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THE INTERNATIONAL JOURNAL OF METROLOGY

METROLOGY 101: PISTON PROVER DESIGN

A New Primary Standard for the Realization of Pressure from 10 to 500 kPa

Metrology: Standardize and Automate!

NEW FEATURE: Automation Corner

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FEATURES

DEPARTMENTS

ON THE COVER: Emil Isgenderli works with a spectrum analyzer calibration setup at Spark Kalibrasyon Hizmetleri Ltd.Sti, an Agilent Authorized Service Provider in Turkey.

CALENDAR

CONFERENCES & MEETINGS 2013

Jun 5-7 GAS2013. Rotterdam, The Netherlands. The 7th International Gas Analysis Symposium & Exhibition (GAS2013) topics in the parallel sessions are Natural gas & LNG; Metrology and standardization; Analytical chemistry; Health and environmental measurements. http://www.gas2013.org/

Jun 7 ARFTG Microwave Measurement Conference. Seattle, WA. The 81st Microwave Measurement Conference is held in conjunction with the 2013 International Microwave Symposium. http://www.arftg.org/.

Jul 14-18 NCSL International. Nashville, TN. The theme for the 2013 NCSLI Workshop & Symposium is "Metrology in a Fast Paced Society." http://ncsli.org.

Jul 18-19 IMEKO/TC-4 Symposium. Barcelona, Spain. The Universitat Politècnica de Catalunya (UPC, Spain) and the International Measurement Confederation – IMEKO, are organizing the 19th IMEKO TC-4 Symposium on Measurements of Electrical Quantities. http://www.imeko2013.es/.

Sep 16-19 AUTOTESTCON. Schaumburg, IL. Military/aerospace automatic test industry and government/military acquirers and users share new technologies, discuss innovative applications, and exhibit products and services. http://autotestcon.com/.

Sep 24-26 The 16th International Flow Measurement Conference (FLOMEKO). Paris, France. Flomeko 2013 will provide the perfect opportunity for practitioners of metrology from a wide variety of industries to exchange ideas with researchers, national laboratories and academics. http://www.flomeko2013.fr/.

Sep 25-27 10th International Congress on Electrical Metrology (X SEMETRO). Buenos Aires, Argentina. Organized by the Instituto Nacional de Tecnología Industrial (INTI) of Argentina and the Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO) of Brazil. http://www.inti.gob.ar/xsemetro/.

Oct 7-10 16th International Congress of Metrology. Paris, France. This 3 day conference offers the opportunity to understand the latest technical developments in measurement, explore industrial challenges and develop solutions that will enhance innovation and performance through a varied conference program. http://www.metrologie2013.com.

Oct 14-18 TEMPMEKO 2013 Symposium. Madeira, Portugal. The 12th Symposium on Temperature & Thermal Measurements in Industry and Science. http://www.tempmeko2013.pt.

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EDITOR'S DESK

Weather vs. Metrology Speak

My first draft of this issue's Editor's Desk got r-e-j-e-c-t-e-d for a mildly flippant tone. So I will begin again. Usually, I begin with references to the weather and digress from there. This is a tactic I use with just about everything, particularly in instances such as this where I do not "speak" metrology… it's just not part of my native vocabulary. Several fellow, small business owners have commented on my previous essays—to my mortification—by which I am truly flattered since I rarely *ever* read the Editor's Desk of less substantial publications that capture my interest.

Now, I am at a huge loss for words, just as we go to press. The Editor's Desk is blank—though in reality it's a total disaster—so let's begin with the weather… California was gorgeous for the Measurement Science Conference in Anaheim this past March! The pineapple guava and jasmine were in bloom. Minnie Mouse and Cinderella were captivating, *as usual* (this California girl will always have a soft spot for Disneyland), but the coffee is better in Pasadena. And hopefully, the Sequestration will have resolved itself by next year, as its effect on MSC was deeply felt. Politics prevented some from attending, even if they wanted to on their own dime/time, though I did enjoy talking with fellow attendees/exhibitors who did make it MSC!

So, what do we have in this issue? We have flow, pressure, automation, and then some more automation. Edward Morrell of Mesa Labs offers some background and introduction into high-speed piston prover design in gas flow. Michael Bair and Tim Francis of Fluke Calibration cover fluid pressure—"A New Primary Standard for the Realization of Pressure from 10 to 500 kPa"—introducing their piston gauge design used as a primary standard to realize pressure in gauge and absolute modes from 10 to 500 kPa. Mark Kuster steers us in another direction with "Metrology: Standardize and Automate!"

In that vein, our publisher begins a new feature called "Automation Corner," where he'll be sounding off about all sorts of things related to the automation of metrology… starting with IEEE communication standards, when automation was still just a twinkle in an engineer's eye.

Now, if you are still reading this, my essay has not been rejected, we have gone to print, and all is well. I hope you have a fantastic spring, or what remains of it!

~ Sita Schwartz
Editor

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SEMINARS: Online & Independent Study

ASQ CCT (Certified Calibration Technician) Exam Preparation Program. Learning Measure. http://www.learningmeasure.com/.

AC-DC Metrology– Self-Paced Online Training. Fluke Training. http://us.flukecal.com/training/courses.

Basic Measurement Concepts Program. Learning Measure. http://www.learningmeasure.com/.

Basic Measuring Tools – Self Directed Learning. The QC Group, http://www.qcgroup.com/sdl/.

Basic RF and Microwave Program. Learning Measure. http://www.learningmeasure.com/.

Certified Calibration Technician – Self-study Course. J&G Technology. http://www.jg-technology.com/selfstudy.html.

Certified Quality Technician Preparation (CQT) – Online Training. J&G Technology. http://www.jg-technology.com

Introduction to Measurement and Calibration – Online Training. The QC Group, http://www.qcgroup.com/online/.

Intro to Measurement and Calibration – Self-Paced Online Training. Fluke Training. http://us.flukecal.com/training/courses.

ISO/IEC 17025 Accreditation Courses. WorkPlace Training, (612) 308-2202, info@wptraining.com, http://www.wptraining.com/.

Measurement and Calibration Overview – Online Training. J&G Technology. http://www.jg-technology.com/mco.html.

Measurement Uncertainty – Self-Paced Online Training. Fluke Training. http://us.flukecal.com/training/courses.

Measurement Uncertainty Analysis – Online Training. The QC Group, http://www.qcgroup.com/online/.

Metrology for Cal Lab Personnel– Self-Paced Online Training. Fluke Training. http://us.flukecal.com/training/courses.

Metrology Concepts. QUAMETEC Institute of Measurement Technology. http://www.QIMTonline.com.

Precision Dimensional Measurement – Online Training. The QC Group, http://www.qcgroup.com/online/.

Precision Measurement Series Level 1 & 2. WorkPlace Training, http://www.wptraining.com/.

Precision Electrical Measurement – Self-Paced Online Training. Fluke Training. http://us.flukecal.com/training/courses.

Vibration and Shock Testing. Equipment Reliability Institute, http://www.equipment-reliability.com/distance_learning.html.

Electric Voltage & Current

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Optional Heads, fs Current	600A*	2,000A*	2,000A	5,000A	10,000A	16,000A	24,000A
Lowest fs Current	40A	125A	—	—	—	—	—
fs Current Range Increment	20A	125A	—	—	—	—	—

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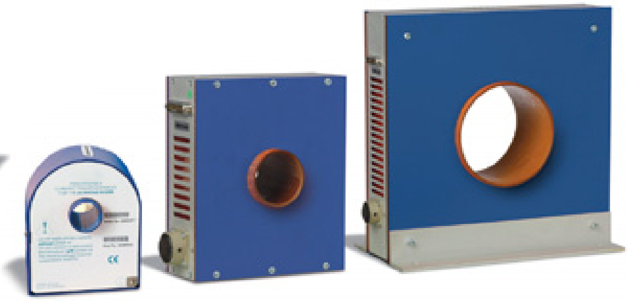

LEM ITZ Ultrastab

* The 600A and 2,000A fs Heads are programmable by a pre-wired plug.

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SEMINARS: Dimensional

Jun 3-4 Hands-On Gage Calibration and Repair Workshop. Las Vegas, NV. http://www.iicttraining.com.

Jun 6-7 Hands-On Gage Calibration and Repair Workshop. Yorba Linda, CA. http://www.iicttraining.com.

Jun 10-11 Hands-On Gage Calibration and Repair Workshop. Phoenix, AZ. http://www.iicttraining.com.

Jun 17-20 Dimensional & Thermodynamic Calibration Procedures. Las Vegas, CA. http://www.ttiedu.com/combos.html.

Jun 18 Dimensional Metrology: Applications and Techniques. Mason, OH. http://www.mitutoyo.com/support/mitutoyo-institute-of-metrology/.

Jun 18-20 Gage Calibration and Minor Repair Training. Cincinnati, OH. Cincinnati Precision Instruments,Inc. http://www.cpi1stop.com/.

Jun 20 Gage Calibration Systems and Methods. Mason, OH. http://www.mitutoyo.com/support/mitutoyo-institute-of-metrology/.

Jul 11-12 Hands-On Gage Calibration and Repair Workshop. Myrtle Beach, SC. http://www.iicttraining.com.

Jul 15-16 Hands-On Gage Calibration and Repair Workshop. Atlanta, GA. http://www.iicttraining.com.

Jul 18-19 Hands-On Gage Calibration and Repair Workshop. Nashville, TN. http://www.iicttraining.com.

Jul 23 Dimensional Metrology: Application and Techniques. Westford, MA. Mason, OH. http://www.mitutoyo.com/support/mitutoyo-institute-of-metrology/.

Jul 25 Gage Calibration Systems and Methods. Westford, MA. Mason, OH. http://www.mitutoyo.com/support/mitutoyo-institute-of-metrology/.

Aug 8-9 Hands-On Gage Calibration and Repair Workshop. Hartford, CT. http://www.iicttraining.com.

Aug 12-13 Hands-On Gage Calibration and Repair Workshop. Newark, NJ. http://www.iicttraining.com.

CALENDAR

SEMINARS: Electrical

Jun 3-6 MET-101 Basic Hands-on Metrology. Everett, WA. Fluke Calibration. http://us.flukecal.com/training/courses/MET-101.

Jun 13-14 Essentials of Electrical Metrology. Chicago, IL. WorkPlace Training. http://www.wptraining.com.

Jun 27-28 Essentials of Electrical Metrology. Minneapolis, MN. WorkPlace Training. http://www.wptraining.com.

Aug 5-8 MET-301 Advanced Hands-on Metrology. Seattle, WA. Fluke Calibration. http://us.flukecal.com/training/courses/MET-301.

Sep 16-19 MET-101 Basic Hands-on Metrology. Everett, WA. Fluke Calibration. http://us.flukecal.com/training/courses/MET-101.

Nov 11-14 MET-101 Basic Hands-on Metrology. Everett, WA. Fluke Calibration. http://us.flukecal.com/training/courses/MET-101.

Nov 18-21 MET-301 Advanced Hands-on Metrology. Seattle, WA. Fluke Calibration. http://us.flukecal.com/training/courses/MET-301.

SEMINARS: Flow & Pressure

Jun 4-5 Wet Gas Measurement Training Course. Lima, Peru. Colorado Engineering Experiment Station, Inc. http://www.ceesi.com.

Jun 6-7 Uncertainty Measurement of Natural Gas and Liquids Training Course. Lima, Peru. Colorado Engineering Experiment Station, Inc. http://www.ceesi.com.

Jul 15 Fundamentals of Ultrasonic Flowmeters Training Course. Denver, CO. Colorado Engineering Experiment Station, Inc. http://www.ceesi.com.

Jul 16-18 Ultrasonic Meter User's Workshop. Denver, CO. Colorado Engineering Experiment Station, Inc. http://www.ceesi.com.

Sep 10-12 Fundamentals of Flow Measurement Training Course. Loveland, CO. Colorado Engineering Experiment Station, Inc. http://www.ceesi.com.

Sep 16-29 Comprehensive Flow Measurement Training Course. Loveland, CO. Colorado Engineering Experiment Station, Inc. http://www.ceesi.com.

CALENDAR

Sep 23-27 Principles of Pressure Calibration. Phoenix, AZ. Fluke Calibration. http://us.flukecal.com/Principles-of-Pressure.

Dec 9-13 Principles of Pressure Calibration. Phoenix, AZ. Fluke Calibration. http://us.flukecal.com/Principles-of-Pressure.

SEMINARS: General

May 20-23 CLM-303 Effective Cal Lab Management. Everett, WA. http://us.flukecal.com/lab_management_training.

Jun 10-12 Cal Lab Manager Training; Beyond 17025. Chicago, IL. WorkPlace Training. http://www.wptraining.com.

Jun 24-26 Cal Lab Manager Training; Beyond 17025. Minneapolis, MN. WorkPlace Training. http://www.wptraining.com.

Sep 4-6 Instrumentation for Test and Measurement. Las Vegas, NV. Technology Training, Inc. http://www.ttiedu.com.

Oct 14-15 Cal Lab Benchmark Challenge Boot Camp. Boca Raton, FL. WorkPlace Training. http://www.wptraining.com.

Nov 4-7 CLM-303 Effective Cal Lab Management. Everett, WA. http://us.flukecal.com/lab_management_training.

SEMINARS: Industry Standards

Jul 23-24 Risk Assessments for Cleanrooms and Controlled Environments. Arlington Heights, IL. Institute of Environmental Sciences and Technology (IEST). http://www.iest.org.

SEMINARS: Measurement Uncertainty

Jun 18-19 Measurement Uncertainty. Dallas/Ft. Worth, TX. WorkPlace Training http://www.wptraining.com.

Jun 24-27 Measurement Uncertainty. Las Vegas, NV. Technology Training, Inc. http://www.ttiedu.com/schedule.html.

Jul 16-17 Estimating Measurement Uncertainty. Westford, MA. http://www.mitutoyo.com/support/mitutoyo-institute-of-metrology/.

Aug 27-28 Introduction to Measurement Uncertainty. Baltimore, MD. WorkPlace Training. http://www.wptraining.com.

Sep 23-25 Measurement Uncertainty Training Course. Loveland, CO. Colorado Engineering Experiment Station, Inc. http://www.ceesi.com.

CALENDAR

Oct 17-18 Introduction to Measurement Uncertainty. Boca Raton, FL. WorkPlace Training. http://www.wptraining.com.

Oct 22-24 MET-302 Introduction to Measurement Uncertainty. Everett, WA. Fluke Calibration. http://us.flukecal.com/training/courses/MET-302.

SEMINARS: Temperature

Jun 11-13 Principles of Temperature Metrology. American Fork, UT. Fluke Calibration. http://us.flukecal.com/training/courses/Principles-Temperature-Metrology.

Sep 17-19 Advanced Topics in Temperature Metrology. American Fork, UT. Fluke Calibration. http://us.flukecal.com/training/courses/Principles-Temperature-Metrology.

Oct 8-10 Principles of Temperature Metrology. American Fork, UT. Fluke Calibration. http://us.flukecal.com/training/courses/Principles-Temperature-Metrology.

SEMINARS: Vibration

Jun 17-19 Vibration and Shock Test Fixture Design. Sunnyvale, CA. Equipment Reliability Institute. http://www.equipment-reliability.com.

Jul 16-18 Simultaneous Multi-Axis Vibration Testing. Burlington, WA. Equipment Reliability Institute. http://www.equipment-reliability.com.

Aug 5-8 Fundamentals of Vibration for Test and Design Applications. Oxnard, CA. Technology Training, Inc. http://www.ttiedu.com.

Aug 20-22 Fundamentals of Random Vibration and Shock Testing, HALT, ESS, HASS (...). Santa Barbara, CA. http://www.equipment-reliability.com.

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for upcoming and future events!

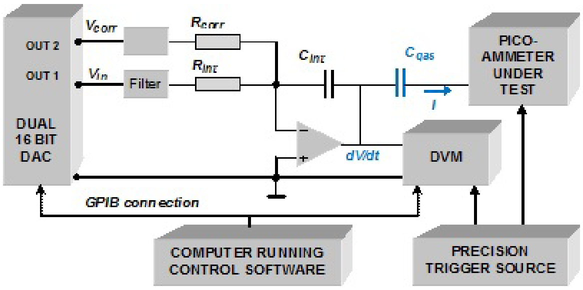
VSL Supports IRMM in Small Current Measurements for Radionuclide Metrology

The accurate measurement of small electrical currents is essential for the measurement of ionizing radiation as generated by radionuclides. VSL has been involved in the current measurement part of the development of a new well-type ionization chamber at IRMM. This well-chamber is meant to be able to replace the 'Système International de Référence' (SIR), the BIPM facility used for international comparisons of radioactivity measurements. If constructed according to specifications, this well-chamber should give reproducible results with an uncertainty of 0.1 % for radionuclides emitting gamma rays in the range from 20 keV to 2000 keV.

