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Force Calibration Guidance for Beginners, Part 1

Practitioner's Perspective on the GUM Revision, Part 1: Two Key Problems and Solutions

U.S. Calibration Occupation Demographics

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THE INTERNATIONAL JOURNAL OF METROLOGY

Volume 29, Number 3

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FEATURES

DEPARTMENTS

ON THE COVER: Brian Miles Environmental Laboratory Supervisor is calibrating a TSI model 9565-P Vane Anemometer at Applied Technical Services' (ATS) facility in Marietta, GA. The Westenberg Engineering Eiffel type wind tunnel shown can reach speeds up to 80 miles per hour.

CALENDAR

UPCOMING CONFERENCES & MEETINGS

The following events are subject to change. Visit the event URL provided for the latest information.

Aug 20-25, 2022 NCSL International Workshop & Symposium. Grapevine, TX. https://ncsli.org/

Aug 29-Sep 1, 2022 AUTOTESTCON. National Harbor, MD. AUTOTESTCON is the world's premier conference that brings together the military/aerospace automatic test industry and government/military acquirers and users to share new technologies, discuss innovative applications, and exhibit products and services. It is sponsored annually by the Institute of Electrical and Electronic Engineers (IEEE). https://2022.autotestcon.com/

Sep 19-21, 2022 IMEKO TC6 International Conference on Metrology and Digital Transformation (M4D). Hybrid with physical attendance in Berlin, Germany. https://www.m4dconf2022.ptb.de/home

Sep 19-22, 2022 MSA Conference. Wellington, New Zealand. Metrology Society of Australasia conferences are a rare opportunity to demonstrate calibration, test and measurement products and services to a cross-section of measurement-focused scientists, engineers and technicians from Australia, New Zealand and beyond. https://www.metrology.asn.au/msaconnected/

Sep 26-30, 2022 Metrology for Climate Action. Online Workshop. The workshop, hosted by BIPM and WMO, is open to experts and stakeholders active in the fields of climate science, observations, GHG mitigation and measurement, modelling and measurement science willing to contribute to the development of recommendations on key technical challenge areas for metrology in these fields. https://www.bipmwmo22.org/

Oct 11-13, 2022 IMEKO TC3, TC5, TC16, TC22. Cavtat-Dubrovnik, Croatia. Conferences on the Measurement of: Force Mass & Torque, Hardness, Pressure & Vacuum, and Vibration. https://conferences.imeko.org/event/1/

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Got Humidity?

For anyone in the temperature measurement business, the International Temperature Symposium is back from its 10 year slumber to celebrate its 100th anniversary, April 3-7, 2023, in Anaheim, California. "Humidity and Moisture Metrology" has been added to the list of topics in their Call for Papers. The event is sponsored by the MSC and NIST, and the proceedings are to be published by the American Institute of Physics (AIP). For details about this event, visit: https://its10.msc-conf.com/. 🌡

Our first two articles are part 1 of a two-part series. The second part of each article will be included in the next issue (Oct-Dec 2022). We value the great amount of knowledge and the research our authors bring to each issue. Whether short or long, we do our best to accommodate authors in order to honor their contributions, while providing an outlet for this resource to be consumed. This is my wordy way of saying this issue is a bit thicker.

For our Metrology 101 section, we asked Henry Zumbrun to provide us with a primer on his forte, force metrology. He delivered with a two-part series called "Force Calibration Guidance for Beginners." Henry is a prolific source of information on torque and force measurement, much of which is freely available online at mhforce.com.

Hening Huang continues his work in retirement on looking into methods of calculating expanded measurement uncertainties in "Practitioner's Perspective on the GUM Revision, Part 1: Two Key Problems and Solutions." In Part 2, he will provide examples of alternative approaches, as well as resolutions to paradoxical results.

And finally, Christopher Grachanen returns to give us an update on the occupational data collected for Calibration Technologists by the U.S. Department of Labor.

Besides feature articles, for "In Days of Old," Dan Wiswell went on a field trip to learn all he could in order to document the story of instrument manufacturing that sprung up in the Merrimack Valley of central New Hampshire in the late 1880s. He visited a couple companies to gather up material for a more complete and accurate account of this historical piece. He also treated himself to a trip to Harvard University to see their antique instrument collection. He had many more photos (mostly from the folks at Hoyt and Beede in Penacook, NH) than we could fit in these pages. For those following Dan's "In Days of Old," I'll post his full written account online with more photos.

This issue should keep you all busy, so until next time…

Happy Measuring,

Sita Schwartz

Oct 25-27, 2022 The Global Flow Measurement Workshop. Aberdeen, UK. To reflect the ongoing changes in the industry, and as we focus on the energy transition and meeting the measurement challenges of vital net-zero greenhouse emissions obligations, "The North Sea Flow Measurement Workshop" has a new name: "The Global Flow Measurement Workshop." https://www.tuvsud.com/en-gb/events/global-flow-measurement-workshop

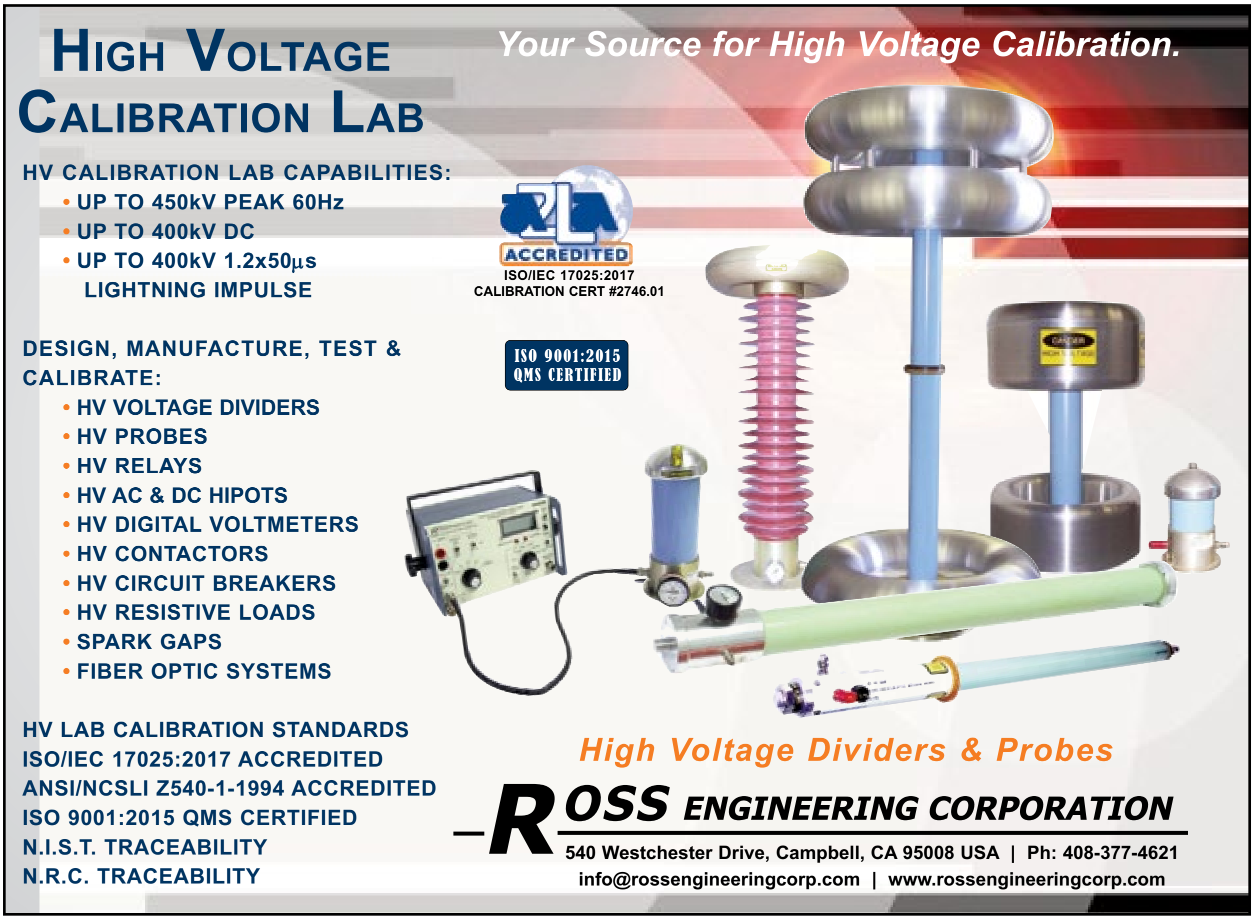
Nov 2-4, 2022 MATHMET. Paris, France. The 5th edition of the Mathmet international conference will take place at the ENSAM (Ecole Nationale Supérieure des Arts et Métiers). Mathmet 2022 is an event of the European Metrology Network (EMN) for Mathematics and Statistics to promote new analytical and computational approaches in measurement science. https://www.lne.fr/en/events/mathmet-2022

Dec 12-16, 2022 Conference on Precision Electromagnetic Measurements (CPEM). Wellington, New Zealand. The Measurement Standards Laboratory of New Zealand (MSL), in collaboration with the National Measurement Institute of Australia (NMIA), enthusiastically welcomes you to CPEM2022. https://www.cpem2022.nz/

SEMINARS & WEBINARS: Dimensional

Sep 13-14 2022 "Hands-On" Precision Gage Calibration & Repair Training. Virtual Class. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

Sep 20-23, 2022 Fundamentals of Geometrical Dimensioning and Tolerancing. Online. National Measurement Institute, Australia. This course is based on ASME Y14.5-2009 standard. You will learn about the symbols, modifiers, rules and concepts of geometric dimensioning and tolerancing (GD&T). https://shop.measurement.gov.au/collections/physical-metrology-training



Sep 22-23, 2022 "Hands-On" Precision Gage Calibration & Repair Training. Bloomington, MN. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

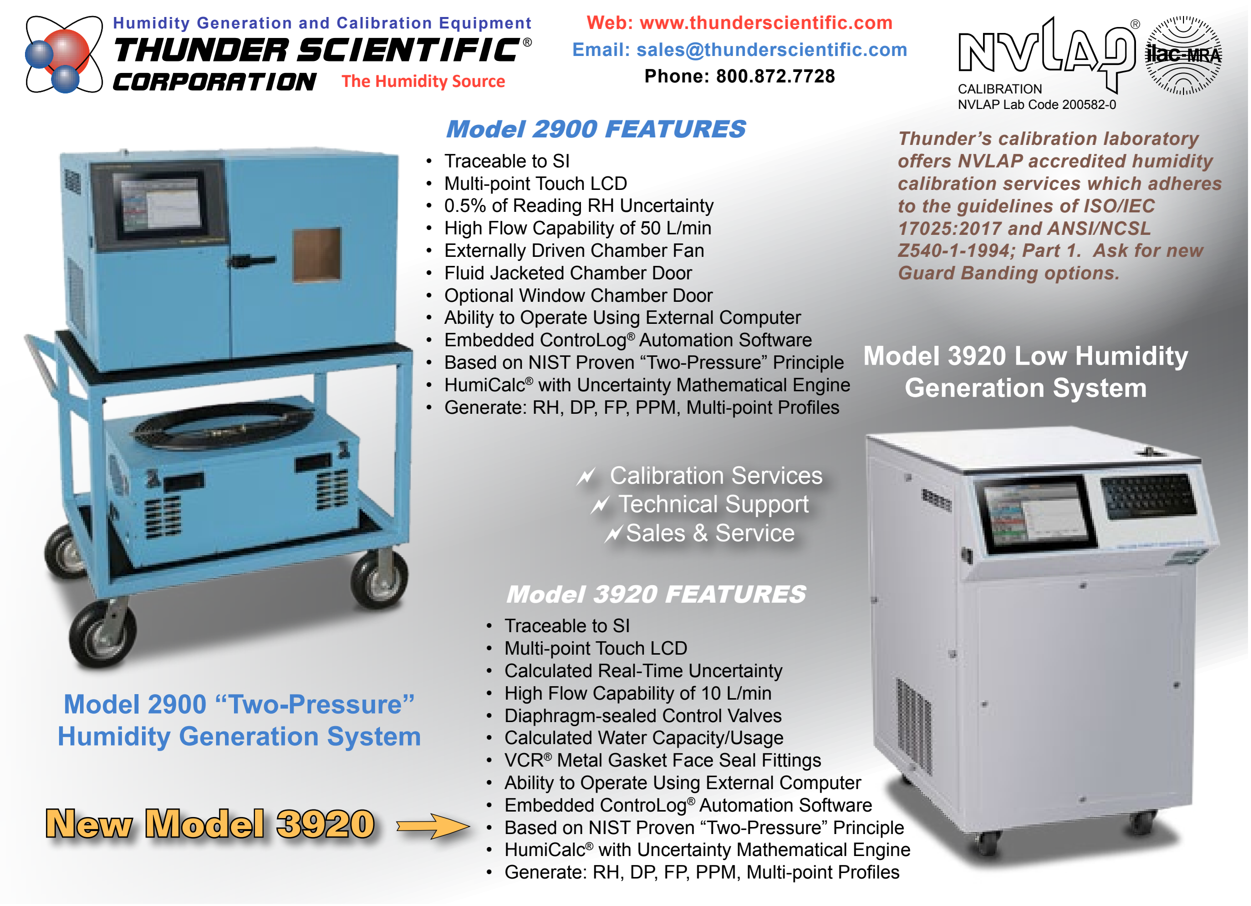
Oct 5-6, 2022 "Hands-On" Precision Gage Calibration & Repair Training. Denton, TX. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

Oct 5-6, 2022 Dimensional Measurement. Port Melbourne VIC, Australia. National Measurement Institute (NMI), Australia. This two-day course (9 am to 5 pm) presents a comprehensive overview of the fundamental principles in dimensional metrology and geometric dimensioning and tolerancing. https://shop.measurement.gov.au/collections/physical-metrology-training

SEMINARS & WEBINARS: Flow

Sep 20-23, 2022 Gas Flow Calibration Using molbloc/molbox. Phoenix, AZ. Fluke Calibration. Gas Flow Calibration Using molbloc/molbox is a four day training course in the operation and maintenance of a Fluke Calibration molbloc/molbox system. https://us.flukecal.com/training

Sep 21-23, 2022 Flow Measurement and Calibration Seminar. Neufahrn, Germany. TrigasFI. Measuring principles of flow meters for liquids and gases. Accuracy, performance, calibration techniques and procedures. Featuring networking event with Lunch hosted at the Munich Oktoberfest. https://www.trigasfi.de/en/training-and-seminars/



CALENDAR

SEMINARS & WEBINARS: Force

Oct 5-7, 2022 Force Fundamentals. York, PA. Morehouse Instruments. This course will cover applied force calibration techniques and potential errors made in everyday force measurements, including errors associated with improper alignment, use of different and/or incorrect adapter types, thread depth and thread loading. This course also covers the importance of calibrating force measurement devices in the manner in which they are being used in order to reduce errors and lower uncertainty. https://mhforce.com/training-programs/

SEMINARS & WEBINARS: General

Oct 17-22, 2022 Fundamentals of Metrology. Gaithersburg, MD. NIST. The 5-day Fundamentals of Metrology seminar is an intensive course that introduces participants to the concepts of measurement systems, units, good laboratory practices, data integrity, measurement uncertainty, measurement assurance, traceability, basic statistics and how they fit into a laboratory Quality Management System. https://www.nist.gov/pml/owm/training

SEMINARS & WEBINARS: Industry Standards

Sep 13-14, 2022 Laboratories: Understanding the Requirements and Concepts of ISO/IEC 17025:2017. Live Online/Milwaukee, WI. ANAB. This introductory course is specifically designed for those individuals who want to understand the requirements of ISO/IEC 17025:2017 and how those requirements apply to laboratories. https://anab.ansi.org/training

Sep 13-15, 2022 Internal Auditing to ISO/IEC 17025:2017 (Non-Forensic). Live Online/Milwaukee, WI. ANAB. ISO/IEC 17025 training course prepares the internal auditor to clearly understand technical issues relating to an audit. Attendees of Auditing to ISO/IEC 17025 training course will learn how to coordinate a quality management system audit to ISO/IEC 17025:2017 and collect audit evidence and document observations, including techniques for effective questioning and listening. https://anab.ansi.org/training

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Sep 20-23, 2022 Forensic Internal Auditing to ISO/IEC 17025:2017. Live Online/Milwaukee, MI. ANAB. An integral part of a successful management system is an effective audit program. An audit program is also essential and required to achieve and maintain accreditation. This ISO/IEC 17025 training course provides a detailed review of ISO/IEC 17025:2017 and the related ANAB accreditation requirements for forensic service providers (AR 3125) as well as a review of ISO 19011, Guidelines for Auditing Management Systems. https://anab.ansi.org/training

