CAL LAB

THE INTERNATIONAL JOURNAL OF METROLOGY

METROLOGY 101: VERIFYING 1 MW 50 MHZ POWER REFERENCE OUTPUT SWR

2013
JANUARY
FEBRUARY
MARCH

Stating Best Uncertainties Over a Range of Values

An Uncertainty Analysis for a Positive Displacement Liquid Flow Calibrator Using the Water Draw Technique

Transient Generators Spectrum Analyzers
RFI/EMI/EMC Synthesizers
DC Power Supplies Digital Multimeters ESD Test
VXI Electronic Loads Arbitrary Waveform Generators
Signal Generators Curve Tracers Ground Bond Calibrators

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Volume 20, Number 1

www.callabmag.com

FEATURES

DEPARTMENTS

ON THE COVER: Micah McDonald is preparing to Cross-Float a customer's Ametek deadweight tester against Alaska Metrology & Calibration Services' Ruska 2485 deadweight tester. Micah is performing this work in a Mobile Calibration Laboratory performing on-site work for BP Exploration and ConocoPhillips in Prudhoe Bay, Alaska.

CALENDAR

CONFERENCES & MEETINGS 2013

Mar 3-4 Southeast Asia Flow Measurement Conference. Kuala Lumpur, Malaysia. http://www.tuvnel.com.

Mar 7-8 METROMEET – 9th International Conference on Industrial Dimensional Metrology. Bilboa, Spain. METROMEET summons international leaders of the sector, to expose the latest advances in the subject and to propose product quality improvements and production efficiency. http://www.metromeet.org.

Mar 18-22 Measurement Science Conference (MSC). Anaheim, CA. This year's theme is "Global Economic Challenges Drive Operational Change In Metrology." Take your knowledge to the next level at our annual user conference and join over a thousand MSC users from all over the world for five days of education from over 30 developers and sessions. http://www.msc-conf.com.

Apr 22-25 FORUMESURE. Casablanca, Morocco. This exhibition and technical workshops on Measurement and Quality, organized by The African Committee of Metrology (CAFMET), brings together industries in the search for process control measurement, testing and analysis to ensure quality products and services. http://www.forumesure.com.

Apr 29-May 2 ESTECH. San Diego, CA. ESTECH 2013, the 59th annual technical conference of the Institute of Environmental Sciences and Technology (IEST), provides a platform for national and international professionals to share crucial strategies, research, and best practices for a wide range of Contamination Control, Test and Reliability, and Nanotechnology applications. http://www.iest.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 17th TC-4 Workshop IWADC on ADC and DAC Modeling and Testing will take place during the 19th IMEKO TC-4 Symposium on Measurements of Electrical Quantities. http://www.imeko2013.es/.

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 and to explain just how new and improved metrology can play a vital part in all their activities. http://www.flomeko2013.fr/.

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EDITOR'S DESK

Many Thanks

We've fallen off the proverbial economic cliff, but the car still reluctantly fires up at five degrees and the house roof is still solid… the world did not end. In fact, the church across the street is still rocking on Wednesday nights and "Junior," the neighborhood skunk, has returned now twice as big.

Since life progresses as usual, I took upon myself to clean up our mailing list for undeliverable addresses and those who may not want to keep receiving the magazine. We source our mailing list from the MSC and NCSLI conferences, as well as paid subscriptions. We would love to send complimentary subscriptions forever, but eventually we have to ask if subscribers would be willing to pay for their subscriptions if they are no longer attending the conferences.

We decided to keep subscription rates static indefinitely and offer a 10% discount to those who sign up for two years in order to attract more paying subscriptions. Because of the increasing rise of printing and postage costs, advertising revenue is not always enough to keep publications continuing today. So I would like to especially thank all those who contribute to Cal Lab Magazine in order to keep us printing—article contributors; Ted Green, the creator of Cal-Toons; advertisers (hoorah advertisers!); subscribers; and peers and community members who provide us with valuable feedback and suggestions… many, many thanks.

For this issue, our Metrology 101 contributor is Charles Sperrazza of Tegam, who wrote about verification of the Standing Wave Ratio (SWR) of a 50 MHz reference. David Deaver contributed a great paper on "Stating Best Uncertainties Over a Range of Values," and Wesley England contributed his paper, "An Uncertainty Analysis for a Positive Displacement Liquid Flow Calibrator Using the Water Draw Technique," which was awarded Best Paper at MSC 2011.

Again, thank you to everyone who makes it possible to print Cal Lab Magazine each quarter!

Regards,

Sita Schwartz

CALENDAR

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.

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, http://www.wptraining.com/.

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.

The Uncertainty Analysis Program. Learning Measure. http://www.learningmeasure.com/.

Magnetic Field Measurement

Fluxgate Transducers

Bartington Instruments

High Sensitivity for Low Fields

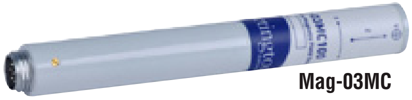
One and Three-axis Transducers with ±10V (±3V Mag640) analog outputs for each axis. For environmental field monitoring, mapping and active cancellation. Cryogenic sensors available.

Field Ranges	70, 100, 250, 500, 1000µT
Frequency Response	dc to 3kHz (-3dB) (Mag03), dc to >1kHz (Mag690, Mag649)
Noise Level	< 20pTrms/√Hz at 1Hz (Mag690), < 10pTrms/√Hz at 1Hz (Mag649), < 12pTrms/√Hz at 1Hz (Mag03 standard), < 6pTrms/√Hz at 1Hz (Mag03 low noise),

Mag648/649

Mag690

Mag-03MS



Mag-03MC

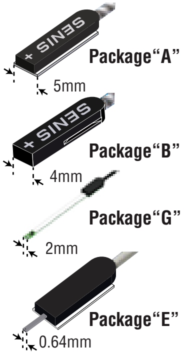
Hall Transducers

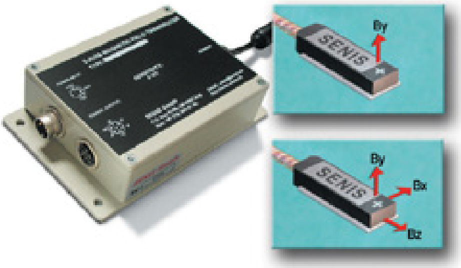
Analog Output for Mapping or Control

One-, Two- and Three-axis Transducers with ±10V analog outputs for each axis.

Field Ranges	20mT, 200mT, 2T, 5T, 10T, 20T
Accuracy	±1% or ±0.1%
Frequency Response	dc to 2.5kHz (-3dB); Special to 25kHz
White Noise at >10Hz	0.12µT/√Hz for 2T range (Y-axis), 2µT/√Hz for 2T range (3-axis)

Hall Transducer Probe Packages





SENIS magnetic & current measurement

USB/Handheld Teslameters

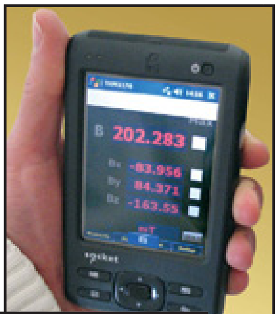
METROlab

USB Connector, 3-Axis, Handheld PDA Available

For pre-installation site surveys for magnetically sensitive equipment. Post-installation surveys of the dc and ac fringe fields of large magnets and magnetic assemblies. Field harmonic measurements over time for non-invasive load and condition monitoring of ac power assemblies like tranformers and motors.

Fluxgate Probe	**TFM1186**	
Field Range	100µT	
Noise	5nT p-p, 8 nT RMS (2kSPS, no averaging); 4nT p-p (100x averaging)	
Hall Probe	**THM1186-LF**	**THM1186-HF**
Field Ranges	8mT	0.1T, 0.5T, 3T, 20T
Resolution	2µT	3mTon 3Trange

TFM1186
Fluxgate Probe



THM1176
Hall Probe

NMR Teslameter

Mapping and Calibration Standard

For field calibration, mapping and control with high resolution,very high stability and absolute accuracy.

Field Ranges	from 0.04T to 13.7T
Resolution	±0.1µT or 1Hz (proton sample)
Absolute Accuracy	±5ppm

RS-232C and IEEE-488 Interfaces

Multiprobe NMR arrays for precision mapping of large magnets

METROlab

PT2025

CALENDAR

SEMINARS: Dimensional

Feb 28-Mar 1 Seminar – Gage Calibration Systems and Methods. Aurora, IL. The Mitutoyo Institute of Metrology. http://www.mitutoyo.com.

Mar 7-8 Hands-On Gage Calibration and Repair Workshop. Minnetonka, MN. http://www.iicttraining.com.

Mar 12-13 Seminar – Dimensional Metrology: Applications and Techniques. City of Industry, CA. The Mitutoyo Institute of Metrology. http://www.mitutoyo.com.

Mar 19-20 Hands-On Gage Calibration and Repair Workshop. Houston, TX. http://www.iicttraining.com.

Mar 19-21 Gage Calibration and Minor Repair Training. Cincinnati, OH. Cincinnati Precision Instruments,Inc. http://www.cpi1stop.com/.

Mar 27-28 Hands-On Gage Calibration and Repair Workshop. Cincinnati, OH. http://www.iicttraining.com.

Apr 4-5 Hands-On Gage Calibration and Repair Workshop. Billings, MT. http://www.iicttraining.com.

Apr 8-9 Hands-On Gage Calibration and Repair Workshop. Portland, OR. http://www.iicttraining.com.

Apr 9-11 Seminar - Hands-On Gage Calibration. Elk Grove Village, IL. The Mitutoyo Institute of Metrology. http://www.mitutoyo.com.

May 14-16 Gage Calibration and Minor Repair Training. Cincinnati, OH. Cincinnati Precision Instruments,Inc. http://www.cpi1stop.com/.

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

SEMINARS: Electrical

Mar 7-8 Essential Electrical Metrology. Orlando, FL. WorkPlace Training. http://www.wptraining.com.

Apr 8-11 MET-301 Advanced Hands-on Metrology. Seattle, WA. Fluke Calibration. http://us.flukecal.com/training/courses/MET-301.

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

CALENDAR

SEMINARS: Flow & Pressure

Feb 25-Mar 1 Principles of Pressure Calibration. Phoenix, AZ. Fluke Calibration. http://us.flukecal.com/Principles-of-Pressure.

Mar 6-7 Fundamentals of Ultrasonic Flowmeters Training Course. Brisbane, Australia. http://www.ceesi.com.

Mar 18-19 NIST Pressure and Vacuum Measurement. Anaheim, CA. NIST Seminar N03, hosted by MSC. http://www.msc-conf.com.

Mar 26-27 Fundamentals of Ultrasonic Flowmeters Training Course. Houston, TX. http://www.ceesi.com.

Apr 15-19 Advanced Piston Gauge Metrology. Phoenix, AZ. Fluke Calibration. http://us.flukecal.com/Advanced-Piston-Gauge.

Apr 16-18 European Ultrasonic Meter User's Workshop. Lisbon, Portugal. http://www.ceesi.com.

May 14-16 Principles and Practice of Flow Measurement Training Course. East Kilbride, UK. http://www.tuvnel.com/tuvnel/courses_workshops_seminars/.

SEMINARS: General

Mar 4-6 Cal Lab Training; Beyond 17025. Orlando, FL. WorkPlace Training http://www.wptraining.com.

Mar 25-27 Instrumentation for Test and Measurement. Las Vegas, NV. Technology Training, Inc. http:// www.ttiedu.com.

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

Apr 8-12 Calibration Lab Operations / Understanding ISO 17025. Las Vegas, NV. Technology Training Inc. http://www.ttiedu.com.

Apr 15 Fundamentals of Metrology. Gaithersburg, MD. http://www.nist.gov/pml/wmd/labmetrology/training.cfm.

SEMINARS: Mass & Weight

Mar 4 Mass Metrology Seminar. Gaithersburg, MD. http://www.nist.gov/pml/wmd/labmetrology/training.cfm.

May 13 Mass Metrology Seminar. Gaithersburg, MD. http://www.nist.gov/pml/wmd/labmetrology/training.cfm.

CALENDAR

SEMINARS: Measurement Uncertainty

Mar 12-13 Estimating Measurement Uncertainty. Aurora, IL. The Mitutoyo Institute of Metrology. http://www.mitutoyo.com.

Mar 18-19 JCGM Guide to the Expression of Uncertainty Measurement. Anaheim, CA. NIST Seminar N04, hosted by MSC. http://www.msc-conf.com.

Mar 20-22 Measurement Uncertainty Workshop. Fenton, MI. QUAMETEC Institute of Measurement Technology. http:// www.QIMTonline.com.

May 7-9 MET-302 Introduction to Measurement Uncertainty. Everett, WA. Fluke Calibration. http://us.flukecal.com/training/courses/MET-302.

May 15-17 Measurement Uncertainty Workshop. Fenton, MI. QUAMETEC Institute of Measurement Technology. http:// www.QIMTonline.com.

SEMINARS: Standards

Mar 18-19 The ISO/IEC 17025 Accreditation Process. Anaheim, CA. NIST Seminar N01, hosted by MSC. http://www.msc-conf.com.

SEMINARS: Temperature

Mar 5-7 Infrared Temperature Metrology. American Fork, UT. Fluke Calibration, http://us.flukecal.com/tempcal_training.

Mar 18-20 Selection, Calibration, and Use of Contact Thermometers. Anaheim, CA. NIST Seminar N02, hosted by MSC. http://www.msc-conf.com.

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

SEMINARS: Vibration

Mar 5-7 Fundamentals of Random Vibration and Shock Testing. Houston, TX. http://www.equipment-reliability.com.

Mar 11-14 Mechanical Shock and Modal Test Techniques. Las Vegas, NV. Technology Training, Inc. http://www.ttiedu.com.

