of measurement
uncertainty

non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

measuring equipment (ISO 14978:2018, 3.5.1)

indicating measuring instrument, material measure, software, measurement standard, reference material or auxiliary equipment used in a measurement

measuring instrument (JCGM 200:2012, 3.1)

device used for making measurements, alone or in conjunction with one or more supplementary devices

measuring system (JCGM 200:2012, 3.2)

set of one or more measuring instruments and often other devices, including any reagent and supply, assembled and adapted to give information used to generate measured quantity values within specified intervals for quantities of specified kinds

metrological characteristic (ISO 14978:2018, 3.5.2)

characteristic of measuring equipment, which may influence the results of measurement when using the measuring equipment

metrological traceability (JCGM 200:2012, 2.41)

property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty

permissible test instance (ISO 14253-5:2015, 3.3)

test instance in compliance with the test protocol, and with the alternatives and stipulations therein

proficiency testing (ISO/IEC 17025, 3.5)

evaluation of participant performance against pre-established criteria by means of interlaboratory comparisons

quantity value (JCGM 200:2012, 1.19)
value of a quantity
value

number and reference together expressing magnitude of a quantity

rated operating condition (JCGM 200:2012, 4.9)

operating condition that must be fulfilled during measurement in order that a measuring instrument or measuring system perform as designed

reference measurement standard (JCGM 200:2012, 5.6)
reference standard

measurement standard designated for the calibration of other measurement standards for quantities of a given kind in a given organization or at a given location

reference quantity value (JCGM 200:2012, 5.18)
reference value

quantity value used as a basis for comparison with values of quantities of the same kind

resolution (JCGM 200:2012, 4.14)

smallest change in a quantity being measured that causes a perceptible change in the corresponding indication

specified requirement (ISO/IEC 17000:2020, 5.1)

need or expectation that is stated

test instance (ISO 14253-5, 3.2)

combination of test equipment, set up, measurement sequence, environmental and instrumental conditions of a test, which yields a test value(s)

test measurand (ISO 14253-5:2015, 3.4)

metrological characteristic of an indicating measuring instrument intended to be verified in a test, based on a single permissible test instance, defined by a test protocol

test operator (ISO 14253-5:2015, 3.7)

predefined sequence of mathematical and/or statistical operations applied to the measured test indications(s) collected in the test to deliver a test value

test point

realization of a permissible test instance during testing where a test value is obtained

NOTE: See further discussion at the end of this glossary

test protocol (ISO 14253-5:2015, 3.5)

predefined detailed specification of a test which defines the test measurand, the required test conditions and a decision rule

test uncertainty ratio (ANSI/NCSL Z540.3-2006, 3.11)
TUR
the ratio of the span of the tolerance of a measurement quantity subject to calibration, to twice the 95% expanded uncertainty of the measurement process used in calibration.

test value (ISO 14253-5:2015, 3.8)
quantity value measured in a test estimating the magnitude of a test measurand

test value uncertainty (ISO 14253-5:2015, 3.9)
test uncertainty
measurement uncertainty associated to a test value

testing (ISO/IEC 17000:2020, 6.2)
determination of one or more characteristics of an object of conformity assessment, according to a procedure

uncertainty budget (JCGM 200:2012, 2.33)
statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination

verification (JCGM 200:2012, 2.44)
provision of objective evidence that a given item fulfils specified requirements

verification test (ISO 14978:2018, 3.5.6)
test
operation that, under specified conditions and with sufficient objective evidence, establishes that measuring equipment conforms or does not conform to stated specifications

Special note on the term *calibrated value*

In this book, the term *calibrated quantity value,* or *calibrated value*, is used to describe a measured value associated with a calibration that is intended to be used as some type of assigned value of the calibrated measuring instrument. This calibrated and assigned value is often used as the reference value for a material measure or as a correction or adjustment value for an indicating measuring instrument.

The term calibrated value was hesitantly chosen for use in this book. This term does not exist in the JCGM 200:2012, or any national or international metrology standard; however, some term is needed to uniquely describe this particular type of measured value. In this book, ISO 14253-5:2015 is discussed in detail, and in that standard the term *test value* is introduced. Test values only apply to the results of verification tests for use in conformity assessment; however, as is discussed in this book, it is common for the results of conformity assessment to be used as the calibration.

In the evaluation of measurement uncertainty in calibration, it is critical to know if the measured value is intended to be used as an assigned calibrated value or if the measured value is a test value to be used in conformity assessment. When discussing test values, it is useful to have a complementary term for the assigned value in calibration.

There is currently no best term to describe this type of quantity value. In this book, calibrated value was chosen. There is some concern that the reader will interpret calibrated value as the term to be used for any and all measured values in calibration. This is not the case, which is why this term was chosen with some reluctance. In ASME B89.7.1-2016 and ISO 14978:2018, the term calibrated value is not used, but rather *reference value* or *assigned reference value*. The intention of all these terms is the same.

In this book, the terms reference value or assigned reference value are also used, but with a slightly different understanding. A calibrated value is frequently assigned to be the reference value, or is used as the reference value, and so in many situations the terms are interchangeable. In this book, it is recognized that while reference values could be calibrated values, this is not always the case. The reference value is determined by the user and is not dictated by a specific calibration. A reference value could be based on additional information, calibration history, or even the nominal value of a material measure.