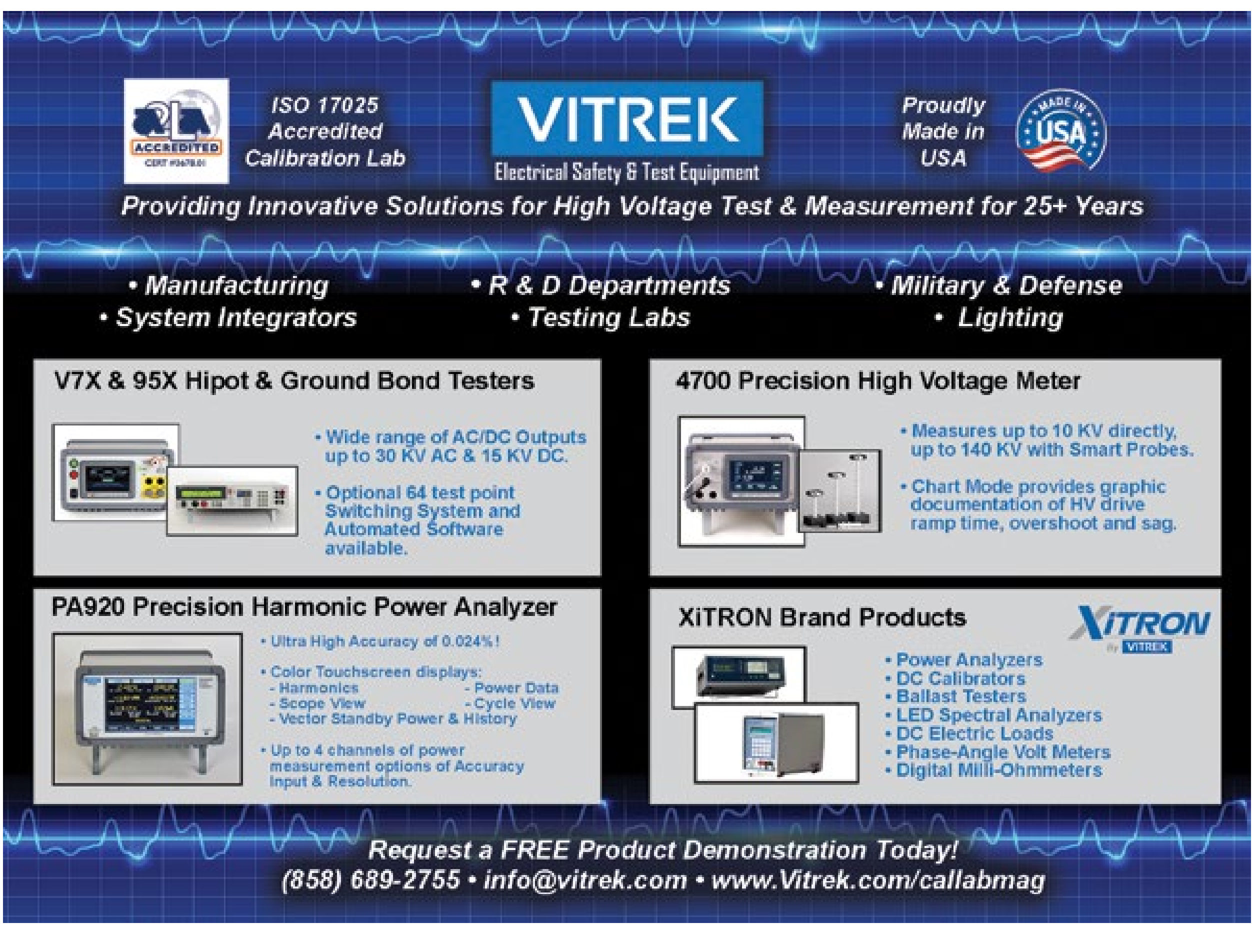
Oct 24-28, 2022 ISO/IEC 17025 Lead Assessor Training. Live Online/Milwaukee, MI. ANAB's ISO/IEC 17025 Lead Assessor Training course uses hands on, exercise-based approach to effectively develop and support the necessary competencies required of a lead assessor. The course is based on ISO 19011 and ISO/IEC 17011 requirements. https://anab.ansi.org/training

Nov 8-9, 2022 (3004) Understanding ISO/IEC 17025 for Testing and Calibration Labs. Online (Americas). International Accreditation Service (IAS). This 2-day Training Course examines structural components of the standard. Quality system and technical requirements are grouped in a manner that makes them clear and understandable. https://www.iasonline.org/training/testing-cal-labs/

Nov 14-15, 2022 Validation and Verification of Analytical Methods. Live Online. ANAB. This course provides an introduction to validation and verification of analytical methods. The common elements of a validation/verification plan and a general approach to performing a validation or verification are presented. The pertinent requirements in ISO/IEC 17025 and ISO/IEC 17020 for method validation and verification are also reviewed. https://anab.ansi.org/training

SEMINARS & WEBINARS: Management & Quality

Sep 1-2, 2022 (3022) Internal Audit Course for All Standards. Online (ME and South Asia). International Accreditation Service (IAS). This 2-day Training Course examines auditing principles and techniques and facilitates the practice of required internal audit skills. It is based



on internationally-recognized approaches to conducting conformant internal audits. https://www.iasonline.org/training/ias-training-schedule/

Nov 1-2, 2022 (3022) Internal Audit Course for All Standards. Online (Americas). International Accreditation Service (IAS). This 2-day Training Course examines auditing principles and techniques and facilitates the practice of required internal audit skills. It is based on internationally-recognized approaches to conducting internal audits. https://www.iasonline.org/training/ias-training-schedule/

SEMINARS & WEBINARS:
Measurement Uncertainty

Sep 13-15, 2022 Uncertainty, Sampling and Data Analysis: Understanding Statistical Calculations. Live Online. ANAB. This course provides an introduction to statistical concepts and techniques used for the collection, organization, analysis, and presentation of various types of data. https://anab.ansi.org/training

Sep 19-20, 2022 Measurement Confidence: Fundamentals. Live Online. ANAB. This Measurement Confidence course introduces the foundational concepts of measurement traceability, measurement assurance and measurement uncertainty as well as provides a detailed review of applicable requirements from ISO/IEC 17025 and ISO/IEC 17020. https://anab.ansi.org/training

Sep 21-23, 2022 Measurement Uncertainty: Practical Applications. Live Online. ANAB. This course reviews the basic concepts and accreditation requirements associated with measurement traceability, measurement assurance, and measurement uncertainty as well as their interrelationships. https://anab.ansi.org/training

Oct 11-12, 2022 (3006) Uncertainty of Measurement for Labs. Online (ME and South Asia). International Accreditation Service (IAS). The training includes case studies and discussions, with application of statistical components in practical examples that are frequently encountered by testing laboratories. https://www.iasonline.org/training/ias-training-schedule/

Nov 2-3, 2022 (3006) Uncertainty of Measurement for Labs. Online (ME and South Asia). International Accreditation Service (IAS). The training includes case studies and discussions, with application of statistical components in practical examples that are frequently encountered by testing laboratories. https://www.iasonline.org/training/ias-training-schedule/

SEMINARS & WEBINARS: Pressure

Aug 29-Sep 2, 2022 TWB 1061 Principles of Pressure Calibration Web-Based Training. Fluke Calibration. This is a short form of the regular five-day in-person Principles of Pressure Calibration class. It is modified to be an instructor-led online class and without the hands-on exercises. It is structured for two hours per day for one week. https://us.flukecal.com/training

Oct 3-7, 2022 Principles of Pressure Calibration. Phoenix, AZ. Fluke Calibration. A five-day training course on the principles and practices of pressure calibration using digital pressure calibrators and piston gauges (pressure balances). https://us.flukecal.com/training

Oct 24-28, 2022 Advanced Piston Gauge Metrology. Phoenix, AZ. Fluke Calibration. Focus is on the theory, use and calibration of piston gauges and dead weight testers. https://us.flukecal.com/training

Nov 7-11, 2022 TWB 1061 Principles of Pressure Calibration Web-Based Training. Fluke Calibration. This is a short form of the regular five-day in-person Principles of Pressure Calibration class. It is modified to be an instructor-led online class and without the hands-on exercises. It is structured for two hours per day for one week. https://us.flukecal.com/training

SEMINARS & WEBINARS: Software

Sep 12-16, 2022 MC-207 Advanced MET/CAL® Procedure Writing. Everett, WA. Fluke Calibration. This course covers advanced topics and requires an existing knowledge of MET/CAL® calibration software. https://us.flukecal.com/training

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Typical Shunt	300	0.001	100	> 10 minutes	0.01%	No spec	10	4	4
6311A	10	0	N/A	< 10 seconds	< 0.0005%	< 20	0.05	0	0
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Oct 3-7, 2022 TWB 1031 MET/CAL® Procedure Development Web-Based Training. Fluke Calibration. This web seminar is offered to MET/CAL users who need assistance writing procedures but have a limited travel budget. https://us.flukecal.com/training

Oct 17-21, 2022 MC-205 MET/TEAM® Asset Management. Everett, WA. Fluke Calibration. This five-day course presents a comprehensive overview of how to use MET/TEAM® Test Equipment and Asset Management Software in an Internet browser to develop your asset management system. https://us.flukecal.com/training

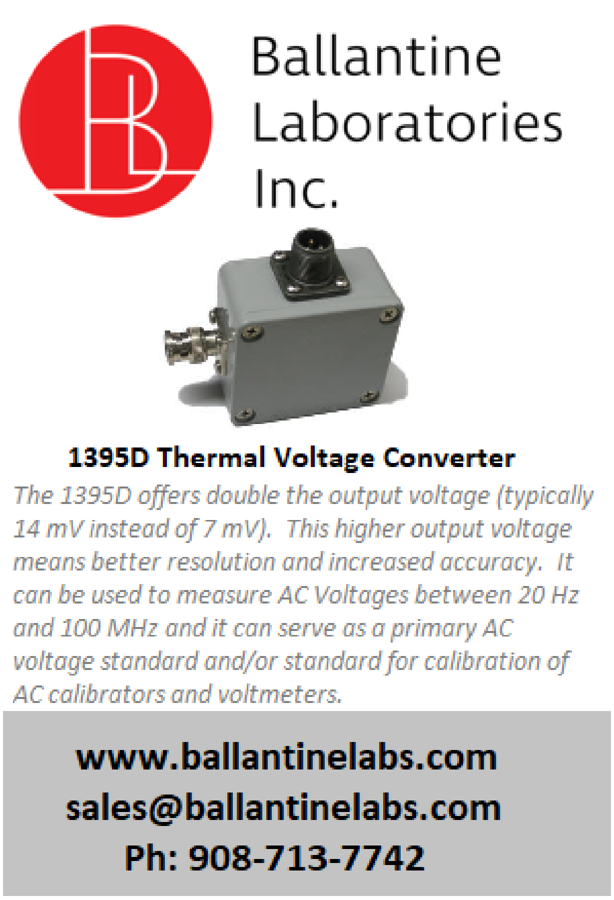
Nov 1-3, 2022 VNA Tools Training Course. Berne-Wabern, Switzerland. Federal Institute of Metrology METAS. VNA Tools is a free software developed by METAS for measurements with the Vector Network Analyzer (VNA). The software is available for download at www.metas.ch/vnatools. The three day course provides a practical and hands-on lesson with this superior and versatile software. https://www.metas.ch/metas/en/home/dl/kurse---seminare.html

Nov 7-11, 2022 MC-206 Basic MET/CAL® Procedure Writing. Everett, WA. Fluke Calibration. In this five-day Basic MET/CAL® Procedure Writing course, you will learn to configure MET/CAL® software to create, edit, and maintain calibration solutions, projects and procedures. https://us.flukecal.com/training

Nov 14-18, 2022 TWB 1051 MET/TEAM® Basic Web-Based Training. Fluke Calibration. This web-based course presents an overview of how to use MET/TEAM® Test Equipment and Asset Management Software in an Internet browser to develop your asset management system. https://us.flukecal.com/training

SEMINARS & WEBINARS: Temperature & Humidity

Sep 12-14, 2022 Advanced Topics in Temperature Metrology. American Fork, UT. Fluke Calibration. A three-day course for those who need to get into the details of temperature metrology. This course is for experienced calibration technicians, metrologists, engineers, and technical experts working in primary and secondary-level temperature calibration laboratories who would



CALENDAR

like to validate, refresh, or expand their understanding of advanced topics in temperature metrology. https://us.flukecal.com/training

Oct 3-5, 2022 Practical Temperature Calibration. American Fork, UT. Fluke Calibration. A three-day course loaded with valuable principles and hands-on training designed to help calibration technicians and engineers get a solid base of temperature calibration fundamentals. https://us.flukecal.com/training

Oct 6-7, 2022 Infrared Calibration. American Fork UT. Fluke Calibration. A two-day course with plenty of hands on experience in infrared temperature metrology. This course is for calibration technicians, engineers, metrologists, and technical experts who are beginning or sustaining an infrared temperature calibration program. https://us.flukecal.com/training

SEMINARS & WEBINARS: Vibration

Sep 13-15, 2022 Fundamentals of Random Vibration and Shock Testing. Longmont, CO. This three-day Training in Fundamentals of Random Vibration and Shock Testing covers all the information required to plan, perform, and interpret the results of all types of dynamic testing. Some of the additional areas covered are fixture design, field data measurement and interpretation, evolution of test standards and HALT/HASS processes. https://equipment-reliability.com/open-courses/

SEMINARS & WEBINARS: Weight

Sep 8, 2022 Calibration of Weights and Balances. Lindfield NSW, Australia. National Measurement Institute (NMI), Australia. This course covers the theory and practice of the calibration of weights and balances. It incorporates hands-on practical exercises to demonstrate adjustment features and the effects of static, magnetism, vibration and draughts on balance performance. https://shop.measurement.gov.au/collections/physical-metrology-training

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NIST Finds Wireless Performance Consistent Across 5G Millimeter-Wave Bands

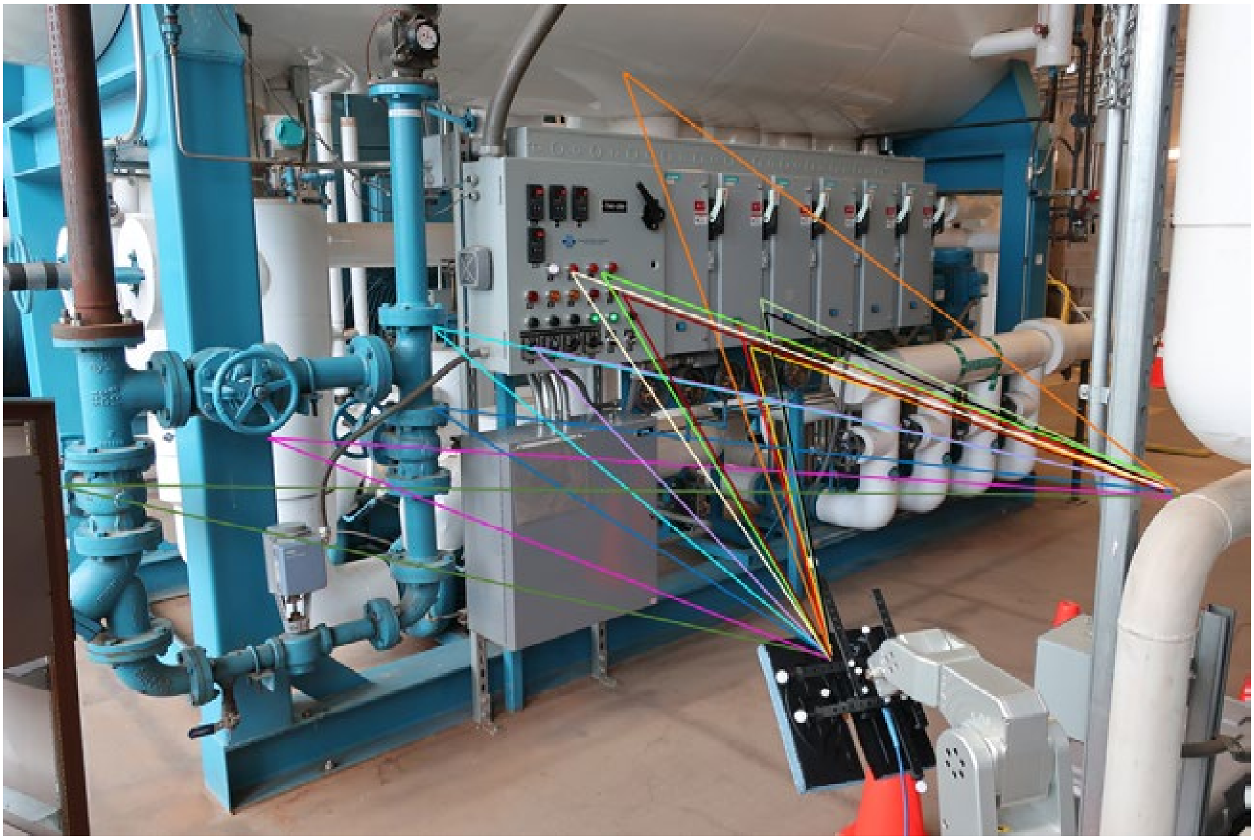
NIST News, May 10, 2022 – Settling a key dispute in the wireless communications field, researchers at the National Institute of Standards and Technology (NIST) found that transmission performance is consistent across different bands of the millimeter-wave (mmWave) spectrum targeted for high-speed, data-rich 5G systems.

Wireless systems are moving to the mmWave spectrum at 10-100 gigahertz (GHz), above crowded cellular frequencies as well as early 5G systems around 3 GHz. System operators tend to prefer lower bands of the new mmWave spectrum. One reason is that they are influenced by a formula that says more signals are lost at higher frequencies due to smaller wavelengths resulting in a smaller useful antenna area. But until now, measurements of this effect by many organizations have disagreed over whether this is true.

NIST researchers developed a new method to measure frequency effects, using the 26.5-40 GHz band as a target example. After extensive study in the laboratory and two real-world environments, NIST results confirmed that the main signal path — over a clear "line of sight" between transmitter and receiver — does not vary by frequency, a generally accepted thesis for traditional wireless systems but until now not proven for the mmWave spectrum. The results are described in a new paper*.

The team also found that signal losses in secondary paths — where transmissions are reflected, bent or diffused into clusters of reflections — can vary somewhat by frequency, depending on the type of path. Reflective paths, which are the second strongest and critical for maintaining connectivity, lost only a little signal strength at higher frequencies. The weaker bent and diffuse paths lost a bit more. Until now, the effects of frequency on this so-called multipath were unknown.

"This work may serve to demyth many misconceptions about propagation about higher frequencies in 5G and 6G," NIST electrical engineer Camillo Gentile said. "In short, while performance will be worse at higher frequencies, the drop in performance is incremental. So we do expect the deployment at 5G and eventually at 6G to be successful."



Wireless transmissions can take many routes to the intended receiver. The colored lines are reconstructions of measured paths of millimeter-wave signals between a transmitter (not visible) and receiver (lower middle) in a NIST industrial control room. Each path is precisely characterized in terms of length and angle to the receiver. These paths are all secondary, meaning reflected or diffracted signals. Credit: NIST

The NIST method emphasizes innovative measurement procedures and enhanced equipment calibration to make sure only the transmission channel is measured. The researchers used NIST's SAMURAI (Synthetic Aperture Measurement UnceRtainty for Angle of Incidence) channel sounder, which supports design and repeatable testing of 5G mmWave devices with unprecedented accuracy across a wide range of signal frequencies and scenarios. The NIST system is unique in that antenna beams can be steered in any direction for precise angle-of-arrival estimates.