Apr 9-11 Fundamentals of Random Vibration and Shock Testing, HALT, ESS, HASS (...). College Park MD. http://www.equipment-reliability.com.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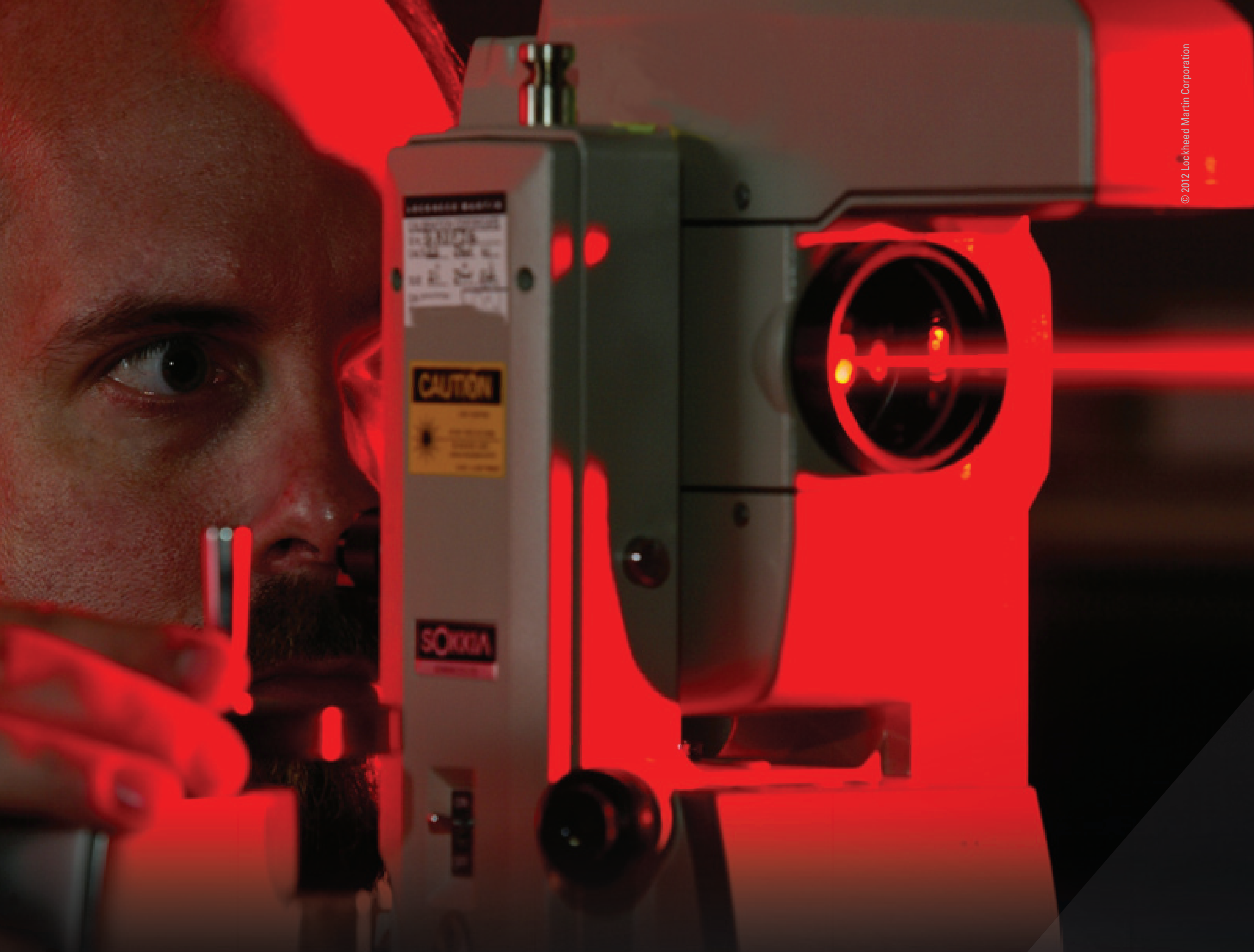

CAUTION
SOKKIA

Carl Zeiss Industrial Metrology Acquires HGV Vosseler

With the acquisition of HGV Vosseler GmbH & Co. KG in Öhringen, Germany, Carl Zeiss Industrial Metrology (IMT) is strengthening its presence in the market for process control and inspection in car making.

HGV is one of the world's three leading companies for 3D inline measuring solutions based on optical 3D measuring technology on robots which are primarily used for car body inspection directly on the production line in the automotive industry. Robot-assisted inline measuring technology for car bodies is an important addition to metrology in the measuring lab. In addition to 3D inline measuring technology, HGV also offers innovative optical image processing systems for quality inspection.

Effective immediately, Dr. Kai-Udo Modrich will be responsible for the new company, Carl Zeiss Machine Vision GmbH & Co KG. Under the ZEISS brand, the approx. 60 employees in Öhringen, Germany, will have future perspectives focused on further growth.

You can find further info here: http://www.zeiss.de/press/pr003cd603.

Transcat Acquisition of Cal-Matrix Metrology Inc.

Transcat, Inc., a leading distributor of professional grade handheld test, measurement and control instruments and accredited provider of calibration, repair, inspection and other compliance services, announced today that it has acquired Cal-Matrix Metrology Inc., a leading Canadian provider of commercial and accredited calibrations and coordinate measurement inspection services. Headquartered in Burlington (Greater Toronto Area), the acquisition greatly expands Transcat's presence in Southern Ontario, the largest market in Canada, and adds a lab in Montreal, Quebec.

Cal-Matrix offers calibration services to clients who require calibration of their RF, DC low frequency, optics, mechanical, torque and pressure measurement equipment. Cal-Matrix maintains a comprehensive ISO/IEC-17025-2005 certified scope for calibration and coordinate measurement inspection.

Lee Rudow, President and Chief Operating Officer of Transcat, added, "In order to continue this superior level of customer service, Cal-Matrix's management team and its nearly 30 employees have been retained by Transcat."

More information about Transcat can be found on its website at: transcat.com.

NIST's 'Nanotubes on a Chip' May Simplify Optical Power Measurements

The National Institute of Standards and Technology (NIST) has demonstrated a novel chip-scale instrument made of carbon nanotubes that may simplify absolute measurements of laser power, especially the light signals transmitted by optical fibers in telecommunications networks.

The prototype device, a miniature version of an instrument called a cryogenic radiometer, is a silicon chip topped with circular mats of carbon nanotubes standing on end.* The mini-radiometer builds on NIST's previous work using nanotubes, the world's darkest known substance, to make an ultraefficient, highly accurate optical power detector,** and advances NIST's ability to measure laser power delivered through fiber for calibration customers.***

"This is our play for leadership in laser power measurements," project leader John Lehman says. "This is arguably the coolest thing we've done with carbon nanotubes. They're not just black, but they also have the temperature properties needed to make components like electrical heaters truly multifunctional."

NIST and other national metrology institutes around the world measure laser power by tracing it to fundamental electrical units. Radiometers absorb energy from light and convert it to heat. Then the electrical power needed to cause the same temperature increase is measured. NIST researchers found that the mini-radiometer accurately measures both laser power (brought to it by an optical fiber) and the equivalent electrical power within the limitations of the imperfect experimental setup. The tests were performed at a temperature of 3.9 K, using light at the telecom wavelength of 1550 nanometers.

The tiny circular forests of tall, thin nanotubes called VANTAs ("vertically aligned nanotube arrays") have several desirable properties. Most importantly, they uniformly absorb light over a broad range of wavelengths and their electrical resistance depends on temperature. The versatile nanotubes perform three different functions in the radiometer. One VANTA mat serves as both a light absorber and an electrical heater, and a second VANTA mat serves as a thermistor (a component whose electrical resistance varies with temperature). The VANTA mats are grown on the micro-machined silicon chip, an instrument design that is easy to modify and duplicate. In this application, the

individual nanotubes are about 10 nanometers in diameter and 150 micrometers long.

By contrast, ordinary cryogenic radiometers use more types of materials and are more difficult to make. They are typically hand assembled using a cavity painted with carbon as the light absorber, an electrical wire as the heater, and a semiconductor as the thermistor. Furthermore, these instruments need to be modeled and characterized extensively to adjust their sensitivity, whereas the equivalent capability in NIST's mini-radiometer is easily patterned in the silicon.

NIST plans to apply for a patent on the chip-scale radiometer. Simple changes such as improved temperature stability are expected to greatly improve device performance. Future research may also address extending the laser power range into the far infrared, and integration of the radiometer into a potential multipurpose "NIST on a chip" device.

* N.A. Tomlin, J.H. Lehman. Carbon nanotube electrical-substitution cryogenic radiometer: initial results. *Optics Letters*. Vol. 38, No. 2. Jan. 15, 2013.

** See 2010 NIST *Tech Beat* article, "Extreme Darkness: Carbon Nanotube Forest Covers NIST's Ultra-dark Detector," at www.nist.gov/pml/div686/dark_081710.cfm.

***See 2011 NIST *Tech Beat* article, "Prototype NIST Device Measures Absolute Optical Power in Fiber at Nanowatt Levels," at www.nist.gov/pml/div686/radiometer-122011.cfm.

Source: NIST Tech Beat, January 24, 2013.

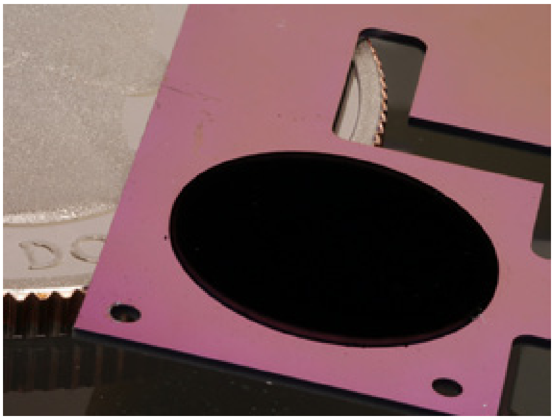
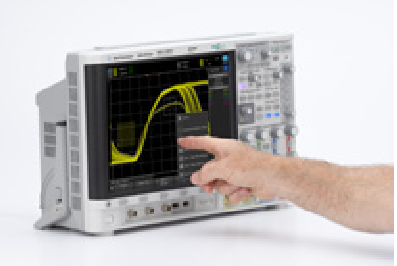


Image Source: National Institute of Standards and Technology. Credit: Tomlin/NIST.

NEW PRODUCTS AND SERVICES

Agilent InfiniiVision 4000 X-Series Oscilloscope



Agilent Technologies Inc. introduces the groundbreaking InfiniiVision 4000 X-Series digital-storage and mixed-signal oscilloscopes. This new series establishes unprecedented levels of flexibility and ease of use among units that use an embedded operating system.

The new lineup offers bandwidths from 200 MHz to 1.5 GHz and several benchmark features. First is an industry-leading update rate of 1 million waveforms per second with standard segmented memory, which uses patented MegaZoom IV smart memory technology. Next are a 12-inch capacitive touch screen-the industry's largest-and the exclusive, all-new InfiniiScan Zone touch-triggering capability. Because the 4000 X-Series was designed specifically for touch operation, engineers can select targets naturally and quickly. For example, InfiniiScan Zone makes triggering as easy as finding the signal of interest and drawing a box around it: If users can see a signal, they can trigger on it.

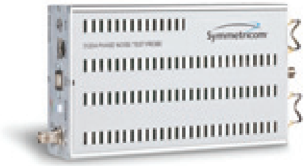
The high level of integration starts with the capabilities of five instruments on one unit: oscilloscope, digital channels (MSO), protocol analysis, digital voltmeter and dual-channel WaveGen function/arbitrary waveform generator. The 4000 X-Series also supports a wide range of popular optional applications: MIL-STD 1553 and ARINC 429; I2S; CAN/LIN; FlexRay; RS232/422/485/UART; I2C/ SPI; and USB 2.0 Hi-Speed, Full-Speed and Low-Speed triggering and analysis (the first hardware-based USB trigger/decode oscilloscope solution).

The InfiniiVision 4000 X-Series includes 200-MHz, 350-MHz, 500-MHz, 1-GHz and 1.5-GHz models. The standard configuration for all models includes 4 Mpts of memory and segmented memory. Information about the InfiniiVision 4000 X-Series oscilloscopes is available at www.agilent.com/find/4000X-Series.

Symmetricom 3120A Test Probe

Symmetricom®, Inc., a worldwide leader in precision time and frequency technologies, announced the launch of a new high-performance, low-cost measurement solution, the Symmetricom 3120A Phase Noise Test Probe. The latest addition to Symmetricom's state-of-the-art timing test set portfolio, the 3120A Test Probe comes in a convenient small form factor and measures Phase Noise and Allan Deviation as part of the base hardware kit. Additional software options are available to measure AM noise floor and signal statistics such as HDEV, TDEV, MDEV and jitter, and for use as a frequency counter and for mask testing.

Unlike traditional solutions that are desktop-bound due to size and weight, Symmetricom's 3120A Test Probe is small enough to be carried around from location-to-location, and inexpensive enough to have at each bench. Whether used on a busy manufacturing floor, in a tight server closet or in R&D labs, the 3120A helps characterize reference clocks, used in high-performance applications, achieve the highest accuracy without requiring calibration.



The 3120A Test Probe comes with easy-to--use, intuitive software to take measurements and conduct analysis. The 3120A Phase Noise Test Software displays results in seconds without the need for external data processing. http://www.symmetricom.com/.

NEW PRODUCTS AND SERVICES

Beamex MC2-IS Calibrator

The 2nd generation of MC2-IS is a lightweight, user-friendly and practical tool for calibration in hazardous environments such as offshore platforms, refineries, and gas pipeline and distribution centers. Features, such as display visibility with LED backlight, more powerful processor and improved battery shelf life have been realized. The ATEX and IECEx certified 2nd generation of MC2-IS is robust and able to perform calibrations for pressure, temperature and electrical measurement. It connects to almost 20 available Beamex intrinsically safe external pressure modules and has a multilingual interface and complete numerical keyboard.

Benefits:

- High accuracy
- Compact and user-friendly
- Display with LED backlight
  Powerful processor
- Almost 20 available external pressure modules
- Wide range of configuration possibilities
- Safe and robust field calibrator
- Delivered with traceable and accredited calibration certificate

Mitutoyo's New "Gold Care" Program

Mitutoyo America Corporation announces a new sales program based on "packaging" select Coordinate Measuring Machines (CMMs) and Vision Systems with related equipment and service packages at no extra cost over the price of the base machine. By closely listening to the "cost of ownership" and "simplified buying" desires of metrology equipment buyers over the last 50 years, Mitutoyo's new "Gold Care" program packages peripheral equipment and multi-year service packages (representing an overall $15,000+ savings) with a larger select group of these types of machines. The program launched January 1, 2013 and is available to US-based companies served by Mitutoyo America for a limited time period throughout the year.

<u>Measuring machines included in this program:</u>

- CNC CMMs: CRYSTA-Plus Series (400/500/700 Models)
- Manual CMMs: CRYSTA-Apex S CNC Series (500/700/900/1200 Models)
- Vision Machines: QV-Apex Pro, QV-Apex TP Systems

<u>"Gold Care" package includes:</u>

- A "Second Year" extended warranty covering all labor and part costs (industry standard is one year)
- A two year "Bronze" calibration agreement (A2LA Accredited)
- A five year technical phone support program covering all of the machine's software needs
- Mitutoyo's exclusive MeasurLink® Pro Edition software

Workholding solutions included in this program: Mitutoyo's own Eco-Fix® Fixturing System, Mitutoyo's Opti-Fix® Fixturing System (helps to facilitate workholding and faster throughput). Measurement devices included: Starter Stylus Kit (multiple probes and extensions for touch applications) for CMMs and our Starter Stylus Kit (multiple probes and extensions for touch applications) for Vision Systems.