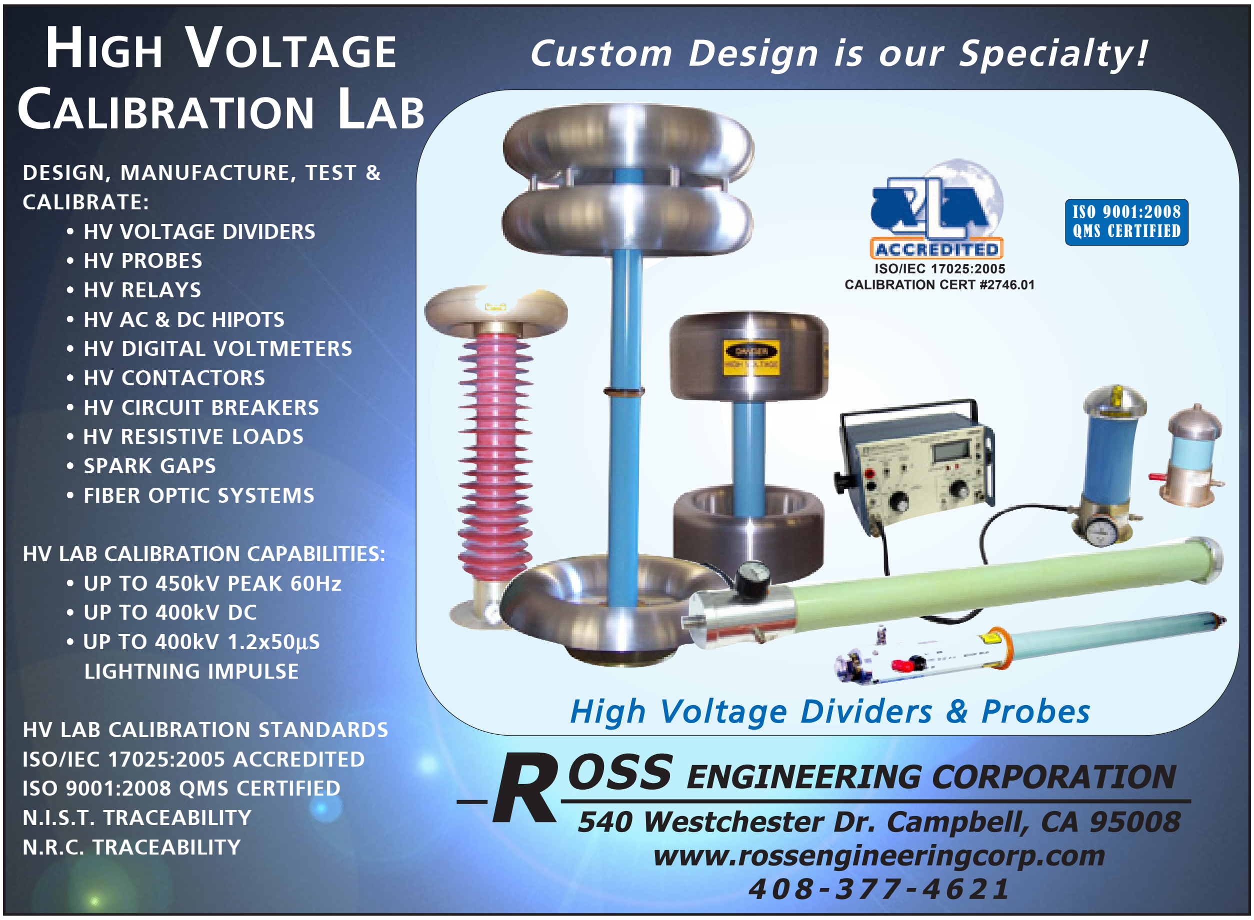
To achieve this goal, accurate and traceable measurements of the ionization current are extremely important. For the prototype ionization chamber, background radiation typically produces a current of about 45 fA, whereas a relatively strong source results in a 1 nA current. IRMM contacted VSL to support the development in this part of their project. A generator equivalent to the VSL primary standard for small currents was duplicated and brought to IRMM. This generator generates a very stable and linear voltage ramp dV/dt that is fed to a capacitor C to convert it to a current $I = C{\cdot}dV/dt$. After some initial testing, two-day training course was organized to discuss the details of high-precision small current measurements.

For small current related issues, VSL will continue to be involved in the further development of the new realization of the becquerel at IRMM. This way, the VSL expertise in electrical current measurement gives a significant contribution to the future international traceability of the becquerel.

For more information on this subject, please contact Helko van den Brom, hvdbrom@vsl.nl.



Schematic overview of the current generator use to calibrate electrometers.



New NIST Measurement Tool Is On Target for the Fast-Growing MEMS Industry

As markets for miniature, hybrid machines known as MEMS grow and diversify, the National Institute of Standards and Technology (NIST) has introduced a long-awaited measurement tool that will help growing numbers of device designers, manufacturers and customers to see eye to eye on eight dimensional and material property measurements that are key to device performance.

The NIST-developed test chips (Reference Materials 8096 and 8097) are quality assurance tools that enable accurate, reliable comparisons of measurements on MEMS (MicroElectroMechanical Systems) devices made with different equipment and by different labs or companies. These capabilities will make it easier to characterize and troubleshoot processes, calibrate instruments and communicate among partners.

MEMS were once considered a stepchild of the semiconductor industry and largely confined to automotive uses—primarily as accelerometers in airbag systems. But the devices have branched out into an array of applications, especially in consumer electronics markets. A high-end smart phone, for example, contains about 10 such devices, including microphones, accelerometers and gyroscopes. MEMS devices also are important components of tablet computers, game consoles, lab-on-a-chip diagnostic systems, displays and implantable medical devices.

Global MEMS industry revenues are projected to grow from about $10 billion in 2011 to $21 billion in 2017, according to the June 2012 forecast by the technology consulting firm Yole Développement.

Widely used reference materials and standardized measurement methods can help to improve process efficiency and to reduce the cost and time devoted to testing and inspecting MEMS devices. Industry-accepted measurements also can promote greater interoperability among devices made by different manufacturers.

The new NIST reference materials are micromachined and further processed to contain miniature cantilevers, beams, stair-like step heights, microscale rulers and test structures for measuring surface-layer thickness. Specifically, the NIST test chips can be used to check customer conformity with internationally established standards for measuring elasticity (Young's modulus), residual strain (and stress), strain (and stress) gradient, as well as thickness, step height and length.

All dimensional and material-property measurements that NIST used to characterize the reference devices conform with SEMI and ASTM International standard test methods. These standard methods are consensus best practices developed by industry committees.

"Reference materials and best-practice test methods provide industry-wide benefits," explains NIST electronics engineer Janet Cassard. "Typically, these tools are prohibitively expensive for a single company to develop on its own. We will work with the MEMS community to facilitate widespread adoption and consistent usage of these standard test methods and reference materials."

One test chip (RM 8096) is manufactured in an integrated circuit (IC) process; the other (RM 8097) in a MEMS process. The test chips are supported by a user's guide, data analysis sheets for each measurement, and other materials accessible via the NIST Data Gateway with the keyword "MEMS Calculator."

For more information, go to: http://www.nist.gov/srm/index.cfm.

Source: NIST Tech Beat - April 30, 2013, http://www.nist.gov/public_affairs/tech-beat/index.cfm#mems.

New NIST Time Code to Boost Reception for Radio-Controlled Clocks

The National Institute of Standards and Technology (NIST) is changing the way it broadcasts time signals that synchronize radio-controlled "atomic" clocks and watches to official U.S. time in ways that will enable new radio-controlled timepieces to be significantly more robust and reliable.

This new time broadcast protocol will not only improve the performance of new radio-controlled clocks and watches, but will encourage the development of new timekeeping products that were not practical with the old broadcast system because of local interference or other limitations. For example, appliances such as refrigerators, microwave ovens and thermostats, as well as traffic light timers and sprinkler systems will be able to take advantage of this new phase modulation broadcast.

Popular radio-controlled timekeepers, which range from wristwatches to wall clocks, are not really atomic clocks—though that's often in their name—but they do set themselves by listening to low-frequency AM time broadcasts from the NIST radio station WWVB in Fort Collins, Colo. Those broadcasts are synchronized to the NIST atomic clock ensemble in nearby Boulder, Colo.

However, sometimes the radio-controlled clocks have difficulty accurately picking up the WWVB time signal because of the clock's location, local radio interference, effects of buildings, and other problems. Moreover, a time broadcast from England on the same frequency also interferes with devices on the east coast of the United States that rely on the NIST broadcast, according to John Lowe, station manager for WWVB.

To solve these problems, Lowe says, NIST has developed, tested and is now beginning to implement the new phase-modulation WWVB signal. Like a traditional AM radio station, time information is encoded in the WWVB broadcast by changes in the strength or amplitude of the radio signal. Phase modulation adds an additional layer of information encoded by shifting the phase of the carrier wave. (The crests of two waves that are "in phase" pass a point at the same time. If one is phase-shifted, the crest will arrive a little before or after the other.)

This change significantly improves signal reception and overall performance of new products that are designed to utilize this new protocol. Legacy clocks and watches will still continue to function as they have because the amplitude modulation remains the same, but they will not benefit from the increased performance of the new phase modulation protocol, Lowe said.

These new products and non-networked systems will be able to take advantage of the improved NIST broadcast format thanks to next generation receiver chips that will begin entering the marketplace in 2013.

For more on radio-controlled clocks work with WWVB, see www.nist.gov/pml/div688/grp40/radioclocks.cfm.

Source: NIST Tech Beat, March 5, 2013, http://www.nist.gov/public_affairs/tech-beat/tb20130305.cfm#wwvb.

WorkPlace Training Metrology Academy

WorkPlace Training, Emc3 Solutions and Quality Systems Laboratory announce the opening of a World Class ISO 17025 accredited training facility in Boca Raton FL. Our new 11,600 sq ft facility contains the most state of the art measurement instruments and standards available. By attending our workshops you will receive hands on metrology training curriculum designed and delivered by WorkPlace Trainings Chief Technical Officer, Dilip Shah. Mr. Shah will lead the training and be assisted by Edward Brown and the staff at QSL. These 2 day workshops will be offered each year in the fall and winter. In addition, workshops can be scheduled throughout the year for your calibration staff by appointment.

WPT Supports your training before the event with of elearning prerequisite; during the workshop with focused classroom and hands on demonstrations with check, working and reference standards; and after the workshop with telephone support. ASQ Recertification Units eligible.

Check our website (www.wptraining.com) for more topics, learning objectives, audience, costs and dates.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NEW PRODUCTS AND SERVICES

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Model 5R7-388 RoHS Compliant controller is a bi-directional control for independent thermoelectric modules or in conjunction with auxiliary or supplemental resistive heaters for both cooling and heating applications. The "H" bridge configuration of the solid state MOSFET output devices allows for the bi-directional flow of current through the thermoelectric modules. Highly efficient N-channel output devices are used for this control mode.

This controller is PC programmable via an RS232 communication port for direct interface with a compatible PC. The easily accessible communications link permits a variety of operational mode configurations. Field selectable parameters or data acquisition in a half duplex mode can be performed. This controller will accept a communications cable length in accordance with RS232 interface speciations. Once the desired set parameters are established, the PC may be disconnected and Model 5R7-388 becomes a unique, stand-alone controller. All parameter settings are retained in non-volatile memory.

FEATURES

- Full H-Bridge
- 36VDC Output using split supply
- P,I,D or On/Off Control
- PC Configurable Alarm Circuit
- RS232 Communication Port
- "T" Thermocouple -328°F - 500°F

From industrial temperature controllers to programmable sensors, Oven Industries creates many detailed and customized solutions for clients, designed by an expertly trained staff of engineers.

For more information about the 5R7-388 controller, visit http://www.ovenind.com/bv/Products/Temperature-Controller-5R7-388__5R7-388.aspx.

R&S SMW200A High-End Vector Signal Generator

The new R&S SMW200A high-end vector signal generator from Rohde & Schwarz combines a baseband generator, RF generator and MIMO fading simulator in a single instrument. The vector signal generator covers the frequency range from 100 kHz to 3 GHz or 6 GHz and features an I/Q modulation bandwidth of 160 MHz with internal baseband. Exceptional modulation and RF characteristics make it ideal for developing high-end components, modules and complete products for wideband communications systems such as LTE-Advanced and WLAN IEEE 802.11ac. The generator performs especially well when it comes to the verification of 3G and 4G base stations as well as aerospace and defense applications.

The R&S SMW200A can be equipped with an optional second RF path for frequencies up to 6 GHz and with a maximum of two baseband and four fading simulator modules, giving users two full-featured vector signal generators in a single unit.

In addition to the two internal RF paths provided, highly compact R&S SGS100A signal generator modules can be connected as additional RF sources and remotely controlled by the R&S SMW200A. This solution takes up only five height units for 4x4 MIMO receiver tests and provides correctly encoded baseband signals, realtime channel simulation, AWGN generation and, if required, phase-locked coupling of multiple RF paths.

The excellent signal quality of the R&S SMW200A ensures high accuracy in spectral and modulation measurements. The SSB phase noise is –139 dBc (typ.) at 1 GHz (20 kHz offset). The R&S SMW200A also comes with a cleverly devised operating concept. The new touchscreen allows users to control the instrument even more intuitively with the tried and tested Rohde & Schwarz block diagram as key operating element to visualize the signal flow. Help functions are provided to quickly achieve success. Presets are provided for all important digital standards and fading scenarios. LTE and UMTS test case wizards simplify complex base station conformance testing in line with the 3GPP specification.

The new high-end R&S SMW200A vector signal generator is now available from Rohde & Schwarz: http://www.rohde-schwarz.com.

On Time Support Tools New Releases

On Time Support is proud to announce the release of four new products based on our dramatically improved METDaemon application server. Unlock the hidden potential of your MET/TRACK database:

- BC Mobile is an add-on product to Barcode Magician 1.7.1 (BCM) Plus. It is a browser based application that automates repetitive database entry tasks such as checking in/out equipment, or changing equipment status simply and consistently for quantities of assets by entering an Action Code.
- New METDaemon Responder is the ideal application for creating and presenting web-based forms for collection and storage of a user's submissions in a database for easy retrieval and analysis.
- Used in conjunction with Email Notification, it's a great value that gives any organization the ability to convert "old fashion" paper forms - that are hard to store and retrieve - into modern web-based forms to capture, record and maintain vital information.
- The new METDaemon Report Viewer enables you to publicly display real-time activity to both lab users and management. The METDaemon Viewer executes and displays SQL or Crystal Reports in a web page. You can easily create activity reports for your lab and use METDaemon Viewer to display a lab status dashboard.

If you use printed barcodes in your business documents, you know how difficult it is to select and use special barcode fonts and provide a sufficiently high resolution image to be readable consistently. Now you can generate barcodes (Code 128, Code 39 or 2D Data Matrix) "on the fly" for any SQL or Crystal reports (including web-based) and reports exported to a PDF format, *WITHOUT THE USE OF SPECIAL INSTALLED FONTS*. Adding these bar-codes to your document is a simple matter of defining the code type and supplying the text to be encoded.

For more information on these products please contact OTS: 281.296.6066 or visit http://www.ontimesupport.com/.

Fluke Calibration 9190A Ultra-Cool Field Metrology Well

Fluke Calibration, a leader in precision calibration instrumentation and software, introduces the 9190A Ultra-Cool Field Metrology Well, a small, lightweight, and accurate dry-block calibrator with best-in-class stability.

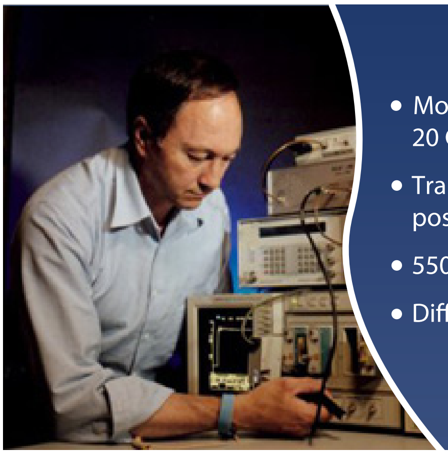
The 9190A is ideal for pharmaceutical, biomedical and food processing applications that demand strict quality control and regulatory process compliance, including on-location validation and calibration of RTDs, thermocouples, thermometers, and other temperature sensors.

The 9190A conforms to EURAMET cg-13 guidelines for best measurement practices for temperature dry-block calibrators. This ensures that the 9190A specifications for accuracy, stability, axial (vertical) uniformity, radial (well-to-well) uniformity, loading, and hysteresis have been thoroughly and carefully defined and tested.

It has a wide temperature range (-95 to 140 degrees Celsius) to cover the coldest and warmest temperatures required in pharmaceutical, biomedical and food processing applications, operating at ultra-cold temperatures not typically available with a calibration bath. The 9190A uses no bath fluids, keeping clean rooms clean, making it easier to transport, and delivering faster heating/cooling rates. It offers best-in-class temperature stability (plus-or-minus 0.015 degrees Celsius) for consistent, accurate results.

The 9190A with "process" option features 4-20 mA connectors, a reference thermometer input, 4-wire PRT/RTD input with an accuracy of plus-or-minus 0.02 degrees Celsius, and a reference sensor control to minimize the effects of the axial gradient when a reference PRT is aligned with short sensors.