NIST's main innovations in the new study, as discussed in the paper, were calibration procedures to remove the effects of channel sounder equipment from the measurements, extension of an existing algorithm to determine from a single measurement how individual paths vary by frequency, and studies in an industrial control center and a conference room to classify the types of paths involved and determine any frequency effects.

*Paper: D. Guven, B. Jamroz, J. Chuang, C. Gentile, R. Horansky, K. Remley, D. Williams, J. Quimby, A. Weiss and R. Leonhardt. Methodology for Measuring the Frequency Dependence of Multipath Channels Across the Millimeter-Wave Spectrum. IEEE Open Journal of Antennas and Propagation. Published online April 19, 2022. DOI: 10.1109/OJAP.2022.3168401

Source: https://www.nist.gov/news-events/news/2022/05/nist-finds-wireless-performance-consistent-across-5g-millimeter-wave-bands

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Discover NIST Education Resources!

NIST Updates, March 27, 2022 – The National Institute of Standards and Technology (NIST) invites learners of all ages to explore and discover a wide variety of Science, Technology, Engineering, and Mathematics (STEM) resources using the recently launched Education portal and NIST Education STEM Resource Registry (NEST-R).

Education Portal

The NIST Education site (https://www.nist.gov/education) is a hub for all things education across the agency. Learn how and why we measure things! Content is free and available to all. Elements include quick links to the new NIST Educational STEM Resource Registry (NEST-R), the Metric Program, experiential learning opportunities, and K-12 curriculum materials, including the SI Superheroes! Periodically, focused topics known as Featured Collections will rotate through. The Weights & Measurements collection was designed to celebrate national Weights and Measures Week, held each 1 to 7 March.

What is NEST-R?

The NIST Educational STEM Resource Registry NEST-R, is an online tool that allows educators, students, parents, and others to easily discover a variety of educational resources published by NIST staff across many program offices and websites. To take NEST-R for a test drive, visit https://nestr.nist.gov/.

NEST-R is a great starting point for both formal and informal (out-of-school) educators, especially measurement science ambassadors, seeking to communicate Science, Technology, Engineering, and Mathematics (STEM) concepts and encouraging career pursuits through education outreach activities. Users search the registry using keywords and customizable filters to pinpoint resources for specific learners, including short videos, real-world applications, and internships.

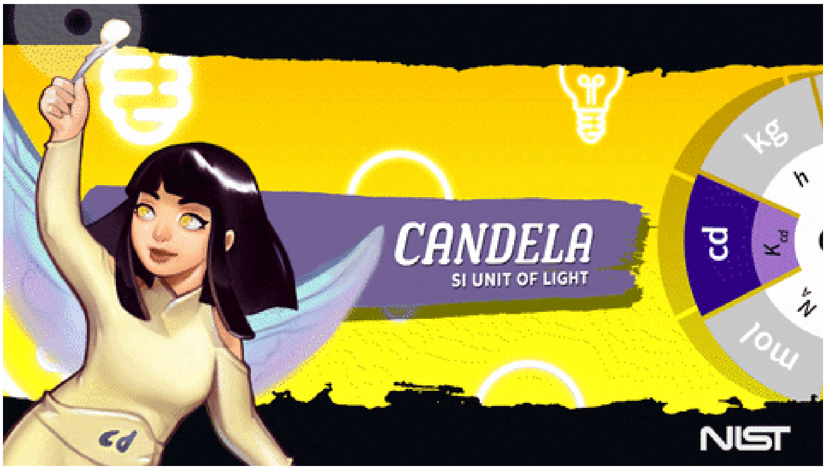
Each resource page includes a green box featuring metadata, such as resource type, format, school subject, and more. The blue box highlights teaching tips. Each resource also includes a record permalink and citation button, which makes lesson or outreach session planning easy.

The registry was developed during the pandemic as a mechanism to help educators and families. Developed by the NIST Educational Outreach Working Group, a multi-divisional team involving staff from the Communications Technology Laboratory, Material Measurement Laboratory, Physical Measurement Laboratory, Information Technology Laboratory, Public Affairs Office, and Information Services Office.

NIST Giphy Site

Check out the NIST Giphy site https://giphy.com/NIST to liven up posts and other digital messages. Each NIST SI Superhero has their own animated graphic, like this one for Candela.

Source: https://www.nist.gov/news-events/news/2022/03/discover-nist-education-resources



GIF of Candela, SI Unit of Light. Credit: NIST

10th International Temperature Symposium (ITS10)

NIST Events, January 14, 2022 – The International Temperature Symposia have been held about every decade or so since 1919 to provide a forum for the major technical advances over the previous decade in Temperature Measurement. The planning for the next Symposium in this series is currently underway. The Tenth International Temperature Symposium (ITS10) will be held in April of 2023 in Anaheim California featuring a technical program covering topics in all areas related to Temperature Measurement. These technical areas encompass the full range of the science and engineering of temperature, including but not limited to: new measurement technologies; new and established temperature measurement applications; calibration methods; thermophysical modeling; sensor design and installation; thermometric fixed points; radiation thermometry; temperature scales; basic and applied thermal metrology. The ITS10 will also include humidity measurement as a new topic for the first time. The Measurement Science Conference (MSC) will host and Sponsor the ITS10 and NIST will act as a co-sponsor. The Conference proceedings will be published by the American Institute of Physics. More information can be found by visiting https://its10.msc-conf.com/.

Past Symposia

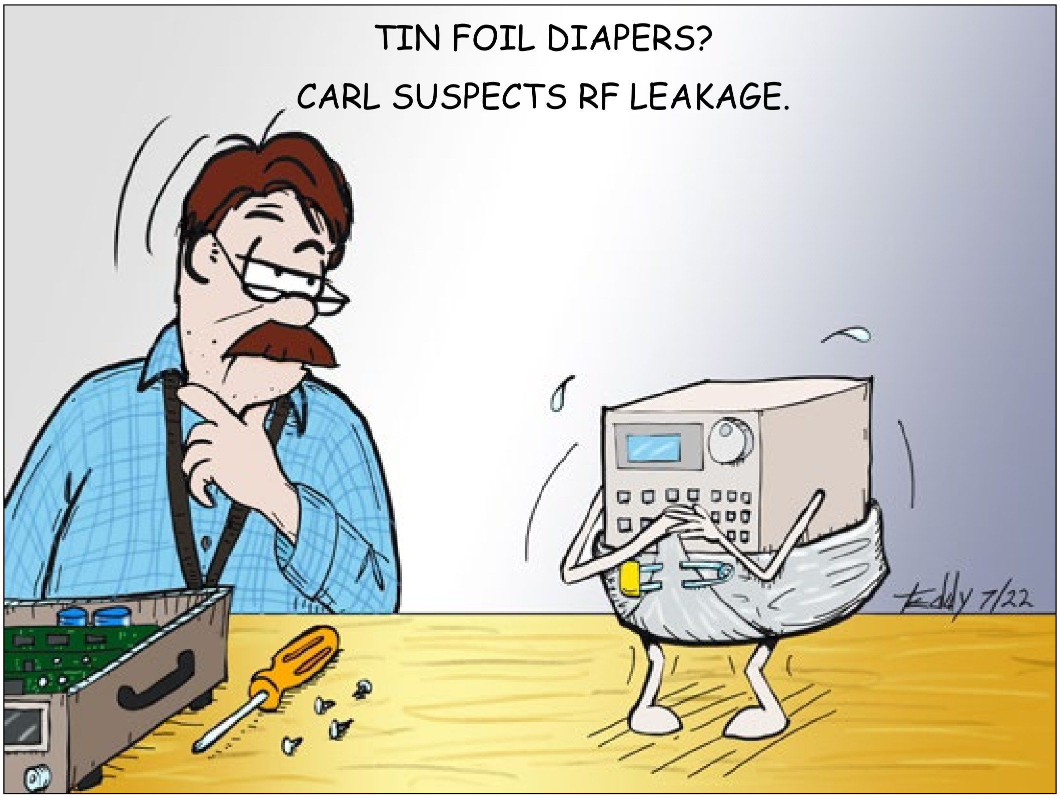
The 9th International Temperature Symposium (ITS9) took place March 19-23, 2012 in Los Angeles, CA. Those proceedings were published by the American Institute of Physics in 2013 as "Temperature, Its Measurement and Control in Science and Industry," Volume 8.

The 8th International Temperature Symposium (ITS8) took place in October of, 2002 in Chicago, IL. Those proceedings were published by the American Institute of Physics in 2003 as "Temperature, Its Measurement and Control in Science and Industry," Volume 7.

Other past Temperature Symposia were held in: Toronto, Canada in 1992; Washington DC in 1982, 1971 and 1954; Columbus, OH in 1961; New York, NY in 1939; and Chicago IL in 1919.

Source: https://www.nist.gov/news-events/events/2023/04/10th-international-temperature-symposium-its10

CAL-TOONS by Ted Green teddytoons@icloud.com



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Force Calibration Guidance for Beginners

Henry Zumbrun
Morehouse Instrument Company

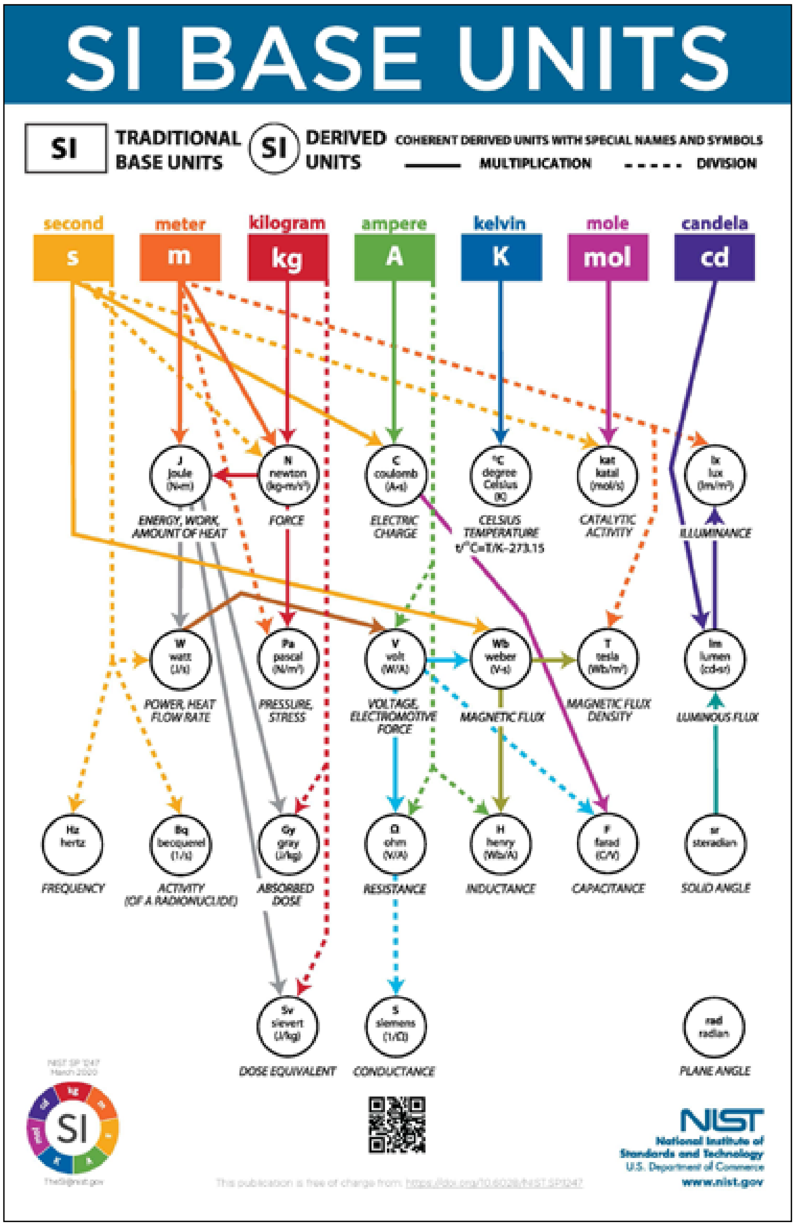

Figure 1. Relationship between SI base and derived units. Download free of charge from: https://doi.org/10.6028/NIST.SP.1247. Credit: NIST

Introduction

Morehouse Instrument Company has shared a tremendous amount of knowledge throughout the years with blogs, technical papers, and webinars. This education aligns with our purpose, to create a safer world by helping companies improve their force and torque measurements.

When someone is new to calibration or metrology, the information can be overwhelming. There is so much to digest that people can quickly become overwhelmed. Some have joked that an introduction to metrology is like trying to drink from a firehouse.

To simplify things, this two-part article was written to help anyone new to force. Even seasoned metrologists or technicians with years of experience may learn something new, or maybe this document can act as a refresher for those who are more advanced. In either case, the knowledge gained will ultimately help you become better.

Force Calibration and Its Importance

What is Force Calibration?

In his second law, Sir Isaac Newton stated that force controls motion; therefore, we must control the force if we are to control the motion. An example of force: I have an egg in my hand and want to break it by squeezing it in my hand. This egg will break at X known force. No matter where I am in the world, the same amount of force will be required to break the egg in my hand. It should not take less force to break this egg in Pennsylvania than in Peru.

A simple physics definition for force is mass times acceleration (F = m x a). As shown in Figure 1, force is a derived unit from the SI base units of Mass, Time, and Length. The International Committee for Weights and Measures in the Bureau International des Poids et Mesures (CIPM/BIPM) defines 1 N as the force required to accelerate 1 kg to 1 meter per second per second in a vacuum.

Calibration is the comparison of an unknown (typically referred to as the Unit Under Test or UUT) to a device known within a certain error (typically referred to as the Calibration Standard or Reference Standard) to characterize the unknown. Therefore, force calibration compares a force instrument to a force reference standard to characterize the instrument.

Why is Force Measurement Important?

The most straightforward answer is that bridges and other objects do not collapse when forces are exerted upon them. When building a bridge, it is essential to get the concrete strength measurement correct. It is essential to make sure the steel is tested, and the cables are appropriately checked for pre-stress or post-tension. When these measurements are not done correctly, bad things happen, as shown below.

Figure 2. Bridge Failure

In the example below, the ripeness of apples is being checked. Why may that be important? If you are in California and want to distribute apples across the country, the harder ones will last longer and ripen during shipment. In contrast, the softer ones might be distributed locally.

Figure 3. Testing Apple Ripeness. Photo provided by Tinius Olsen.

The next example shows fishing line being tested (Figure 4). I am sure any fisherman would not want the line to break as they haul in their prized fish.

In general, the measurement of force is performed so frequently that we tend to take it for granted. However, almost every material item is tested using some form of traceable force measurement.

Figure 4. Testing Fishing Line. Photo provided by Tinius Olsen.

Testing may vary from sample testing on manufactured lots and might include anything from the materials used to build your house to the cardboard on a toilet paper roll.

How a Transducer Measures Force

What is a Transducer?

In the broad sense of the term, a transducer is a device that turns one type of energy into another type. Some examples are:

1. A battery is a transducer that converts chemical energy into electrical energy. The chemical reactions involve electrons' flow from one material to another through an external circuit.
2. A thermometer is a transducer that converts heat energy into the mechanical displacement of a liquid column. As the temperature around the bulb heats up, the liquid expands and rises.
3. A load cell is a transducer that converts mechanical energy into electrical signals. As compressive or tensile force is exerted on a load cell, the mechanical energy is converted into equivalent electrical signals.

Figure 5. Load Cell

How a Load Cell Measures Compression and Tension Force

As force is exerted on a load cell, the material deflects. The deflection is typically measured by a strain gauge, which is placed on the material inside the load cell.

When placed appropriately, the strain gauge will measure the change in resistance as force is applied. The ideal load cell only measures force in defined directions and ignores force components in all other directions. Approaching the ideal involves optimizing many design choices, including the mechanical structure, the gage pattern, placement of the gages, and the number of gages.

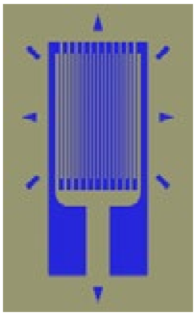

Figure 6. Strain Gauge

When a meter or indicator is hooked up to a load cell, it displays the force measurement value. A load cell may be calibrated at a company like Morehouse using deadweight primary standards known to be within 0.002 % of applied force. The machine's deadweights are adjusted for local gravity, air density, and material density to apply the force accurately. The weights are used to calibrate the load cell, which may be used to calibrate and verify a testing machine.

Compression and Tension Force Calibration

This section covers the terms compression and tension and how they relate to force calibration.

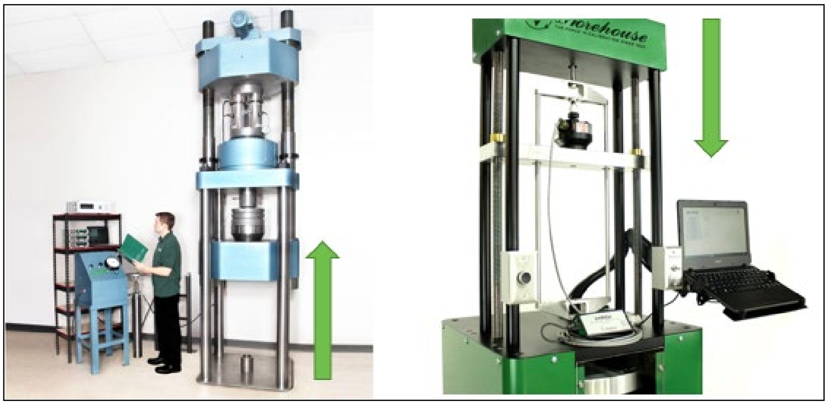

Figure 7. Compression calibration can be thought of as compressing or pushing.

What is a Compression Calibration?

When discussing compression calibration, we should think about something being compressed or something being squeezed. I like to describe compression calibration as pushing or squeezing something.

Figure 7 shows two examples of a compression setup in a calibrating machine. The machine on the left is compressing both load cells by creating an upward force. The picture on the right is a compression setup in the deadweight machine where a downward force compresses the load cell.