For more information, visit: www.mitutoyo.com.

Pasternack VNA Cal Kits

Pasternack Enterprises, Inc., a leading ISO 9001:2008 certified manufacturer and global supplier of RF and microwave products, introduces their new lines of vector network analyzer calibration kits.

The new vector network analyzer (VNA) calibration kits from Pasternack provide the RF components needed to enable stable and accurate error corrected measurements of devices under test (DUT) using a VNA from DC to 26.5 GHz in one convenient kit. Calibration of a DUT using Pasternack's kit allows for precise measurements needed to meet IEEE 287 standards. Pasternack's VNA calibration kits offer broad VNA coverage for the most popular models including Agilent®, Anritsu®, Rohde & Schwarz® and other VNAs. The Pasternack VNA calibration kits yield the most complete calibration, as it accounts for the three major sources of systematic error correction by one-port calibration at both ports.

VNA calibration kits from Pasternack contain both male/plug and female/jack connector interfaces to perform full two port error corrections. Pasternack's 3.5mm / SMA VNA and Type N VNA calibration kits are designed for equipment that utilizes the open-short-load (OSL) calibration method. The network analyzer calibration kit from Pasternack is packaged in a durable, protective wood box and includes a preset torque wrench for Type N or 3.5mm and SMA connectors. Complimentary in-series phase matched adapters, armored test cable kits and 3-port field calibration (OSL) devices are available individually.

VNA calibration kits from Pasternack are available now by visiting our new website at http://www.pasternack.com/vna-calibration-kits-category.aspx. Pasternack Enterprises, Inc. can also be contacted at +1-949-261-1920.

PolyScience Liquid Cooling

A line of low temperature coolers that provide rapid, low cost cooling of liquids to temperatures as low as -100 °C is available from PolyScience. Available in both immersion probe and flow through styles, these compact systems are ideal for cooling exothermic reactions, freeze point determinations, freeze drying, impact testing, lyophilization, and vapor and solvent trapping.

Excellent for trapping, Dewar-type applications, and the rapid cool down of small volumes of liquids, PolyScience Immersion Probe Style Coolers reduce the expense of using dry ice or liquid nitrogen and are capable of reaching temperatures as low as -100 °C. A flexible hose allows convenient placement of the cooling probe. Seven different models as well as a variety of probe types are available.

Capable of reaching temperatures as low as -25 °C, PolyScience Flow-Through Style Coolers are ideal for extending the temperature range of non-refrigerated circulators to below ambient as well as boosting the cooling capacity of refrigerated circulators. These coolers also offer an extremely economic alternative to tap water cooling of heated circulating baths when rapid cool-downs or operation at or near ambient is needed.

For more information on PolyScience Low Temperature Coolers, visit www.polyscience.com or call toll-free, 1-800-229-7569, outside the US call 847-647-0611, email sales@polyscience.com.

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Rohde & Schwarz Step Attenuators Up to 67 GHz

With the R&S RSC family, Rohde & Schwarz is launching a unique range of switchable step attenuators. The product family encompasses the world's first step attenuator up to 67 GHz and a precision model with 0.1 dB step size offering excellent accuracy and stability.

The new R&S RSC family from Rohde & Schwarz consists of four models of the R&S RSC base unit and two external step attenuators. The base unit is available with or without internal step attenuator. The internal step attenuators come in three versions and can handle signals up to max. 18 GHz. The two external step attenuators cover frequencies up to max. 67 GHz. Every base unit can control up to four external step attenuators in parallel.

The R&S RSC step attenuators allow users to attenuate signal power step by step either manually or by remote control. A typical field of application is the calibration of measuring instruments, especially receiver linearity testing.

The R&S RSC base unit with internal step attenuator is available in three versions. The standard version covers an attenuation range of 139 dB with a 1 dB step size up to 6 GHz. Rohde & Schwarz also offers a precision step attenuator especially for users in aerospace and defense. It covers the frequency range from DC to 6 GHz and features a maximum attenuation of 139.9 dB and a step size of 0.1 dB, which is unique worldwide. The third version handles the frequency range up to 18 GHz with a maximum attenuation of 115 dB and a step size of 5 dB.

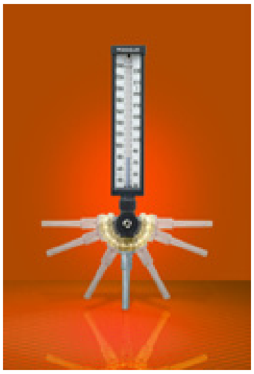
Every R&S RSC base unit can control a maximum of four external step attenuators. The instrument family includes two base unit models up to 40 GHz and 67 GHz, respectively. Both attenuate the signal by max. 75 dB at a step size of 5 dB. The 67 GHz step attenuator from Rohde & Schwarz is the only one in the world for this frequency range. The external step attenuators are configured and controlled via the base unit, a PC with Rohde & Schwarz control program or via an application program.

To achieve the highest possible measurement accuracy, the frequency response of each step attenuator is measured in the factory and stored in the instrument. At the current operating frequency, an R&S RSC can automatically correct its absolute attenuation by its frequency response, which reduces attenuation uncertainty to a minimum. Test setup components such as cables or high-power attenuators can be included in the displayed overall attenuation.

All models are equipped with IEC/IEEE, LAN and USB interfaces. Legacy Rohde & Schwarz attenuators are supported via the compatibility mode of the R&S RSC so that customers do not have to change their control programs. The R&S RSC step attenuators are now available from Rohde & Schwarz. For detailed information, visit www.rohde-schwarz.com/product/RSC.

NEW PRODUCTS AND SERVICES

Weksler Adjustable Angle Glass Thermometer



The Weksler® Model A935AF5 universal "adjust-angle" thermometer is rated at ±1% accuracy and is available with either a seven or nine-inch scale. 360° case and stem rotation and large graduations make it easy to read in nearly all types of installations.

Other standard features include a high impact, lightweight Valox® V-shaped black case, a protective glass front and blue spirit fill that eliminates the use of mercury. An aluminum case is also available along with an optional plastic window and a choice of several additional stem lengths.

For more information, visit www.weksler.com or call (800) 328-8258. For Technical Sales, contact: Diana Lescinsky at 203/385-0739 or email Diana.lescinsky@ashcroft.com.

Agilent Technologies USB Thermocouple Power Sensors

Agilent Technologies Inc. recently introduced the Agilent U8480 Series, the world's fastest USB thermocouple power sensors. Based on the same front-end design as the Agilent 8480 and N8480 Series power sensors, the new U8480 Series offers improved specifications, including a measurement speed of 400 readings per second, 10 times faster than the legacy series.

The U8480 Series provides the best accuracy in Agilent's power-meter and sensor portfolio and comes with a power linearity of less than 0.8 percent. As Agilent's first power sensor with the ability to measure down to DC, the U8480 Series covers a broader range of test applications. DC-range measurements are frequently used for source calibration, as power-measurement references, and for testing select electromagnetic compatibility.

With USB functionality, U8480 Series power sensors plug directly in to PCs or USB-enabled Agilent instruments and offer users the ability to measure power without needing an external power meter or power supply. With their built-in trigger function, Agilent's thermocouple power sensors give test engineers the ability to synchronize measurement capture without needing an external module. The internal calibration function saves time and reduces wear and tear on connectors. These power sensors also come bundled with Agilent's N1918A Power Panel software, making the U8480 Series one of the most cost-effective solutions in the company's power-meter and sensor portfolio.

The Agilent U8480 Series USB thermocouple power sensors are now available worldwide. The U8481A-100 (10 MHz to 18 GHz) and U8485A-100 (10 MHz to 33 GHz) are priced at $2,835 and $4,028, respectively. The DC-coupled versions of the sensors, U8481A-200 (DC to 18 GHz) and U8485A-200 (DC to 33 GHz) are priced at $3,043 and $4,236, respectively.

Information on the U8480 Series is available at www.agilent.com/find/usbthermosensor_pr.

Radian Research Portable On-Site Testing Solutions

Radian Research, a provider of advanced solutions for power and energy measurement, introduces three new products for portable on-site meter testing. The newly released Bantam Plus portable three-phase meter test solution, Tx Auditor portable transformer analyzer and Model 430 ultra-compact portable meter test kit are the ultimate choice for energy meter testing.

The Bantam Plus is the newest and most technologically advanced portable three-phase meter site test solution available for today's metering professional. This innovative solution supplies a safe, accurate and highly versatile answer to the diverse test requirements of today's electric metering. The Bantam Plus is equipped with an automated test socket, embedded RD reference standard, fully isolated synthesized current and voltage source, on board operating system and a choice of 0.02% or 0.04% accuracy class.

The Tx Auditor TM is designed with Radian's years of leadership and experience in electricity measurement. The result is a technologically advanced and industry-leading solution for in service testing of current and potential transformers. Tx Auditor can test burden ratio, admittance and demagnetize CTs.

The Model 430 is the first Ultra-Compact Portable Phantom Load Test Kit to support both the Radian Dytronic (RD) and the installed base of Radian Metronic (RM) reference standards. The Model 430 can perform open or closed link meter testing. Lightweight with convenient quick connect cabling the 430 is an ideal budgetary solution for on-site meter testing.

Bantam Plus portable three-phase meter test solution, Tx Auditor portable transformer analyzer and Model 430 ultra-compact portable meter test kit allow integration of data throughout your organization. All three new products are compatible with Watt-Net Plus meter data management software. Watt-Net Plus tracks metering equipment over its life cycle and automates meter shop functions, including; clerical and administrative, meter and transformer testing, purchase order tracking, manufacturer and contact test data import. In addition, data can be customized to fit your organization's business rules.

Radian is recognized throughout the world for the absolute unparalleled accuracy, precision and stability of electric energy measurement products. The new Bantam Plus, Tx Auditor and Model 430 are Radian's proud addition to that tradition.

Radian is dedicated to providing effective solutions for power and energy measurement. For additional information on the Bantam Plus, Tx Auditor and Model 430, please email your request to radian@radianresearch.com or contact your local Radian Representative. Information is also available on the web at http://www.radianresearch.com.

METROLOGY 101

Verifying 1 mW 50 MHz Power Reference Output Standing Wave Ratio (SWR)

By Charles Sperrazza
TEGAM Inc.

Part I

Introduction

Verification of the Standing Wave Ratio (SWR) of the 50 MHz 1 mW output power reference is a key step in performing a calibration of a RF power meter. Higher than desired SWR can impact the amount of power delivered to the load (power sensor), therefore we must know that the SWR is within limits at our reference point.

Figure 1. 50 MHz 1 mW Reference.

A thermistor power sensor as shown in Figure 3 coupled with a thermistor power meter, such as the TEGAM 1830A, can accurately estimate through calculation the SWR of a 50 MHz reference. By utilizing a unique function that most modern power meters do not offer; the 1830A allows the user to change the value of the thermistor mounts terminating resistance. Utilizing this method for measuring source match works well because it presents the source with two distinctly different values of Γ_{Load} which allows accurate measurement of the power absorbed under two different conditions.

This article will explain how we make this SWR measurement with the 1830A thermistor power meter and a thermistor power sensor.

Understanding How a Thermistor Power Meter Works in Conjunction with a Thermistor Power Sensor

Before getting into the actual SWR measurement, it is first important to understand how a thermistor sensor operates and why by simply changing the resistance that the reference resistor balances can accurately determine SWR.

First we need to understand SWR: Standing Wave Ratio (SWR) is the ratio of the amplitude of a partial standing wave at an antinode (maximum) to the amplitude at an adjacent node (minimum), in an electrical transmission line. The SWR is usually defined as a voltage ratio and is called VSWR, for voltage standing wave ratio. For example, the VSWR value 1.3:1 denotes maximum standing wave amplitude that is 1.3 times greater than the minimum standing wave value. The smaller the ratio is, the better the match. Refer to Figure 2 to understand the contrast between desirable SWR vs. undesirable SWR.

The method of using a transfer of power to verify the SWR is a function of the combination of the source and load port match. When talking about port match; SWR, Γ, and termination impendence are strictly related and can be talked about interchangeably. By varying the termination impedance and knowing the ρ at each impedance allows us to calculate Γ_S. Knowing Γ_S allows us to calculate SWR. To accomplish this we first present a DC Resistance of 200 Ω is used which presents an RF impedance of 50 Ω with a negligible ρ (for this we will use 0), and the then having the ability to change the load resistance to 100 Ω the RF impedance becomes 25 Ω giving a nominal ρ of 0.33. Because the effective efficiency of the thermistor sensor remains constant at both 200 Ω and 100 Ω a power ratio can be measured accurately. Thermistor sensors like the TEGAM Model M1130A or the Agilent 478A with option H75 or H76 are an ideal choice[1].

Figure 3 shows how series resistance of two thermistors at the nominal bridge resistance, typically 200 Ω. The thermistors (T) are matched so each thermistor is biased at 100 Ω. The thermistors are in parallel for the RF signal path, since each are biased at 100 Ω the pair make a good 50 Ω termination.

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[1] From 1 MHz to 1 GHz maximum, VSWR is less than 1.3:1, except at 50 MHz, maximum VSWR of 1.05:1.

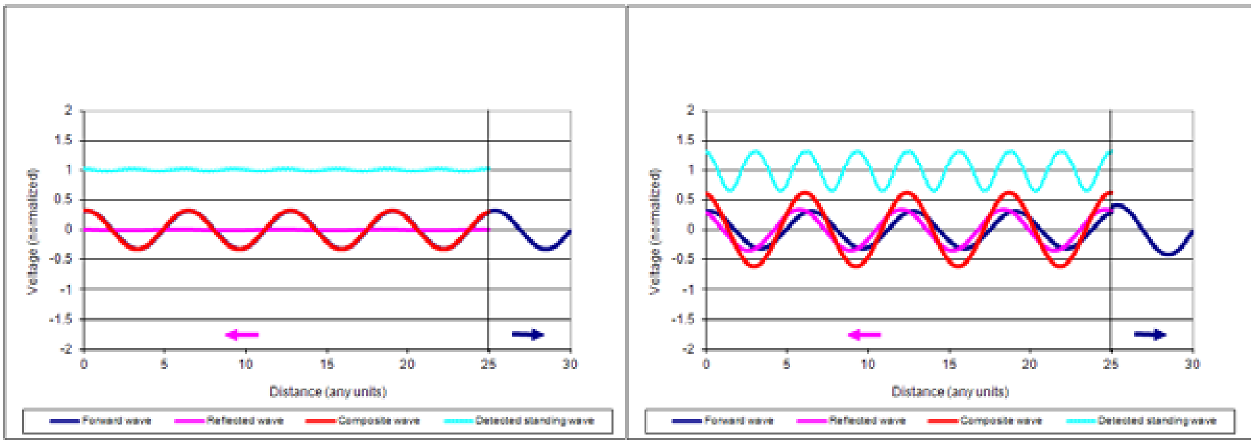

Figure 2. Contrasts SWR of 1.03 vs. 2.0 (http://www.microwaves101.com/encyclopedia/vswr_visual.cfm).