For more information, visit: http://us.flukecal.com/products/temperature-calibration/industrial-calibrators/field-metrology-wells/9190a-ultra-cool-field.



NEW PRODUCTS AND SERVICES

Agilent High-Sensitivity Multiport Optical Power Meters

The two- channel N7747A and four-channel N7748A bring the industry-leading sensitivity of the 81634B sensor module to the compact multichannel N77 platform, with updated memory size and data-transfer speed.

The Agilent N7747A and N7748A optical power meters enable engineers to make parallel multiport measurements and monitor weak signals and small signal changes with high precision in, for example, communications or sensing applications. The meters can detect power levels down to -110 dBm and log data at intervals down to 25 µs with up to 1 million points per channel. An equally large data buffer supports simultaneous measurement and data transfer.

With these features and specifications, the meters make it easy for engineers to monitor signal stability and transient events for long periods. Up to eight power-meter channels fit in a single 19-inch rack-height unit. Each channel also has a front-panel BNC connector that delivers analog output voltage proportional to the measured signal.

Like the faster N7744A and N7745A, these new power meters can be used with N77xx viewer software for simple control and reading and are programmable with the same set of SPCI commands as the rest of Agilent's optical power-meter portfolio. The latest version of the popular 816x VXI plug&play driver also adds support for these products. Computer interfaces are provided for USB 2.0, LAN and GPIB.

In addition to high sensitivity, low noise and solid stability, the N7747A and N7748A also provide high relative accuracy like the 81634B modules, with extremely low polarization dependence and spectral ripple as well as specified linearity. This combines to make these power meters an excellent choice in setups for measuring insertion loss and lowest PDL in passive optical components.

Additional information about Agilent's new high-sensitivity optical power meters is available at www.agilent.com/find/N7747A and www.agilent.com/find/N7748A.

Rohde & Schwarz NRP-Z58 Coaxial Power Sensor

Users working with a frequency range over 67 GHz now also benefit from the unique features of the thermal power sensors from Rohde & Schwarz. The new R&S NRP-Z58 is the world's first power sensor that covers the frequency range continuously from DC to 110 GHz.

Rohde & Schwarz has added the R&S NRP-Z58 to its successful portfolio of power sensors. The sensor's high measuring speed of over 300 measurements per second in buffered mode allows especially fast power measurements. With a range of 55 dB (–35 dBm to 20 dBm), it offers the largest dynamic range (DC to 110 GHz) of any thermal power sensor on the market.

When performing relative measurements such as amplification and reflection measurements, the R&S

NRP-Z58 delivers extremely precise measurement results thanks to its high linearity of 0.01 dB. The ball bearing 1.00 mm coaxial plug can be screwed conveniently and securely onto the jack of the measuring instrument to provide extremely high measurement reproducibility.

Like all thermal power sensors from Rohde & Schwarz, the R&S NRP-Z58 can be connected directly to a PC via a USB interface in order to analyze measurement results.

For users of the R&S ZVA110 network analyzer, the power sensor is the perfect addition. It comes equipped with the appropriate 1 mm socket for connecting the R&S NRP-Z58. The power sensor makes it possible to achieve a consistent power calibration up to 110 GHz using a single instrument and without any adapter. Before, this required multiple power sensors and various adapters.

In addition, the power sensor helps users working in development, production and maintenance to determine the average power of CW signals, pulsed signals or even complex digitally modulated signals. The new R&S NRP-Z58 thermal power sensor is now available from Rohde & Schwarz.

The Modal Shop 9110D

The 9110D Digital Portable Vibration Calibrator is the newest product in the 9100 Series Portable Accelerometer Calibrators from The Modal Shop, a PCB Group Company. The 9110D stands out with new features that enable users to take that extra step in portable calibration, including generating ISO 17025-compliant calibration certificates.

The 9110D Digital Portable Vibration Calibrator is a compact, battery-powered and completely self-contained vibration reference source which can be conveniently used to calibrate individual sensors, vibration switches and data collectors, as well as to validate the entire measurement channel of a condition monitoring or recording system.

Designed for use in-situ, including on the manufacturing plant floor, the unit calculates and displays test sensor sensitivity on the readout screen in real time. It also has built-in ICP® input for common piezoelectric accelerometers and can save up to 500 calibration records directly to the unit's internal memory. Users can copy records to the included USB flash drive with Report Generation Workbook via the unit's USB port. Saved calibration data is then transferred to a computer where the user can easily generate and print an ISO 17025-compliant customizable calibration certificate. This product provides enhanced stability and superior vibration calibration over an extended 7 Hz (420 CPM) to 10 kHz (600,000 CPM) frequency range, at amplitudes up to 20 g pk (196 m/s²).

The 9110D features an integral precision quartz reference accelerometer and closed-loop level control, packaged in a rugged Pelican® Storm case with two press and pull latches. The 9110D is always ready for travel to industrial test sites or bringing laboratory accuracy to the field.

Visit our calibration web page at www.modalshop.com/calibration.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SWITCHBOX INTERFACE
LEVEL IV
LEVEL I
PRIMARY REFERENCE STANDARD
THERMOMETRY SYSTEM
EUROTHERM
287.14
INSCO
767

Low-Temperature Benchtop Chillers from PolyScience

A line of compact, powerful, and highly affordable low-temperature chillers are available from PolyScience. Designed to maximize bench space, LS-Series / LM-Series / MM-Series Chillers provide up to 1290 watts of cooling at 20°C, making them ideal for use with rotary evaporators, jacketed incubators, small reaction vessels, spectrophotometers, chromatography columns, condensers, and other devices that require robust heat removal.

Three different models of PolyScience compact chillers are available: The LS-Series, which has a working temperature range of -20° to +40°C and provides 475 watts of cooling at -10°C; the LM-Series, with a working temperature range of -10° to +30°C and a 230 watt cooling capacity at -10°C; and the MM-Series, which has a working temperature range of -5° to +50°C and provides 129 watts of cooling at -5°C. All three models control temperature with ±0.1°C stability and are equipped with a low flow rate alarm, user-adjustable high and low temperature alarms, a top-mounted fill port with built-in fluid filter, lighted fluid level indicator, and washable rigid-frame air filter.

LS-Series Chillers are available with either a centrifugal or turbine pump. LM- and MM-Series Chillers are available with two different centrifugal pumps. For more information, visit the PolyScience website at www.polyscience.com.

LaserLinc SmartLinc™ Processor

The SmartLinc processor integrates easily into the line control system communicating via Ethernet or serial port to the PLC. A single unit provides a communications link for one, two, or three of LaserLinc's full line of single, dual, and triple-axis laser scanning micrometers.

To simplify communication management, the processor transmits data to the PLC at user-defined intervals and to user-specified locations in the PLC via tags. Once configured and integrated, the SmartLinc provides unattended and reliable operation.

Easy-to-use configuration and diagnostics tools enable the user to access and manage all SmartLinc devices over the plant network, or by Ethernet cable-connection from a laptop directly to a SmartLinc device.

LaserLinc is the preeminent manufacturer of accurate and adaptable non-contact laser and ultrasonic systems for OD, ID, wall thickness, eccentricity, and concentricity across many industries including wire, cable, medical and other tubing, hose, pipe and fiber.

LaserLinc's systems can provide a time-to-payoff in months, even weeks by reducing scrap and waste, shortening startup times, ensuring product quality, and through process improvement and optimization. www.laserlinc.com.

Agilent Technologies E5810A LAN/GPIB/USB Gateway

Agilent Technologies Inc. announced the Agilent E5810B LAN/GPIB/USB gateway, the next-generation replacement for the E5810A with added USB capability. The new gateway allows users to connect and control, over a standard local-area network, up to 14 GPIB instruments, up to four USB instruments via a self-powered hub, and an RS-232 instrument.

With the gateway's improved GPIB transfer rate of 1.2 MB/s, engineers can reduce test time and improve production. The E5810B supports 1000BASE-T (1 Gigabit) LAN/Ethernet as well as 100BASE-TX and 10BASE-T to meet the demands of higher network bandwidth.

Designed for ease of use, the E5810B comes with a built-in LCD display, allowing users to check the IP address of the gateway for quick setup. Users can easily configure the gateway via a password-protected Web interface.

The E5810B allows multiple users in different locations to access a centrally located test system. Connecting a wireless router to the E5810B enables engineers to wirelessly control instruments from a PC where LAN connection is unavailable or inconvenient.

The E5810B LAN/GPIB/USB gateway is now available worldwide. Information on the E5810B is available at www.agilent.com/find/E5810B_pr.

NEW PRODUCTS AND SERVICES

New High Stability Hygrometer 473

Rotronic Instrument Corporation New York has agreed to represent the RH Systems 473 dew point hygrometer throughout the Americas. RH Systems is a world renowned developer of precision chilled mirror hygrometers that are the first choice for standards laboratories and research organizations worldwide

The 473 features a cable mounted dew point measuring head that can be directly mounted into the chamber working space. Temperature is measured with a PRT (platinum resistance thermometer) than can be directly mounted to the measuring head for simple use, or cable-mounted for easy repositioning to determine spatial temperature and %RH variations of the test environment. Dew point and temperature values are used to calculate relative humidity (%RH) or any other humidity units required by the user.

Measurement data is displayed on a three line, user configurable touch-screen display in either numerical or graphical format. Serial digital and optional analog outputs allow the user to log and record data for later analysis or to meet validation requirements.

The 473 provides highly precise and stable reference measurements that are essential to achieve low uncertainty calibration validation of RH generators, climatic test facilities and pharmaceutical stability chambers. With the proven long term stability and intuitive user interface, the 473 makes attaining the most precise humidity measurements possible for any user. http://rotronic-usa.com/.

Micro-Dimensionair® II by Mahr Federal

Mahr Federal is introducing the new Micro-Dimensionair® II as the next generation of its well-established Micro-Dimensionair line of portable air gages.

The new Micro-Dimensionair II incorporates the enhanced Micro-Maxum® II Digital Indicator and an interchangeable handle to provide accurate, convenient readouts at the measurement site. The digital dial on the new Micro-Dimensionair II rotates through 270 degrees for easy viewing, and the IP-54 rated gage provides the exceptional accuracy and repeatability Mahr Federal users have come to expect.

Micro-Dimensionair II incorporates all the benefits of the enhanced Micro-Maxum II line including: Dynamic Max, Min, TIR; two point difference measurement; Multiplier Factor for ratio measurements; indicator serial number identification; resolution to 20 µin; selectable, continuous output; and longer battery life. All standard features are retained, such as inch/metric measurement in digital or analog display; bi- and unilateral tolerances with presets; multiple data output formats; auto-zeroing; and normal/reverse settings for ID/OD.

For more information visit http://www.mahr.com.

NEW PRODUCTS AND SERVICES

CAL-TOONS by Ted Green teddytoons@verizon.net

Digital Surf Mountains® 7 Release

Digital Surf announced the official release of its new Mountains® 7 software for surface imaging and metrology. New cutting-edge 3D imaging, compatible with OpenGL and Direct3D, makes it possible to visualize every detail of micrometric and nanometric surfaces in near-perfect lighting conditions. New solutions for scanning electron microscopes and Raman and FT-IR spectrometers - combined with enhanced existing solutions for 3D optical microscopes, scanning probe microscopes and profilometers - mean that Mountains® 7 is the most complete surface analysis solution in its class. Furthermore, MountainsÒ 7's new smart user environment makes metrology report creation faster and sleeker than ever.

To speed up analysis report creation, the visual and analytical studies that make up the body of a report have been streamlined in Mountains® 7. All metrological results are grouped in a single results manager panel where tolerances can be specified, pass/fail status is displayed automatically, and results can be exported in Excel-compatible format. Layers in multi-layer surface data files - from multi-channel 3D optical microscopes and from scanning probe microscopes – are easily identified and selected with miniature icons that provide a preview of each layer. New functions include mapping of local surface properties and the automatic removal of outliers present on surfaces measured by 3D optical microscopes.

Mountains® 7 includes two major additions to the Mountains® software product line. MountainsMap® SEM is a new 3D imaging and metrology product for SEM's and includes reconstruction of 3D surfaces (x, y and z in length units) from stereo pairs, anaglyphs and quads. MountainsMap® Hyperspectral is a new product for Raman and FT-IR spectrometers that makes it possible to manipulate spectra and hypercubes interactively, filter them, generate compositional density maps and visualize "flattened" hypercubes in 3D. Key MountainsMap® SEM and MountainsMap® Hyperspectral functions are also available, respectively, in the new SEM and Spectrometry optional modules for some MountainsMap® products.

Web site: www.digitalsurf.com.

California Instruments BPS Series High-Power Converters

AMETEK Programmable Power, the global leader in programmable AC and DC power test solutions (www.programmablepower.com), has released the California Instruments BPS Series of high-power AC sources/frequency converters.

Available with outputs ranging from 30 kVA to 180 kVA, the BPS is the latest series of products to use AMETEK's high-performance, pulse-width modulation (PWM) switching technology to provide cost-effective solutions for AC power test applications. The BPS Series supports four different communications busses and has a powerful AC transient generation capability, making it ideal for commercial instrumentation manufacturing, automatic test stations, AC motor test, and avionic frequency conversion.

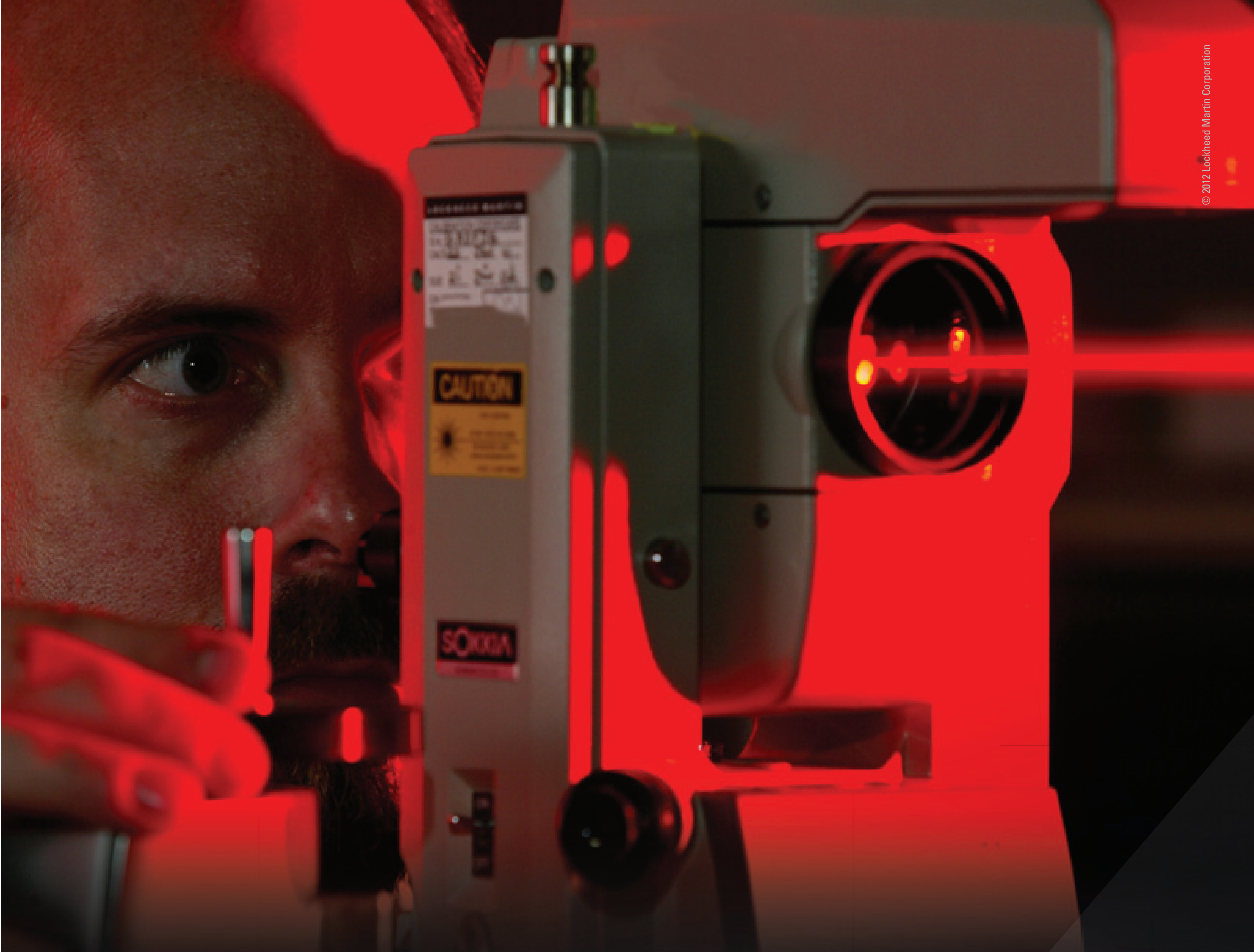
Modular architecture allows chassis to be paralleled for high power. The BPS Series offers a wide output frequency range of 16 to 819 Hz, making it well-suited for aerospace applications. For higher power requirements, users can simply parallel the BPS Series in a multi-cabinet configuration.