The key to this type of calibration is making sure everything is aligned and that the line of force is as straight as possible—I like to say free from eccentric or side forces. The key to proper alignment is using the right adapters in the calibrating machine, from alignment plugs to top adapters.

Morehouse has a technical paper on recommended compression and tension adapters for force calibration that can be found on our website[1].

What is a Tension Calibration?

When discussing tension calibration, we should think of something being stretched. I like to describe tension calibration as a pull.

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1 https://mhforce.com/wp-content/uploads/2021/04/Recommended-Compression-and-Tension-Adapters-for-Force-Calibration.pdf

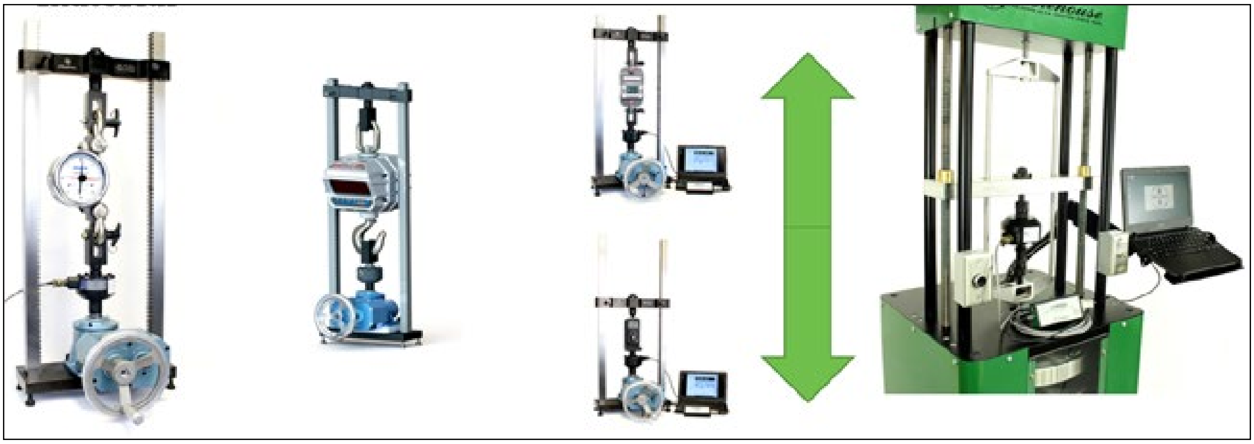

Figure 8. Tension Calibration can be thought of as pulling or stretching the material.

Above are multiple examples of tension setups in calibrating machines. The machine on the left is a benchtop calibrating machine. A dynamometer is fixed to a stationary beam, and force is generated by pulling on the load cell and the dynamometer. More examples are shown with different instruments, from crane scales to hand-held force gauges. The picture on the right shows a load cell fixtured for tension calibration in a deadweight machine. The load cell is fixtured to the frame, and the weights are applied and hung, which stretches the material. The key to getting great results in tension calibration is also adapters.

The ISO 376 Annex gives excellent guidance on adapters that help keep the line of force pure. It states, "Loading fittings should be designed in such a way that the line of force application is not distorted. As a rule, tensile force transducers should be fitted with two ball nuts, two ball cups, and, if necessary, with two intermediate rings, while compressive force transducers should be fitted with one or two compression pads [1]." Morehouse follows the ISO 376 standard for several of our products. We also design adapters to help technicians and end-users to replicate and reproduce calibration results.

Calibration Versus Verification

Calibration and verification are not the same. This section describes the differences between calibration and verification.

What is a Calibration?

Let me start by stating that there are several definitions of calibration across multiple standards. The following are my favorite definitions.

Calibration is the comparison of an unknown (typically referred to as the Unit Under Test or UUT) to a device known within a certain error (typically referred to as the Calibration Standard or Reference Standard) to characterize the unknown. Thus, we are comparing something that we know to some degree of certainty to something that may not be known or that needs to be checked at a time interval to assure drift and other characteristics are kept under control. Thus, in simple terms, calibration can be thought of as validation.

The definition from the International Vocabulary of Metrology (VIM) in section 2.39 is interesting in that many people assume calibration is also an adjustment. It is not. The VIM is clear in Note 2, stating, "Calibration should not be confused with a measuring system, often mistakenly called "self-calibration," nor with verification of calibration [2]." Think about it this way; when you send most instruments to a National Metrology Institute such as NIST, they will only report the value of the device at specific points and the associated measurement uncertainties. Why? Because the end-user can take those values and use those values with the associated measurement uncertainties as a starting point to characterize whatever is being tested. Measurement uncertainty will be explained in the next section.

When an end-user uses a calibrated device, it is often under different conditions than when it was calibrated. For example, if Morehouse calibrates a device in one of our deadweight machines known to better than 0.002 % of applied force, and the end-user later uses this device, then the conditions will vary. It is almost certain that their use conditions do not replicate those exactly of the lab performing the calibration. For example, the temperature, rigidity of the machine, and hardness of adapters could vary, and their machine could introduce torsion, etc. These are only a few of several conditions that can impact the results.

I like to explain that Morehouse calibrates the device and assigns a value that can be considered the expected performance of the device under the same conditions at which it was calibrated. The end-user then varies those conditions, which adds additional measurement uncertainty. Therefore, the end-user can use the calibration data as a starting point to evaluate their measurement uncertainty.

What is Verification?

The VIM in section 2.44 defines verification as the "provision of objective evidence that a given item fulfills specified requirements [3]." Then the VIM goes on to list three examples, followed by multiple notes. I would highly recommend going online to view this page.

When you do check out this page, pay particular attention to Note 5 which states, "Verification should not be confused with calibration. Not every verification is a validation." Verification, per Note 6 "requires a description of the structure or properties of that entity or activity." For example, a 10,000-load cell, like the one shown below in Figure 9, is submitted to Morehouse, and found to be within ± 5 lbf, as per the customer's required tolerance of 0.05 % of full scale.

Figure 9. Morehouse Ultra-Precision Load Cell

In this scenario, verification is more of a conformity assessment and should not be confused with calibration. However, many commercial laboratories perform a calibration by reporting the applied force and the device's corresponding measurement values for calibration. Then they make a conformity assessment, which is a statement to the end-user that the device is either in or out of tolerance. They typically say a device passes calibration or it fails calibration.

The critical detail here is that to ensure measurement traceability, measurement uncertainties must be reported. You should not perform a calibration with a statement of verification without reporting the measurement uncertainty. That uncertainty should be considered when making a statement of conformance to a specification.

Measurement Uncertainty

What is Measurement Uncertainty?

What measurement uncertainty is not is an error. It is imperative to understand the difference between these two terms as they are often confused. Error is the difference between the measured value and the device's actual value or artifact being measurement. In many cases, we try to correct the known errors by applying corrections sometimes from the calibration certificate. These corrections can be all items found in Note 1 of the calibration definition from the VIM: "A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty [2]."

Uncertainty, often referred to as 'doubt,' is the quantification of 'doubt' about the measurement result. The VIM in section 2.26 defines uncertainty as a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used. The VIM goes into further detail with several notes about the included components of measurement uncertainty, such as those arising from systematic effect, components associated with corrections, assigned quantity values of measurement standards, etc. Measurement Uncertainty compromises many components.

OIML G 19:2017 sums the

definition of uncertainty as "the concept of measurement uncertainty can be described as a measure of how well the 'true' value of the measurand is believed to be known [5]."

One of the best guides to uncertainty is JCGM 100:2008 *Evaluation of measurement data — Guide to the expression of uncertainty in measurement*, free to download at https://www.bipm.org/en/publications/guides/gum.html.

In general, when you calculate measurement uncertainties following ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) and ILAC (International Laboratory Accreditation Cooperation) P-14 as required by ISO/IEC 17025 guidelines, you will need to consider the following:

- Repeatability (Type A)
- Resolution
- Reproducibility
- Reference Standard Uncertainty
- Reference Standard Stability
- Environmental Factors

Morehouse has written several published documents on the topic of measurement uncertainty. We have created a spreadsheet tool to help everyone correctly calculate uncertainty for force following accreditation requirements and in line with JCGM 100:2008. That tool can be found at https://mhforce.com/documentation-tools/.

Why is Measurement Uncertainty Important?

The uncertainty of the measurement is required to be reported on a certificate of calibrations if you are accredited to ISO/IEC 17025:2017, as well as several other standards. It is essential if your customer may want you to make a statement of conformance on whether the device or artifact is in tolerance or not. It may need to be considered if you do a test and want to know if the device passes or fails. Measurement Uncertainty is required to establish your measurement traceability, which is defined in the VIM as property of a measurement result whereby the result can be related to a reference through a documented, unbroken chain of calibrations contributing to the measurement uncertainty.

In simplistic terms, the measurement uncertainty is crucial because you want to know that the laboratory performing the calibration of your device or artifact can perform the calibration. If you need a device to be known to be within less than 0.02 %, you must use a calibration provider that gives you the best chance of achieving that result. If the calibration provider has a stated measurement uncertainty of 0.04 %, mathematically, they are not the

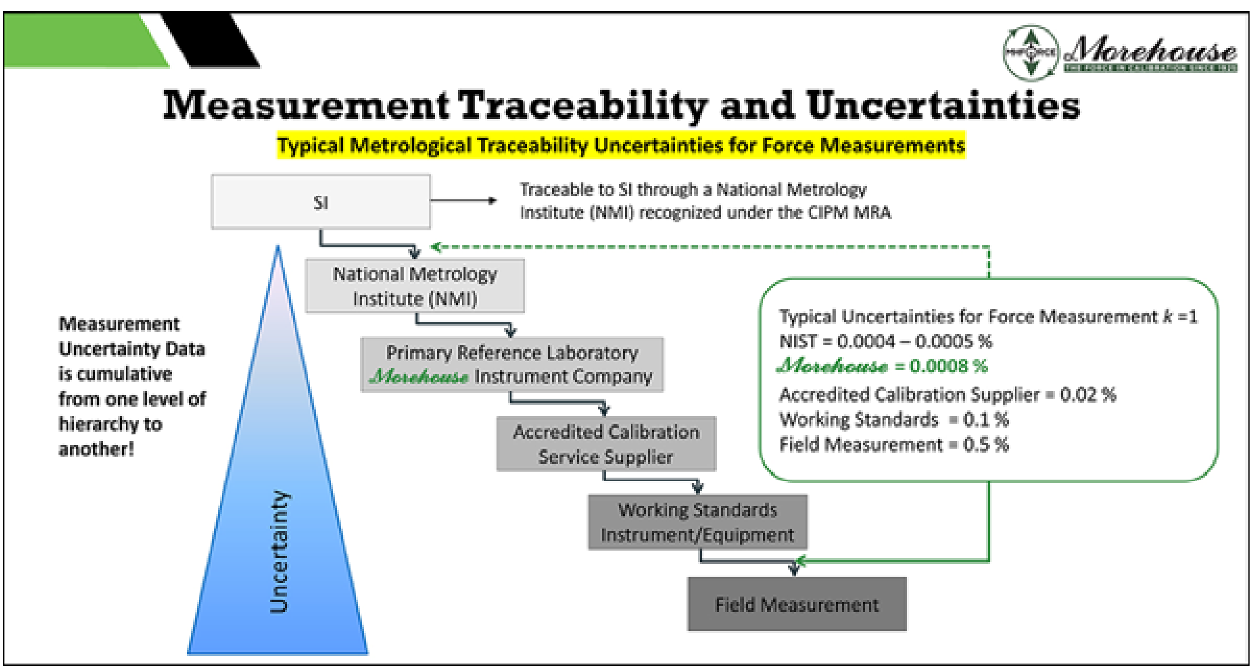

Figure 10. An Example of Measurement Traceability for Force

right calibration lab to calibrate or verify your device or artifact.

Measurement uncertainty also keeps us honest. If a laboratory claims traceability to SI through NIST, the larger the uncertainty becomes, the further away from NIST. The above picture shows this concept as the further away from SI units, the more significant the uncertainty.

Conclusion

In this first part of force calibration guidance, we defined force calibration, its importance, and some devices used to measure force. We differentiated compression and tension in relation to force calibration, as well as defining what we mean by "calibration." Since ISO/IEC 17025 requires a corrective value for measurement uncertainties on certificates of calibration, we covered the documentation to help define these values. And above all, we explained the importance of measurement uncertainties and traceability.

Look for Part 2 in the next issue, where we talk about load cells: terminology, types, and trouble-shooting. We'll also explain what a digital indicator does and provide a glossary of terms often used in force calibration.

Additional Information

Our purpose is to create a safer world by helping companies improve their force and torque measurements. We have several other technical papers, guidance documents, and blogs that can add to your knowledge base. Visit www.mhforce.com for additional guidance on adapters, uncertainty, calibration techniques, and more.

References

[1] ISO 376:2011(en) *Metallic materials — Calibration of force-proving instruments used for the verification of uniaxial testing machines,* Annex A.4.1. https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en

[2] *International vocabulary of metrology - Basic and general concepts and associated terms (VIM),* (JCGM 200:2012, 3rd edition). https://jcgm.bipm.org/vim/en/2.39.html

[3] *International vocabulary of metrology - Basic and general concepts and associated terms (VIM),* (JCGM 200:2012, 3rd edition). https://jcgm.bipm.org/vim/en/2.44.html

[4] *OIML G 19:2017 The role of measurement uncertainty in conformity assessment decisions in legal metrology,* p.44. https://www.oiml.org/en/files/pdf_g/g019-e17.pdf

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Practitioner's Perspective on the GUM Revision, Part I: Two Key Problems and Solutions

Hening Huang
Teledyne RD Instruments (retired)

As a practitioner in the field of measurement science, the author strongly concurs in the need for revision of the GUM (*Guide to the Expression of Uncertainty in Measurement*), as it has some shortcomings and limitations. This paper is the first one (Part I) in a series of two papers (Part I and Part II) designated to provide practitioner's perspective on the GUM revision. This paper (Part I) focuses on two key problems: (1) inconsistency in GUM's two definitions of measurement uncertainty, and (2) limitations of GUM's method for calculating the expanded uncertainty. The first problem can be solved by defining 'uncertainty of measurement' as the 'probabilistic error bound' based on the law of error. The second problem can be solved by either of two alternative approaches for calculating the expanded uncertainty. We argue that, on the one hand, a revised GUM should correct GUM's shortcomings and address its limitations, thereby providing better guidance; on the other hand, it should minimize potential impact of the revision on GUM's current practice; both should contribute to the success of the GUM revision. Part II will examine four examples of the GUM in detail using the two alternative approaches, and describe the resolutions to the Ballico paradox due to GUM's method for calculating the expanded uncertainty.

1. Introduction

The *Guide to the Expression of Uncertainty in Measurement* (GUM) was first published in 1993 and republished in 1995. In 2008, the Joint Committee for Guides in Metrology (JCGM) reissued the GUM with minor corrections to the 1995 version (JCGM 2008a). Since its publication, the GUM has been used in many fields of science, engineering, and industry. However, it is well known that the GUM exhibits philosophical and methodological inconsistencies with respect to its two later Supplements: GUM-S1 (JCGM 2008b) and GUM-S2 (JCGM 2011). This is because the GUM uncertainty framework is essentially based on the frequentist concept of confidence intervals, while the GUM-S1 and GUM-S2 are based on the Bayesian methodology. JCGM decided to make a major revision of the GUM by fully adopting the Bayesian methodology (Bich et al. 2012, Bich 2014, Kyriazis 2015, Lira 2016). The committee draft of the revised GUM was circulated to the member organizations of the JCGM and all national metrology institutes in December 2014. The JCGM received more than 1000 comments and the feedback was largely negative (Bich et al. 2016). According to Lira (2019), some of the criticisms have to do with emphasizing Bayesian statistics at the expense of frequentist statistics. Other negative comments relate to the perceived increase in mathematical complexity and the fact that the uncertainty values reported under the (current) GUM uncertainty framework would be understood as incorrect. Therefore, the committee draft "was not well received by the metrological community (Lira 2019)."

One of the main reasons why the committee draft of the revised GUM was rejected by the industry is that the Bayesian methodology for uncertainty analysis is controversial. In recent decades, Bayesian methods are widely used in many scientific fields. However, the application of Bayesian methods in other scientific fields does not imply that it is suitable for measurement uncertainty analysis in measurement science (Huang 2020). Some authors expressed their concerns and/or opposition to the revision of the GUM based on Bayesian statistics (Willink and White 2011, Attivissimo et al. 2012, Giaquinto et al. 2014, Giaquinto and Fabbiano 2016, White 2016, Willink 2016, Huang 2020). Willink and White (2011) discussed several issues as the consequences of the shift from GUM's frequentist approach to the Bayesian approach. They stated, "It is our view that the GUM should be revised, but not according to the Bayesian philosophy." Giaquinto et al. (2014) discussed some limitations and weaknesses of the Bayesian approach. Huang (2019) revealed that the scaled and shifted *t*-distribution, which is a result of the objective Bayesian approach, is inappropriate for Monte Carlo simulation for uncertainty analysis. Huang (2020) discussed the potential biases caused by the Bayesian approach for estimating the measurand and the associated uncertainty, and pointed out that the Bayesian Type A standard uncertainty is invalid because it is significantly biased when the sample size (or degree of freedom) is small. Wubbeler and Elster (2020) demonstrated that the Bayesian Type A standard uncertainty fails to ensure the requirement of transferability, which is the key requirement for uncertainty analysis. White (2016) discussed the key differences between the frequentist paradigm and Bayesian paradigm for uncertainty analysis. He argued, "… the change from a frequentist treatment of measurement error to a Bayesian treatment of states of knowledge is misguided." Lira (2019) reviewed some comments on the committee draft of the revised GUM. He cited a comment, "We believe that switching the approach completely to Bayesian statistics will significantly hamper the application of the guide and will, eventually, result in a lower acceptance of the need to estimate and use measurement uncertainties."

White (2016) proposed five requirements for a revised GUM: (1) simplicity, ideally, the mathematics should be no more difficult than summing uncertainties in quadrature, (2) harmony, not only a revised GUM should produce very similar numerical results, the underpinning rationale should also be similar to the (current) GUM, (3) uncertainty analysis as a theory of error, (4) objective probability, and (5) measurement uncertainty as a minimal summary. White (2016) commented that the committee draft of the revised GUM fails to meet any of these five requirements.