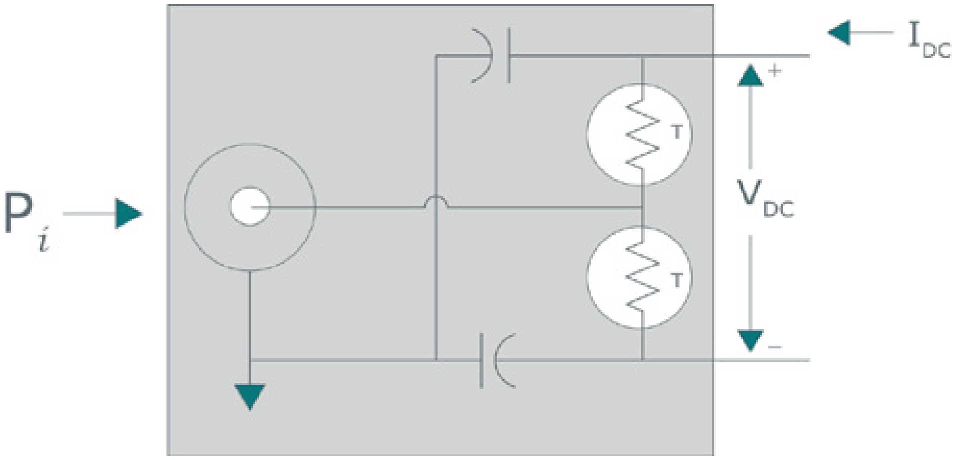

Figure 3. Thermistor Sensor.

About the TEGAM 1830A

The TEGAM Model 1830A thermistor power meter was designed for metrology, has reduced uncertainties[2], and accommodates a wide variety of RF power sensors. The combination of a modern DC substitution bridge with a DC voltage measurement system provides consistent normalized RF power readings manually or automatically. The ability to very termination resistance from 50 Ω to 300 Ω (RF termination 12.5 Ω to 75 Ω) makes the 1830A perfect for this type of measurement.

1830A Supported Sensors

TEGAM/Weinschel: 1107-7, 1107-8, 1807, M1110, M1111, M1118, M1120, M1125, M1130, M1135, F1109, F1116, F1117, F1119, F1125, F1130, F1135

Agilent: 478A, 8478B, S486A, G486A, J486A, H486A, X486A, M486A, P486A, K486A, R486A

Additional supported sensors include but are not limited to; Micronetics, Struthers, and Harris/Polytechnic Research & Development.

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[2] Measurement Uncertainty: ±0.05% of reading, ±0.5 μW (0.1% at 1 mW).

Part II

SWR Verification Procedure

Equipment:

- TEGAM 1830A RF Power Meter
- Thermistor Mount
    - TEGAM M1130A
    - Agilent 478A with options H85 or H76
- DUT Power Meter with 50 MHz, 1 mW Reference Port

Procedure:

The following procedure should be used for solving Output SWR:

1. Connect thermistor mount to 1830A.
2. Power ON all equipment and allow proper warm up time for each. If using a temperature compensated thermistor mount allow for proper temperature stabilization[3].
3. Manually configure the 1830A for selected thermistor mount.
4. Make sure the 50 MHz reference is turned off prior to connecting the thermistor mount[4].
5. Connect thermistor mount to 50 MHz Reference Output Connection.
6. Record RHO_{200} the S22 Magnitude of the thermistor mount at 50 MHz at 200 Ω[5].
    a. For an M1130A this value is available on the calibration report.
    b. For a 478A use the value of .0012 as an estimated value.

Recorded Values	Value
Power (mW) (200 ohms Ref Resistor)	0.9936
Power (mW) (100 ohms Ref Resistor)	0.8939
Fixed Values (From Thermistor Mount Calibration Data)	
RHO (200 ohms Ref Resistor)	0.0014
RHO (100 ohms Ref Resistor)	0.33
Calculations	
Calculate Factor M	0.990485764
Calculate Output voltage reflective coefficient(+)	0.01451123
Calculate Output voltage reflective coefficient(-)	6.020735385
Output SWR (+)	1.029449814
Output SWR (-)	-1.39834802

Figure 4. Worked Example of Output SWR.

7. Record RHO_{100} the S22 Magnitude of the Thermistor Mount at 50 MHz at 100 Ω.
    a. For an M1130A use the value of .33 as an estimated value.
    b. For a 478A us the value of .33 as an estimated value.
8. Verify the 1830A reference resistor is configured for 200 Ω.
9. Zero the 1830A.
10. Turn on the 50 MHz 1mW reference on the DUT Power Meter.
11. Record the power level from the front panel of the 1830A.
12. Turn off the 50 MHz 1mW reference on the DUT power meter.
13. Configure the 1830A reference resistor to 100 Ω.
14. Repeat steps 10-12.
15. Calculate M using the following equation.

$$M = \frac{P_{200}\left(1-|RHO_{100}|^2\right)}{P_{100}\left(1-|RHO_{200}|^2\right)}$$

16. Calculate the output voltage coefficient using the following equation.

$$|\Gamma_S| = \frac{\left(2|RHO_{200}|M-2|RHO_{100}|\right)\pm\sqrt{\left(2|RHO_{100}|-2|RHO_{200}|M\right)^2-4\left(|RHO_{200}|^2M-|RHO_{100}|^2\right)(M-1)}}{2\left(|RHO_{200}|^2M-|RHO_{100}|^2\right)}$$

17. Calculate the output SWR using the following equation[6].

$$SWR = \frac{(1+|\Gamma_S|)}{(1-|\Gamma_S|)}$$

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[3] Verify on 1830A front panel that heating is complete and unit has a stable zero.

[4] Please refer to the DUT Power Meter Manual for operating instructions.

[5] Gamma of the load is a complex value; however we can give a sufficiently accurate answer providing the phase angles are within a reasonable range. For this reason all calculations in this application note will only use RHO portion of Gamma.

[6] With the output voltage coefficient a positive and negative root is returned causing a positive and negative SWR. Use only the positive SWR result.

Worked Example of Output SWR

For this example (Figure 4), the DUT was an Agilent E4418B Power Meter. Output SWR is required to be maximum 1.06. A TEGAM 1830A with a M1130A were also used for this example. The output SWR is 1.029.

NOTE: A downloadable spreadsheet with all formulas is located in TEGAM Forums: http://geneva.tegam.com/forums/.

Conclusion

A thermistor power sensor like the TEGAM M1130A, has the ability to change load resistance which makes it useful for accurate estimations of port SWR. In addition, these sensors are extremely rugged, highly accurate, and stable with time and temperature, and are ideal for use as standards wherever an accurate RF power measurement is required. The M1130A is designed for use with DC self-balancing bridges such as the TEGAM 1830A which is a Direct Reading Thermistor Power Meter. The Model M1130A is a terminating thermistor Reference Standard. It is designed to be calibrated directly by a national standards agency such as NIST. The M1130A is used for the calibration of feedthrough devices such as bolometer mount-coupler and bolometer mount-splitter RF standards. It is also used in other applications requiring direct measurement of RF power, such as the calibration of the 50 MHz reference on RF power meters and verifying the linearity of power sensors.

Sources

- *TEGAM 1830A Power Meter User Manual*
- *TEGAM Coaxial RF Power Transfer Standards Manual*
- *Agilent Technologies E4418B/E4419B Power Meters Service Manual*
- *Radio Frequency & Microwave Power Measurement,* Alan Fantom, IEE Electrical Measurement Series 7, 1990: Peter Peregrinus, London UK.
- Microwaves101.com

Stating Best Uncertainties Over a Range of Values

David Deaver
Metrologist

The Guides to Measurement Uncertainty (GUMs) give very prescriptive methods for calculating measurement uncertainty at individual points. Some laboratories undertake the calculation of uncertainty at many points and state them in their Scope of Accreditation as their Calibration and Measurement Capability (CMC) values. Other laboratories attempt to simplify the effort to generate CMC values by stating them as a formula which spans a number of values. However, there is less guidance as how to use a detailed uncertainty analyses at just a few points to support a large parameter space. This paper shows some of the serious errors being made currently that result in grossly understating some uncertainties and proposes a methodology that is simple but eliminates some of these transgressions.

1. Introduction

A Scope of Accreditation (scope) is designed to represent the uncertainties a laboratory is capable of achieving. Accreditation bodies do not allow their laboratories to issue accredited certificates containing points that are not on their scope nor points with associated uncertainties less than those listed in their Scope. An exception is made for points which are clearly designated as not being part of the accredited certificate. Laboratories work very hard to develop a scope which represents their capabilities as simply as possible.

Two approaches can be taken when developing a scope. The first is to perform uncertainty analyses at a representative number of points in the parameter space being described and then list those points on the scope. The accreditation bodies then allow reasonable interpolation of uncertainties between the points. The accreditation bodies provide some guidance but individual assessors also have their own opinions as to how uncertainties should be calculated for the points interpolated between those listed. The second method is to perform sufficient uncertainty analyses over the parameter space and to simplify the presentation of the uncertainties into a more continuous presentation. The fewer points that are analyzed, the greater the reliance on a model describing the uncertainty of the measurement system between points. The concepts in this paper were originally presented in 2011 [1] and 2012 [2].

2. An Example of Uncertainty Dependent on Frequency

Consider an example of a laboratory wanting to write a Scope for their CMC for measuring voltage at the 2 V level from 10 Hz to 1 MHz. For how many points would a detailed uncertainty analysis need to be performed and how would the CMC values be stated on their Scope of Accreditation?

2 Volts AC - Measure	
Frequency (Hz)	CMC (µV/V)
10	180
20	90
50	40
80	38
100	36
200	35
500	35
800	37
1000	41
2000	43
5000	47
8000	51
10k	53
20k	57
50k	65
80k	72
100k	81
200k	95
500k	115
800k	139
1M	175

Table 1. Lab1 CMC.

2.1 Laboratory 1: Exhaustive Analysis at Every Point

This laboratory decided to analyze the uncertainties at many frequency points. Their CMC values are stated on their scope of accreditation as shown in Table 1. If the lab wants to report other frequencies, they must interpolate the uncertainties. These CMC values are plotted in Figure 1. Lines interconnect the points assuming the lab is authorized to linearly interpolate between the points.

2.2 Laboratory 2: Analysis at Full Scale and Minimum Scale

Laboratory 2 decided that it would analyze a full scale (1 MHz) and a minimum scale point (10 Hz). The results of the analysis are shown in Table 2.

Frequency	Uncertainty (µV/V)
10 Hz	180
1 MHz	175

Table 2. Measurement uncertainties for 2V at 10Hz and 1 MHz.

Laboratory 2 then picked the larger of the two nearly equal uncertainties to state their CMC over the entire range of frequencies for their Scope of Accreditation:

AC Voltage Measure at 2 V,
10 Hz to 1 MHz: 180 µV/V

This value is plotted in Figure 1. A comparison of these first two labs shows Laboratory 2 is overstating its uncertainties by a huge amount over most of the frequency range. However, even if Laboratory 2 had performed a more rigorous analysis, it may still have decided to state its CMC at 180 µV/V over the entire frequency range. It may have determined it did not have a requirement for tighter uncertainties and desired to have a very simple CMC statement for its Scope of Accreditation. This example also points out the huge risk of understating uncertainties if analyses are only conducted at the minimum and maximum values of the range. If the uncertainty values had been much greater at points other than the end points, the lab could have been misrepresenting its CMC by using a constant value throughout the range.

2.3 Laboratory 3: Analysis for a Few Sub-Ranges

Now consider Laboratory 3 which performs a rigorous uncertainty analysis like Laboratory 1 but would like to have a simpler statement of the CMC values. It decides to break up the range into 4 regions and then, like Laboratory 2, assign a CMC value which is at least as large as all the uncertainty values calculated for the range. These CMC values are shown in Table 3 and Figure 1.

Frequency	CMC (µV/V)
10-50 Hz	180
50-5000 Hz	50
5-20k Hz	100
20 kHz -1 MHz	180

Table 3. CMC values for Laboratory 3.

Laboratory 3 has a much simpler table of CMC values than Laboratory 1 but it can be seen that the CMC values are not optimized for all of the sub-ranges. However, if the laboratory's main need is to have low CMC values from 50 Hz to 5 kHz, this may be a very reasonable approach.

2.4 Laboratory 4: Modeling Equations

Laboratory 4 demonstrates the benefits of developing a good model for the behavior of the uncertainties vs. frequency. By performing a bit more analysis of the data than Laboratory 1, it is able to curve fit the uncertainties into two regions. The equations for the CMC values do not understate the capabilities of the laboratory but still allow the lab's capabilities to be stated in a compact manner in Table 4. These equations are plotted in Figure 1.

Frequency (F)	**CMC (µV/V)** (F = Frequency in Hz)
10 Hz to 50 Hz	$40 + 140 \cdot \left(\frac{50-F}{40}\right)^3$
50 Hz to 1 MHz	$40 + 0.135 \cdot \sqrt{F}$

Table 4. Laboratory 4 CMC values for 2 V AC – Measure from 10 Hz to 1 MHz.

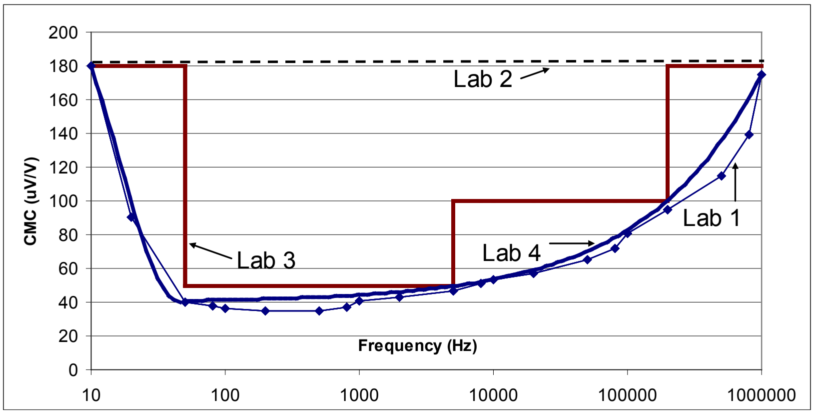

Figure 1. Summary of 4 methods of stating CMCs over a range of values.