To meet the needs of manufacturers of high-power equipment and appliances that must test their products over a wide range of input line conditions, the BPS Series offers built-in output transient generation. This feature allows users to simulate a wide variety of AC line conditions. Transient generation is independent, yet time synchronized, on all three phases. Accurate phase angle control and synchronized transient list execution provides accurate positioning of AC output events.

The BPS Series combines compactness, robustness and functionality in a compact floor-standing chassis. This higher power density has been accomplished without the need to resort to elaborate cooling schemes or additional installation wiring. Users simply roll the unit to where they want it, plug it in, and the BPS Series is ready to operate.

The BPS Series can be programmed manually via the front panel or remotely with USB, RS-232, IEEE-488 (GPIB) or optional Ethernet interfaces. A Graphical Users Interface Software is included with all BPS Series allowing easy programming of all functions. Users can monitor the output of an AC source on the BPS' high-contrast 6"x8" LCD display, whether or not the unit was programmed from the front panel or via one of the remote-control interfaces.

To learn more about any of the company's programmable power supplies and programmable loads, contact AMETEK Programmable Power Sales toll free at 800-733-5427, or 858-458-0223, or by email at sales.ppd@ametek.com or an authorized AMETEK Programmable Power sales representative, who can be located by visiting http://www.programmablepower.com/contact/.



Piston Prover Design with Additional Measurement Capabilities and Reduced Flow Interaction

Edward Morrell
Mesa Laboratories

High-speed clearance sealed piston provers for measuring gas flow rates have been available for over twenty years and have gained wide acceptance as a fast, cost-effective, primary calibration instrument for gas flow. High-speed piston provers are available for measuring flow rates from 0.5 sccm to 500,000 sccm with measurement uncertainties of up to 0.15% [1, 2, 3, 4]. This paper describes new advances in high-speed piston prover design.

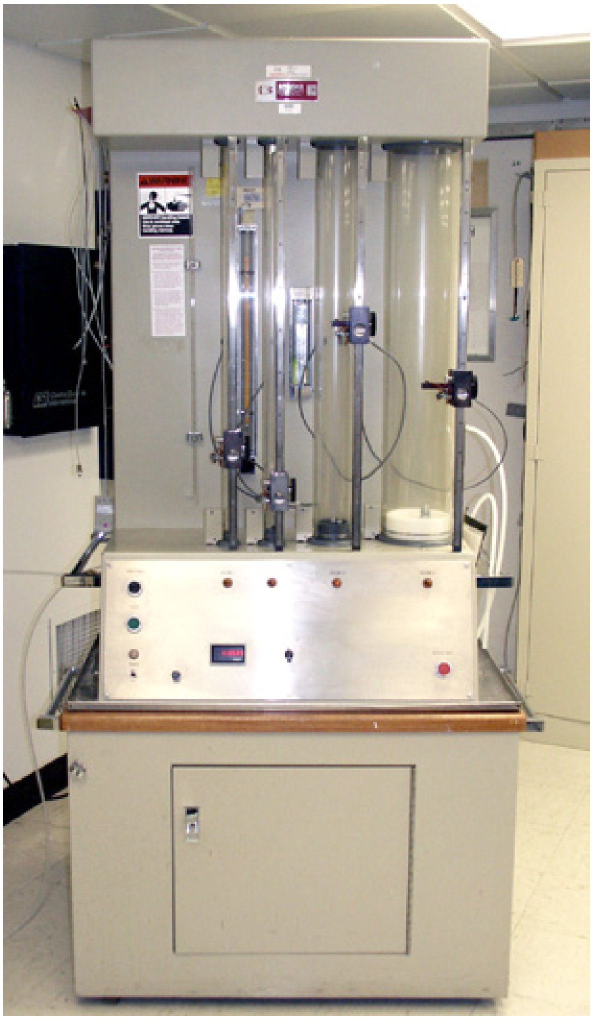


Figure 1. Mercury Seal Piston Prover.

I. Introduction

Many technologies exist to measure gas flow rates. A few are:

- Differential pressure instruments – measure pressure drop as gas flows past an obstruction.
- Constant-volume (rate-of-rise) instruments – measure pressure and temperature rise as gas fills an evacuated volume.
- Thermal based instruments – measure heat transfer as gas flows over a heated element.
- Constant-pressure positive displacement instruments, such as piston provers – measure the physical displacement of a mechanical element by the flow of gas.

Piston prover designs have evolved over many years. This paper discusses the latest piston prover evolution featuring a horizontal piston design, which can measure corrosive gases, and automatically apply compressibility factor correction for non-ideal gases. The horizontal design, while more complex than previous vertical tube design, allows for faster measurement speed with reduced dynamic pressure changes that can introduce measurement uncertainty. Additionally, this new unit is engineered from corrosive resistant materials allowing many non-inert gases to be measured.

II. Piston Prover Design Chronology

1. Mercury-sealed provers were in use for many years and featured a rigid machined piston of significant mass that utilized a mercury seal between a glass tube and the outside diameter of the piston. A significant advantage to these instruments was that the mercury provided a

Figure 2. High-Speed Vertical Clearance-Sealed Piston Prover.

Figure 3. High-Speed Horizontal Clearance-Sealed Piston Prover.

gas-tight low friction seal between the glass and the tube. However, mercury has the disadvantage of toxicity and the piston speed must be kept very slow to avoid loss of the mercury seal. Most mercury sealed piston provers have by now been removed from service due to environmental concerns. Mercury piston provers required a skilled operator to adjust a valve increasing the gas pressure on the bottom of the piston to the point that the piston floats. After this adjustment, the valve was fully closed and the time required to slowly displace the piston was used to determine the volumetric gas flow rate.

2. High-speed vertical clearance-sealed piston provers have been in existance for more then 20 years and feature a piston machined to very tight tolerances minimizing clearance between the piston and tube, typically less than 10 microns. The tightly fitted piston reduces leakage around the piston to almost negligible rates. A 44 mm diameter piston with a measurement range of 500 to 50,000 ccm will typically have a clearance leak rate of 1 ccm. Piston leakage for these instruments is measured and stored in the electronics memory and added to the flow measurement.

   The piston and cylinder are made of materials with matching coefficients of expansion, thus maintaining a consistant clearance dimension with changing temperature. Measurements are automated with a button push closing a bypass valve. The piston is displaced by the flowing gas through a set acceleration distance until a timing start point is reached and the time required to displace the piston through a calibrated volume is measured. After the measurement is complete, the bypass valve opens and the piston falls to the bottom of the tube at which time another measurement cycle can begin.

3. High-speed horizontal clearance-sealed piston provers replace the vertical tube with a horizontal tube and a piston re-engineered for low-mass and low-friction. In comparison to the vertical tube, which requires a piston of sufficient mass to return the piston to the bottom of the tube, the horizontal tube uses a low mass, low friction piston and valves which alternate the gas flow direction in the tube. As gas flows, optical sensors measure the piston oscillation across the tube. The horizontal tube-piston requires less gas pressure to displace the piston resulting in faster bi-directional readings and reducing pressure effects on the measured flow source.

III. Clearance Seal Piston Dynamics

The flow dynamics for the piston in a clearance sealed piston prover can be modeled as a combined laminar Couette – Poiseuille Flow (Figure 4).

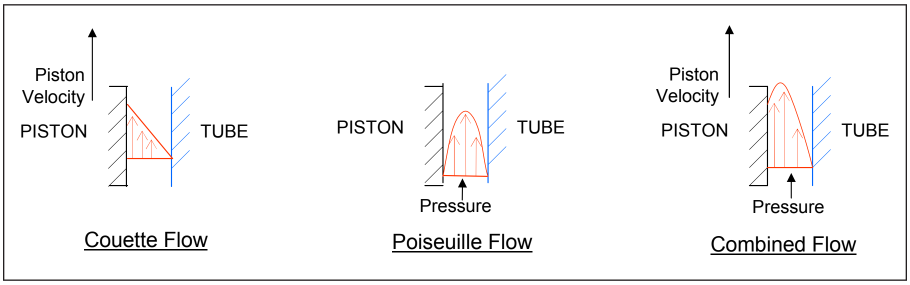


Figure 4. Piston Clearance Flow Dynamics.

The Couette flow component represents the piston motion relative to the cylinder wall and is accounted for by setting the effective piston diameter at the mid-point between the tube inside diameter and the piston outside diameter. The Poiseuille flow component is driven by the pressure differential P displacing the piston and is accounted for by the piston leakage calibration. The piston leakage rate for a vertical piston prover is given by:

$$Q = (P/x)\, h^3 W / 12\mu, \qquad (1)$$

where

Q = Gas Leak Rate,
P = Gas Pressure,
x =Piston Height,
h = Gap Clearance,
W = Piston Radius, and
μ = Gas Viscosity.

The gas pressure P, once the piston of mass m is fully accelerated and assuming the piston moves without drag, is given by:

$$P = mg. \qquad (2)$$

For the horizontal piston prover, the gas pressure P required to displace the piston is proportional to the coefficient of friction k of the piston material:

$$P = kmg. \qquad (3)$$

The horizontal piston prover piston was designed from materials with a coefficient of friction of 0.1 to 0.2. Additionally, the horizontal piston was engineered with a lower mass piston further reducing the pressure. As previously noted, the piston leakage with a precision fitted piston is very small. But with the lighter mass piston of the horizontal design and the use of low friction materials, the pressure reduction to displace the piston proportionally reduces the piston leak rate Q.

IV. Horizontal Piston Prover Application Advantages

A piston prover initiating flow reading requires the measuring piston to accelerate. This acceleration will cause a pressure pulse to occur [2, 5]. For this reason, high-speed vertical pistons provers delay flow measurement to allow the piston to accelerate and the pressure pulse to subside [2]. Under typical laboratory conditions, the pressure pulse has no effect on measurement uncertainty. However, accurate flow measurements can be compromised on a system with large connecting gas volume between the source of the gas and the piston prover. The large connecting volume of gas between a flow generator and the piston prover act as storage for the gas as pressure changes occur. Many operators may be unaware of this or cannot reduce connecting volumes. For this reason, it is desirable to minimize any pressure pulses produced during flow measurement by a piston prover.

The vertical design piston prover required a piston of sufficient mass to allow gravity to return the piston to the bottom of the tube after a measurement is complete. In the horizontal piston prover, the piston is displaced in both directions by the flow of the gas. Since the horizontal piston does not use gravity to reset the piston, the piston mass was reduced. In our instruments, the piston mass of the horizontal piston is approximately 50% less than the vertical piston. As previously noted for a horizontal piston, the pressure required to slide the piston is proportional to the weight of the piston times the coefficient of friction. Figure 5 shows the pressure pulse of a vertical piston prover and the reduced pressure pulse generated by the horizontal piston prover at the same flow rate.

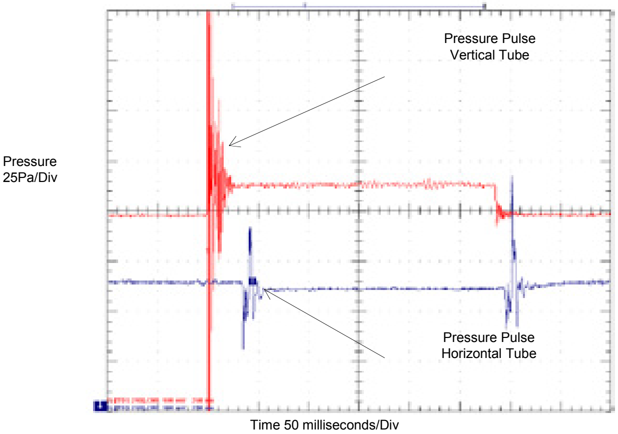


Figure 5. Piston Prover Pressure Pulse.

V. Corrosive Gas Measurement

An additional advancement made in the engineering of the horizontal piston design was to add measurement capability for many corrosive gases. Internal components were designed from corrosive resistant materials: stainless steel, borosilicate glass, Teflon, and high purity graphite. In addition, positive displacement gas flow instruments measure volumetric flow. Since gases are compressible, volumetric flow measurements are converted to standardized flow measurements. The definition of a standardized flow rate is the volume of gas transported per unit time across a boundary with the measured gas volume converted to the volume the gas would occupy at a defined pressure and temperature. To make this conversion, a temperature transducer and pressure transducer inside the piston prover measure gas temperature and gas pressure. The conversion between volumetric flow and standardized flow can be derived from the ideal gas law giving the formula:

$$V_s = V_f \times \left(\frac{Pg}{101.325}\right) \times \frac{(273.15 + Ts)}{(273.15 + Tg)}, \tag{4}$$

where V_s is the flow rate for standardized conditions, V_f is the measured volumetric flow rate, Pg is the measured gas pressure in kPa, Ts is the specified standardization temperature in degrees centigrade and Tg is the measured gas temperature in degrees centigrade.

While the ideal gas law provides sufficient accuracy when measuring inert gases across the narrow temperature and pressure of a typical laboratory environment, corrosive gases deviate from the ideal gas law. For this reason we have added compressibility factor correction needed for the non-ideal behavior of corrosive gases. Compressibility factor is a correction for gas property deviation from ideal behavior. With compressibility factor the conversion formula becomes:

$$V_s = V_f \times \left(\frac{Z_{(Ps,Ts)}}{Z_{(Pm,Tm)}}\right) \times \left(\frac{Pg}{101.325}\right) \times \frac{(273.15 + Ts)}{(273.15 + Tg)}. \tag{5}$$

The additional terms: $Z_{(Ps,Ts)}$ is the gas compressibility factor at standardized conditions and $Z_{(Pm,Tm)}$ is the gas compressibility factor at the measured gas temperature and pressure. To automatically apply compressibility factor, the operator of the instrument selects the gas species being tested and a look up table in the instrument applies compressibility factor corrections. The compressibility factors used are derived from the NIST Reference Fluid Thermodynamics and Transport Properties Database (REFPROP) [6] .

VI. Conclusions

The horizontal design piston prover expands the use of high-speed, clearance-sealed piston prover technology by reducing dynamic measurement pressure pulses. While under controlled conditions, pressure pulses do not present measurement difficulties. Many industrial installations requiring accurate flow measurement have large connecting or even unknown connecting volumes between the flow generator and the point of flow measurement. Similarly, many industrial applications, particularly the semiconductor industry, use corrosive gases in the manufacturing process. By engineering a piston prover with corrosive resistant material, non-inert gases can now be measured where previously measurements could only be done with great difficulty or with less accurate measurement technologies.

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Metrology:
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Pantex Metrology

Metrology revolves around standards—measurement standards, normative standards, standard measurement practices, etc.—to achieve consistent quality results. To remain competitive, metrology, like other industries, also depends on automation and standardized interoperability to attain and enhance that quality at reduced cost. Witness the long history of automated calibration software and the more recent laboratory management systems. But metrology encompasses more than just calibration and workload management: Consider documentation, uncertainty analysis, conformance testing risk analysis, service procurement, accreditation, interlaboratory comparisons and proficiency tests, specification use and development, product inspections, etc. How many tasks have we standardized and automated, and how many consume resources at every repetition? Why do we still handle paper calibration certificates and their PDF cousins, and manually search accreditation scopes? Why don't our certificates contain full traceability chains? Do we provide customers obviously valuable services or just increase their overhead costs? This paper highlights some technological opportunities that the measurement community has not embraced widely, if at all, and suggests that more aggressive standardized information infrastructure adoption would help meet global economic and quality challenges.

Introduction

Ask yourself the following questions:

- Why do we still handle paper calibration certificates or their PDF cousins and manually extract their content?
- Why do we manually search and interpret accreditation scopes and instrument specifications?
- Why do our certificates not include full traceability chains to the SI and itemize each intermediate measurement process uncertainty contributor?
- Why do we manually create and maintain uncertainty budgets for the thousands of unique test points a typical laboratory supports?
- Why do we provide customers a list of calibration points but do not quantify their instrument's measurement quality over its full range and function set?
- Why do some (most?) customers consider metrology an unavoided overhead cost rather than a valuable service?

This paper and a recent *Metrologist* article [1] suggest an answer: Our computing machinery (potential automation) does not "talk shop"; it shares no standard language (semantic structure) by which to record and interpret metrology information, and thus the machine servants leave many routine tasks to their supposed masters. The same article introduced and discussed a Metrology Information Infrastructure (MII or MI^2) concept: A set of normative standards, data structures, and communication protocols to advertise, communicate, share, and leverage the gold mine of information generated by everyday metrology operations. In such a paradigm, data-filled, machine-readable electronic versions of calibration certificates, instrument spec sheets, accreditation scopes and other metrology communication vehicles would seamlessly carry information with known meaning between organizations and down the traceability chain. As discussed below, an MII might increase analytical rigor, improve traceability, its transparency, and understanding thereof, clarify instrument specifications, link customer measurement quality at arbitrary test points to historical calibration points, and reduce product test errors.