Rossi (2019) suggested a revision direction that is different from the one currently being considered by the JCGM. He proposed to revise the GUM by adopting a probabilistic approach to express uncertainty and evaluating uncertainty based on a probabilistic modeling of the measurement process. Zakharov et al (2019) discussed the main requirements for a revised GUM and described the criteria for compliance with the listed requirements.

As a practitioner in the field of measurement science, the author strongly concurs in the need for revision of the GUM. In the author's opinion, the GUM does have some shortcomings and limitations. On the one hand, a revised GUM must correct the shortcomings, address its limitations, thereby providing better guidance; on the other hand, it should minimize the potential impact of the revision on GUM's current practice; both of these should contribute to the success of the GUM revision.

This paper is the first one (Part I) in a series of two papers (Part I and Part II). It focuses on two key problems: (1) inconsistency in GUM's two definitions of measurement uncertainty, and (2) limitations of GUM's method for calculating expanded uncertainty. The author identified these two problems from the practice and research of using the GUM, especially when analyzing the uncertainty of streamflow measurements using acoustic Doppler current profilers (e.g. Huang 2015) and studying the Ballico paradox (Huang 2016).

In the following, sections 2 and 3 discuss these two key problems respectively. Section 4 presents solutions to these two key problems. Section 5 presents discussion. Section 6 presents conclusion and recommendation.

2. Inconsistency in GUM's Two Definitions of Measurement Uncertainty

Surprisingly, the GUM actually defines 'uncertainty of measurement' in two ways. The first definition can be found on page 2 of the GUM (JCGM 2008a, p2) where 'uncertainty of measurement' is defined as "Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand (JCGM 2008a, p2)." Under the normality assumption for "the values" (i.e. the estimates of the measurand), this definition implies that 'uncertainty' is the scale parameter of the normal distribution.

Consider a measurement with multiple (n) observations. The sample mean is the usual estimate of the measurand. According to this definition of uncertainty, when the standard deviation of the parent distribution, denoted by σ, is known, the standard uncertainty (SU) of the sample mean (denoted by $\bar{x}$) is calculated as $\sigma/\sqrt{n}$; the expanded uncertainty of the sample mean is calculated as

$$\text{expanded uncertainty} = z_p\frac{\sigma}{\sqrt{n}} = U_{p,z} \tag{1}$$

where p is the coverage probability, z_p is the corresponding z-value, and $U_{p,z}$ is referred to as the z-based uncertainty (e.g. Huang 2014). Note that $\sigma/\sqrt{n}$ or $z_p \frac{\sigma}{\sqrt{n}}$ is a Type B uncertainty according to GUM's classification of Type A/Type B uncertainties. Also note that the Type B uncertainty is treated as exactly known in the GUM (JCGM 2008a, p76).

However, the first definition of 'uncertainty of measurement' is followed by a note, "The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence (JCGM 2008a, p2)." This note means that the GUM also defines 'uncertainty of measurement' as the half-width of a confidence interval (or coverage interval). For the problem of multiple observations, when the standard deviation of the parent distribution σ is unknown, the corresponding confidence interval is the t-based confidence interval: $\left(\bar{x} - t_{p,n-1}\frac{s}{\sqrt{n}}, \bar{x} + t_{p,n-1}\frac{s}{\sqrt{n}}\right)$ that satisfies the following statement about confidence level

$$\text{confidence level} = \Pr\left(\left[\bar{x} - t_{p,n-1}\frac{s}{\sqrt{n}}, \bar{x} + t_{p,n-1}\frac{s}{\sqrt{n}}\right] \ni \mu\right) = p \quad (2)$$

where $t_{p,n-1}$ is the t-value at the confidence level p, (n-1) is the degree of freedom (DOF), μ is the true value of the measurand X, and $\mu = \mathrm{E}(\bar{x})$, the expectation of the sample mean.

Thus, according to GUM's second definition of uncertainty, the Type A expanded uncertainty of the sample mean is the half-width of the t-based confidence interval when σ is unknown. That is,

$$\text{Type A expanded uncertainty} = t_{p,n-1}\frac{s}{\sqrt{n}} = U_{p,t} \quad (3)$$

where $U_{p,t}$ is referred to as the t-based uncertainty (e.g. Huang 2014).

It is important to note that $\sigma/\sqrt{n}$ is the scale parameter of the sampling distribution of $\bar{x}$: $N(\mathrm{E}(\bar{x}), \frac{\sigma}{\sqrt{n}})$; the z-based uncertainty $U_{p,z} = z_p \frac{\sigma}{\sqrt{n}}$ is also the scale parameter of the sampling distribution of $\bar{x}$ because it is "a given multiple of the standard uncertainty $\frac{\sigma}{\sqrt{n}}$." However, the t-based uncertainty $U_{p,t} = t_{p,n-1}\frac{s}{\sqrt{n}}$ is a random variable or sample statistic; it is not the scale parameter of the sampling distribution of $\bar{x}$ at all; it is not even a reasonable estimate of the scale parameter $U_{p,z} = z_p \frac{\sigma}{\sqrt{n}}$ because it is significantly biased when the sample size is small. Apparently, when defining the measurement uncertainty, the GUM unconsciously mixes the scale parameter, e.g. $U_{p,z} = z_p \frac{\sigma}{\sqrt{n}}$, with the half-width of a confidence interval (sample statistic), e.g. $U_{p,t} = t_{p,n-1}\frac{s}{\sqrt{n}}$. These two quantities are not the same in statistics. Therefore, GUM's two definitions of uncertainty are inconsistent. As a result, the Type A expanded uncertainty $U_{p,t} = t_{p,n-1}\frac{s}{\sqrt{n}}$ is not compatible with the Type B expanded uncertainty $U_{p,z} = z_p \frac{\sigma}{\sqrt{n}}$. This is known as the 'uncertainty analysis paradox' (Huang 2010, 2018a).

3. Limitations of GUM's Method for Calculating the Expanded Uncertainty

3.1 The True Expanded Uncertainty

The GUM mainly considers the problem of indirect measurement, where the quantity of interest (i.e. the measurand, denoted by Y) is related to N influence quantities (i.e. input quantities, denoted by X_i) through a measurement model, written as (formula (1) in JCGM 2008a, p8)

$$Y = f(X_1, X_2, \ldots, X_N). \quad (4)$$

An estimate of the measurand Y, denoted by y, can be obtained using the input estimates x_1, x_2, … x_N for the quantities X_1, X_2, … X_N, respectively. That is (formula (2) in JCGM 2008a, p9),

$$y = f(x_1, x_2, \ldots, x_N). \quad (5)$$

The true combined standard uncertainty (CSU), denoted by $u_{c,T}(y)$, can be calculated by the law of propagation of uncertainty when the true standard uncertainty (SU), denoted by $u_T(x_i)$, and the population correlation coefficient, denoted by $\rho(x_i x_j)$, of all influence (input) quantities are known. That is

$$u_{c,T}(y) = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u_T^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u_T(x_i)\,u_T(x_j)\rho(x_i x_j)}. \quad (6)$$

According to the Central Limit Theorem, the measurement error $e = y - \mathrm{E}(Y)$ is approximately normally distributed: $N[0, u_{c,T}(y)]$. Thus, the true CSU $u_{c,T}(y)$ is the scale parameter of the normal distribution of the measurement error e. Accordingly, the true expanded uncertainty, denoted by $U_{p,T}$, is calculated as

$$U_{p,T} = z_p u_{c,T}(y). \quad (7)$$

Note that $u_{c,T}(y)$ or $U_{p,T}$ conforms to GUM's first definition of uncertainty as the scale 'parameter.'

3.2 GUM's Method

The GUM states, "The estimated standard deviation associated with the output estimate or measurement result y, termed *combined standard uncertainty* and denoted by $u_c(y)$, is determined from the estimated standard deviation associated with each input estimates, x_i, termed standard uncertainty and denoted by $u(x_i)$ (JCGM 2008, p9)." It is important to note that the GUM uses the word "estimated" for both $u_c(y)$ and $u(x_i)$. That is, $u_c(y)$ is an "estimator" of the true CSU $u_{c,T}(y)$, and $u(x_i)$ is an "estimator" of the true SU $u_T(x_i)$.

According to GUM's classification of Type A/Type B uncertainties, the uncertainty components $u(x_i)$ can be separated into two groups: Type A SUs $u_A(x_i)$ and Type B SUs $u_B(x_k)$. In the GUM, the Type A SU is calculated as the standard error of the sample mean, i.e. $u_A(x_i) = \frac{s(x_i)}{\sqrt{n_i}}$, where $s(x_i)$ is the sample standard deviation. For simplicity, we use s_i for $s(x_i)$ and $u_{B,k}$ for $u_B(x_k)$ hereafter. Furthermore, we assume that only Type A (influence) quantities may be correlated, and there is no correlation between a Type A quantity and a Type B quantity, or between two Type B quantities.

The estimated population correlation coefficient $\rho(x_i x_j)$ from data is denoted by $r_{i,j}$. Then, the CSU $u_c(y)$ is calculated as an approximation of the law of propagation of uncertainty, Eq. (6). That is,

$$u_c(y) = \sqrt{\sum_{i=1}^{N_A} c_i^2 \frac{s_i^2}{n_i} + \sum_{k=N_A+1}^{N} c_k^2 u_{B,k}^2 + 2\sum_{i=1}^{N_A-1}\sum_{j+1}^{N_A} c_i c_j \frac{s_i}{\sqrt{n_i}} \frac{s_j}{\sqrt{n_j}} r_{i,j}} \approx u_{c,T}(y) \tag{8}$$

where $c_i = \frac{\partial f}{\partial x_i}$ is the sensitivity coefficient, N_A is the number of the Type A quantities (or Type A uncertainty components).

The CSU $u_c(y)$ is a reasonable estimator of the true CSU $u_{c,T}(y)$. However, the CSU $u_c(y)$ is slightly negatively biased, just as the sample standard deviation s is a slightly biased estimator of the population standard deviation σ.

The GUM calculates the expanded uncertainty of y as the half-width of the t-based confidence interval, written as (in the same notations in formula (G.1d) in JCGM 2008a, p72)

$$U_{p,\mathrm{GUM}} = k_p u_c(y) = t_p(\nu) u_c(y) \tag{9}$$

where k_p is the coverage factor, and $t_p(\nu)$ is the t-value for a given value of ν – the degrees of freedom (DOF) – such that the fraction p of the t-distribution is encompassed by the interval $-t_p(\nu)$ to $+t_p(\nu)$ (JCGM 2008a, p72). Hereafter, we denote $t_p(\nu)$ as $t_{p,\nu}$ for the notation consistency in this paper.

The GUM assumes that the distribution of the standardized variable $[y - \mathrm{E}(Y)]/u_c(y)$ is approximated by a t-distribution with an effective DOF ν_{eff} calculated from the Welch-Satterthwaite formula (formula (G.2b) in JCGM 2008a, p73)

$$\nu_{\mathrm{eff}} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{c_i^4 u_i^4}{\nu_i}} = \frac{\left[\sum_{i=1}^{N} c_i^2 u_i^2\right]^2}{\sum_{i=1}^{N} \frac{c_i^4 u_i^4}{\nu_i}} \tag{10}$$

where ν_i is the DOF associated with the ith uncertainty component $u_i = u(x_i)$. Note that the sensitivity coefficient is missing in GUM's formula (G.2b).

The Welch-Satterthwaite formula, Eq. (10) is only valid when the correlations are zero, so $u_c(y) = \sqrt{\sum_{i=1}^{N} c_i^2 u^2(x_i)}$. However, Willink (2007) demonstrated by simulation examples that it can be used as an approximation in the presence of correlations.

Substituting $u_c(y)$ and ν_{eff} into Eq. (9) yields

$$U_{p,\mathrm{GUM}} = t_{p,\nu_{\mathrm{eff}}} \sqrt{\sum_{i=1}^{N_A} c_i^2 \frac{s_i^2}{n_i} + \sum_{k=N_A+1}^{N} c_k^2 u_{B,k}^2 + 2\sum_{i=1}^{N_A-1}\sum_{j+1}^{N_A} c_i c_j \frac{s_i}{\sqrt{n_i}} \frac{s_j}{\sqrt{n_j}} r_{i,j}}. \tag{11}$$

Equation (11) is the method for calculating the expanded uncertainty under the GUM uncertainty framework; it is known as GUM's WS-t approach (Huang 2016). The GUM claims that the expanded uncertainty $U_{p,\mathrm{GUM}} = k_p u_c(y) = t_{p,\nu_{\mathrm{eff}}} u_c(y)$ provides an interval $Y = y \pm U_{p,\mathrm{GUM}}$ having an approximate level of confidence p (JCGM 2008a, p73). That is

$$\Pr\left\{\left[y - t_{p,\nu_{\mathrm{eff}}} u_c(y), y + t_{p,\nu_{\mathrm{eff}}} u_c(y)\right] \ni \mathrm{E}(Y)\right\} \approx p \tag{12}$$

Therefore, the expanded uncertainty $U_{p,\mathrm{GUM}} = t_{p,\nu_{\mathrm{eff}}} u_c(y)$ is the half-width of the t-based confidence interval: $\left[y - t_{p,\nu_{\mathrm{eff}}} u_c(y), y + t_{p,\nu_{\mathrm{eff}}} u_c(y)\right]$.

That is, the expanded uncertainty $U_{p,\mathrm{GUM}}$ conforms to GUM's second definition of uncertainty as the half-width of a confidence interval.

3.3 Limitations of GUM's Method

However, the expanded uncertainty $U_{p,\mathrm{GUM}} = t_{p,\nu_{\mathrm{eff}}} u_c(y)$ is not a good estimator of the true expanded uncertainty $U_{p,T} = z_p u_{c,T}(y)$ in terms of conformity and reliability. In fact, it is a biased estimator. That is, the expectation of $U_{p,\mathrm{GUM}}$ is not equal to $U_{p,T}$

$$\mathrm{E}(U_{p,\mathrm{GUM}}) = t_{p,\nu_{\mathrm{eff}}} \mathrm{E}\left[u_c(y)\right] \neq z_p u_{c,T}(y) = U_{p,T}. \qquad (13)$$

Numerical examples using Monte Carlo simulations show that $U_{p,\mathrm{GUM}}$ is not only significantly positively biased, but also unreliable (having high precision error) when the effective DOF is small (e.g. smaller than 5); $U_{p,\mathrm{GUM}}$ approaches $U_{p,T}$ only when the effective DOF is large (e.g. greater than 19) (Huang 2018c). Therefore, GUM's WS-*t* approach is generally too conservative, and in the worst case, it may produce unrealistic estimates of uncertainty when the DOF or effective DOF is small.

It is easy to recognize that GUM's WS-*t* approach is too conservative (and sometimes even unrealistic) by considering a special case that the measurement model only involves one Type A quantity (i.e. Y=X). In this situation, GUM's WS-*t* approach reduces to the *t*-based uncertainty $U_{p,\mathrm{GUM}} = U_{p,t} = t_{p,n-1}\frac{s}{\sqrt{n}}$. D'Agostini (1998) gave an example: "…having measuring the size of this page twice and having found a difference of 0.3 mm between the measurements… Any rational person will refuse to state that, in order to be 99.9% confidence in the result, the uncertainty interval [i.e. the *t*-based uncertainty $U_{p,t}$] should be 9.5 cm wide (any carpenter would laugh…). This may be the reason why, as far as I known, physicists don't use the Student distribution."

It is important to note that uncertainty evaluation must be realistic, neither 'optimistic' nor 'conservative' are acceptable in practice. Willink and White (2011) considered an example of the cost-risk compromise in measurement-based decision-making. They stated, "Effective cost-risk compromises can only be reached if those making the decisions have realistic (i.e., not 'optimistic' or 'conservative') estimates of the uncertainties in the measurements on which the decisions are based." They further pointed out, "… realistic estimates of uncertainty are the goal of uncertainty analysis, and our economies, our environment, and our lives depend on it." Therefore, the excessive conservativeness is a serious limitation of GUM's WS-*t* approach.

Another serious limitation of GUM's WS-*t* approach is that it may produce paradoxical results when one or more of the influence (input) quantities have few DOF. This problem is known as the Ballico paradox. Ballico (2000) first discovered this problem during the calibration of a thermometer at the CSIRO National Measurement Laboratory in Australia. The thermometer was calibrated for a high precision range (1 mK) and a low precision range (10 mK). Five error sources contributed to the calibration error Y. The measurement model is written as $Y = X_1 + X_2 + X_3 + X_4 + X_5$. The SUs of X_1, X_2, and X_3 are the same for the 1 mK and 10 mK ranges. The SUs of X_4 and X_5 are 1 and 0.3 mK respectively for the 1 mK range, which are significantly smaller than the SUs 7 and 3 mK respectively for the 10 mK range. Therefore, intuitively and logically, the uncertainty of the thermometer in the 1 mK range must be smaller than the uncertainty in the 10 mK range. However, counter-intuitively, the estimated expanded uncertainty using GUM's WS-*t* approach is 37.39 mK for the 1 mK range, which is *greater* than 35.07 mK for the 10 mK range (Ballico 2000)! This paradoxical result is unacceptable. It would be ridiculous if the CSIRO issued a calibration certificate for the calibrated thermometer based on these uncertainty analysis results.

The Ballico paradox is a counterinstance to GUM's WS-*t* approach; it essentially invalidates GUM's WS-*t* approach (Huang 2016). It is important to note that the Ballico paradox is not accidental; it reveals the methodological flaw inherent in GUM's WS-*t* approach. The Ballico paradox is not due to the Welch-Satterthwaite formula. The Welch-Satterthwaite formula is valid for estimating the effective DOF. The Ballico paradox is because the expanded uncertainty is calculated as the half-width of the approximate *t*-based confidence interval, i.e. $U_{p,\mathrm{GUM}} = t_{p,\nu_{\mathrm{eff}}} u_c(y)$ (Huang 2016). Hall and Willink (2001), Huang (2016), and Burr et al. (2021) visited the Ballico paradox by examining a simplified problem using Monte Carlo simulation: the sum of two uncertainty components, a Type A SU with few

DOF and a Type B SU with an infinite DOF. Their results show that, for a fixed Type A SU, the mean of the expanded uncertainty, or the mean width of the simulated t-based confidence intervals, sometimes decreases as the Type B SU increases. In the author's opinion, this anomalous behavior again invalidates GUM's WS-t approach.