3. An Example of Uncertainty Dependent on Current

Now consider an example for a laboratory needing to state CMCs for its scope for measuring current from 0 to 1 mA using a 100 ohm current shunt and a DMM measuring the shunt voltage on its 100 mV range. The configuration is shown in Figure 2.

Table 5 shows a summary of the uncertainty analysis for this measurement system at full scale, 1 mA. Column A lists the error contributors and Column B their magnitudes. Those listed in percentage are proportional to the input signal and those in units, independent. In Column C, the coverage factor for each of the uncertainties is used as a divisor to calculate the standard uncertainty for each error contributor. Note that the DMM is specified as 0.005% of Reading + 0.0035% of Range. In this case the voltage readings corresponding to 0-1 mA with a 100 Ohm shunt will all be taken on the 100 mV range of the DMM. So, the DMM floor spec is 0.1 × 0.0035% = 3.5 μV. The shunt uncertainty includes its calibration as well as its expected drift during its calibration interval. The shunt's power coefficient at 1 mA is assumed to be negligible. The errors due to the temperature coefficient (TC) of the shunt are not adequately captured in the repeatability data as the laboratory temperatures did not exhibit reasonable representation during the relatively short time that the data was taken. Therefore, the TC effects of the shunt were estimated from the manufacturer's TC specification and the distribution of the historical temperatures of the laboratory. Likewise, the errors due to thermal EMFs in the connecting leads were not measured, but estimated. The procedure does not call out for reversing the connections to cancel some of the thermal EMF errors.

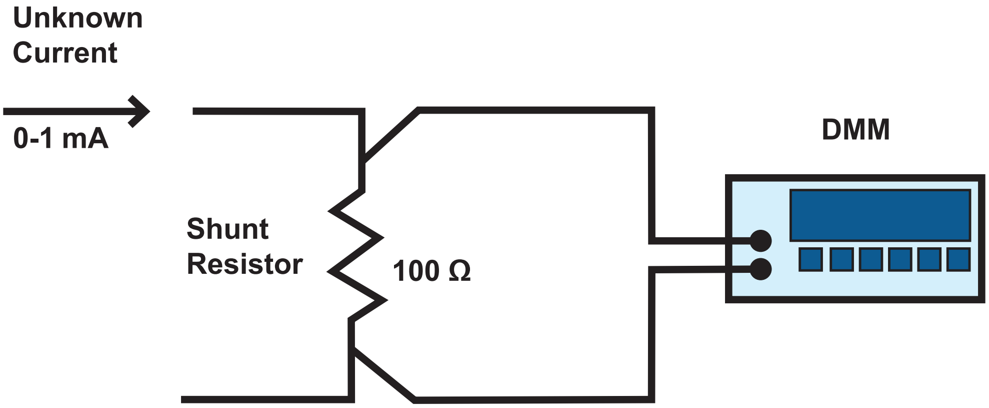

Figure 2. Measuring current with a shunt resistor and a voltmeter.

A	B	C	D (Lab 5)	E (Lab 6)
Uncertainty Contributor	Magnitude	Divisor	Standard Uncert. at 1 mA (μV)	Standard Uncert. at 1 mA excluding DMM Floor Spec (μV)
DMM Specifications			4.91	
0.005% of Rdg +	0.005%	√3	2.89	2.89
0.0035% Rng	3.5 μV	√3	2.02	
Shunt Accuracy	0.001%	2	0.50	0.50
Shunt TC	0.002%	√3	1.15	1.15
Thermal EMF	2 μV	√3	1.16	1.16
Repeatability	2 μV	1	2.00	2.00
Resolution	0.1 μV	2√3	0.03	0.03
Combined Std. Uncertainty at 1 mA			5.57 μV	3.91 μV
Expanded Standard Uncertainty at 1 mA			11.14 μV or 111 nA	7.82 μV + 3.5 μV 78 nA + 35 nA
Lab 6 CMC over the Range 0-1 mA				0.0078% + 3.5 μV or 0.0078% + 35 nA

Table 5. Summary uncertainty analysis for measuring 1 mA with the system of Figure 2.

Fifteen sets of data were taken which was deemed to result in high enough effective degrees of freedom that a coverage factor of 2 can be used to calculate expanded uncertainty from the combined standard uncertainty.

The final uncertainty is expressed in terms of current using the shunt resistance value (100 ohms) as the sensitivity coefficient for the units conversion. Thus, an uncertainty calculated as 0.0039% + 2 µV would be expressed as 0.0039% + 20 nA as a final result.

3.1 Laboratory 5: Exhaustive Analysis at Every Current Level

The uncertainty calculations for Laboratory 5 at 1mA are shown in Column D of Table 5. The uncertainty is calculated in consistent units of µV though the original magnitude of the individual uncertainties may have been expressed in %, ppm, A, mA, Ohms, and µV. To properly combine the uncertainties they must be in the same units and at the same confidence level.

Note that the specification for the DMM should be handled as prescribed by the manufacturer. There should be little allowance for creativity by the metrologist if the analysis is based on the manufacturer's specifications. The metrologist can, of course, develop alternate specifications or uncertainties based on analysis of additional data. In this case, Laboratory 5 properly arithmetically adds the % of Reading (2.89 µV) and the % of Range (2.02 µV) standard uncertainties to get a DMM standard uncertainty of 4.91 µV which is combined by root-sum-square (RSS) with the other uncertainties to get a combined standard uncertainty of 5.57 µV. This is multiplied by a coverage factor of two which results in an expanded uncertainty of 11.1 µV or 111 nA when converted to current.

For another current within the range of 0-1 mA, Laboratory 5 generates another complete uncertainty analysis. It re-computes a new DMM uncertainty for the % of Reading portion of the DMM specification and arithmetically adds it to the % of Range portion before proceeding. This lab re-computes the uncertainties shown in the bold box of Column D which are proportional to the current being measured. However, for different currents, it assumes the error contributions thermal EMFs, repeatability, and resolution will be the same at all current levels. It requires some experience to be able to use reasonable judgment to decide which of the error contributors will be highly correlated to the current level and which are not.

Figure 3 shows the results of Laboratory 5's calculation of uncertainty for 0 to 1 mA for the measurement system of Figure 2. For reference, the specifications of the DMM are shown as well.

3.2 Laboratory 6: Analysis Near Full Scale with Floor Equal to Floor Spec of the Standard

Now consider Laboratory 6. Like Laboratory 5, it wants to calculate uncertainties in support of CMCs for its Scope of Accreditation for 0 to 1 mA. However, unlike Laboratory 5, it doesn't want to have to recalculate uncertainties for each current it measures. Much as Laboratory 4 in the AC Voltage example previously, it would like to have a simplified model which could both reduce the number of points that need to be analyzed and which could simplify stating the CMCs. Laboratory 6, whose uncertainty analysis is summarized in Column E of Table 5, represents an example of a number of laboratories using a model which, in this author's opinion, grossly mis-represents the uncertainties that would be encountered over much of the span the CMCs claim.

For this model, Laboratory 6 calculates the uncertainty near full scale by RSS'ing all the components of uncertainty including the % of Reading portion of the DMM specification and then arithmetically adds the % of Range floor spec of the DMM. The calculations are summarized in Column E of Table 5 and are shown both in µV and a percent of the 1mA current being applied. At full scale, this actually overstates the combined uncertainty as lab has taken liberties in combining the components of the DMM specification.

To calculate the uncertainties for less than 1 mA, the laboratory considers all the error contributors except the DMM floor spec to be proportional to the input. These are shown within the bold box of Column E. This is not a good assumption for many contributors and is clearly wrong treatment of resolution. The claimed CMC values for Laboratory 6 are shown in Figure 3. If we consider Laboratory 5 to have properly stated the uncertainty of the system, Laboratory 6 is understating them for much of the range of 0 to 1 mA.

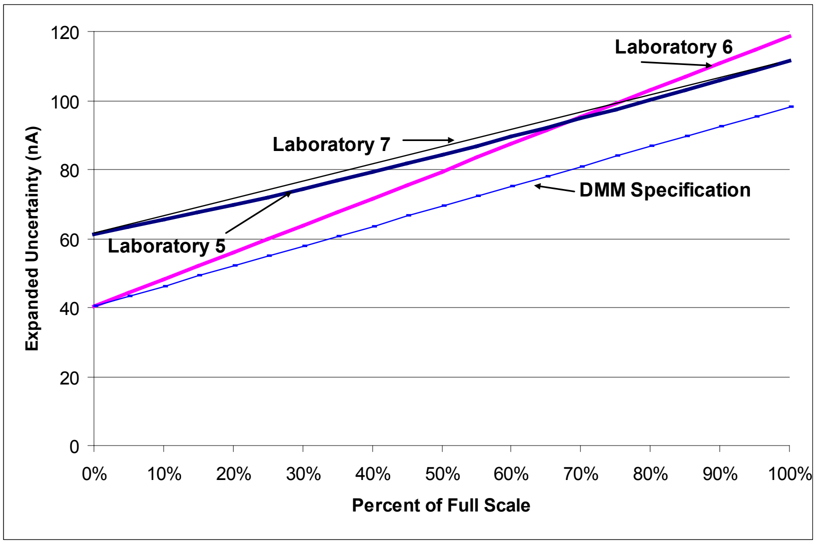

Figure 3. CMCs for Labs 5, 6, & 7 with DMM specifications of 0.005% Rdg + 0.0035% FS.

3.3 Comparison of Laboratories 5 and 6 Using a more Accurate DMM

Understating the CMC values would be even worse had the lab chosen a more accurate DMM. Unfortunately, this is often the case for laboratories wanting to use their best equipment when calculating the uncertainties for their CMCs. Figure 4 plots the DMM accuracy and the CMC values for the laboratories for the uncertainties shown in Table 5 except for a DMM specification of

0.0005% of Reading + 0.0003% of Range.

3.4 Laboratory 7: Analysis at FS and MS with Linear Interpolation

This laboratory seeks to avoid the pitfall of Laboratory 6 but is also reluctant to have to calculate uncertainties for each point it wishes to calibrate like Laboratory 5. It is this author's recommendation that the straight line approximation method of Laboratory 7 be encouraged and Laboratory 6 methods which understate the uncertainty over much of the range be disallowed.

Equation 1 is the formula for calculating the CMC values using a linear interpolation of the uncertainties

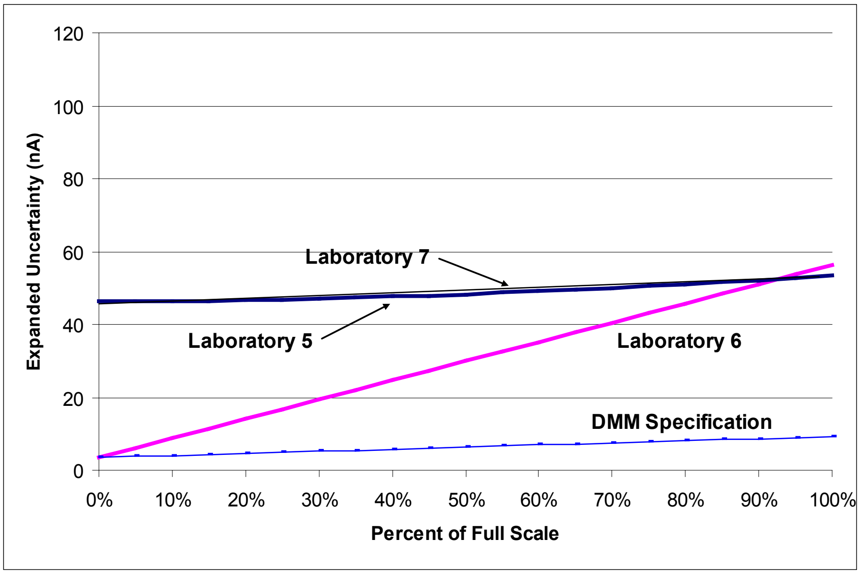

Figure 4. CMCs for Labs 5 & 6 with DMM specifications of 0.0005% Rdg + 0.0003% FS.

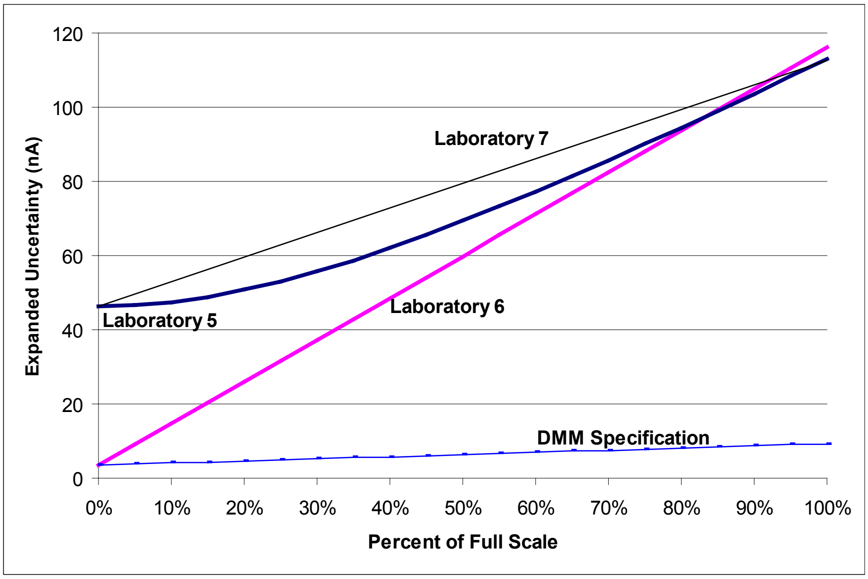

Figure 5. Labs 5 & 6 CMCs with nearly equal gain and floor uncertainties.

within the range of X values from full scale (FS) to minimum scale (MS). The corresponding uncertainties are UFS at full scale and UMS at minimum scale:

$$CMC = UMS + (UFS - UMS) \cdot \frac{(X - MS)}{(FS - MS)} \tag{1}$$

Equation 2 rearranges the terms into Gain and Floor terms. This allows the CMC for the range to be presented as a Gain + Floor such as XX% + YY.

$$CMC = \underbrace{\left[\frac{(UFS - UMS)}{(FS - MS)}\right]}_{\textbf{Gain}} \cdot X + \underbrace{\left[UMS - (UFS - UMS) \cdot \frac{MS}{(FS - MS)}\right]}_{\textbf{Floor}} \tag{2}$$

Equation 3 shows the calculation can be simplified a little if the bottom of the range of values (MS) is zero.

$$CMC_{MS=0} = \underbrace{\left[\frac{(UFS - UMS)}{FS}\right]}_{\textbf{Gain}} \cdot X + \underbrace{[UMS]}_{\textbf{Floor}} \tag{3}$$

The straight line approximation of Laboratory 7 is also plotted in Figures 3 and 4. It can be seen that, because the point by point calculation of CMC for Laboratory 5 is slightly curved, the straight line approximation slightly overstates the uncertainties near mid scale.