While many of the preceding possibilities await normative standards for data formats and communication, and software to implement them, other initiatives also await research and recommended practices. This paper illustrates some technical problems that standards and software would solve and introduces avenues that may approach the recommended practices we lack. First, we consider the difference between human and automated shortcuts.

Metrology Made Easy?

When we face complexity, we often make economic or conservative choices and take analytical shortcuts. For example, when we calculated on abaci, slide rules and napkins, multi-digit numbers inconvenienced us and we invented significant-figures rules to make life easier. Sooner or later though, shortcuts incur penalties. Consider the skeleton uncertainty budget in Table 1 for a nominal 10.00000 unit measurand at full resolution:

Error Source	Uncertainty
Measurement Standards	0.00050
Resolution	0.0000029
Stability	0.0000
Combined	0.000501
95 % Confidence Interval: ±0.001	

Table1. Example Uncertainty Budget.

Say we apply this budget to numerous calibrations over a multi-year period, and per whatever significant-figures rules we follow, report values in the format XX.XXX. Afterward, we learn that someone grossly overestimated the measurement standards uncertainty or we otherwise refine that component estimate to 0.000005, applicable to past calibrations. At 95 %, the new confidence interval would come to ±0.000011, but we suspect that the previously under-investigated repeatability and stability might affect that. To update our estimate, we review the historical data and unfortunately find all values either 10.000 or 9.999. The significant-figures rules effectively inflated our resolution uncertainty to 0.00029, swamped out the important uncertainty information, and undercut years of calibration work. So, we expend resources on a new stability study and make our metrology "cost center" that much less attractive.

With the right infrastructure, computing resources save us from inconvenience—and complexity-driven shortcuts. Unlike humans, CPUs save nothing by rounding; in fact, rounding just increases CPU time, numeric errors, software complexity, and bug likelihood. So what if we had a standard to delineate inclusion of machine-readable data in calibration certificates? An MII-based electronic calibration certificate would imbed full precision measurement results and uncertainties for the next machine's computing pleasure and still present us humans conveniently formatted values on the surface. An MII would give certificates and other documents depth and substance beneath their shiny surfaces.

A more serious shortcut, misinterpreting instrument specs, may have originally caused our uncertainty estimation error. Perhaps we conveniently took a reputable manufacturer's warranted specification on a complex multifunction instrument as a $k = 2$ confidence interval. Or worse, we committed the uniform (rectangular) distribution misapplication sin and used an even more conservative $k = 1.7$. In reality, in order to keep warranty costs low, the manufacturer conservatively specified the instrument such that all its functions would reliably remain in tolerance for a long interval under strenuous usage, meaning that each individual function would have an in-tolerance probability far closer to 100 %. The coverage factor for a single measurement may come closer to $k = 15$, even without considering meticulous laboratory instrument care. We will see how an MII might prevent this problem later, but let us discuss uncertainty analysis shortcuts first.

Some laboratories may see few reasons beyond accreditation scope competitiveness to perform rigorous uncertainty analyses. Full analyses drive support costs higher than desired. Simplified, conservative uncertainty analyses suffice to ensure adequate accuracy for uncertainty ratios (or false accept risk) and proficiency tests. If we overestimate measurement process uncertainty, then we underestimate ratios and more safely claim sufficiently high ratios. Likewise, our $E_n = |x_{\mathrm{us}} - x_{\mathrm{them}}| / u_c$ proficiency test (PT) scores will more likely pass muster. However, inflated uncertainties stealthily drive up costs. Inventory and maintenance costs increase when conservative uncertainty estimates push laboratory instruments to the next price and accuracy level to support the same product test limits. Consequence costs increase when conservative uncertainty estimates cause widened product tolerances or less competitive accreditation scopes. Inaccurate uncertainties lead to inaccurate risk estimates and inefficient operating points, and derail the end-to-end cost analyses [2] that would demonstrate and quantify metrology's value to management or customers.

A MII may not rectify PT bias,[1] but it might significantly reduce analytical costs. To reduce uncertainty budget maintenance, analytical metrology and lab management software would import upstream uncertainties directly from the calibration certificates and relate them electronically to the calibration points in the laboratory's central database. That would eliminate separate spreadsheets and other files of individual analyses that humans manually update every time new uncertainties flow down the chain. Some laboratory software[2] [3, 4, 5] and in-house solutions [6] have ventured down this path and already include measurement standard specification ↔ calibration point relations.

Standardized uncertainty calculation software libraries that any application package might use would encourage more software developers to include such functionality in their laboratory management systems, analysis software, automated calibration software, etc. Ubiquitous automated uncertainty calculations would alleviate pressures to take shortcuts. If software handled such complexities as error

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[1] Presumably to protect the calibration service customer, the current accreditation scheme penalizes low, but not high, uncertainty estimates ($E_n > 1$) and thus biases uncertainty estimates upward. If we calculated our uncertainties and E_n scores accurately, we would *expect* to have $E_n > 1$ about 5 % of the time. Then, only when that rate signicantly deviated from 5 % (either way!) would it impact accreditation status.

[2] Though this paper credits known prior work, it endorses no specific products or companies.

distribution details, sensitivity coefficients, correlations, correct (as opposed to convenient) coverage factors, *t*-distribution-based confidence intervals, Bayesian and Monte Carlo approaches as appropriate, multiple-output matrix methods, all the related shortcuts would evaporate, whether they cause significant error or not. The GUM [7] and its relatives already established the standards in this case, and many uncertainty analysis applications already exist; at most, we lack collecting them into standard libraries and a validation process that the industry widely accepts.

Standardized measurement scenario uncertainty templates would save resources also and avoid shortcuts related to which uncertainty components to include. A finite, though increasing, number of quantities and measurement methods underlie all our work, so a bit of effort and cooperation, and perhaps a web site to collect and discuss them, might soon produce standardized and extensible templates that cover most combinations. The NCSLI RP-12 working group has discussed such a possibility already. Most metrology organizations use uncertainty budgets, and though some uncertainty components in similar scenarios matter more or less at different traceability levels, why should every analyst reinvent the budget structures and components? Also, if software calculates the results, practitioners may include all components without worry as to their significance—no shortcuts.

In similar fashion, we may standardize and automate other analytical processes. Bottom line: When we take shortcuts to "make metrology easy" we simply pass costs on to customers. Instead, we should standardize and automate to eliminate the costs and obviate the shortcuts.

Traceability Improvements

As discussed previously, MII-based certificates would pass unadulterated data down the traceability chain and avoid information loss, not to mention accumulated rounding errors. However, current calibration certificates omit much more valuable information than extra digits, information that MII-based certificates might include. Currently, we often reduce multiple traceability chains into a single measurement result and report the requisite boiled-down information: some subset of uncertainty, coverage factor, confidence interval, and degrees of freedom (DOF). Unfortunately, the typical calculation and reporting process discards upstream information that downstream analysts have no way to recover and use; information on individual uncertainty components combined at one traceability link rarely survives past the next calibration certificate. When traceability chains converge in a measurement process, then diverge and merge again, correlations between chains become relevant.

One MII solution would have the certificate imbed or point to full traceability information, including all uncertainty contributors, correlations, and DOF from each traceability link back to the SI unit realizations. GUIDs (Globally Unique IDentifiers) or URIs (Uniform Resource Identifiers) might distinguish uncertainty components in order to identify common contributors appearing in different traceability tree branches. We humans might consider that information overload or just a curiosity, but our computing systems would use it transparently for our benefit.

An Example Traceability Problem

Review the GUM's example[3] H.2.4 [7], which we have extended to include DOF and 95 % confidence intervals:[4] A primary lab measures the voltage across and the current through a component, and the voltage phase relative to the current. From that, the lab computes resistance, reactance, and impedance. Table 2 collects the pertinent information.

The customer requested resistance and reactance, so the calibration certificate only contains those two lines from Table 2. Later however, the customer wishes to know the component's impedance and phase angle and so back-calculates those values, uncertainties, and DOF from the certificate data. Table 3 shows the customer's first attempt.

Ideally, the customer results match the data the lab used to generate the certificate (but did not include!). Unfortunately, only the values agree; the uncertainty, DOF, and confidence limits have large errors. In this case, the primary lab failed to include the −0.588 resistance-reactance correlation coefficient, a common omission—especially when certifying multiple values over a range—even though the GUM recommends reporting all relevant data. The customer, having no correlation information, assumed independence between the values, or perhaps took that shortcut for simplicity. Unity correlation, usually another easy assumption, causes trouble with the phase uncertainty in this case, so zero makes an easier choice.

After some expense and time, the customer notices the overestimated uncertainties, calls the primary lab, and eventually discovers the problem. After accounting for the correlation, the new customer calculation yields the Table 4 results.

We notice that that fixed the uncertainty but left the DOF

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[3] The example considers only some Type A errors and does not constitute a full uncertainty analysis but serves to illustrate the concept.

[4] See the GUM for the detail not included here. Since neither the GUM nor this paper imbed any MII features, not all the least signicant digits shown here match. To reproduce the results, calculate everything from the example's source data without intermediate rounding.

Quantity	Value	Uncertainty	DOF	95 % Confidence Limits
Voltage, magnitude	4.9990 V	3.2 mV	4	±8.9 mV
Current, magnitude	19.6610 mA	9.5 µA	4	±26.3 µA
Phase, $\phi_V - \phi_I$	1.044 46 rad	0.75 mrad	4	±2.09 mrad
Resistance	127.732 Ω	0.071 Ω	4.4	±0.190 Ω
Reactance	219.847 Ω	0.296 Ω	5.1	±0.756 Ω
Impedance	254.260 Ω	0.236 Ω	6.0	±0.577 Ω

Table 2. Primary Laboratory Calibration Data.

Quantity	Value	Uncertainty	DOF	95 % Confidence Limits
Impedance	254.260 Ω	0.488 Ω	5.9	±1.201 Ω
Phase, $\phi_V - \phi_I$	1.044 46 rad	1.41 mrad	9.4	±3.158 mrad

Table 3. Customer Impedance and Phase Results, Attempt 1.

Quantity	Value	Uncertainty	DOF	95 % Confidence Limits
Impedance	254.260 Ω	0.236 Ω	5.3	±0.597 Ω
Phase, $\phi_V - \phi_I$	1.044 46 rad	0.75 mrad	5.6	±1.870 mrad

Table 4. Customer Impedance and Phase Results, Attempt 2.

and confidence limits wrong; the certificate combined the upstream DOF and correlations into those (fewer) values reported. To prevent DOF propagation errors, certificates should include the original upstream information for all uncertainty contributors [8, 10, 11]. Note that Table 2 and Table 4 include DOF calculated for correlated errors, something the GUM does not cover. A recent paper [8] surveys and evaluates several published ways to perform that calculation, one of which NCSLI RP-12 [9] now includes. In this case, we calculated the Table 2 output quantities' DOF as if the primary lab had analyzed the measurement and determined three fundamental (independent) error sources that explain the observed errors and correlations according to the relation

$$\begin{pmatrix} e_V \\ e_I \\ e_\phi \end{pmatrix} = \begin{pmatrix} 0.9799 & 0.1997\ \mathrm{V/rad} & 2.209\ \mathrm{m\Omega} \\ -1.0726\ \mathrm{S} & 16.32\ \mathrm{mA/rad} & -0.9999 \\ 0.1997\ \mathrm{rad/V} & -0.9797 & -16.21\ \mathrm{mrad/A} \end{pmatrix} \cdot \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix}, \tag{1}$$

with fundamental uncertainties and DOF

$$\boldsymbol{u}_f = \begin{pmatrix} 3.274\ \mathrm{mV} \\ 379.1\ \mu\mathrm{rad} \\ 6.251\ \mu\mathrm{A} \end{pmatrix}, \boldsymbol{v}_f = \begin{pmatrix} 4.0 \\ 0.6 \\ -2.3 \end{pmatrix}. \tag{2}$$ [5]

Using that fundamental per [8] will reproduce the correct results. The customer, or anyone downstream, may use the same fundamental information to eliminate all correlation and DOF discrepancies. An MII that revealed such information would have saved the customer analysis and consequence errors, calls to the primary lab, and perhaps a repeat calibration. Furthermore, if in a complete analysis, the resistance and impedance have common elements among their traceability chains (likely), an MII would have exposed that to all parties' software for automatic handling. Some efforts have begun: A recent uncertainty analysis application [11] has built fundamental uncertainty information into its storage format in order to correctly propagate uncertainties.

Vector Uncertainty Analysis

In the above example, we posited an MII that would pass co-variances down the traceability chain to resolve traceability problems. That would work, but at least one simpler solution exists. To sketch it out, suppose we imagine a fundamental (orthogonal) vector space whose dimensions correspond to the independent uncertainties comprising a traceability chain. Dimension candidates would include a small independent SI unit and CODATA[6] constant set, plus the random uncorrelated errors that arise in measurements. BIPM[7], CODATA, and measurement process owners might publish GUIDs to uniquely identify these unit vectors. So, for example, Table 5 describes some components of a fundamental uncertainty vector space for length measurements, along with sensitivities and DOF for a particular measurement.

The GUID list alone defines the vector space. The notation GUID[x] represents the GUID assigned to the error source x. Some measurements will propagate the same random error to multiple traceability chains, say, through GPS time signals, and thus those uncertainty sources have unique identifiers for the particular dissemination. Null GUIDs indicate quantities independently and identically-distributed (iid) over time that did not provide traceability for more than one simultaneous measurement and thus will not correlate with an uncertainty from any other measurement at any time or place. Note that the meter

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[5] We would typically avoid fundamentals with negative DOF to prevent potential problems downstream. The negative DOF indicates that the example DOF and covariance data or this *ad hoc* fundamental structure do not represent physically real measurements. However, this fundamental does produce completely consistent results for this example. See [8] for ways to avoid and handle negative DOF.

[6] The Committee on Data for Science and Technology, www.codata.org.

[7] Bureau International des Pois et Mesures, www.bipm.org.

Quantity	Dimension ID	Ex. Uncertainty	Ex. DOF
Time	GUID[BIPM second]	0 s	∞
Velocity, Light in Vacuum	GUID[CODATA *c*]	0 m/s	∞
Allan Variance	GUID[NIST-F1(timestamp)]	10^{-14} s/s	10^5
Unique Random Error	NULL	10^{-7} s/s	50
⋮	⋮	⋮	⋮

Table 5. Example Independent Uncertainties for a Length Measurement.

does not appear in the list, except in the CODATA light velocity constant; all length measurements will trace back to time or frequency.

As long as we reference all uncertainty calculations to such an orthogonal vector space, we have no correlations to worry about. Every measurement has a certain sensitivity to one or more components in the vector space, the sensitivities determined by the derivatives of its measurement equation with respect to each component. We may represent a particular measurement's uncertainty vector in that space with the component-by-component product of its sensitivities and uncertainties. To calculate measurement uncertainty we compute the uncertainty vector's magnitude (Euclidean length), $u = \|\boldsymbol{u}\| = \sqrt{\boldsymbol{u}^T\boldsymbol{u}}$, just the root-mean-square of its components. To combine multiple uncertainty vectors further down the traceability chain, we simply multiply each by the measurement's sensitivity to that quantity's error and add the resulting vectors—no correlation complications, just multiply and add.[8] The combined uncertainty then just becomes the length of the final vector (see Figure 1).