In summary, GUM's WS-t method for calculating expanded uncertainty has two serious limitations: (1) it is generally too conservative and may produces unrealistic estimates of uncertainty when the DOF or effective DOF is small, and (2) it may produce paradoxical results, such as the Ballico paradox, when one or more of the influence quantities have few DOF. Although these two limitations may not arise when the effective DOF is large or all influence quantities have large DOFs, they are the inherent flaws of GUM's WS-t approach and must be addressed in a revised GUM.

4. Solutions to the Two Key Problems

4.1 Define 'Uncertainty of Measurement' as 'Probabilistic Error Bound'

Huang (2018b) proposed to redefine 'uncertainty of measurement' as the 'probabilistic error bound' with a specified coverage probability p, based on the law of error. The law of error refers to the normal distribution, also known as the law of probability of errors (Lehmann 1999).

For the problem of multiple observations, the measurement error $\varepsilon = \bar{x} - \mathrm{E}(\bar{x})$ follows the normal distribution $N(0, \frac{\sigma}{\sqrt{n}})$ according to the Central Limit of Theorem. The law of error can be written as

$$\Pr\left(\varepsilon \in \left[-z_p \frac{\sigma}{\sqrt{n}}, +z_p \frac{\sigma}{\sqrt{n}}\right]\right) = p. \tag{14}$$

The z-based uncertainty $U_{p,z} = z_p \frac{\sigma}{\sqrt{n}}$ is the probabilistic error bound at the coverage probability p. Equation (14) defines an uncertainty interval $(-U_{p,z}, +U_{p,z})$, which is a *probability interval*, not a confidence interval. The law of error, Eq. (14), shows that for a measurement we have made, we have p percent certainty that the measurement error ε is within the uncertainty interval $\left(-U_{p,z}, +U_{p,z}\right)$. Therefore, the coverage probability p is also called "degree of certainty" (Huang 2020).

Replacing σ with $\mathrm{E}(s)/c_{4,n-1}$, the law of error, Eq. (14), can be rewritten as

$$\Pr\left(\varepsilon \in \left[-z_p \frac{\mathrm{E}(s)}{c_{4,n-1}\sqrt{n}}, +z_p \frac{\mathrm{E}(s)}{c_{4,n-1}\sqrt{n}}\right]\right) = p \tag{15}$$

where $\mathrm{E}(s)$ is the expectation of the sample standard deviation s, $c_{4,n-1}$ is the bias-correction factor for s at the DOF=n-1, $c_{4,n-1} = \sqrt{\frac{2}{n-1}}\frac{\Gamma(\frac{n}{2})}{\Gamma(\frac{n-1}{2})}$, and $\Gamma(.)$ stands for Gamma function (Wadsworth 1989). The bias correction factor can be calculated using an Excel spreadsheet. However, it should be noted that Excel's built-in Gamma function is valid for DOF≤342 or n≤343; it fails for DOF>343 or n≥344. For n≥344, it is reasonable to use $c_{4,n-1} = 1$.

As a first-order approximation to the true SU $\frac{\sigma}{\sqrt{n}} = \frac{\mathrm{E}(s)}{c_{4,n-1}\sqrt{n}}$, the Type A SU (modified) can be calculated as

$$\text{Type A SU (modified)} = \frac{s}{c_{4,n-1}\sqrt{n}}. \tag{16}$$

Accordingly, the Type A expanded uncertainty (modified) can be calculated as

$$\text{Type A expanded uncertainty (modified)} = z_p \frac{s}{c_{4,n-1}\sqrt{n}}. \tag{17}$$

Defining 'uncertainty of measurement' as the 'probabilistic error bound' is actually consistent with GUM's first definition of uncertainty as the scale 'parameter', because the probabilistic error bound, $\frac{\sigma}{\sqrt{n}}$ or $z_p \frac{\sigma}{\sqrt{n}}$, is the scale parameter of the sampling distribution of ε or $\bar{x}$. Note that $\frac{s}{c_{4,n-1}\sqrt{n}}$ is an unbiased estimator of the true (or Type B) SU $\frac{\sigma}{\sqrt{n}}$ and $z_p \frac{s}{c_{4,n-1}\sqrt{n}}$ is an unbiased estimator of the true (or Type B) expanded uncertainty $z_p \frac{\sigma}{\sqrt{n}}$. Therefore, the modified Type A expanded uncertainty $z_p \frac{s}{c_{4,n-1}\sqrt{n}}$ is compatible with the Type B expanded uncertainty $U_{p,z} = z_p \frac{\sigma}{\sqrt{n}}$. Consequently, the 'uncertainty analysis paradox' disappears. Therefore, defining uncertainty as the 'probabilistic error bound' solves the problem of inconsistent definitions of uncertainty in the GUM.

4.2 Use One of Two Alternative Approaches for Calculating the Expanded Uncertainty

The first alternative is known as the WS-z approach; it was originally developed by Huang (2016) to resolve the Ballico paradox. The second alternative is called new estimator 2 in the unified theory of errors and uncertainties (Huang 2018c). However, the original formulations of these two approaches did not take into account the correlation between the influence quantities. We add the correlation to the formulas in this paper.

4.2.1 The First Alternative Approach

In the WS-z approach, it is assumed that the measurement error $e = y - \mathrm{E}(Y)$ is approximately normally distributed according to the Central Limit Theorem. Then, the law of error for indirect measurements is approximately written as

$$\Pr\left(e \in \left[-z_p \frac{u_c(y)}{c_{4,\nu_{\text{eff}}}}, +z_p \frac{u_c(y)}{c_{4,\nu_{\text{eff}}}}\right]\right) \approx p \tag{18}$$

where $c_{4,\nu_{\text{eff}}}$ is the bias correction factor for the CSU; it is calculated from $c_{4,\nu_{\text{eff}}} = \sqrt{\frac{2}{\nu_{\text{eff}}}}\frac{\Gamma\left(\frac{\nu_{\text{eff}}+1}{2}\right)}{\Gamma\left(\frac{\nu_{\text{eff}}}{2}\right)}$. The CSU $u_c(y)$ is defined by Eq. (8), and the effective DOF ν_{eff} is calculated according to the Welch-Satterthwaite formula, Eq. (10), same as the GUM.

Let subscript 1 denote the first alternative approach. The expanded uncertainty, $U_{p,1}$, is calculated as

$$U_{p,1} = z_p \frac{u_c(y)}{c_{4,\nu_{\text{eff}}}} = z_p \frac{1}{c_{4,\nu_{\text{eff}}}}\sqrt{\sum_{i=1}^{N_A} c_i^2 \frac{s_i^2}{n_i} + \sum_{k=N_A+1}^{N} c_k^2 u_{B,k}^2 + 2\sum_{i=1}^{N_A-1}\sum_{j+1}^{N_A} c_i c_j \frac{s_i}{\sqrt{n_i}}\frac{s_j}{\sqrt{n_j}} r_{i,j}}. \tag{19}$$

Thus, $U_{p,1} = z_p \frac{u_c(y)}{c_{4,\nu_{\text{eff}}}}$ is the half-width of the probability interval $\left[-z_p \frac{u_c(y)}{c_{4,\nu_{\text{eff}}}}, +z_p \frac{u_c(y)}{c_{4,\nu_{\text{eff}}}}\right]$, which is an estimator of the true uncertainty interval $\left[-z_p u_{c,T}(y), +z_p u_{c,T}(y)\right]$.

4.2.2 The Second Alternative Approach

Let subscript 2 denote the second alternative approach. The expanded uncertainty, $U_{p,2}$, is calculated as

$$U_{p,2} = z_p u_c'(y) = z_p\sqrt{\sum_{i=1}^{N_A} c_i^2 \frac{s_i^2}{c_{4,ni-1}^2 n_i} + \sum_{k=N_A+1}^{N} c_k^2 u_{B,k}^2 + 2\sum_{i=1}^{N_A-1}\sum_{j+1}^{N_A} c_i c_j \frac{s_i}{c_{4,ni-1}\sqrt{n_i}}\frac{s_j}{c_{4,nj-1}\sqrt{n_j}} r_{i,j}} \tag{20}$$

where $c_{4,ni-1}$ is the bias correction factor for the Type A SU, it is calculated from $c_{4,ni-1} = \sqrt{\frac{2}{n_i-1}}\frac{\Gamma\left(\frac{n_i}{2}\right)}{\Gamma\left(\frac{n_i-1}{2}\right)}$, and $u_c'(y)$ is the modified CSU

$$u_c'(y) = z_p\sqrt{\sum_{i=1}^{N_A} c_i^2 \frac{s_i^2}{c_{4,ni-1}^2 n_i} + \sum_{k=N_A+1}^{N} c_k^2 u_{B,k}^2 + 2\sum_{i=1}^{N_A-1}\sum_{j+1}^{N_A} c_i c_j \frac{s_i}{c_{4,ni-1}\sqrt{n_i}}\frac{s_j}{c_{4,nj-1}\sqrt{n_j}} r_{i,j}}. \tag{21}$$

Accordingly, the approximation of the law of error, Eq. (18), can be rewritten as

$$\Pr\left(e \in \left[-z_p u_c'(y), +z_p u_c'(y)\right]\right) \approx p. \tag{22}$$

Thus, $U_{p,2} = z_p u_c'(y)$ is the half-width of the probability interval $\left[-z_p u_c'(y), +z_p u_c'(y)\right]$, which is also an estimator of the true uncertainty interval $\left[-z_p u_{c,T}(y), +z_p u_{c,T}(y)\right]$.

4.2.3 Comments on the Two Alternative Approaches

Either the CSU $u_c(y)$ or the modified CSU $u_c'(y)$ is an estimator of the true CSU $u_{c,T}(y)$, the scale parameter of the distribution of the measurement error $e = y - \mathrm{E}(Y)$. Theoretically, $u_c(y)/c_{4,\nu_{\text{eff}}}$ is approximately an unbiased estimator of $u_{c,T}(y)$, just as $s/c_{4,n-1}$ is an unbiased estimator of the population standard deviation σ. Accordingly, $U_{p,1} = z_p \frac{u_c(y)}{c_{4,\nu_{\text{eff}}}}$ is approximately an unbiased estimator of the true expanded uncertainty $U_{p,T} = z_p u_{c,T}(y)$. That is,

$$\mathrm{E}(U_{p,1}) = z_p \mathrm{E}\left[\frac{u_c(y)}{c_{4,\nu_{\text{eff}}}}\right] \cong z_p u_{c,T}(y) = U_{p,T}. \tag{23}$$

Although the unbiased estimator $s_i/c_{4,ni-1}$ is used in computing the modified CSU $u_c'(y)$ (refer to Eq. (21)), $u_c'(y)$ may not be an unbiased estimator of the true CSU $u_{c,T}(y)$. In fact, $u_c'(y)$ will be slightly positively biased according to Jensen's inequality (Jensen 1906, *Perlman 1974*). That is, Jensen's inequality guarantees that $\mathrm{E}\left[u_c'(y)\right] \geq u_{c,T}(y)$. Accordingly

$$\mathrm{E}(U_{p,2}) = z_p \mathrm{E}(u_c'(y)) \geq z_p u_{c,T}(y) = U_{p,T}. \tag{24}$$

That is, $U_{p,2} = z_p u_c'(y)$ is a conservative estimator of the true expanded uncertainty $U_{p,T}$.

Therefore, in principle, when the effective DOF is large enough, $U_{p,1} \cong U_{p,2} \cong U_{p,T}$; when the effective DOF is small, generally, $U_{p,1} \leq U_{p,2}$. Numerical simulation examples show that $U_{p,1}$ is slightly negatively biased and $U_{p,2}$ is slightly positively biased when the effective DOF is small; both are robust methods that do not give rise to any paradoxical estimates of the expanded uncertainty (Huang 2018c).

The first alternative approach, $U_{p,1} = z_p \frac{u_c(y)}{c_{4,\nu_{\text{eff}}}}$, i.e. the WS-$z$ approach, is the counterpart of GUM's WS-t approach. The formula for the Type A SU and the formula for the CSU $u_c(y)$ are the same in both approaches. Both approaches require the Welch-Satterthwaite formula to calculate the effective DOF. The only difference is that the coverage factor k_p in the WS-z approach is $z_p/c_{4,\nu_{\text{eff}}}$, while the coverage factor k_p in GUM's WS-t approach is $t_{p,\nu_{\text{eff}}}$.

The second alternative approach, $U_{p,2} = z_p\, u'_c(y)$, does not require the effective DOF. Therefore, the Welch-Satterthwaite formula is not required. This will greatly simplify uncertainty analysis, and avoid the difficulty and subjectivity of determining the DOF of Type B uncertainty components and the limitation of the Welch-Satterthwaite formula (Huang 2018c). The modified CSU $u'_c(y)$ can be easily calculated using the bias correction factor $c_{4,\text{n-1}}$ for each Type A uncertainty component. In addition, the second alternative approach is slightly conservative. Therefore, the author prefers to include the second alternative approach in a revised GUM.

In addition, for the special case where only one Type A influence quantity is involved in the measurement model, i.e. Y=X, the effective DOF reduces to n−1 and the CSU reduces to $\frac{s}{\sqrt{n}}$. The two alternative approaches give the same estimate of the Type A expanded uncertainty. That is

$$U_{p,1} = U_{p,2} = z_p \frac{s}{c_{4,n-1}\sqrt{n}}. \qquad (25)$$

5. Discussion

5.1 The Concept of Errors Should be Restored

The GUM avoids the concept of true values and the concept of errors. However, Willink (2016) found out, "The GUM accepts the idea of a true value but fails to involve the consequent ideas of accuracy, error and 'success' in measurement…" In fact, the concept of errors can still be found in the GUM (Van der Veen and Cox 2003). For example, the GUM interprets the derivation of the law of propagation of uncertainty from the standpoint of true value and error (JCGM 2008a, p59). In addition, the GUM acknowledges the random and systematic effects of error sources. The author agrees with Van der Veen and Cox (2003), "The concept of errors should, however, not be ignored, and certainly not by those involved in modelling measurements for the purpose of evaluating measurement uncertainty."

The Type B evaluation of uncertainty discussed in the GUM is actually based on the concept of errors. A Type B uncertainty is often related to calibration errors and determined based on manufacturer's specification in terms of maximum permissible error (MPE). MPE is a probabilistic error bound at the coverage probability (or degree of certainty) p=100%. In this situation, p is not a Bayesian subjective probability or degree of belief (Huang 2018c).

Moreover, GUM's method for calculating the CSU $u_c(y)$ is essentially based on the theory of errors and the theory of point estimation. The CSU $u_c(y)$ is a point estimator of the true CSU $u_{c,T}(y)$, the scale parameter of the distribution of the measurement error $e = y - \mathrm{E}(Y)$. However, GUM's WS-t approach for calculating the expanded uncertainty, Eq. (11) or Eq. (12), is based on the theory of confidence intervals. In statistics, the concept of errors is different from the concept of confidence intervals; the theory of errors is different from the theory of confidence intervals. Strictly speaking, these two theories are incommensurable. Therefore, the GUM is methodologically inconsistent in calculating the CSU and expanded uncertainty. This internal inconsistency should be solved in a revising GUM by fully restoring the concept of errors and removing the concept of confidence intervals. In fact, some statisticians and practitioners have questioned the use (or misuse) of confidence intervals in science and industry (e.g. Karlen 2002, Lewandowsky 2015, Morey et al. 2016, Huang 2018b). Interested readers are referred to Morey et al. (2016); they revealed three fallacies of confidence intervals and suggested abandoning confidence intervals in science.

5.2 The Conflict Between the Coverage Criterion and the Magnitude Criterion

The statement about the confidence level, e.g. Eq. (12), is a coverage criterion for a confidence interval procedure according to the theory of confidence intervals. This coverage criterion is often simply referred to as "coverage." On the other hand, according to the unbiased criterion in the theory of point estimation, the expectation of an estimator of a parameter must be equal to the true value of the parameter. This statement is a magnitude criterion, e.g. Eq. (23).

It is important to note that the coverage criterion and the magnitude criterion are incompatible, even incommensurable, because they come from different schools of thought in statistics: the theory of confidence intervals and the theory of point estimation; these two theories are incommensurable. If a statistical method satisfies the coverage criterion, it will not satisfy the magnitude criterion. For example, GUM's WS-*t* approach satisfies the coverage criterion, Eq. (12), but it does not satisfy the magnitude (unbiasedness) criterion, Eq. (13). For another example, the first alternative approach $U_{p,1}$ satisfies the magnitude criterion, Eq. (23), but it does not satisfy the following coverage criterion

$$\Pr\left\{\left[y - z_p \frac{u_c(y)}{c_{4,\nu_{\mathrm{eff}}}}, y + z_p \frac{u_c(y)}{c_{4,\nu_{\mathrm{eff}}}}\right] \ni \mathrm{E}(Y)\right\} \neq p. \tag{26}$$

Similarly, the second alternative approach $U_{p,2}$ satisfies the magnitude criterion, Eq. (23), but it does not satisfy the following coverage criterion

$$\Pr\left\{\left[y - z_p u_c'(y), y + z_p u_c'(y)\right] \ni \mathrm{E}(Y)\right\} \neq p. \tag{27}$$

Proponents of confidence intervals argue that the performance of any uncertainty calculation method should be judged by its "coverage," say 95% (e.g. Hall and Willink 2001, Willink 2010). However, "coverage" is meaningful only for a confidence interval *procedure*; it is meaningless for a realized interval because the true value would be either captured or missed by the realized interval (Huang 2018d). More importantly, the coverage criterion does not guarantee that an uncertainty calculation method will produce realistic estimates of uncertainty. For example, GUM's WS-*t* approach satisfies the coverage criterion, Eq. (12), but it leads to the Ballico paradox and exhibits some anomalous behavior in the numerical simulation examples of Hall and Willink (2001), Huang (2016), and Burr et al (2020). In the author's opinion, the Ballico paradox and the anomalous behavior are unacceptable, which invalidates GUM's WS-*t* approach and the associated coverage criterion. However, Hall and Willink (2001) argued, "Although it [the anomalous behavior] may cause the validity of the [GUM's WS-*t*] approach to be questioned, such behavior is acceptable if one adheres to the frequentist model, in which the coverage probability is the primary performance measure."