This curve becomes more pronounced as the uncertainties that are proportional to the measured value are more equal to those that are independent of the measured value. Figure 5 shows the CMC values for the laboratories for the DMM with better specifications but with a larger Shunt Accuracy of 0.01% instead of 0.001% in the previous examples. Now the linearly approximated CMC values of Laboratory 7 at 25% of the range are reported about 20% higher than those reported by Laboratory 5 which calculated the CMCs for every point. However, note that at MS, Laboratory 6 is claiming CMCs which are less than 10% of those that should be allowed!

3.5 Laboratory 7: Summary of Straight Line Approximation Method

- Calculate the fullscale uncertainty (UFS) per the GUM by converting all uncertainties to common units and a common confidence level (1 sigma) and combine by RSS to get a standard uncertainty. Apply the appropriate coverage factor (usually 2) to achieve a 95% confidence level at the full scale of the range of values.
- Separate the error contributors into those that are proportional to the reading and those that are independent of the range of values. This involves some judgment. For uncertainties that are not zero or 100% correlated, it may be necessary to separate the error estimate into a portion that is 0% correlated and a portion that is 100% correlated with the input.
- Calculate the uncertainty at the minimum of the range of values (UMS) appropriately combining by RSS the uncertainties that are proportional to the range of values and those that are not.
- The linear interpolation of the CMC value for any value MS ≤ X ≤ FS is given by Equation 2. If MS = 0, use Equation 3 instead of Equation 2.

4. Conclusion

Curve fitting and models are useful tools in simplifying the presentation of CMC values. However, some of the models being used by labs currently are misrepresenting their actual CMC values. The author suggests that a straight line approximation of the uncertainties between the minimum and maximum of the range of values is a far better approach to the method being practiced by many labs currently which treats all uncertainties as proportional to the value within the range except the floor specification of the calibration standard. The straight line approximation will overstate the uncertainties rather than understate them as some labs are currently doing. A more sophisticated equation than linear approximation could be used such as for Laboratory 4 in the frequency dependent model.

References

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2. D.K. Deaver, "Stating Best Uncertainties Over a Range of Values," NCSL International Workshop and Symposium, Sacramento, CA, July 29–August 2, 2012.

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An Uncertainty Analysis for a Positive Displacement Liquid Flow Calibrator Using the Water Draw Technique

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This paper is an uncertainty analysis performed by the Liquid Flow Lab of the Army Primary Standards Laboratory (APSL) for the calibration of positive displacement piston prover using a volumetric water draw. The water draw calibration is conducted to establish a precise relationship between translator pulses and the volume of liquid displaced by the draw and is known as the K-Factor (given in pulses/unit volume). For the APSL the term "Water Draw" is a misnomer, because the APSL uses hydrocarbons that are already in the flow calibrator at the time of the draw calibration.

Introduction

The purpose of a water draw calibration is to provide traceability either volumetrically or gravimetrically to a Positive Displacement Piston Liquid Flow Calibrator. A simple schematic of a Positive Displacement Liquid Flow Calibrator is shown below in Figure 1.

The positive displacement liquid flow calibrator consists of a piston cylinder flow element and measures flow rates through a Device Under Test (DUT) as illustrated in the following manner. In Figure 1 above the piston starts at position 1 (x_1) at time (t_1) on the x axis and being set into motion by air pressure moves in a positive direction along the x axis to position 2 (x_2) in time (t_2). The displacement of the piston ($x_2 - x_1$) divided by the time duration it took for the piston to move from position 1 to position 2 ($t_2 - t_1$) gives us the rate in [Unit Length/Unit Time] the piston has traveled in the positive x direction and is given by the following expression as

$$Rate = \left(\frac{x_2 - x_1}{t_2 - t_1}\right) = \frac{\Delta x}{\Delta t} = \frac{dx}{dt}\,. \qquad (1)$$

Since the piston and cylinder are circular, the area of the piston cylinder arrangement is given by $A = \pi r^2$ and if we know the radius of the circle we can calculate its area. If we multiply the constant area by the rate in

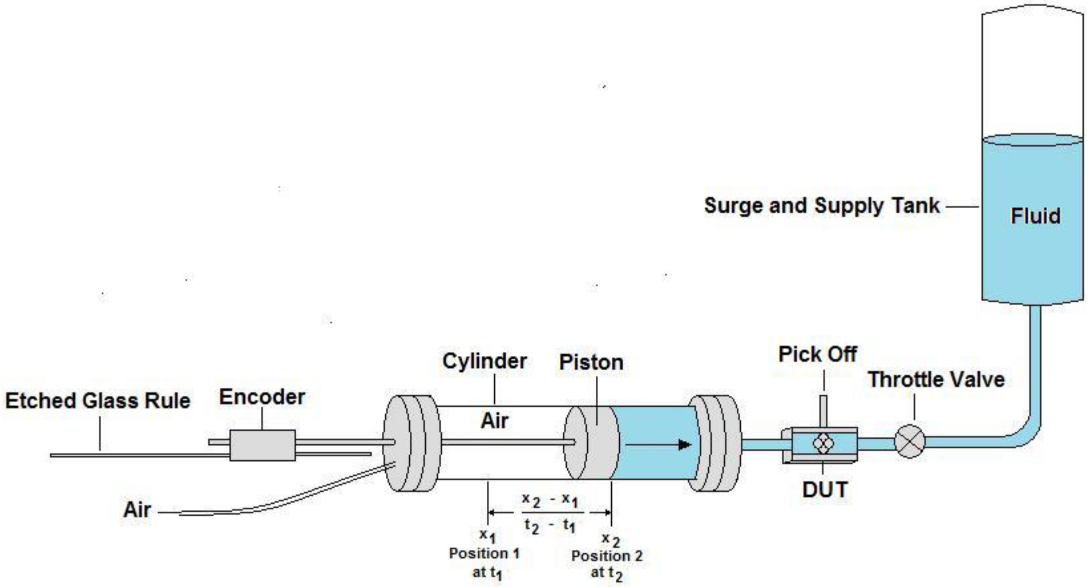

Figure 1. A Simple Schematic of a Positive Displacement Liquid Flow Calibrator.

Equation 1 the volumetric flow rate $\dot{v}$ in [Unit Volume/Unit Time] of the positive displacement calibrator can easily be determined by

$$\dot{v} = Area \times Rate = A\frac{dx}{dt} = \pi r^2 \frac{dx}{dt} = \frac{dv}{dt}. \tag{2}$$

The distance x, traveled by the piston in Figure 1 is determined by a graduated etched glass rule (with a typical grating pitch of 20 µm) that is read by an encoder which produces a pulse each time a graduation on the rule is encountered. The rate the piston travels in the x direction is influenced by the Throttle Valve. If the area of the piston cylinder element has been measured one can easily determine the volume flow as the area times the distance traveled. However, a water draw calibration can be performed to determine how many translator pulses are required to fill a flask of a precisely known calibrated volume thus not having to disassemble the piston cylinder element to do a dimensional calibration. Instead, a K-factor for the liquid flow calibrator can be determined in pulses per unit volume as illustrated in Equation 3 below.

$$K_C = \frac{P_{Calibrator}}{V} = \frac{[Pulses]}{Unit\_Volume} \tag{3}$$

The water draw calibration [1] is conducted to establish a precise relationship between translator pulses and the volume of liquid displaced by the draw. The piston of the calibrator is set into motion displacing the liquid medium into a flask of a precisely known volume while the translator counts the number of pulses required to fill the flask to its fill line. Corrections for temperature and pressure are then made to determine a calibration constant for the prover. This process is repeated several times to establish an average and obtain a repeatability figure for the calibration.

Although this technique is referred to as a "water draw," it is a misnomer, because the draws conducted by the Army Primary Standards Laboratory (APSL) Flow Laboratory will use media other than water. Typically, water is used because its properties are better understood than all other liquid media. While this provides a lower uncertainty draw, it requires removing the old liquid media in the prover, cleaning the prover with solvent, and filling the prover with clean water. This process is wasteful, tedious, and time consuming. Furthermore, water has an erosive effect on the piston prover surfaces and is hard on the piston prover seals. It is for this reason that the APSL Flow Laboratory chooses not to use water.

The APSL Flow Laboratory keeps the ambient environment of the piston provers at a temperature of 68 °F ± 3.6 °F (20 °C ±2 °C) and a relative humidity of 20% to 70%. This uncertainty analysis was conducted at these conditions and therefore is only valid at these conditions.

Calculations and Corrections

Calculations

The calibrator constant is determined as follows:

$$K = \frac{p}{V} \tag{4}$$

where p is the number of linear encoder pulses, and V is the volume of liquid media displaced by the piston at actual draw.

Corrections

Correction for Thermal Expansion of Water Draw Vessel

$$C_{tm} = 1 + \alpha_V \left(T_V - T_S\right) \tag{5}$$

Correction for Compressibility

$$C_{pl} = \frac{1}{1 - P_{CAL} \cdot Z} \tag{6}$$

Correction for Thermal Expansion of Flow Tube

$$C_{ts} = 1 + \alpha_A \cdot \left(T_W - T_S\right) \tag{7}$$

Correction for Thermal Expansion of Encoder

$$C_{td} = 1 + \alpha_{ENC} \cdot \left(T_d - T_S\right) \tag{8}$$

Correction for Pressure Expansion of Flow Tube

$$C_{ps} = 1 + \left(\frac{P_{CAL} \cdot d}{\gamma \cdot T}\right) \tag{9}$$

Correction for Thermal Expansion of Fluid in Vessel

$$C_{vs} = 1 - \alpha \cdot \left(T_V - T_W\right) \tag{10}$$

Applying Corrections to Calibrator Constant

$$K = \frac{p}{V} \cdot \frac{C_{pl} \cdot C_{ts} \cdot C_{td} \cdot C_{ps}}{C_{tm} \cdot C_{vs}} \tag{11}$$

Calibrator Constant with Corrections

$$K = \frac{p}{V} \cdot \frac{\left(\frac{1}{1-P_{CAL} \cdot Z}\right) \cdot \left(1+\alpha_A \cdot \left(T_W - T_S\right)\right) \cdot \left(1+\alpha_{ENC} \cdot \left(T_d - T_S\right)\right) \cdot \left(1+\left(P_{CAL} \cdot d\right)/\left(\gamma \cdot T\right)\right)}{\left(1+\alpha_V \cdot \left(T_V - T_S\right)\right) \cdot \left(1-\alpha \cdot \left(T_V - T_W\right)\right)} \tag{12}$$

Where:
K = Calibrator Constant [pulses/L]
p = pulse count [counts]
V = Volume [L]
C_{tm} = Correction for Thermal Expansion of Water Draw Vessel [-]
C_{pl} = Correction for Compressibility of Fluid Medium [-]
C_{ts} = Correction for Thermal Expansion of Flow Tube [-]
C_{td} = Correction for Thermal Expansion of Encoder [-]
C_{ps} = Correction for Pressure Expansion of the Flow Tube [-]
C_{vs} = Correction for Thermal Expansion of Fluid Vessel [-]
α_V = Volume Thermal Expansion Coefficient of Draw Vessel [°F^{-1}]
T_V = Temperature of Draw Vessel [°F]
T_S = Reference Temperature (68 °F) [°F]
P_S = Reference Pressure (0 psig) [psi]
P_{CAL} = Calibrator Pressure during Draw [psi]
Z_{7024} = Compressibility of Fluid Media [psi^{-1}]
α_A = Area Thermal Expansion Coefficient of Flow Tube [°F^{-1}]
T_W = Calibrator Temperature [°F]
α_{ENC} = Linear Thermal Expansion of Encoder [°F^{-1}]
T_d = Detector Temperature [°F]
d = Flow Tube Inside Diameter [in]
T = Flow Tube Wall Thickness [in]
γ_{FT} = Modulus of Elasticity of Flow Tube [psi]
α_{7024} = Thermal Expansion Coefficient of Fluid Media [°F^{-1}]
M_E = Error in Mencius Reading [%]

Calculation of Sensitivity Coefficients Using Partial Differentiation

Meniscus Reading Error Sensitivity Coefficient for Flow Tube M_E [L]

The Meniscus Reading Error is applied to the calibration constant by simply multiplying it with the Calibration Constant equation. Therefore, the sensitivity coefficient is determined by partial differential calculus as are all the sensitivity coefficients shown below.

$$\frac{1}{K}\cdot\frac{\partial K}{\partial M_E}=\frac{1}{M_E} \tag{13}$$

Pulse Count Sensitivity Coefficient p [counts]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial p}=\frac{1}{p} \tag{14}$$

Volume Sensitivity Coefficient V [L]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial V}=\frac{1}{V} \tag{15}$$

Calibrator Temperature Sensitivity Coefficient T_W [°F]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial T_W}=\frac{\alpha_A\cdot\left[1-\alpha\cdot\left(T_V-T_W\right)\right]-\alpha\cdot\left[1+\alpha_A\cdot\left(T_W-T_S\right)\right]}{\left[1-\alpha\cdot\left(T_V-T_W\right)\right]\cdot\left[1+\alpha_A\cdot\left(T_W-T_S\right)\right]} \tag{16}$$

Detector Sensitivity Coefficient T_d [°F]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial T_d}=\frac{\alpha_{ENC}}{1+\alpha_{ENC}\cdot\left(T_d-T_S\right)} \tag{17}$$

Vessel Temperature Sensitivity Coefficient T_V [°F]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial T_V}=\frac{\left[1-\alpha\cdot\left(T_V-T_W\right)\right]\cdot\left[-\alpha\cdot\left(1+\alpha_V\cdot\left(T_V-T_S\right)\right)-\alpha_V\cdot\left(1-\alpha\cdot\left(T_V-T_W\right)\right)\right]}{\left[1+\alpha_V\cdot\left(T_V-T_S\right)\right]} \tag{18}$$

Reference Temperature Sensitivity Coefficient T_S [°F]

The sensitivity coefficient for the reference pressure is not calculated here because the gauge pressure of 0 psi is fixed defined constant.

Reference Pressure Sensitivity Coefficient P [psi]

The sensitivity coefficient for the reference pressure is not calculated here because the gauge pressure of 0 psi is fixed defined constant.