To illustrate, let us compute the GUM H.2.4 example by vector analysis. We note here that all the following calculations, though they take different forms, equate exactly to the GUM procedure. First, we define our orthogonal vector space by the primary lab's independent[9] uncertainty components, $\boldsymbol{u}_f$, and denote the corresponding error sources f_1, f_2, f_3. The individual basis vectors take the form

$$\boldsymbol{u}_{f1} = \begin{pmatrix} 3.274 \\ 0 \\ 0 \end{pmatrix} \text{mV},\ \boldsymbol{u}_{f2} = \begin{pmatrix} 0 \\ 379.1 \\ 0 \end{pmatrix} \mu\text{rad},\ \boldsymbol{u}_{f3} = \begin{pmatrix} 0 \\ 0 \\ 6.251 \end{pmatrix} \mu\text{A}, \tag{3}$$

and comprise our fundamental vector space

$$\boldsymbol{U}_f = \begin{pmatrix} 3.274\text{ mV} & 0\ \mu\text{rad} & 0\ \mu\text{A} \\ 0\text{ mV} & 379.1\ \mu\text{rad} & 0\ \mu\text{A} \\ 0\text{ mV} & 0\ \mu\text{rad} & 6.251\ \mu\text{A} \end{pmatrix}. \tag{4}$$

Equation 1's matrix, which we now denote $\boldsymbol{C}_{pf}$, gives the voltage, current, and phase sensitivities to the fundamental uncertainty vector; each sensitivity vector lies in one matrix row. To specify an uncertainty in the vector space, we multiply its sensitivities by the fundamental uncertainties component-by-component. So in vector form, the primary lab voltage measurement has the uncertainty vector

$$\boldsymbol{u}_V = \begin{pmatrix} 0.9799 \cdot 3.274\text{ mV} \\ 0.1997\text{ V/rad} \cdot 379.1\ \mu\text{rad} \\ 2.209\text{ m}\Omega \cdot 6.251\ \mu\text{A} \end{pmatrix} = \begin{pmatrix} 3.208\text{ mV} \\ 75.71\ \mu\text{V} \\ 13.81\text{ nV} \end{pmatrix}. \tag{5}$$

Thus we have the first uncertainty vector in the primary lab's results. The numeric values mean nothing, however without the fundamental vector space definition. We may compute all uncertainty vectors at once as columns in a matrix by the simple propagation

$$\boldsymbol{U}_y = \boldsymbol{U}_x \boldsymbol{C}_{yx}{}^T, \tag{6}$$

which defines a new vector space, though not orthogonal unless $\boldsymbol{C}_{yx}$ has a diagonal form. So the primary voltage-current-phase uncertainty space becomes

$$\boldsymbol{U}_p = \boldsymbol{U}_f \boldsymbol{C}_{pf}{}^T = \begin{pmatrix} 3.208\text{ mV} & -3.512\ \mu\text{A} & 0.6539\text{ mrad} \\ 75.71\ \mu\text{V} & 6.189\ \mu\text{A} & 0.3714\text{ mrad} \\ 13.81\text{ nV} & -6.250\ \mu\text{A} & -0.1013\ \mu\text{rad} \end{pmatrix}. \tag{7}$$

At the next traceability level we have the resistance-reactance space

$$\boldsymbol{U}_m = \boldsymbol{U}_f \boldsymbol{C}_{mf}{}^T = \begin{pmatrix} 38.97 & -263.9 \\ -43.39 & 113.3 \\ -40.63 & -69.87 \end{pmatrix} \text{m}\Omega, \tag{8}$$

where $\boldsymbol{C}_{mf} = \boldsymbol{C}_{mp}\boldsymbol{C}_{pf}$ and $\boldsymbol{C}_{mp}$ contains the sensitivity coefficients from the measurement equations relating resistance and reactance to voltage, current, and phase. Finally, the customer computes the desired impedance magnitude-phase uncertainty space

$$\boldsymbol{U}_z = \boldsymbol{U}_f \boldsymbol{C}_{zf}{}^T = \begin{pmatrix} -208.6\text{ m}\Omega & -653.9\ \mu\text{rad} \\ 76.19\text{ m}\Omega & 371.4\ \mu\text{rad} \\ -80.82\text{ m}\Omega & 101.3\text{ nrad} \end{pmatrix}, \tag{9}$$

where $\boldsymbol{C}_{zf} = \boldsymbol{C}_{zm}\boldsymbol{C}_{mf}$. Of course, a smart package would use the phase information already present rather than recalculating it but we find it comforting to know the calculation will agree with prior data in all aspects.

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[8] Digital signal processor (DSP) chips love to multiply and add; with vector methods, they would make short work of even massive uncertainty problems.

[9] This example has no SI traceability to correlate voltage, phase, and current errors.

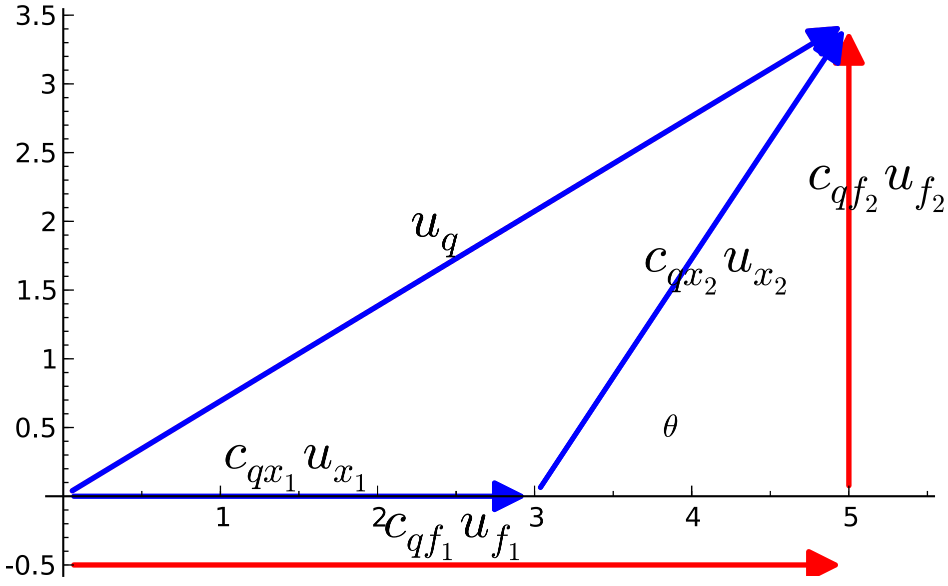

Figure 1. Combining two uncertainty vectors (blue) in an orthogonal uncertainty vector space (red).

The reader may verify all the above uncertainty vectors by computing their magnitudes (lengths-RSS the components in each column) and comparing to the uncertainties in the previous example. For DOF, we use the standard Welch-Satterthwaite (W-S) formula—we have no correlation issues as long as we retain and compute from the fundamental DOF. Therefore, we use the sensitivity coefficients from the quantity of interest to the fundamental quantities. For example, the impedance has fundamental sensitivity coefficients

$$\boldsymbol{C}_{Zf} = (-63.71\ \mathrm{A}^{-1} \quad 201.0\ \Omega/\mathrm{rad} \quad -12.93\ \mathrm{k}\Omega\ \mathrm{A}^{-1})\,, \tag{10}$$

and so after the units cancel out, the W-S formula yields

$$v_Z = \frac{0.236^4}{\frac{(-63.71 \cdot 3.274 \times 10^{-3})^4}{3.9956} + \frac{(201.0 \cdot 3.791 \times 10^{-4})^4}{0.5565} + \frac{(-12.93 \cdot 6.251 \times 10^{-6})^4}{-2.2996}} = 6.0. \tag{11}$$

If we ever want the correlation between two error sources, we may calculate the “co-linearity” or normalized dot product of the two associated uncertainty vectors as

$$\rho_{i,j} = \frac{\boldsymbol{u}_i \cdot \boldsymbol{u}_j}{\|\boldsymbol{u}_i\|\ \|\boldsymbol{u}_j\|}\ . \tag{12}$$

Note that the equation yields zero for any two fundamental uncertainty vectors. For the resistance-reactance correlation, the formula works out to

$$\rho_{R,X} = \frac{0.03897 \cdot -0.2639 + -0.04339 \cdot 0.1133 + -0.04063 \cdot -0.0699}{0.07107 \cdot 0.29558} = -0.588. \tag{13}$$

To recover any covariance matrix from an uncertainty vector set ***U***, for example to use the GUM matrix uncertainty framework [14], we calculate all the vector lengths and cross-lengths by the single matrix product

$$\boldsymbol{\Sigma} = \boldsymbol{U}^T \boldsymbol{U}. \tag{14}$$

To implement this method, an MII certificate would store or point to the nominal values, vector space definition, fundamental uncertainties and DOF, along with the sensitivity coefficients between each measurement and the fundamental in full precision. It might optionally store them in sparse or compact array format. A more sophisticated tactic would optionally store the measurement equations instead of the sensitivity coefficients. Either way, software would then

Quantity	Dimension ID	Uncertainty	DOF
Voltage, source and meter stability	GUID[f_1]	3.274 mV	4.0
Phase, component and meter repeatability	GUID[f_2]	379.1 µrad	0.6
Current, component and meter repeatability	GUID[f_3]	6.251 µA	-2.3

Table 6. MII Certificate Data, Fundamental Uncertainty.

Dimension ID	GUID[f_1]	GUID[f_2]	GUID[f_3]
GUID[V]	0.9799	0.1997 V/rad	2.209 mΩ
GUID[I]	-1.0726 S	16.32 mA/rad	-0.9999
GUID[ϕ]	0.1997 rad/V	-0.9797	-16.21 mrad/A
GUID[R]	11.90 A^{-1}	-114.4 Ω/rad	-6.499 kΩ A^{-1}
GUID[X]	-80.60 A^{-1}	298.9 Ω/rad	-11.18 kΩ A^{-1}
GUID[$\|Z\|$]	-63.71 A^{-1}	201.0 Ω/rad	-12.93 kΩ A^{-1}

Table 7. MII Certificate Data, Sensitivities.

consistently and accurately re-compute all other quantities on demand rather than store them. Tables 6 and 7 lay out the encapsulated uncertainty data from all the stages discussed (rounded for human consumption). Table 6 contains no more than the fundamental because we simply calculated derived quantities without further measurements; normally each successive traceability link would add a basis vector for each independent error source. A further table would provide nominal values and names for each GUID.

Instrument Specifications

Next, we break from math and think about how to capture instrument specifications electronically in a format with semantic meaning. Such a format would ideally also describe accreditation scopes and measurands of all types. Paraphrasing, the VIM [12] indicates that measurand specifications should include the measured quantity, the state of the associated item, and the measurement conditions. We suggest here that we may capture almost all such descriptors numerically. For example, the specification

- Measurand: Voltage Indication, RMS, Channels 1-4, 1 V, 10 V and 100 V Ranges, 20 Hz to 1000 Hz, Voltage Offset −1 V to 1 V
- Tolerance: (0.01 % of stimulus + 1 µV + 1 LSD[10])

has obvious numeric attributes to which we might attach semantic meaning to enable automatic tolerance calculations, matching measurands to specifications, automated calibration quality checks, etc. Past [6] and ongoing [3] work has proven this concept's effectiveness in proprietary formats. We may extend such formats indefinitely to handle measurand qualifiers regarding any influence quantity: temperature, pressure, humidity, power quality, noise, vibration, etc. One such existing arrangement [3] hierarchically organizes instrument features into measurement functions of multiple ranges, each with numeric qualifiers and specifications. A problem yet unsolved remains: How to properly interpret warranted specifications as confidence intervals and hence convert them to uncertainties. The MII for specifications should address this and incorporate the data (realistic coverage factors or confidence levels, probably other data) that software (and humankind!) now lacks. An MII would allow companies to market their equipment specifications while including true uncertainty information below the surface for metrologists. NCSLI currently has a Recommended Practice RP-5 (specifications) under revision; perhaps it will lay some groundwork for a solution.

The SI and the VIM already specify meaning for measurement units and quantities. ISO-IEC 80000 [13] series standards exhaustively detail quantities for multiple measurement disciplines. We do not lack much beyond a common data structure for electronic storage; ISO has even developed standards for developing standardized meta data, storage formats, and data exchange techniques. This MII element appears ripe for tackling.

If we incorporate a standard specification format into our MII, we would realize many benefits. For example, manufacturers might publish instrument specifications electronically, enabling MII-aware software to automatically search for equipment meeting detailed criteria. Accreditation scopes published in MII formats would allow similar searches for qualified calibration services.

A General Instrument Model

If we establish MII elements that communicate specifications between systems, what about actual instrument performance? Why not enable software to not only interpret specifications, but also understand instrument performance, automatically select test points, and build calibration procedures per specified calibration quality requirements? This subject deserves considerable research on its own but we describe one possibility at high level here.

Every instrument, whether a simple gage block or a complex spectrum analyzer, has a set of intrinsic parameters corresponding to physical or virtual user settings, device physics, environmental inputs, and adjustments. With or

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[10] Least Significant Digit, or count.

against the designer's intention, each parameter will vary, and thus has some statistical distribution or uncertainty in its value at any given time.

From the user's perspective, the instrument offers a set of black-box measurands with specified accuracy or uncertainty. From a metrology perspective, the external measurands relate in some manner to the intrinsic parameters. For instance, a dimensional end standard's measurands (e.g., length, flatness, parallelism, surface roughness) depend on its rough dimensions, material characteristics, surface condition, calibration corrections, etc. A spectrum analyzer offers many measurements whose accuracy depends on internal component stabilities, user settings, and mathematical correction coefficients. We may use that relationship during calibration and adjust the intentionally variable parameters to bring measurands closer to nominal. We may also turn a blind eye and treat the instrument as a black box to determine its before- or after-adjustment state.

Unfortunately, we rarely determine an instrument's complete state for the customer, but rather its state at a finite set of test points. In some cases, this satisfies the customer completely as they will use it only at those points. In other cases, we simply assume that passing the test points means the instrument meets all specifications over all its ranges. Substituting, deleting, or adding test points will likely alter the instrument's specification conformity across the measurand space in a way we presently do not quantify.

To provide our test and measurement customers higher quality services, we should quantify instrument measurement quality across the entire measurand space of interest and communicate that information electronically for testing software to discover and use. Metrics we might supply include measurand bias, uncertainty, or false accept risk—measurement reliability—relative to specifications. Let us examine how an MII might assist us.

A Proposal

First, we want some way to quantify quality at points we have not tested. Given a vector of intrinsic parameters, $\boldsymbol{x}_{int}$, and a vector of measurand values, $\boldsymbol{m}$, we assume some unknown functional relation $\boldsymbol{F}$ exists that determines the measurand errors, namely

$$\boldsymbol{e}_m = \boldsymbol{F}(\boldsymbol{m}, \boldsymbol{x}_{int}), \tag{15}$$

and that we may approximate that relationship with a vector function, $\boldsymbol{f}$, and vector error (determined at calibration), $\boldsymbol{\epsilon}$, such that

$$\boldsymbol{e}_m = \boldsymbol{f}(\boldsymbol{m}, \boldsymbol{x}_{int}) + \boldsymbol{\epsilon}. \tag{16}$$

The vector function $\boldsymbol{f}$ has one component for each measurand and constitutes a general instrument model that predicts external measurands from intrinsic parameters. If we knew the uncertainties and interrelationships between the intrinsic parameters, we might form their covariance matrix, $\boldsymbol{\Sigma}_{int}$, and propagate that uncertainty through f per the GUM. This takes the form [14, 15]

$$\begin{gathered}\boldsymbol{\Sigma}_m = \boldsymbol{C}_{m,\,int}\,\boldsymbol{\Sigma}_{int}\,\boldsymbol{C}_{m,int}{}^T + \boldsymbol{\Sigma}_\epsilon, \\ \boldsymbol{C}_{m,int} = \nabla \boldsymbol{f}(\boldsymbol{m},\boldsymbol{x}_{int})_{\overline{\boldsymbol{m},\boldsymbol{x}_{int}}}.\end{gathered} \tag{17}$$

Once we have the instrument uncertainty at arbitrary points, we may imbed the model, values determined at calibration, and uncertainties into the calibration certificate for the user's testing or analysis software. Combined with an instrument accuracy specification, calibration or testing software may also calculate false accept risk, beginning-of-period (BOP) measurement reliability, calibration ratios, or other quality metrics that interest the laboratory or customer.

Model Creation and Validation

Fine and dandy, but where do we get instrument models? Ideally, since engineering and design information defines the internal-external parameter relationships, the manufacturer would provide models with their instruments. However, this assumes a number of things, including a standard methodology and data format (MII) we currently lack.

Lacking a model handed to us, or for that matter, if we have this task as a manufacturer, what then? A cooperative project between NIST and Fluke Corporation provided one answer [16]. Essentially, the method boils down to type testing—we would take measurements densely covering the measurand space, guided by instrument knowledge and metrology experience. Once we have a large enough superset of predicted points we may apply linear algebra to decompose the data set and determine a subset of points for calibration that capture all significant instrument errors, very similar to decomposing a covariance matrix to find a fundamental set of error sources. Along the way we get a numeric model. So, applying singular value decomposition,

$$(\boldsymbol{C}_{m,int}, \boldsymbol{\Sigma}_{int}, \boldsymbol{C}_{m,int}) = \mathrm{SVD}(\boldsymbol{\Sigma}_m), \tag{18}$$

and eliminating noise, we get the model sensitivities and internal co-variances we sought. Note that this procedure provides the long-sought connection between instrument specifications and uncertainty: Having the uncertainty at any measurement point and the manufacturer's specification, we may calculate the actual coverage factors or confidence levels associated with the specifications.

No matter who develops the model, or by what method, it has no value without validation. As part of type testing, we may take the calibration point subset and use those measurements and the model to predict the other measurands and compare to actual results, refining the test points, measurement procedure, or model as appropriate, all the while keeping an eye on maintaining a quality calibration process.

Uncertainty Growth

Problem over? Not quite. The equipment owner will use the instrument over the calibration interval and we should not expect the instrument's uncertainty, reliability, or other quality metrics to remain constant during that time. NCSLI Recommended Practice RP-1 [17] provides many reliability and uncertainty growth estimation tools and models. If we extend our instrument type testing over a suitable period we may detect and characterize drift in the measurands and use the model in reverse to calculate intrinsic parameter drift. Then we may adjust our model accordingly for time after calibration, t: $\mathbf{f}(\mathbf{m}, \mathbf{x}_{int}, t)$. Though third-party testing may become viable, manufacturers likely have the most resources and incentive for such characterization. But again, we should further research this topic and establish MII elements to handle it.