We argue that the performance of any uncertainty calculation method should be judged by the magnitude criterion, i.e. unbiasedness. It is important to note that what practitioners really care about is the estimated uncertainty (magnitude), which is the output of a procedure (or statistical method). Coverage probability is the property of a procedure; it is not the output of the procedure. In practice, there is no way to verify the "coverage" of a procedure from samples at hand. By contrast, the magnitude, i.e. the output of the procedure, can be judged from samples, as is the case with the Ballico paradox. Therefore, the magnitude criterion makes much more sense than the coverage criterion. In fact, both the unbiasedness and the nominal degree of certainty (i.e. nominal coverage probability) associated with either of these two alternative approaches will be satisfied at the population level, or asymptotically (Huang 2018b). Therefore, we should adopt the magnitude criterion and remove the coverage criterion in a revised GUM.

5.3 The t-Distribution is Misleading

The *t*-distribution plays an important role in the GUM uncertainty framework and in GUM-S1's Monte Carlo method. In the GUM, the expanded uncertainty, or the *t*-based confidence interval, requires the coverage factor $t_{p,\nu_{\mathrm{eff}}}$, i.e. *t*-value, which comes from the standard *t*-distribution. In the GUM-S1, the Monte Carlo method requires the scaled and shifted *t*-distribution assigned to Type A quantities. In addition, the Bayesian Type A SU is derived from the scaled and shifted *t*-distribution.

Although frequentists and Bayesians have a long-standing philosophical and methodological debate, they consider the t-distribution to be the "standard way" to deal with small samples in uncertainty analysis. Indeed, the Bayesian t-based creditable interval has the same look as the frequentist t-based confidence interval.

However, many studies have questioned the use of the t-distribution for uncertainty analysis (e.g. D'Agostini 1998, Jenkins 2007, Huang 2010, 2014, 2015, 2018a,b,d). Huang (2020) summarized the main problems of the t-based methods for uncertainty analysis, which are not repeated here. We want to emphasize that, (1) the t-distribution is a distorted z-distribution due to the t-transformation distortion (Huang 2018a), (2) the Central Limit Theorem leads to a scaled and shifted z-distribution, not a scaled and shifted t-distribution, and (3) the coincidence that the Bayesian t-based creditable interval has the same look as the frequentist t-based confidence interval actually reaffirms that both are a result of the distorted statistical inference (Huang 2018a). Moreover, it is worth mentioning that Matloff (2014a) deliberately excludes the t-distribution and t-interval in his statistics textbook. Matloff (2014b) said, "I advocate skipping the t-distribution, and going directly to inference based on the Central Limit Theorem."

If we stick to the theory of errors, the theory of point estimation, and the Central Limit Theorem, the t-distribution and t-based inference methods have no place in measurement uncertainty analysis or uncertainty-based measurement quality control. It is worth mentioning that, a recent ISO standard: ISO:24578:2021(E) does not use the GUM Type A expanded uncertainty $U_{p,\mathrm{GUM}}$, i.e. the t-based uncertainty $U_{p,t} = t_{p,n-1}\frac{s}{\sqrt{n}}$, in the measurement quality control of streamflow measurements; instead, it uses the modified Type A expanded uncertainty $z_p \frac{s}{c_{4,n-1}\sqrt{n}}$.

5.4 Practical Benefits of These Two Alternative Approaches

These two alternative approaches have two important practical benefits or advantages compared to GUM's WS-t approach. First, they guarantee that the estimates of uncertainty do not contradict themselves like the Ballico paradox. Second, they are guaranteed to provide realistic estimates of uncertainty even with very small DOFs or effective DOFs. Thus, a reduction in uncertainty can be achieved relative to GUM's WS-t approach, which is too conservative and may produces unrealistic estimates when the DOF or effective DOF is small.

For the first alternative approach, its reduction in uncertainty at p=95% (relative to GUM's WS-t approach) can be calculated as

$$\frac{U_{95,\mathrm{GUM}} - U_{95,1}}{U_{95,\mathrm{GUM}}} = 1 - \frac{z_{95}}{c_{4,\nu_{\mathrm{eff}}} t_{95,\nu_{\mathrm{eff}}}}. \tag{28}$$

Figure 1 shows the reduction in uncertainty when using the first alternative approach, Eq. (19), relative to GUM's WS-t approach, Eq. (11), as a function of the effective DOF.

It can be seen from Figure 1 that, the reduction is significant for the effective DOF≤10. Clearly, when approaching the effective DOF>50, the difference between the two approaches is negligible.

For the second alternative approach, its reduction in uncertainty (relative to GUM's WS-t approach) cannot be expressed analytically. However, since the second alternative approach is slightly more conservative than the first, its reduction should be slightly less than the first.

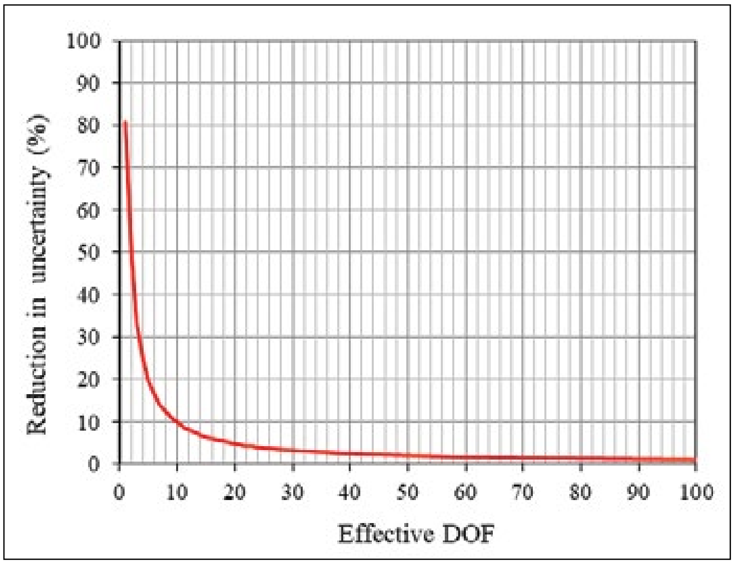

Figure 1. Reduction in uncertainty when using the first alternative approach, relative to GUM's WS-t approach, as a function of the effective DOF.

6. Conclusion and Recommendation

The GUM unconsciously mixes two different definitions of measurement uncertainty: (1) the scale parameter of the distribution of the measurement error or the measurand, and (2) the half-width of the t-based confidence interval. These two definitions are philosophically inconsistent. This inconsistency problem can be solved by defining measurement uncertainty as the probabilistic error bound based on the law of error.

GUM's WS-t method for calculating the expanded uncertainty has two serious limitations: (1) it is generally too conservative and may produces unrealistic estimates of uncertainty when the DOF or effective DOF is small, and (2) it may produce paradoxical results, such as the Ballico paradox, when one or more of the influence quantities have few DOF. These two limitations can be addressed by either of the two alternative approaches discussed. However, the second alternative approach is preferred because it does not require the effective DOF; consequently, the Welch-Satterthwaite formula is not required. This will greatly simplify uncertainty analysis. In addition, the second alternative approach is slightly conservative. A revised GUM should include one of the two alternatives, but not both.

The second part of the two-part series will examine four examples of the GUM in detail using these two alternative approaches. It will also describe the resolutions to the Ballico paradox.

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U.S. Calibration Occupation Demographics

Christopher L. Grachanen
Metrology Advocate

While researching to determine if calibration occupations had been included in the U.S. Department of Labor's (DOL) Occupational Outlook Handbook (OOC)[1], I came across a May 2021 DOL report with a wealth of information about calibration practitioners. Folks may remember there was a successful industry initiative to petition the U.S. DOL to formally recognized calibration occupations as denoted in its Standard Occupation Classification (SOC)[2] system, the first step in getting calibration occupations included in the OOC. The OOC is the government's premier source of career guidance featuring hundreds of occupations widely used by councilors and educators to inform students about different occupations and forecasted job growth. The following is a snippet from the OOH for Electrical and Electronic Engineering Technologist and Technicians showing a cornucopia of information for the occupation. It is anticipated OOH next revision will include calibration occupation.

1 https://www.bls.gov/ooh/
2 https://www.bls.gov/soc/

The U.S. DOL's Calibration Occupation report I stumble upon is entitled, "Occupational Employment and Wages, May 2021 17-3028 Calibration Technologists and Technicians" under the title, *Occupational Employment and Wage Statistics*. The preamble to this report is from the SOC's occupation description for Calibration Technologists and Technicians which reads,

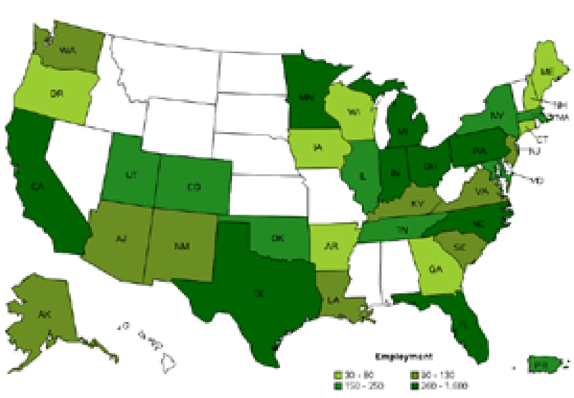
> Execute or adapt procedures and techniques for calibrating measurement devices, by applying knowledge of measurement science, mathematics, physics, chemistry, and electronics, sometimes under the direction of engineering staff. Determine measurement standard suitability for calibrating measurement devices. May perform preventive maintenance on equipment. May perform corrective actions to address identified calibration problems. Excludes "Medical Equipment Preparers" (31-9093) and "Timing Device Assemblers and Adjusters."

The first section of the report is an Industry profile sighting Industries with the highest published employment for Calibration Technologists and Technicians.

Industry	Employment	Percent of industry employment
Architectural, Engineering, and Related Services	2,460	0.16
Electronic and Precision Equipment Repair and Maintenance	860	0.84
Scientific Research and Development Services	420	0.05
Aerospace Product and Parts Manufacturing	380	0.08
Navigational, Measuring, Electromedical, and Control Instruments Manufacturing	280	0.07

This is followed by a geographic profile by states and areas with the highest published employment, location quotients, and wages for Calibration Technologists and Technicians.

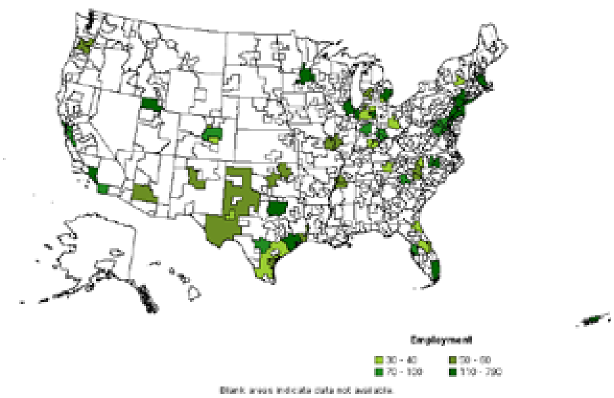
Employment of calibration technologists and technicians, by state, May 2021



State	Employment	Employment per thousand jobs	Location quotient
Texas	1,680	0.14	2.27
California	680	0.04	0.68
Indiana	550	0.18	3.06
Florida	450	0.05	0.86
Michigan	430	0.11	1.77

The report then does a deep dive by area.

Employment of calibration technologists and technicians, by area, May 2021



Metropolitan area	Employment
Houston-The Woodlands-Sugar Land, TX	790
Dallas-Fort Worth-Arlington, TX	280
Detroit-Warren-Dearborn, MI	260
Chicago-Naperville-Elgin, IL-IN-WI	220
Los Angeles-Long Beach-Anaheim, CA	220
Minneapolis-St. Paul-Bloomington, MN-WI	170
Boston-Cambridge-Nashua, MA-NH	150
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	150
New York-Newark-Jersey City, NY-NJ-PA	140
Raleigh, NC	120

I saw that the highest area for employment of Calibration Technologists and Technicians was the Houston-The Woodlands-Sugar Land, TX (my old stomping grounds), home to NASA's Johnson Space Center and Transcat's new state of the art calibration laboratory, just to name a few employers of Calibration Technologists and Technicians in the area.

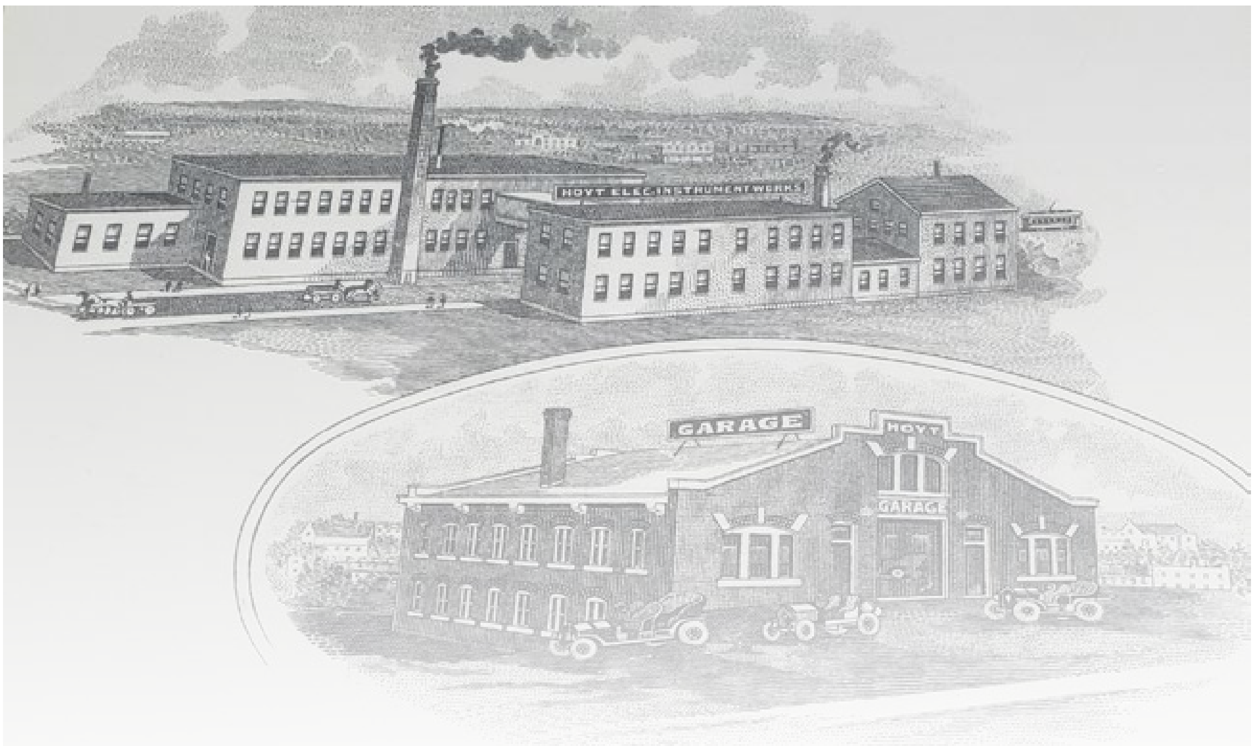
The last section of the report focuses on Calibration Technologists and Technicians wages. It was interesting to note that for the Denver-Aurora-Lakewood, CO area wages are approaching 6 digits.

The U.S. DOL's "Occupational Employment and Wages, May 2021 17-3028 Calibration Technologists and Technicians," report may be found at https://www.bls.gov/oes/current/oes173028.htm.

I am delighted to see the U.S. DOL reporting vital statistics for the calibration occupation and I am looking forward to OOH's next release.

Ghosts in the Landscape

Dan Wiswell
Cal-Tek Company, Inc.



Growing up in the Merrimack Valley of Massachusetts I have always been aware of the mills that are in my area. I knew at an early age the difference between an old mill and a really old mill. I used to look at the large water wheels on display outside of some of them that used to distribute mechanical power to the looms and spinning machines on the various floors inside. Most of the mills were for spinning yarn and thread or for making cloth. Some were used for more heavy industrial production of things like boots, axles, bearings and machine parts. Alongside of the mills you can still see the homes and housing for people that worked in these places. But I always wondered. How did things go from a Victorian-esque, mechanical world to the electrified one that we see before us today? The answer is that it all started with the flip of a switch. Electricity broke the bonds between industrial manufacturing and waterpower. When that happened, industrial manufacturing no longer needed to be located on or near river systems. The effect of this was the creation of what we now call "suburbia."

When electric power first became available to society in the late nineteenth century it set off a kind of pre-Cambrian-like explosion of innovation. It seems to have happened with such speed that it is hard to comprehend today. The imaginations of inventors around the world were literally and suddenly electrified. What burst forth became an unending myriad of electrical creation that could barely satisfy the appetites of an increasingly prosperous and educated consumer class. Appliances and electrified products literally leaped into existence. This fueled a decades-long economic boom. Nations in various parts of the globe began to embrace the advantages that modern technology could bring, and in many instances, used technological superiority successfully in conflicts with their enemies. It's easy to see the larger picture of how the world changed when electrical energy became available. It actually all started on the local level, everywhere, and nearly all at once. By taking a step back in time we can see the foundations of our own electrical instrument industry in some surprising places. Surely the suburbs of Boston, Philadelphia, Baltimore and Chicago can be likened to the petri dishes of our national industry, but instrument manufacturing occurred in more bucolic settings as well. As it is with many things, sometimes change comes when the right individual arrives at the perfect moment. A good example of this happened in the Merrimack Valley of central New Hampshire in the late 1880s.

Whitney Electrical Instrument Company photo taken in 1893. Starting in the back row, standing left to right: Fred Goldsmith, Bill Chamberlain, Nelson Gould, Dr. Adrian Hoyt, Horace Bean, Charles Prescott, Ed Cody, Charles Shedrick, Robert Weir, William "Billy" Corbett, Herbert Young, the "Bartlett Brothers," Billy Graves, Lewis Prescott, Albert "Nuppy" Huff, Fred Dodge, and Adelbert Whitney. Image courtesy of Jeffrey Hoyt.