Calibrator Pressure Sensitivity Coefficient P_{CAL} [psi]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial P_{CAL}}=\frac{d+\gamma\cdot T\cdot Z}{\gamma\cdot T\cdot\left(1-P_{CAL}\cdot Z\right)\cdot\left(1+\left(P_{CAL}\cdot d/\gamma\cdot T\right)\right)} \tag{19}$$

Compressibility Factor Sensitivity Coefficient for Liquid Media Z [psi^{-1}]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial Z}=\frac{P_{CAL}}{1-P_{CAL}\cdot Z} \tag{20}$$

Volume Thermal Expansion Sensitivity Coefficient for Liquid Media α [°F^{-1}]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial \alpha}=\frac{\left(T_V-T_W\right)}{1+\alpha\cdot\left(T_V-T_W\right)} \tag{21}$$

Flow Tube inside Diameter Sensitivity Coefficient d [in]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial d}=\frac{P_{CAL}}{\gamma\cdot T+P_{CAL}\cdot d} \tag{22}$$

Flow Tube Wall Thickness Sensitivity Coefficient T [in]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial T}=\frac{P_{CAL}\cdot d}{T\cdot\left(T\cdot\gamma+P_{CAL}\cdot d\right)} \tag{23}$$

Linear Thermal Expansion Sensitivity Coefficient for Encoder α_{ENC} [°F^{-1}]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial \alpha_{ENC}}=\frac{(T_d-T_S)}{1+\alpha_{ENC}\cdot(T_d-T_S)} \tag{24}$$

Area Thermal Expansion Sensitivity Coefficient for Flow Tube α_A [°F^{-1}]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial \alpha_{A}}=\frac{(T_W-T_S)}{1+\alpha_{A}\cdot(T_W-T_S)} \tag{25}$$

Volume Thermal Expansion Sensitivity Coefficient for Flask α_V [°F^{-1}]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial \alpha_{V}}=\frac{(T_V-T_S)}{1+\alpha_{V}\cdot(T_V-T_S)} \tag{26}$$

Modulus of Elasticity Sensitivity Coefficient for Flow Tube γ_{FT} [psi]

$$\frac{1}{K}\cdot\frac{\partial K}{\partial \gamma}=\frac{P_{CAL}\cdot d}{\gamma\cdot(\gamma\cdot T+P_{CAL}\cdot d)} \tag{27}$$

Uncertainty Analysis

Meniscus Reading Error, M_E [L]

The error associated with reading the fluid meniscus at the etched line in the fluid collection flask was determined from the ASTM E 694-99 (Reapproved 2005) *"Standard Specification for Laboratory Glass Volumetric Apparatus"* ANNEX A1. *"Limit of Volumetric Error in Relation to Diameter at the Meniscus"* [2]. This standard provides the following equation for determination of the error due to reading the meniscus:

$$p=\frac{H\cdot D}{2\cdot d+D} \tag{28}$$

where

p = error in reading in [mm],

d = distance of the operator's eye from the etched line on the flask in [mm],

H = distance of the operator's eye above or below the plane of the etched line tangential to the meniscus in [mm], and

D = the diameter of the tube or neck of the flask which carries the scale in [mm].

At the time of making the volume measurements using the flask the following values for d and H were assumed as: d = 203 mm or 8 inches, and H = 5.08 mm or 0.2 inches.

The diameter of the neck of the flask was measured using Federal 16EX Calipers, Serial Number P1, and Calibrated on May 27, 2009 [3]. The value for the diameter of the flask at the etched line was measured at 23.44 mm (0.923 inches). Therefore, D = 23.44 mm or 0.923 inches.

Calculating the error:

$$p=\frac{(5.08\ mm)\cdot(23.44\ mm)}{2\cdot(203\ mm)+(23.44\ mm)}=0.277\ mm \tag{29}$$

The inside diameter of the 5680-1L flask is nominally 22 mm which translates into

$$A=\pi r^2=\pi\cdot\left(\frac{D}{2}\right)^2=\pi\cdot\left(\frac{22}{2}\right)^2=380.1327\ mm^2. \tag{30}$$

Therefore, the total error in volume will be

$$V_{err}=(0.277\ mm)(380.1327\ mm)=105.403\ mm^3. \tag{31}$$

This translates into

$$V_{err}=0.000105403266\ L. \tag{32}$$

The total error in the measurement for the 0.999580L flask volume is then given in percent as

$$V_{err}=\frac{0.000105403266\ L}{0.999580\ L}\cdot 100\ \%=0.0105\ \%. \tag{33}$$

Uncertainty Summary for Meniscus Reading:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial M_E}=\frac{1}{M_E}$

Distribution: Rectangular

One Standard Uncertainty:

$$\frac{0.000105403266}{\sqrt{3}}=6.085460\times10^{-5}\ L$$

Calibrator Pulses, P [counts]

The uncertainty of the encoder pulse counts is determined by two components, the uncertainty of the pulse spacing generated by the linear encoder; and the position error of the encoder on the glass rule.

First, the Mitutoyo encoder used in the Flow Calibrator for this uncertainty is a model AT102 which has a grating pitch of 20 µm/pulse. A total of 4607 pulse were collected during this water draw.

Therefore, the piston traveled (4607 *pulses*)(20 *µm*) = 92.14 *mm*. The uncertainty provided by *Mitutoyo Spec Sheet for Model AT102-500 Code No. 539-119 Linear Scale Unit Manual No. 4739GB Series No. 539* [4] provides the uncertainty for the Model AT102-500 Code 539-119 as $U=(5+5\ L/10000\ \mu m)$ where L is the distance traveled by the encoder, which in this case is 92.14 mm. Then,

$$U=\pm(5+5\cdot(92.14/10000))\times10^{-3}\ mm=\pm0.005046\ mm \tag{34}$$

With a grating pitch of 20 μm/pulse, this can be converted into

$$(0.005046\times10^{-3}\,m)/(20\times10^{-6}\,m/pulse)=0.2523\,pulses. \qquad (35)$$

The total number of pulses collected during a water draw was 4607. Converting to percent error we obtain the following:

$$\frac{(0.2523\,pulses)}{(4607\,pulses)}\cdot 100\% = 0.0055\%. \qquad (36)$$

Second, there is an error due to the fact that it is impossible to count only full pulses during the water draw (i.e. there is an unknown fraction of a pulse because the exact position of the encoder between etchings on the glass rule is not known). This fact creates an uncertainty $\pm\frac{1}{2}$ of a pulse out of 4607 pulses or ± 0.010853%. See Figure 2 to illustrate this point.

Uncertainty Summary for Calibrator Pulses:

Type of Uncertainty of Pulse Spacing:
Relative Type B

Type of Uncertainty for Ecoder Position Error:
Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial p}=\frac{1}{p}$

Distribution of Pulse Spacing Error: Normal

Distribution of Encoder Position Error: Rectangular

One Standard Uncertainty of Pulse Spacing:

$$\frac{(0.2523\,pulses)}{2}\cdot = 0.1262\,pulses$$

One Standard Uncertainty of Encoder Position:

$$\frac{1}{2\sqrt{3}}\,pulses$$

Flask Volume, V [L]

The volume value for the Corning Pyrex Flask provided by the APSL's *Calibration Report for Flask Serial Number D07116*, Calibration Report Number QM-D07116, dated 19 Jan 2010 [5] is 0.999580 L ±0.11mL. Therefore:

Uncertainty Summary for Flask Volume:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial V}=\frac{1}{V}$

Distribution: Rectangular

One Standard Uncertainty: $\frac{(0.11\,mL)}{\sqrt{3}}\cdot = 6.35085\times10^{-5}\,L$

Calibrator Temperature, T_W [°F]

The uncertainty associated with the Instrulab box and probe used for measuring the Calibrator Temperature was taken from APSL Report No. 4078 Dated May 12, 2009 [6] and the uncertainty was given as ±0.008 °C which is converted to ±0.0144 °F.

There exists a correlation between the Calibrator Temperature, the Encoder Temperature and the Vessel Temperature since the same standard was used by the APSL to Calibrate the probes used for these measurements. Therefore all uncertainties associated with temperature will be summed together instead of being root sum squared together when combining uncertainties.

Uncertainty Summary for Calibrator Temperature:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient:

$$\frac{1}{K}\cdot\frac{\partial K}{\partial T_W}=\frac{\alpha_A\cdot[1-\alpha\cdot(T_V-T_W)]-\alpha\cdot[1+\alpha_A\cdot(T_W-T_S)]}{[1-\alpha\cdot(T_V-T_W)]\cdot[1+\alpha_A\cdot(T_W-T_S)]}$$

Distribution: Normal

One Standard Uncertainty: $\frac{(0.0144\ °F)}{2}\cdot = 0.0072\ °F$

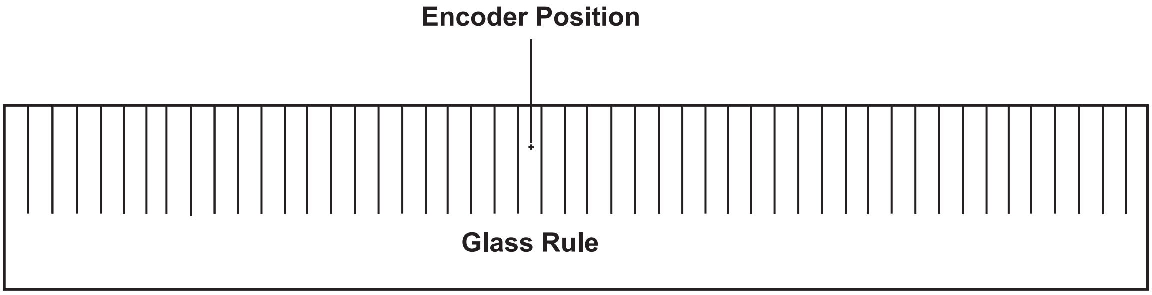

Figure 2. Position Error of Encoder.

Detector Temperature, T_d [°F]

The uncertainty associated with the Instrulab box used for measuring the calibrator temperature was taken from APSL report No. 5820 [7] and the uncertainty was given as ±0.01 °C which is converted to ±0.018 °F. For the reason stated in the section above all temperature device measurement uncertainties are correlated. Therefore all uncertainties associated with temperature will be summed together instead of being root sum squared together when combining uncertainties.

Uncertainty Summary for Detector Temperature:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K} \cdot \frac{\partial K}{\partial T_d} = \frac{\alpha_{ENC}}{1 + \alpha_{ENC} \cdot (T_d - T_S)}$

Distribution: Normal

One Standard Uncertainty: $\frac{0.0180\ °F}{2} \cdot = 0.009\ °F$

Vessel Temperature, T_V [°F]

The uncertainty associated with the Instrulab box used for measuring the calibrator temperature was taken from an APSL report No. 4078 Dated May 12, 2009 [6] and the uncertainty was given as ±0.008 °C which is converted to ±0.0144 °F. For the reason stated in the paragraphs above all temperature measurement uncertainties are correlated. Therefore all uncertainties associated with temperature will be summed together instead of being root sum squared together when combining uncertainties.

Uncertainty Summary for Vessel Temperature:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient:

$$\frac{1}{K} \cdot \frac{\partial K}{\partial T_V} = \frac{[1-\alpha \cdot (T_V - T_W)] \cdot [-\alpha \cdot (1 + \alpha_V \cdot (T_V - T_S)) - \alpha_V \cdot (1 - \alpha \cdot (T_V - T_W))]}{[1 + \alpha_V \cdot (T_V - T_S)]}$$

Distribution: Normal

One Standard Uncertainty: $\frac{(0.0144\ °F)}{2} \cdot = 0.0072\ °F$

Reference Temperature, T_S [°F]

The reference temperature used by the APSL Liquid Flow Laboratory is 68 °F. This constant is arbitrary and is defined to be exact. Therefore, no uncertainty is associated with this value.

Reference Pressure, P_S [psi]

The reference pressure is considered always to be exactly zero gauge pressure: like the reference temperature above, there is no uncertainty associated with this value.

Calibrator Pressure, P_{CAL} [psi]

During this water draw calibration, the run pressure was read directly off the Calibrator Pressure Gauge and the accuracy of this crude gauge is 3% of full-scale.

Uncertainty Summary for Calibrator Pressure:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient:

$$\frac{1}{K} \cdot \frac{\partial K}{\partial P_{CAL}} = \frac{d + \gamma \cdot T \cdot Z}{\gamma \cdot T \cdot (1 - P_{CAL} \cdot Z) \cdot (1 + (P_{CAL} \cdot d / \gamma \cdot T))}$$

Distribution: Normal

One Standard Uncertainty: $\frac{((3/100) \cdot 160\ psi)}{2} = 2.4\ psi$

Compressibility Factor of MIL-PRF-7024E Type II and Gear Oil Mixture, $Z_{7024\ \&\ Oil}$ [psi^{-1}]

The compressibility factor for MIL-C-7024 and oil mixture was determined from using "API Manual of Petroleum Measurement Standards Chapter 11.2.1M-Compressability Factors for Hydrocarbons: 638-1074 Kilograms per Cubic Metre Range First Edition," August 1984 [8]. The actual density of a sample of the mixture was measured with an Anton Paar DMA 5000 M and determined to be 0.8113 g/cm^3. The number corresponding to 0.8113 g/cm^3 density was located on page 76 of the manual. This number was interpolated from the tables and determined to be 0.848. According to the API standard this number was to be divided by 1×10^6. Therefore, the following was obtained:

$$\frac{(0.848)}{(1\times10^{6})} \cdot kPa = 8.48\times10^{-7}\ kPa. \quad (37)$$

By converting kPa to psi, the following is obtained:

$$\frac{(8.48\times10^{-6}\ kPa)}{(0.14503773801\ kPa/psi)} = 5.846754\times10^{-6}\ psi. \quad (38)$$

The recommended uncertainty by COSM and COPM Survey is 0.1% which is outlined in Section 11.2.1.5.1M of "API MPM CH 11.2.1M Compressibility Factors for Hydrocarbons: 638 - 1074 Kilograms per Cubic Metre Range" [11]. Therefore, $(0.1\%/100) \cdot (5.847\times10^{-6}\ psi) = 5.847\times10^{-9}\ kPa$.

Uncertainty Summary for Compressibility Factor for MIL-PRF-7024E Type II and Gear Oil Mixture:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K} \cdot \frac{\partial K}{\partial Z} = \frac{P_{CAL}}{1 - P_{CAL} \cdot Z}$

Distribution: Rectangular

One Standard Uncertainty:

$$\frac{(5.847\times10^{-9}\ psi)}{\sqrt{3}} \cdot = 3.376\times10^{-9}\ psi$$

Volume Thermal Expansion Coefficient of MIL-PRF-7024E Type II and Gear Oil Mix, $\alpha_{7024\ \&\ Oil}$ [°F^{-1}]

Using an Anton Paar DMA 5000 M, the value for the thermal expansion coefficient was calculated from a set of measurements that were taken over the operating range of the Flow Calibrator used in this uncertainty. These measurements are shown below in Table 1.