In this book, a gauge block example is used. When a gauge block is used in a measurement, the reference value used for the gauge block is frequently either the nominal value, marked on the gauge block, or the calibrated value, found on the calibration certificate. In some advanced cases, the user might evaluate the gauge block calibration history and calculate the best reference value. The term calibrated value directly refers to the measured value on a calibration certificate that is not a test value. This calibrated value is not necessarily the reference value, and in this book, the decision was to use the term calibrated value.

Special note on the term *test point*

The term *test point* is a common and practical term used in calibration practice but is not well defined. As used in this book, a test point is a realization of a permissible test instance during testing where a test value is obtained.

A test point sometimes refers to a location within a measuring range where a test value is obtained. For example, for a 0 to 150 mm caliper, there may be a test point at 100 mm. That definition applies in this book but with the added concept that test points also vary in time. This is important in testing as the performance of a measuring instrument may vary in time and therefore the measurand with each test point is unique. Following the caliper example, a second test value obtained at 100 mm is not a second measurement at the same test point but rather a second test point.

With this definition of test point, there is now a practical term that works with the concept of a permissible test instance from ISO 14253-5:2015 and provides language to better describe what happens in the testing of measuring instruments. Each test point may be taken at different locations in the measuring range, at different times during testing, or both.

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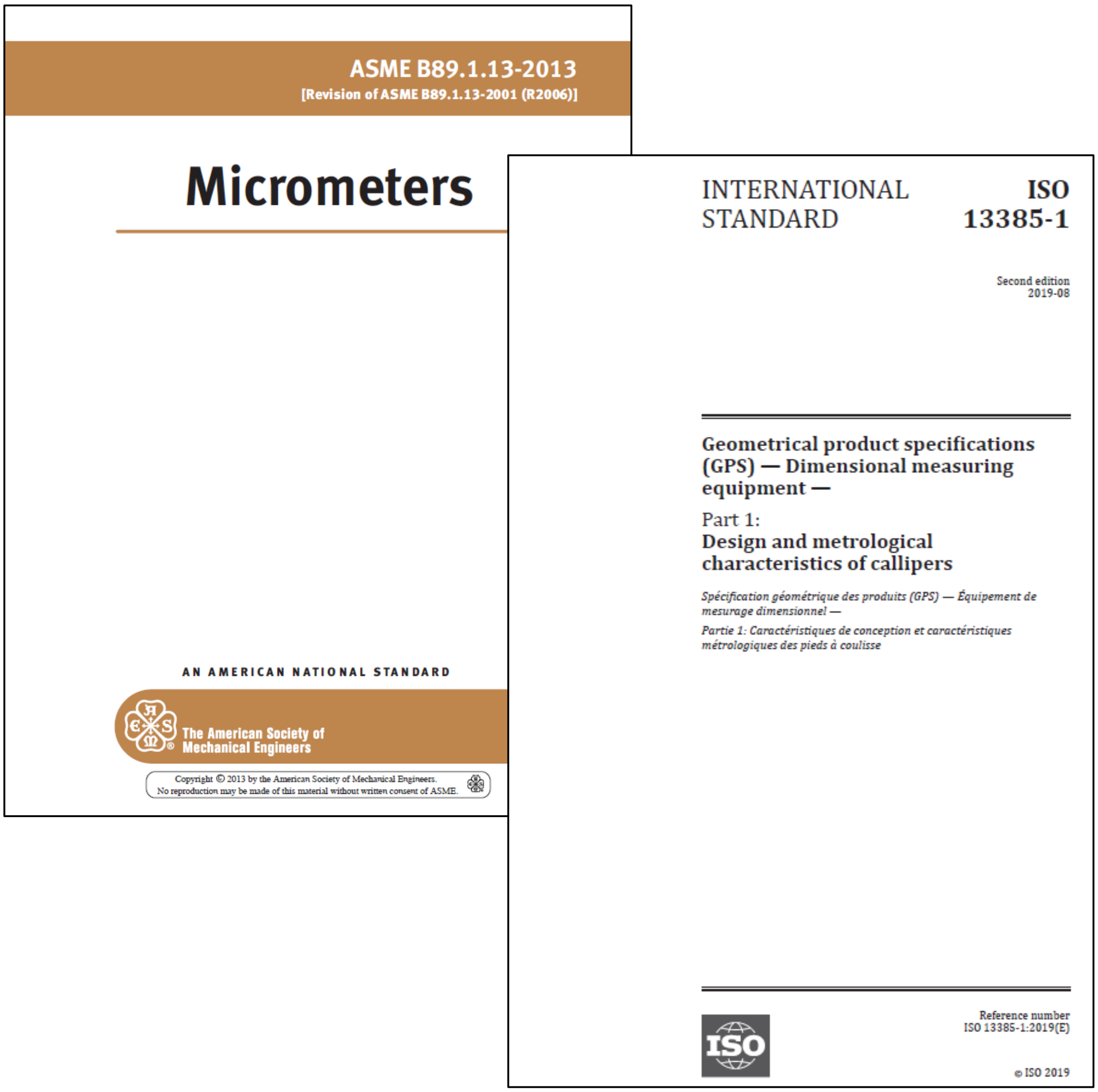

The American national micrometer standard, ASME B89.1.13-2013, and the international caliper standard, ISO 13385-1:2019, were two of the first standards to specifically implement test uncertainty concepts.

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