Dr. Adrian Hazen Hoyt

Dr. Adrian Hazen Hoyt was that kind of guy. Born in 1862 in Magog, Quebec he attended grammar school there and went on to attend the business college of Davis and Dewie in Montreal. He graduated from Dartmouth College in 1887 with a degree in medicine. However, it wasn't an interest in medicine that attracted him to Dartmouth. In those days courses in electricity were part of the medical curriculum. Shortly after college he began working for Standard Electric Company in St. Johnsbury, Vermont. These were heady times in the newly developing instrumentation industry. Edward Weston had just patented his version of the d'Arsonval meter movement in 1888. Science journals and magazines of the day were full of articles that discussed the latest developments in electrical research. After a brief tenure at Standard Electric Company, Adrian Hoyt moved to Manchester, New Hampshire and began his work in electrical research. He is credited with patenting over twenty-five electrical measuring instruments and scientific apparatus. One of his first patents was for an alternating-current ammeter which caught the interest of investors.

In 1891, the Penacook Electric Light Company began operations just a few years after the Boston Edison Company was established about eighty miles to the south. The business grew rapidly and in 1900 it purchased a large tract of land with waterpower rights on the Merrimack River in Concord, New Hampshire. The purchase included several mills and buildings, one of which was

A voltmeter manufactured by Whitney Electrical Instrument Company.

known as the Electric Mill that had been built ten years before in 1890. The company leased the Electric Mill to the newly formed Whitney Electrical Instrument Company that had been organized by investors from Manchester, Lowell and Boston. The Whitney Electric Instrument Company manufactured electrical measuring instruments under patents granted to Dr. Adrian Hazen Hoyt, whom they retained as an "electrician."

The business was an immediate success. The operation grew so rapidly that in 1892 a considerably larger factory was constructed in West Penacook, New Hampshire. Dr. Hoyt became the general manager just a few years later in 1894 and became a resident of the town as well. Whitney Electrical Instrument Company was very well regarded for the high quality of its measuring instruments. They were very popular in laboratories and universities all over North America.

As the company grew, Dr. Hoyt was also able to pursue his other interests, particularly in automobiles. He began manufacturing automobiles and electrical instruments at his own company called the American Manufacturing Company, also in Penacook. He has been credited as being the first person in New Hampshire to have owned a car, obtain a driver's license, and was one of the founders of the New Hampshire Automobile Club. He was a long-time friend of Henry Ford. He owned the first car dealership in New Hampshire. The building still exists to this day.

In 1904 Dr. Hoyt founded the Hoyt Electrical Instrument Works. The company manufactured dashboard panel meters for vehicles, and gentlemen's pocket meters that men fashionably wore in vest pockets that had been previously used for pocket watches.

At the cusp of the nineteenth and twentieth centuries, the electrical instrument manufacturing industry began moving in many new directions and it diversified as its applications grew. Many larger companies purchased their competitors to seek market share and to expand their product lines. In 1909 The Whitney Electrical Instrument Company was purchased by the Roller-Smith Company and moved to Bethlehem, Pennsylvania. When this occurred Dr. Hoyt took ownership of the factory that The Whitney Electrical Instrument Company vacated.

Dr. Hoyt owned the first car dealership in New Hampshire, the original building of which still stands today.

A collection of Hoyt Electrical Instrument pocket meters, to be worn in vest pockets previously used for pocket watches.

During the First World War, Adrian Hoyt developed a magnetic explosive device that would attach itself to submerged U-boats and detonate. This caused Germany to nearly halt its submarine activity. The Hoyt Electrical Instrument Company also produced a broad variety of panel instruments for the general electronics manufacturing industry. It has been a fixture in the town of Penacook for nearly one hundred and twenty years and still produces high quality panel instrumentation.

Today, it is perfectly situated in the center of its universe in the Wallace Hoyt building at 23 Meter Street.

Another founding father of Penacook's test and measurement industry was Walter E. Beede. Born in 1879, Walter Beede founded the Beede Electrical Instrument Company, Inc. in Penacook, NH in 1917. Walter Beede sold the company in 1927 but reassumed control after the stock market crash in 1929. In its early years the company made small, hand-held portable meters used to test batteries in portable equipment such as radios, flashlights and other consumer goods. It also made pocket meters similar to the Hoyt meters that were designed for the same purpose. From its inception, Beede Electrical Instrument Company was also a supplier

Hoyt Electrical Instrument Company and Beede Electrical Instrument Company made dashboard instruments for the early automotive, avionics and marine industries.

Q.C. testing of a product run of Hoyt panel meters.

of dashboard instruments that included voltmeters, speedometers and tachometers that were used in the automotive, avionics and marine industries. There was quite a bit of overlap between the two companies' product lines.

In the early twentieth century, Beede meters were sold domestically through a variety instrument distributors and dealers that began to appear around this time. Like other manufacturers, Beede Electrical Instrument Company offered a broad range of what were called "mod" meters through these vendors. Mod meters were designed to be easily modified by the metrologists that worked in this instrument after-market by providing value-added instrumentation solutions as well as instrument repair and calibration services. These meters were modified for unique customer applications that often included the printing of a customer's logo on the meter's scale or dial. This relationship allowed panel instrument manufacturers to concentrate on the production of stock instruments and allowed the after-market distributors to focus on the specific and often unique needs of their customers. Hundreds of people all over the United States and Canada were employed in this second-tier industry which contributed significantly to size of the metrological workforce.

A signature piece of instrumentation that will always be associated with Beede Instruments is the Beede Meter Relay. This device was sold as a mod meter and looked like a panel meter with a beer can attached to the back of its meter housing. Inside this elongated case were relays that could be programmed to trip when the meter's pointer crossed adjustable setpoints on its front panel. This device was one of the first products to combine measurement and control technology in one convenient package.

Mr. Beede's nephew, Paul Pelletier, began working at the company in 1934 and became its president when Walter Beede passed away in 1948. Paul's son, Walter Pelletier, assumed control of the business in 1988, and by 2001 the company employed approximately seven hundred people at its locations in Penacook,

Current day building of Hoyt Electrical Instrument Works, Inc. in Penacook, NH.

Belmont, and Northfield, New Hampshire. The Thomas G. Faria Corporation of Montville, Connecticut purchased the company upon the retirement of Walter Pelletier in 2013. The company's 60,000 square foot building, built in 1957, can still be seen at its Village Street location in Penacook, New Hampshire.

There are many test and measurement companies in New Hampshire that can trace their beginnings to these early days. Marion Electrical Instrument Company for example, produced hermetically sealed panel meters and was bought by the Jewell Instrument Company, presently located at 850 Perimeter Road in Manchester, New Hampshire. In later years, the Jewell Instrument Company also purchased Modutec, a panel meter manufacturing company that was also located in Manchester, New Hampshire.

These companies were just a few of the many test and measurement companies that appeared on the scene in northern New England at the turn of the last century. Some are still around today. They created an environment that nurtured the development of a talented, technical workforce. Thousands of people worked in these companies, and many went on to start companies of their own. Back then, generations of families made their livelihoods by working in jobs that are still employing people to this day. After a full day of work, they went home, fed their families, went on vacations, and celebrated life. And ultimately, they became us.

Beede Electrical Instrument Company supplied dashboard instruments (left) and the Beede Meter Relay (right).

Once again, I wonder. Did people like Adrian Hoyt and Walter Beede have an inkling as to how their dreams would play out over time? As I have written previously, I believe that we all owe these gentlemen a debt of gratitude, for they are both directly responsible for making the American Dream a reality for many of us.

During the research phase of writing this article the thing that stood out the most for me is how similar the times were back at the beginning of the last century when compared to the world we live in today. I would like to thank Jeffery Hoyt and the employees at Hoyt Electrical Instrument Works, Inc. for taking the time to meet with me and for allowing me to take a deep look into the way things were in those days of old.

Dan Wiswell (dcwiswell@repaircalibration.net) is a self-described Philosopher of Metrology. He is President/CEO of Cal-Tek Company, Inc. and Amblyonix Industrial Instrument Company.

The remaining building of Beede Electrical Instrument Co. (now Faria Beede) in Penacook, NH.

Tektronix 2 Series MSO

BEAVERTON, Ore., June 7, 2022 -- Tektronix, Inc. today unveiled the 2 Series Mixed Signal Oscilloscope (MSO), reimagining what is possible in test and measurement. The new 2 Series MSO can go seamlessly from the bench to the field and back, enabling workflows previously unimagined on a scope. It is the first portable oscilloscope to offer benchtop performance and the award-winning Tektronix user interface. Weighing less than four pounds and 1.5 inches thin, the 2 Series MSO can fit into a small backpack, delivering unmatched performance and portability.

With the 2 Series MSO, engineers can achieve things not possible on previous oscilloscopes. The easy to use 10.1" touchscreen display makes working on the go easier and faster. The built-in capabilities of the optional Arbitrary Function Generator (AFG), pattern generator, voltmeter and frequency counter mean users have versatility built into one instrument – increasing what they can do while reducing the number of instruments to carry or purchase.

Intuitive and Easy-to-Use

The 2 Series MSO joins the strong line-up of other Tektronix oscilloscopes with the award-winning user experience also found on the 3, 4, 5, and 6 Series oscilloscopes. This makes it easier for engineers to work effortlessly across these Tektronix products, while the easy-to-use experience means engineers can do more in less time. With the feel of a mobile device, debugging is faster and more intuitive. The colored LED ring lights around the knobs indicate active sources or parameters to adjust or to indicate status.

Portability and Performance

With a variety of integrated options, the 2 Series MSO is equipped for advanced debugging in a single instrument, including:

- Bandwidths from 70 MHz-500 MHz
- Two or four analog channel inputs
- 16 digital channels (available with future software release)
- 2.5 GS/s sample rate
- Optional 50 MHz Arbitrary Function Generator
- Built-in pattern generator, voltmeter, and frequency counter (available with future software release)
- Optional battery provides up to eight hours of power

Unlocks Remote Work and Team Collaboration

Natively integrated software tools allow engineers to collaborate, troubleshoot, and debug designs across time zones. The 2 Series MSO includes TekDrive, a test and measurement data workspace in the cloud where engineers can upload, store, organize, and share any file from a connected device. Users can also perform analysis on a waveform and save it back to the cloud for immediate viewing and feedback from peers.

The 2 Series Mixed Signal Oscilloscope is available globally. To access pricing and other information, visit: https://www.tek.com/2-series-mso

Meatest 9010+ Multifunction Calibrator

Brno, August 1, 2022 – One year after the 9010 Multifunction Calibrator debut at NCSLI Workshop & Symposium, Meatest launches its long awaited high performance version 9010+. Voltage and current specifications have been improved, aiming at calibrations of popular 6½ digit multimeters. However, the list of new features goes far beyond 10 ppm VDC accuracy.

Two other major improvements are 30A current output and 1.1GHz scope option. 30A range is available in all 9010+ current functions including power, harmonics and energy as well as current coil output mode. New scope option (exclusive to 9010+) boosts sinewave frequency range to 1.1 GHz and square wave frequency to an impressive 400 MHz – a unique feature in the multifunction calibrator market. Original 9010 options are compatible with the 9010+, covering the same extra workload like transducers, insulation testers or power analyzers.

Meatest claims their calibrators are "Made to Last" and supports the statement by offering up to 5-year warranty plans for the 9010+. Software drivers and calibration procedures are available for popular metrology software solutions including Caliber, Metrology.NET and MET/CAL, making it easier to include 9010+ into existing laboratory work environments. Furthermore, comprehensive remote control manual and variety of PC interfaces allow 9010+ users to set up customized, fully automated test systems for online checks on metering equipment production lines. Learn more about the 9010+, upcoming shows and local dealerships at www.meatest.com.

New MI Model 6311A

Prescott, Ontario, August 22, 2022 – Measurements International Ltd. (MI), the industry leader in resistance and current measurement, has launched the Model 6311A Precision Current Divider as a direct replacement for current shunts, calibration of DC current and as a current detector device.

The MI 6311A Precision Current Divider builds upon years of experience in shunt and current calibrations. With two available ranges, 10A and 300A, the 6311A offers current division by 100:1 and 1000:1 respectively. The output can then be measured directly with a laboratory DMM or measured with a reference resistor to calculate the current input. The 6311A employs an enhanced version of the Direct Current Current Transformer (DCCT) at the heart of many MI products and offers users a much more stable and predictable method for measuring currents compared to the traditional and often outdated DC Current Shunt. Additionally, the 6311A is capable of dividing AC Currents up to 1kHz as well.

Key benefits include:

- Zero Temperature Coefficient – The current output and internal electronics have no noticeable temperature dependency.
- Zero stabilization period – There is no more waiting for a Current shunt to stabilize at current before making a measurement and therefore measurement time goes down improving productivity.
- Zero Power Coefficient – The unique design does not suffer any linearity issues due to currents applied above 1% of range.
- AC and DC Current Operation

For more information about the MI 6311A, please visit www.mintl.com

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Additel's New 762 Automated Hydraulic Pressure Calibrator

Brea, Calif., May 17, 2022 – Additel Corporation introduces their new ADT762 Automated Hydraulic Pressure Calibrator. As Additel continues to strive to meet the needs of their customers through innovation and automation, the new ADT762 expands their automatic pressure calibrator series with portable and automated pressure generation up to 10,000 psi (700 bar). Customers can choose between accuracies of 0.01%FS and 0.02%FS at the time of ordering. The all-new calibrators include an integrated fluid management system, full HART field communicator, touchscreen, onboard datalogging, as well as Wi-Fi, Bluetooth, USB & Ethernet communications.

The ADT762 is offered in two distinct models based on accuracy. Both 0.01%FS and 0.02%FS are available, with each unit including the unique ability to automatically select between different internal calibrations depending on the current control pressure of the ADT762 (also known as dual-range calibration). Additel's world class calibration laboratory in Brea, CA provides calibrations unique to each ADT762 for ranges of 0-3,000 PSI (200 Bar) and 0-10,000 PSI (700 Bar). As the calibrator is pressurized, it will automatically select the range with the lowest uncertainty for any specific control pressure.

With a patented built-in pump and fluid management system, the ADT762 hydraulic pressure calibrator provides users with convenient and portable automated pressure generation and control. The ADT762 also features HART and PROFIBUS communication capabilities for use with UUT's. With 8GB of internal data storage, users can store up to 1,000,000 time and date stamped readings.

Product Availability

The Additel 762 Automated Hydraulic Pressure Calibrator is available now. For more information visit: https://additel.com/products/Portable-Automated-Pressure-Calibrator/

For information on Additel products and applications, or to find the location of your nearest distributor, contact Additel corporation, 2900 Saturn Street, #B, Brea, CA 92821, call 1-714-998-6899, Fax 714-998-6999, email sales@additel.com or visit the Additel website at www.additel.com

Ultra-Fast Development of Automated Calibration Procedures

Michael L. Schwartz
Cal Lab Solutions, Inc.

My last Automation Corner was about Model Driven Engineering, and this one is an example of how Model Driven Engineering makes software development easier and faster.

Over the past 25 years of writing automated calibration software, my goal has been to develop better programming methods that facilitate our company's ability to create a high-quality product in less time. This is the core of any business to create efficiencies in their day-to-day operations; the more efficient, the better the profit.

25 years ago, I had a breakthrough moment while working for a company called Intercal. All they did was Fluke MET/CAL® procedures. I got tired of the "Cut & Paste" methodology used by most MET/CAL programmers. This was a huge no-no one of my college professors explained to me. Instead, he said, "Make it a function!"

MET/CAL is not good with functions and reusable code. So, I created a little application where I entered the test point and test limits for a Unit Under Test (UUT), then pressed a button and it would write about 50% of my MET/CAL procedure. Over the years, I have rewritten and improved that application. Today it can auto-write about 80% of a MET/CAL procedure.

The biggest difference between my first MET/CAL code generation applications and the one we are using today is the integration of a standardized Metrology Taxonomy. With each version of the software, we found a better, more efficient way of creating working software ultra-fast.

We constantly track our metrics, in this case, the hours it took to create a MET/CAL procedure for a Siglent SDM3045X Digital Multimeter. Our goal is to create the fully tested automation for MET/CAL in under 10 times the manual calibration time. This procedure should take less than 10 hours to develop.

We started by creating a Metrology.NET® Test Package. This took 2.5 hours of our total development budget. We use Metrology.NET to enter the Test Points and Test Limits. But unlike my V1 tool, the Metrology.NET test package also stores the SDM3045X settings and details about the test requirements.

Next, we used the current CodeGen tool to download the test package and create the MET/CAL procedures. This took an additional hour out of our budget.

Now we have 80% of the MET/CAL procedure ready to test. The CodeGen tool will create the main procedure, test points subprocedure, and test routines subprocedure. It has all the code required to calibrate the UUT. What is missing is the code that links to the standards.

This customer wants to calibrate the SDM3045x with a Fluke 5522A, so now we need to modify the config subprocedure, adding the specific connection messages and calls to the Fluke 5522 Drivers. This takes an hour.

To make a Fluke 5730A, or Meatest 9010, or Transmille 4010 version of this procedure, it would only be about 30 minutes of work. This is one of the key advantages of Model Driven Software Engineering. The code required for alterations like this is minimal.

Our Goal to write the automated procedure was 10 hours, but in under 4.5 hours, we are 100% done with version one of this procedure and ready to test. Testing the procedure only takes an additional 2 hours.

This is ultra-Fast development! The development of a simple DMM procedure used to take more than 10 hours. Now, from scratch, a fully functional calibration procedure with data in hand, takes less than 6.5 hours of development time! That is ultra-fast! In addition, we created a Metrology.NET Test Package for the Siglent SDM3045X in the process, free to all Metrology.NET customers.

This is the power of Model Driven Software Engineering! Low-Code to No-Code also means faster development, in this case, Ultra-Fast procedure creation.

If you want a Free Example of a Code Generated MET/CAL Procedure, check this out:

https://store.callabsolutions.com/index.php?route=product/product&product_id=50.

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