Conclusion

We all look for the easiest or most effective way to meet our quality goals. When we do not automate, we achieve "easy" by taking shortcuts that sacrifice rigor for "close enough." Automation changes that. The right standards and software combination would obviate current shortcuts and still contain costs. As a practical matter, standardization and automation will likely advance by small steps so we will likely maintain "easy" and gradually replace human shortcuts with automated quality. "Metrology made easy" shortcuts have contributed to customers and management perceiving metrology as overhead to minimize, a cost center in the accountant's eye. On the other hand, "Metrology made easy" automation should lead to ways to tangibly demonstrate metrology's value and turn the metrology lab into a cost savings and revenue center.

Moreover, a widely-implemented and standardized MII applied to instrument specifications, accreditation scopes, and calibration certificates would streamline general operations, from equipment and service procurement to analysis and traceability. Storing uncertainties as vectors referenced to orthogonal bases would simplify uncertainty computations without sacrificing correctness and improve uncertainty estimation accuracy. Validated instrument models would harden multi-parameter instrument traceability, quantify customer measurement quality, and allow optimized calibration point selection.

This paper hit a few high points among a potential MII's elements. I encourage everyone to find a role to play and contribute to this venture.

Acknowledgments

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A New Primary Standard for the Realization of Pressure from 10 to 500 kPa

Michael Bair
Tim Francis
Fluke Calibration

Fluid pressure is a derived measurand (N/m^2) that is realized primarily through manometers and piston gauges at the NMI level. Piston gauges are becoming more useful as primary standards due to the ability to characterize the effective area, the most difficult variable to measure in a piston gauge, with enough confidence and low enough uncertainty to support the needs of an NMI or private laboratories with the need to resolve pressure at the highest level [1].

Fluke Calibration has introduced a piston gauge to be used as a primary standard to realize pressure in both gauge and absolute modes from 10 to 500 kPa called a PG9607. All variables in the pressure equation for a piston gauge were addressed in the design of the piston gauge to ensure the lowest uncertainty in pressure that could be attained.

This paper discusses the design of the piston gauge and the projected uncertainties than can be resolved with a fundamental characterization.

I. Piston Gauge Design

A. Overview

The piston gauge is a pressure reference that uses a close fit piston-cylinder, aligned with the direction of gravitational acceleration. The piston or the cylinder floats when the pressure to be measured applied to the area of the piston-cylinder equals the downward force of mass being accelerated by gravity. The PG9607 is of a less frequent design where the cylinder floats and the piston is stationary. When the cylinder floats it is rotated at a rate from approximately 5 to 40 RPM min $^{-1}$ (rpm) so the gyroscopic effect can equalize very small horizontal forces and to center the cylinder on and around the piston. No rotation would cause the cylinder to "tip over" and touch the outer diameter of the piston and sensitivity would be lost. When floating, rotating and stable, the measured pressure is calculated using the equation:

$$\frac{Mg_l\left(1-\frac{\rho_{(air)}}{\rho_{(mass)}}\right)+\pi DT}{A_{(20,0)}\left[1+(\alpha_p+\alpha_c)(\theta-20)\right](1+\lambda P)}+Vac-(\rho_{(fluid)}-\rho_{(air)})g_l h \qquad (1)$$

where

M = Total true mass load [kg],
g_l = Local acceleration due to gravity [m/s^2],
$\rho_{(air)}$ = Density of air [kg/m^3],
$\rho_{(mass)}$ = Average density of mass load [kg/m^3],
T = Surface tension (considered 0 with gas) [N/m],
$D = 2\sqrt{\frac{A_{(20,0)}}{\pi}}$ Diameter of the piston [m],
$\rho_{(fluid)}$ = Density of the test medium (gas or oil) [kg/m^3],
h = Difference in height between PG9000 reference level and test reference level [m],
Vac = Back pressure in bell jar (absolute with vacuum) [Pa],
$A_{(20,0)}$ = Piston-cylinder effective area at 20 °C and 0 gauge pressure [m^2],
α_p = Linear thermal expansion coefficient of piston [°C^{-1}],
α_c = Linear thermal expansion coefficient of cylinder [°C^{-1}],
θ = Temperature of the piston-cylinder [°C],
λ = Elastic deformation coefficient of the piston-cylinder [Pa^{-1}], and
P = Pressure applied to the piston-cylinder [Pa].

In the case of the PG9607, the fluid medium is always gas. The gas can be air, nitrogen or helium. The correction for surface tension can be ignored since the surface tension for gas is negligible. This equation applies to both absolute and gauge modes so long as the term for the density of ambient air is zero in absolute mode and the VAC term is ignored in gauge mode.

Figure 1 shows the main components of the PG9607 platform. The sections that follow discuss these components and the role that improvements in design play in lower uncertainties in pressure.

B. Piston-Cylinder

The piston-cylinder designed to be used with the PG9607 is a nominal 20 cm^2 area, made of tungsten carbide and is a floating cylinder on a stationary piston. A picture of the piston cylinder is shown in Figure 2.

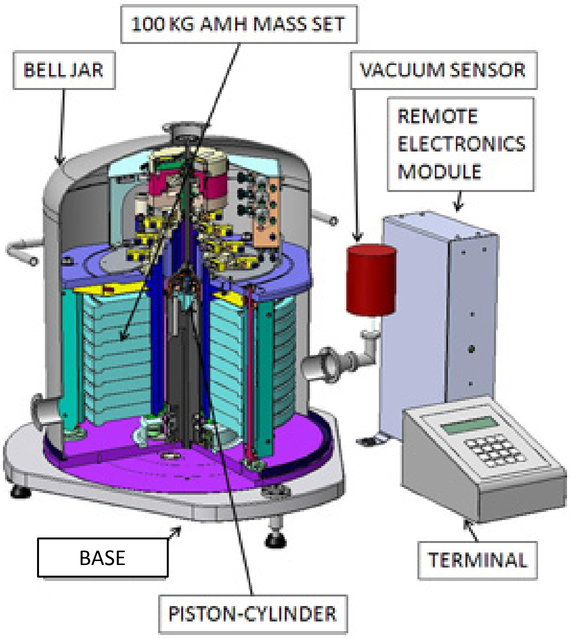

Figure 1. PG9607 Platform Main Components.

The design is the same used in the PTB project described in [2]. The cylinder mass is 1.3 kg which is larger than the 20 cm^2 cylinder previously available which is 0.7 kg. The larger cylinder wall size allows for better cylinder geometry than the lighter cylinder since there is less deformation from the cap installed on the top of the cylinder. The tolerance on dimensional roundness for both the piston and the cylinder is 100 nm peak to peak. This is an improvement of 150 nm from the previous cylinder design and minimizes uncertainties due to imperfect geometry in a dimensional characterization.

Figure 2. Picture of the 20 cm^2 area piston-cylinder.

In addition to the improved geometry, the thicker walled cylinder also provides for lower elastic deformation. The theoretical deformation coefficient is 4.57 x 10^{-6} MPa^{-1}. This is equivalent to 2.3 parts in 10^6 change in effective are over its pressure range of 500 kPa. If the 2.3 parts in 10^6 were represented completely as a change in gap size, the change in gap from 0 to 500 kPa would be only 28 nm. This is advantageous because the predictions of effective area based on dimensional data must include the pressure distribution at a specific pressure. The dimensional data can only be taken at zero pressure so the assumption that the dimensions are the same at higher pressures should not introduce significant uncertainty to the prediction. A change in gap of 28 nm would not significantly change the integration of the pressure distribution discussed in section II.A.

The mounting post is a controlled clearance mounting post where a separate pressure of up to 3 MPa can be applied to the inside surface of the piston to control the gap of the piston-cylinder. This can be used for studies of the elastic distortion coefficient. Figure 3 shows a drawing of the piston-cylinder installed in the mounting post.

C. *Mass Load*

The mass set defined with the PG9607 is a 100 kg binary mass set. Mass loading is automated using the AMH automated mass handler that allows for the exchange of mass while under a vacuum. This is significant since a very low vacuum can be applied while making multiple pressure measurements at different mass loads. The predecessor to the PG9607 would only allow 38 kg of mass to work inside a vacuum. Table 1 shows the breakdown of the masses in the set.

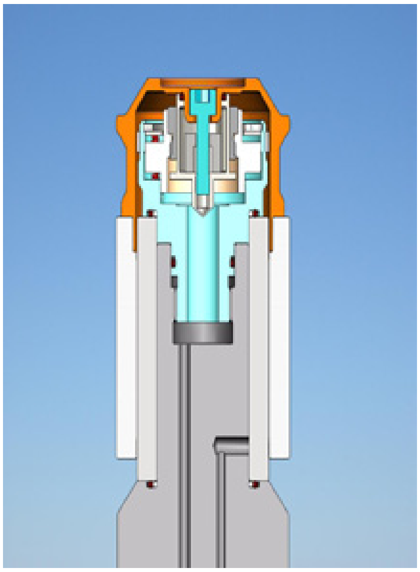

Figure 3. Drawing of piston-cylinder assembly and mounting post.

AMH Mass Set Breakdown
(9 each) main mass of 10.1 kg
6.4 kg binary
3.2 kg binary
1.6 kg binary
0.8 kg binary
0.4 kg binary
0.2 kg binary
0.1 kg binary
0.8 kg mass carrying bell assembly

Table 1. AMH-100 Mass Set.

The minimum mass is 2.1 kg defined by a cylinder mass of 1.3 kg and a mass carrying bell assembly of 0.8 kg. The actual full scale mass load is approximately 105 kg which provides a nominal range of 10.5 to 525 kPa in gauge or absolute mode, or 110.5 to 625 kPa in absolute by addition of atmospheric pressure mode. The resolution of the automated masses is 100 g providing a pressure resolution of 0.5 kPa. There is a mass tray that allows some trim masses to be loaded manually if desired to improve the resolution.

The only time the AMH mass set is handled is when the piston-cylinder needs to be exchanged or cleaned. Since the PG9607 only allows one piston-cylinder size the frequency of handling the mass set is greatly reduced. This significantly improves the stability of the mass set.

D. Piston Gauge Base, Terminal and Remote Electronics Module

With the exception of the motor drive assembly used to automatically rotate the cylinder and mass load, all heat producing electronics are kept outside of the base. This was designed this way to ensure there was as little heating of the piston-cylinder and masses as possible.

The Remote Electronics Module, which in the PG9607 predecessor was inside the base, is external to the base and has the following functions:

- Supplies power to the motor drive and AMH
- Reads dual piston-cylinder temperature
- Reads ambient humidity, temperature and pressure
- Connects and reads the residual vacuum sensor
- Connects to the user interface terminal
- Performs all calculations
- Provides remote interfaces for automated control

Because of the inherent precision and expected lower uncertainties of the PG9607, the system was designed with dual platinum resistance thermometers that are installed in the mounting post on opposite sides of the mounting post. There are two reasons for the dual PRT arrangement. One is for redundancy of the same temperature measurement to help reduce type A uncertainties. The other is to better predict the piston-cylinder temperature by measuring each side of the mounting post and account for the possibility of small gradients.

E. Residual Vacuum Sensor

When in absolute mode the residual vacuum sensor is measured by a 13.3 Pa (100 mTorr) capacitance diaphragm gauge (CDG). The default vacuum sensor in the predecessor to the PG9607 was a thermal conductivity gauge (TCG). The CDG has a significantly lower uncertainty than the TCG. The REM discussed in 2.3 allows for the configuration of other types of vacuum transducers as well.

The residual vacuum sensor and its display can be seen in figure 4 which is a photograph of the complete system and the complete system with the vacuum bell jar removed. Note that the bell jar does not have to be removed to measure gauge pressure.

F. Reference Level

The reference level of the PG9607 is close to the top of the cylinder. This reference level is not easily accessible to compare head height measurements with the AMH loaded and especially with the bell jar on. To help with this a precise height difference between the reference level and the base plate, which is accessible with all components installed, is documented.

Figure 4. Picture of PG9607 complete (above) and with vacuum bell jar removed (below).

II. Uncertainties

The PG9607 can be fundamentally characterized to realize pressure. To accomplish this, all the parts of the pressure equation must be fundamentally characterized. This primarily includes mass, gravity and effective area and change of effective area with temperature and pressure.

A PG9607 delivered from Fluke Calibration will not be fundamentally characterized but will have a product uncertainty that is the lowest available from Fluke. This uncertainty specification is still significantly conservative compared to what is possible if a laboratory seeks the lowest uncertainty in pressure through fundamental characterization. This section concentrates more on what is possible, yet very reasonable for a laboratory to achieve.

A. Effective Area

The dimensional fundamental characterization of effective area for a large diameter piston-cylinder is no longer considered to be reserved for just high end national metrology institutes. Many NMIs and non-NMI laboratories are able to perform the proper steps to dimensionally characterize a piston-cylinder and perform a proper uncertainty analysis.

What does seem to be less standardized is a specific procedure to perform the dimensional characterization and also to perform the uncertainty analysis. PTB (Germany) in their efforts to realize the Boltzmann constant have produced what seems to be the most comprehensive method for dimensional characterization [2], [4].

This method involves producing a three dimensional model of the piston-cylinder by combining diameter, straightness and roundness measurements for each piece. This is done by ensuring the measurements connect at strategic points in the z axis and orthogonal position. The amount of measurements to take is not specifically defined, but should ensure that all significant deviations in cylindrical geometry are covered. For the PG9607, 50 mm diameter piston-cylinder there has been enough experience that 10 diameter measurements, 5 on each orthogonal plane, 5 roundness measurements and 4 straightness measurements provide sufficient data to characterize the effective area. Roundness measurements are made at the same z axis coordinates and straightness measurements are made at the four orthogonal positions the diameters were taken. Figure 5 is a graphical representation of this dimensional measurement scheme. This figure shows measurements at 7 z axis locations and is just to demonstrate the concept.

The measurements can then be related by least squares to both the radii needed to calculate the effective area at pressure and also to determine the uncertainty of the effective area based on dimensional measurements. The equations to calculate effective area at pressure are given by Dadson [3] and are:

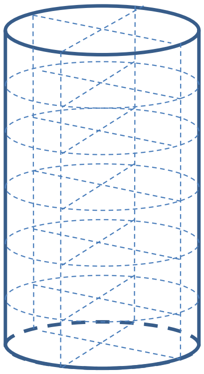

Figure 5. Example of three dimensional characterization using diameters, straightness and roundness measurements.

$$A_P = \pi {r_0}^2 \left\{ 1 + \frac{h_0}{r_0} + \frac{1}{r_0(P_1 - P_2)} \int_0^l (P - P_2) \frac{d(u+U)}{dx}\, dx \right\}. \qquad (2)$$

And

$$P = \left[{P_1}^2 - ({P_1}^2 - {P_2}^2) \frac{\int_0^x \frac{1}{h^3}\, dx}{\int_0^1 \frac{1}{h^3}\, dx} \right]^{1/2} \qquad (3)$$

where

r_0 = Piston radius at gap entrance [m],
h_0 = Gap at entrance [m],
U = Cylinder radius deviation [m],
u = Piston radius deviation [m],
P_1 = Pressure at gap exit [Pa],
P_2 = Pressure at gap entrance [Pa],
l = P-C engagement length [m],
x = Axial coordinate in engagement length [m], and
P = Pressure at axial coordinate [Pa].

What is advantageous about PTB's dimensional method is that the diameter measurements do not have to be made at z coordinate positions based on the integration method used. Instead, evenly spaced diameter measurements can be interpolated from the three dimensional model developed.

It should be noted that Equations 2 and 3 are intended for viscous flow and are not necessarily for molecular or transitional flow that can occur at low pressures in absolute. However the deviations from using this method are considered to be minimal.

A method for calculating uncertainty in effective area based on this method is also proposed by PTB [2], [4]. The method uses the uncertainty in diameter measurements and the deviations found between the diameter and roundness measurements and the diameter and straightness measurements.

$$u(r_S) = \left\{\left[\frac{u(D)}{2}\right]^2 + \delta^2\,(r_{D-S}) + \delta^2\,(r_{R-S})\right\}^{0.5} \tag{4}$$

$$u(r_R) = \left\{\left[\frac{u(D)}{2}\right]^2 + \delta^2\,(r_{D-R}) + \delta^2\,(r_{R-S})\right\}^{0.5} \tag{5}$$

In these equations, *u*(D) are the uncertainty in diameter measurements, $\delta(r_{D-R})$ is the difference between the diameter and roundness measurements, $\delta(r_{R-S})$ the difference of the roundness and straightness and $\delta(r_{D-S})$ the difference between diameter and straightness measurements. A more thorough discussion of the least squares method and uncertainty analysis is given in [4].

Equations 4 and 5 are unique in that they capture the uncertainty of the full three dimensional model. With the dimensional measurement capabilities of most NMI dimensional laboratories, and the manufacturers tolerance on geometry of the 50 mm piston-cylinder it is not unreasonable to assume an uncertainty of ±2 parts in 10^6 with a 95% confidence can be attained.

B. Change In Effective Area With Pressure

The PG9607 piston-cylinder uses a theoretical deformation coefficient developed by Fluke Calibration. The value is 4.57×10^{-6} MPa^{-1} and is considered to have a conservative uncertainty of 10%. Even if this is considered a rectangular distribution one standard uncertainty is equal to 0.13 parts in 10^6 for 500 kPa and introduces very little uncertainty to the final uncertainty in pressure.

Though this value is theoretical, as was previously stated the PG9607 is a controlled clearance piston gauge and allows for further studies of the validity of the theoretical deformation coefficient.

C. Change In Effective Area With Temperature

The thermal expansion coefficient for tungsten carbide piston cylinders has been well documented to be 9×10^{-6} $^\circ\text{C}^{-1}$. A conservative estimate in uncertainty of 5% provides a 1 standard uncertainty of 0.22 parts in 10^6 for each degree of correction.

The temperature of the piston-cylinder for a PG9607 is not measured directly. However, the design of the mounting post is such that two platinum resistance thermometers are placed in close proximity to the inner piston wall. During the development of the PG9607 studies were performed by comparing the piston-cylinder mounting post PRTs with a PRT placed in the internal bore of the mounting post where the cylinder would normally be positioned. The agreement was within ±0.03 ˚C.

What helps significantly in the assumption that the piston-cylinder is the same as the mounting post temperature is the stability of temperature. This is one of the primary reasons for designing as much heat producing electronics outside of the platform. Figure 6 is a chart showing the difference between ambient and piston-cylinder temperature in a lengthy test of a PG9607 and another commercial piston gauge offered by Fluke Calibration (PG7601). The tests were performed automatically in absolute mode with an automated mass handler and were performing the exact same test on the same device.

The difference between the ambient temperature and the piston-cylinder temperature is significantly higher for the PG7601. Note that this effect is usually only noticed in long automated absolute tests using automated mass handlers and does not jeopardize the uncertainty in pressure for a PG7601. Whereas for the PG9607 there was no detectable ramp in piston-cylinder temperature over the course of the test. This offers confidence that the temperature is stable and has equalized well between the mounting post and piston-cylinder temperatures.

The uncertainty of the temperature of the piston-cylinder depends on the uncertainty of the device making the measurement and the assumption that the piston-cylinder is the same as the temperature of the mounting post. With the capabilities of high end temperature laboratory to calibrate over a very short range of 20 to 25 ˚C, it is reasonable to assume an uncertainty of ±0.05 ˚C in piston-cylinder temperature measurement or one standard uncertainty of 0.22 parts in 10^6.

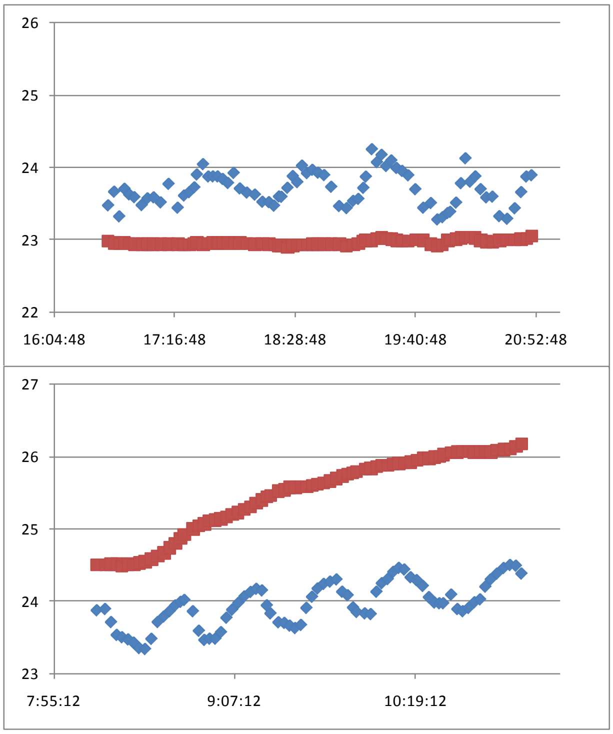

Figure 6. Piston-cylinder temperature (red) and ambient temperature (blue) of a PG9607 (top) and a PG7601 (bottom) performing the same pressure test.

D. Other Uncertainties Associated With The Piston-Cylinder

Other uncertainties that are normally included and are associated with the piston-cylinder are linearity and stability.

Linearity is an uncertainty associated with the assumption that the effective area is linear over its range. Though the uncertainty of the elastic deformation encompasses much of this, there is still a possibility that the effective area is not linear due to gap modelization effects not mechanical linearity errors in the elastic deformation. One standard uncertainty for this influence is estimated to be 0.23 parts in 10^6.

It has always been difficult to predict what the stability of a 50 mm tungsten carbide piston-cylinder is. Fluke Calibration has been using one of these piston-cylinders as a primary reference for approximately 10 years. The three determinations of effective area for this reference have not changed more than 1 part in 10^6. So one standard uncertainty of 0.5 parts in 10^6 is used as an estimate.

E. Mass

Uncertainty in mass for piston gauge applications has traditionally been relatively easy to maintain. This was primarily because the uncertainty in effective area was so high that it was not worth putting in the effort to reduce mass uncertainties. But with the expected low uncertainties of a PG9607, mass uncertainty becomes a significant focus. The main contributors to mass uncertainty are the method and reference used to calibrate the mass, the uncertainty in density, and the uncertainty due to changes over time.

One of the most significant attributes of an automated mass handler (AMH) is the fact that there is virtually no wear. The amount of movement required to load a mass is only a few mm. This is significant especially when compared to a manual mass set where it is almost impossible not to scrape masses when loading and unloading along the entire length of the bell assembly. For an AMH used with a PG9607, this would only occur when the piston-cylinder needs to be removed. Because of this, an estimated uncertainty due to stability of the masses is ±2 parts in 10^6 and a standard uncertainty of 1 part in 10^6.

The Fluke Calibration mass measurement uncertainty is accredited to an uncertainty of approximately 3 parts in 10^6. The product uncertainty analysis assumes 5 parts in 10^6 and is valid for 2 years for an AMH mass set. However, it is reasonable to assume the AMH masses could be calibrated to a level of ±2 parts in 10^6 at 95% confidence.

The density of the AMH mass set is stated to be 7920 kg/m^3 ± 40 kg/m^3, k=2, for all the main and binary masses. The cylinder mass has a density of 11 988 kg/m^3 ± 100 kg/m^3 and the mass carrying bell assembly has a density of 4537 kg/m^3 ± 100 kg/m^3. The higher uncertainties for the bell and the cylinder are due to the fact they are a combination of different materials, primarily tungsten for the cylinder and primarily titanium for the mass carrying bell. For the main and binary masses one standard uncertainty is listed as a relative uncertainty of 0.38 parts in 10^6. One standard uncertainty for the mass carrying bell assembly and the cylinder density is listed in pressure and is 0.023 Pa. Note that these uncertainties are listed in absolute mode and not in gauge mode. This is because the masses are calibrated in ambient air, so the error due to the mass density is greater as conditions change from the calibration. Since the worst case condition is when the ambient air is removed, as is the case in absolute mode, then the uncertainty is the greatest there and insignificant when ambient air is reasonably close to calibration conditions as it is in gauge mode.

An additional uncertainty is added to account for Krytox grease lubrication on the threads that connect the mass carrying bell assembly. If the proper procedure is followed to apply the lubrication, approximately 15 to 20 mg of the grease will be on the threads when calibrated. Measurements have shown that the grease will reduce its mass by 5 to 10 mg over the course of one year. Using ±10 mg as an uncertainty in pressure and one standard uncertainty is approximately 0.025 Pa.

One possible uncertainty contribution of the AMH mass set is the fact that the masses loaded are physically very close to the masses that are unloaded. If there were undefined forces from magnetism this could affect the uncertainty in pressure. The masses are manufactured using non-magnetic stainless steel and recent magnetic susceptibility tests have shown this influence to be minimal. However, for this level of uncertainty, if it is available, it is recommended to perform magnetic susceptibility tests at the time of mass determination.

F. Residual Vacuum

The residual pressure measured inside the bell jar is performed by an MKS 100 mTorr (13.3 Pa) unheated capacitive diaphragm gauge. The uncertainty is expanded to ±0.5% of reading + 0.05 Pa, whichever is greater. History has shown that this specification is easily met without regular zeroing for one year. This is with the condition that the sensor is isolated with a vacuum valve and continually kept under a vacuum.

Since the system operates in absolute without having to break the vacuum to change mass, and assuming a sufficient vacuum pump is used, the residual pressure is more frequently below 0.5 Pa. In this case one standard uncertainty is 0.025 Pa.

G. Type A

Type A uncertainty is estimated from crossfloats maintained to support the Fluke Calibration piston cylinder pressure calibration chain. This was also verified in crossfloats performed with the piston-cylinders manufactured for the PTB Boltzmann constant determination project. All crossfloats at various mass loads were well within ±2 parts in 10^6 and one standard uncertainty of 1 part in 10^6.

Variable or Parameter	Absolute	Gauge
Full Mass Load	100 kg	100 kg
(relative unc's)	[parts in 10^6]	[parts in 10^6]
Mass (M)	1	1
Local G	0.5	0.5
Air Density	n/a	0.38
Mass Density	0.38	n/a
Head (height)	0.35	0.35
Head (density)	0.23	0.23
Resolution	0.29	0.29
PC Temp	0.22	0.22
Verticality	0.1	0.1
Effective Area	1	1
Linearity	0.23	0.23
Elastic Deformation	0.23	0.23
Thermal Expansion	0.22	0.22
Stability Mass	0.5	0.5
Stability Ae	0.5	0.5
Sensitivity	0.14	0.14
Type A	1	1
COMBINED	**2.1 ppm + 0.042 Pa**	**2.1 ppm + 0.025 Pa**
EXPANDED	**4.2 ppm + 0.08 Pa**	**4.2 ppm + 0.05 Pa**
(absolute unc's)	[Pa]	[Pa]
Vacuum	0.025	n/a
Sensitivity	0.002	0.002
Mass Bell Grease	0.025	0.025
Bell Assembly Density	0.023	n/a

Table 2. Proposed Uncertainty Budget of a Fundamentally Characterized PG9607 Piston Gauge.

H. Sensitivity

The uncertainty due to the sensitivity of a piston-cylinder used in a piston gauge is similar to resolution. What is detected as sensitivity is considered a full width uncertainty at 95% confidence and is therefore reduced by a factor of the square root of 12 to represent one standard uncertainty. The sensitivity has been measured to be 0.005 Pa + 0.5 parts in 10^6. Since it is given as the sum of a pressure and a relative value it is entered twice in the uncertainty budget after being reduced by the square root of 12.

I. Combined and Expanded Uncertainty

Table 2 provides an uncertainty budget listing all uncertainties. Many of the influences are not discussed here and are easy to maintain. These include gravity, fluid head correction, ambient air density, resolution and verticality. Table 2 is structured so that all relative uncertainties are listed above the combined and expanded values and all the uncertainties listed in pressure are below. The uncertainty analysis does not combine the relative and pressure uncertainties. However being careful to avoid any correlation, these uncertainties could be root-sum-squared at specific pressures.

The uncertainty budget in Table 2 is not a Fluke Calibration product uncertainty budget. An explanation of the product uncertainty budget can be found in [5]. The uncertainty budget shown in Table 2 is a very reasonable estimate of what a laboratory could maintain with this system as discussed throughout this paper.

Conclusion

Following a strict and well founded procedure and uncertainty analysis for the dimensional characterization of the piston-cylinder allows the PG9607 to be used as a primary standard for pressure for either an NMI or any metrology laboratory wanting pressure realized at the highest levels. The uncertainties should be lower than what is currently used for mercury manometers and extends to a range that is higher than the mercury manometer in absolute and gauge modes.

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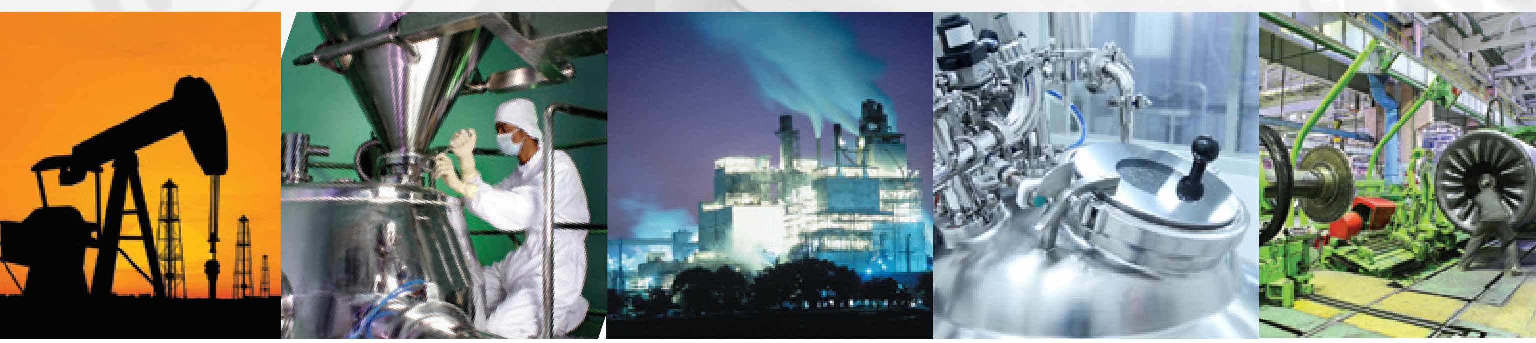

Could the Tried and True IEEE 488 Communication Standard Be Nearing the End of Its Reign?

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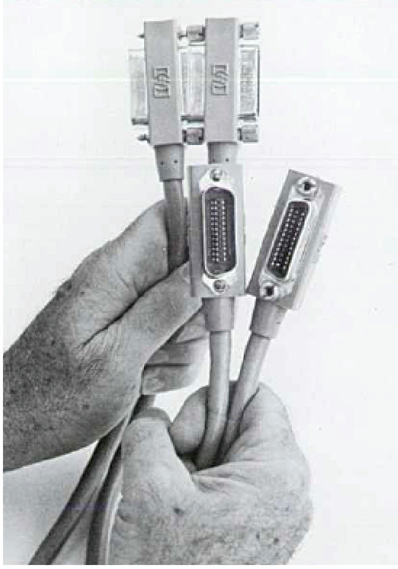
Today, less and less test equipment comes standard with a GPIB communication interface. Many don't even offer it as an option. It wasn't that long ago manufacturers included a GPIB interface standard on most test equipment. If you wanted to sell your electronic test equipment and get top dollar, it had to be GPIB compatible. But not anymore!

For more than 40 years, GPIB was the defacto standard for instrumentation control. It was simple to set up, easy to use, cross platform compatible. It controlled everything—not just test equipment; printers, hard drives, and all kinds of computer peripherals had GPIP versions at one time. At 8MB/S, it was also screaming fast running, supporting up to 15 instruments at one time and communicating with a device as far as 20 meters away. It also supported bi-directional communications, as well as instrument to instrument communications.

When I was first introduced to the General Purpose Interface Bus (GPIB), I thought it was amazing. I was new to automation, and computers at that time were not user friendly. Low level programming in C was the norm, and instrument control commands were more like cryptography. What has stuck in my mind all these years was when an engineer I was working with told me when they created the HPIB standard back in the late 60s, 8MB/S was theoretical. At that time, I was programming on a 286 computers with a top speed of 6 MHz.

GPIB gave us more than just communications; its simplicity allowed engineers to easily rack up a set of test equipment. Before, most calibration labs had all their standards located on their work bench. GPIB allowed us to take test equipment from different manufacturer's, rack them up into a single system, and have it all work.



Interconnecting cables used with interface system have dual connectors. These can be stacked to accommodate variety of physical layouts by allowing more than one cable to be attached to any device. Photo and caption used with permission of Hewlett-Packard. Source: *HP Journal*, October 1972.

But in today's fast paced world standards, GPIB is slow. Today's computers are running Quad Core 3.4GHz microprocessor—multi-tasking, streaming videos, surfing the web, and crunching numbers—then they have to change gears, by slowing down to push data through GPIB cable that is 400 times slower. If you have ever tried to upload a signal to an arbitrary waveform generator or pull a trace from an oscilloscope, you know what I am talking about.

The demise of GPIB is not just going to be speed; economics is also one of the driving forces. GPIB chips are expensive, because they lack the economy of scale compared to other more predominate communication chips like TCP/IP. The average GPIB cards cost over $350 dollars, whereas a USB and network interface cards are under $5 bucks.

Today, we are witnessing a change in instrumentation standards and computer technologies. As test equipment and computers become more hybridized, we will continue to see more of the innovations in computing technologies spill over into test equipment. USB and TCP/IP is just the start of this evolution—soon, things like Blue Tooth and even WiFi enable test equipment will be common. Everything new in computing technology will eventually be integrated into test equipment.

As communication standards like LXI and USB-UTMC are adopted by the industry, GPIB is slowly becoming a relic of the past. Technicians of tomorrow will be both measurement experts and information technology professionals. They will have to understand TCP/IP configuration for both LAN & WAN configurations—security, virus protection, computer backup operations, as well as imaging a full computer system. They will need full administrative privileges to install USB instruments. In a sense, your calibration labs will become a microcosm of computer support specialists.

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