	DMA 5000M	Vol Exp	
Temp	**Density**	**β**	**Δ**
°F	**g/cm³**	**°F⁻¹**	**°F⁻¹**
50.00	0.816897		
59.00	0.813368	0.000482	-0.000008
68.00	0.809837	0.000484	-0.000006
77.00	0.806301	0.000487	-0.000003
86.00	0.802762	0.000490	0.000000
95.00	0.799219	0.000493	0.000002
104.00	0.795672	0.000495	0.000005
113.00	0.792115	0.000499	0.000009
		Average	**Stdev**
		0.000490	0.000012

Table 1. Thermal Expansion Determined from Temperature and Density Reading Taken from Anton Paar DMA 5000 M Density Meter.

The data from the DMA 5000 is shown in the two left columns (the Temperature and the corresponding Density). The Thermal Expansion β of the liquid was then calculated as follows.

The equation for determining volume based on a change in temperature is given below as

$$V_t = V_0 \cdot [1 + \beta \cdot (t_t - t_0)] \tag{39}$$

where

V_t = Final Volume,
V_0 = Initial Volume,
β = Thermal Expansion of the liquid,
t_t = Final Temperature, and
t_0 = Initial Temperature.

Since Density ρ is m/V (mass over volume), V is m/ρ (mass over density) and the above equation becomes

$$\frac{m}{\rho_t} = \frac{m}{\rho_0} \cdot [1 + \beta \cdot (t_t - t_0)]\,. \tag{40}$$

Due to the conservation of mass, the mass is the same for the initial and final measurement and the only value that changes is the density due to a change in volume. Therefore,

$$\frac{1}{\rho_t} = \frac{1}{\rho_0} \cdot [1 + \beta \cdot (t_t - t_0)]$$

$$\rho_0 = \rho_t \cdot [1 + \beta \cdot (t_t - t_0)]$$

$$\rho_t = \frac{\rho_0}{[1 + \beta \cdot (t_t - t_0)]}\,. \tag{41}$$

Solving for β the following relationship is obtained.

$$\beta = \frac{\left(\frac{\rho_0}{\rho_t} - 1\right)}{(t_t - t_0)} \tag{42}$$

The average of the expansion coefficient over all the measurements was determined to be 4.90069x10^{-4} °F^{-1}.

The uncertainty of this value was determined from the standard deviation calculated in Table 1 and the temperature accuracy specification of the Anton Paar DMA 5000 M. The accuracy of the Anton Paar 5000 M is given as: Density ρ accuracy of DMA 5000 is 5x10^{-6} g/cm³ [9]; and uncertainty of Water used for Air Water Adjustment of DMA 5000 is 11x10^{-6} g/cm³ from SH Calibration Certificate Number 19595 Dated 14 May 2009 [10].

Total Accuracy of DMA is

$$U_{DMA} = 2\sqrt{\left(\frac{5\times10^{-6} g/cm^3}{2}\right)^2 + \left(\frac{11\times10^{-6} g/cm^3}{2}\right)}$$

$$= 1.2083\times10^{-5} g/cm^3. \tag{43}$$

Temperature T is measured to an accuracy of 0.018 °F. However, using the volume expansion equation above to calculate thermal expansion, we notice that the same probe and density meter is used to find the initial and final temperatures and densities: this means that the initial temperature and the final temperature uncertainties are correlated and the same is true for the initial density and final density. Therefore, these uncertainties instead of being root sum squared must be simply added together.

Initial Density, ρ_0 [g/cm³]

The initial density uncertainty was determined by the first measurement using the Anton Paar DMA 5000 M. Using the accuracy of the DMA 5000 M and the accuracy of the dionized water used to characterize it the overall accuracy of the DMA 5000 M is calculated above to be ±12x10^{-6} g/cm³. This uncertainty will be correlated to the final density measurement and must be added to the final density measurement uncertainty; they cannot simply be Root Sum Squared together.

Uncertainty Summary for Initial Density:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{\beta} \cdot \frac{\partial \beta}{\partial \rho_0} = \frac{1}{(\rho_0 - \rho_t)}$

Distribution: Rectangular

One Standard Uncertainty:

$$\frac{12.083\times10^{-6}\ g/cm^3}{\sqrt{3}} = 6.97615\times10^{-6}\ g/cm^3$$

Final Density, ρ_t [g/cm³]

Uncertainty Summary for Final Density:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{\beta}\cdot\frac{\partial\beta}{\partial\rho_t}=\frac{\rho_0}{\rho_t^2\cdot\left(\frac{\rho_0}{\rho_t}-1\right)}$

Distribution: Rectangular

One Standard Uncertainty:

$$\frac{12.083\times10^{-6}\ g/cm^3}{\sqrt{3}}=6.97615\times10^{-6}\ g/cm^3$$

Initial Temperature, t_0 [°F]

The initial temperature uncertainty was determined by the first measurement using the Anton Paar DMA 5000 and according to the manufacturer's specification; this measurement was accurate to within ±0.018 °F [9]. This uncertainty will be correlated to the final temperature measurement and must be added to the final temperature measurement uncertainty; they cannot simply be Root Sum Squared together.

Uncertainty Summary for Initial Temperature:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{\beta}\cdot\frac{\partial\beta}{\partial t_0}=\frac{1}{(t_t-t_0)}$

Distribution: Rectangular

One Standard Uncertainty: $\frac{0.018\ °F}{\sqrt{3}}=0.010392\ °F$

Final Temperature, t_t [°F]

Uncertainty Summary for Final Temperature:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{\beta}\cdot\frac{\partial\beta}{\partial t_t}=\frac{1}{\rho_t}$

Distribution: Rectangular

One Standard Uncertainty: $\frac{0.018\ °F}{\sqrt{3}}=0.010392\ °F$

Repeatability of the Thermal Expansion Measurement, β [°F^{-1}]

The repeatability of the Thermal Expansion Measurements was calculated from the Standard Deviation of the Thermal Expansion measurements and determined to be 1.1991x10^{-5} °F^{-1} which is already one standard uncertainty.

Uncertainty Summary for Thermal Expansion Measurement:

Type of Uncertainty: Relative Type A

Sensitivity Coefficient: $\frac{1}{\beta}$

Distribution: Normal

One Standard Uncertainty: $1.1991\times10^{-5}\ °F^{-1}$

Combined and Expanded MIL-PRF-7024E Type II and Gear Oil Blend Thermal Expansion Uncertainty

See the following Table 2 for the total uncertainty for the determination of the calculated thermal expansion of MIL-C-7024 and Gear Oil blend. The total uncertainty is calculated by summing the uncertainties for the temperature and density measurements and Root Sum Squaring them with the repeatability. Therefore,

$$U=2\sqrt{(0.198029\%+0.196322\%)^2+(0.1272168\%+1.277688\%)^2+(2.446842\%)^2}=7.111769\%. \tag{44}$$

Influence Quantity	Var	Val	Unit	Rect	Norm	One Std Unc	Sensitivity Coefficient	Sens Value	Std Unc (1σ)
Final Density	ρ_t	0.8169	g/cm³	1.2E-05		6.93E-06	$\frac{\rho_0}{\rho_t^2\cdot\left(\frac{\rho_0}{\rho_t}-1\right)}$	285.831	0.00198
Initial Density	ρ_0	0.8134	g/cm³	1.2E-05		6.93E-06	$\frac{1}{(\rho_0-\rho_t)}$	283.366	0.00196
Final Temp	t_t	50.00	°F	0.0180		0.01039	$\frac{1}{\rho_t}$	1.224	0.01272
Initial Temp	t_0	59.00	°F	0.0180		0.01039	$\frac{1}{(t_t-t_0)}$	1.229	0.01278
Repeatability	β	4.90E-04	°F^{-1}		2.40E-05	1.20E-05	$\frac{1}{\beta}$	2.04E+03	0.02447

Overall Uncertainty of Thermal Expansion of Fluid: 7.11 %

Table 2. Combined and Expanded Uncertainty of Expansion of 7024 and Gear Oil Blend.

Uncertainty Summary for Thermal Expansion of MIL-C-7024 and Gear Oil Blend:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial \alpha}=\frac{(T_V-T_W)}{1+\alpha\cdot(T_V-T_W)}$

Distribution: Normal

One Standard Uncertainty:

$$\frac{(7.111769\ \%/100)\cdot(4.90069\times10^{-4}\ °F)}{2}=1.742629\times10^{-5}\ °F$$

Flow Tube Inside Diameter, d [in]

The Flow Tube inside diameter of 4.625 inches was taken from the Flow Technology Test Report for MT10 SN: MT02060175, Report No. 75888, dated July 31, 2002 [11]. It was assumed that the nominal value of 4.625 inches was measured accurately to within 0.0001 in. Therefore:

Uncertainty Summary for Flow Tube Inside Diameter:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial d}=\frac{P_{CAL}}{\gamma\cdot T+P_{CAL}\cdot d}$

Distribution: Rectangular

One Standard Uncertainty: $\frac{0.0001\ in}{\sqrt{3}}=5.7735\times10^{-5}\ in$

Flow Tube Wall Thickness, T [in]

The Flow Tube wall thickness of 0.312 inches was taken from the Flow Technology Test Report for MT10 SN: MT02060175, Report No. 75888, dated July 31, 2002 [11]. It was assumed that the nominal value of 0.312 inches was measured accurately to within 0.0001 in. Therefore:

Uncertainty Summary for Flow Tube Wall Thickness:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial T}=\frac{P_{CAL}\cdot d}{T\cdot(T\cdot\gamma+P_{CAL}\cdot d)}$

Distribution: Rectangular

One Standard Uncertainty: $\frac{0.0001\ in}{\sqrt{3}}=5.7735\times10^{-5}\ in$

Linear Thermal Expansion Coefficient of Encoder, α_{ENC} [°F^{-1}]

This Flow Calibrator utilizes a Mitutoyo Model AT112 Encoder that, according to the Mitutoyo online catalog specifications [12], has a thermal expansion coefficient of $(8\pm1)\times10^{-6}\ °C^{-1}$ with an uncertainty of $\pm1\times10^{-6}\ °C^{-1}$ which converts into $(5/9)\ °C/°F\cdot 8\times10^{-6}/°C=4.44\times10^{-6}/°F$ with an uncertainty of $(5/9)\ °C/°F\cdot\pm1\times10^{-6}/°C=5.56\times10^{-7}/°F$.

Uncertainty Summary for Linear Thermal Expansion Coefficient of the Encoder:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial \alpha_{ENC}}=\frac{(T_d-T_S)}{1+\alpha_{ENC}\cdot(T_d-T_S)}$

Distribution: Rectangular

One Standard Uncertainty: $\frac{5.56\times10^{-6}\ °F^{-1}}{\sqrt{3}}=3.21\times10^{-7}\ °F^{-1}$

Area Thermal Expansion Coefficient of Flow Tube, α_A [°F^{-1}]

The Flow Tube is constructed from 316 Stainless Steel, which according to API Manual of Petroleum Measurement Standards Chapter 12-Calculation of Petroleum Quantities page 16 Table 6 [13] has a linear thermal expansion coefficient of $8.83\text{x}10^{-6}\ °F^{-1}$. Since we want an area thermal expansion coefficient this value must be multiplied by 2 therefore the area thermal expansion coefficient of the stainless steel flow tube is $2(8.83\times10^{-6})=1.766\times10^{-5}\ °F^{-1}$. The NIST online Engineering Tool Box [14] States that the value for the linear thermal expansion of 316 stainless steel is known within 3 to 5%. Therefore, taking 5% as the worst case, the following is obtained for the uncertainty in the volume area thermal expansion coefficient:

$$U=\sqrt{((5/100)\cdot\ (8.83\times10^{-6}\ °F^{-1}))^2+((5/100)\cdot(8.83\times10^{-6}\ °F^{-1}))^2}=6.2438\times10^{-7}\ °F^{-1}. \qquad (45)$$

Uncertainty Summary of Area Thermal Expansion Coefficient of 316 Stainless Steel:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial \alpha_A}=\frac{(T_W-T_S)}{1+\alpha_A\cdot(T_W-T_S)}$

Distribution: Rectangular

One Standard Uncertainty:

$$\frac{6.2438\times10^{-7}\ °F^{-1}}{\sqrt{3}}=3.605\times10^{-7}\ °F^{-1}$$

Volume Thermal Expansion Coefficient of Flask α_V [°F^{-1}]

The volume thermal expansion of Coefficient for PYREX® Borosilicate Glass is given by ASTM E 542 [15] as: 1×10^{-5} / °C or 1×10^{-5}/°C × 5 / 9 °C / °F or 5.56×10^{-6}/°F. The estimated Uncertainty for the Thermal Expansion Coefficient for PYREX® Borosilicate Glass was taken from NIST Report 836/277141-08 [16] for a 5000 ml PYREX® Borosilicate Glass flask SN AVA782. This number was estimated by NIST on this report to be 3.89×10^{-7} °F^{-1}.

Uncertainty Summary for Volume Thermal Expansion Coefficient of Flask:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient: $\frac{1}{K}\cdot\frac{\partial K}{\partial \alpha_V}=\frac{(T_V-T_S)}{1+\alpha_V\cdot(T_V-T_S)}$

Distribution: Rectangular

One Standard Uncertainty:

$$\frac{3.89\times10^{-7}\,°F^{-1}}{\sqrt{3}}=2.24526\times10^{-7}\,°F^{-1}$$

Modulus of Elasticity for Flow Tube, γ_{FT} [psi]

The API Manual of Petroleum Measurement Standards Chapter 12-Calculation of Petroleum Quantities Table 7 Modulus of Elasticity Discrimination Levels (E) page 17 [17] states that the modulus of elasticity for 316 Stainless Steel is 28,000,000 psi. The uncertainty associated with this value is given by the Materials Metrology and Standards for Structural Performance book on page 157 to be accurate to within ±2%.

Uncertainty Summary for Modulus of Elasticity of Flow Tube:

Type of Uncertainty: Relative Type B

Sensitivity Coefficient:

$$\frac{1}{K}\cdot\frac{\partial K}{\partial \gamma}=\frac{P_{CAL}\cdot d}{\gamma\cdot(\gamma\cdot T+P_{CAL}\cdot d)}$$

Distribution: Normal

One Standard Uncertainty:

$$\frac{(28{,}000{,}000\ psi)\cdot(2\%/100)}{2}=280{,}000\ psi$$

Volumetric MIL-PRF-7024E Type II and Pennant 406 Gear Oil Blend Volumetric Draw

	Draw	Draw	Draw	Draw	Draw	Draw	Draw	Draw
	1	2	3	4	5	6	7	8
Pulses	4606	4607	4606	4607	4606	4607	4606	4606
V (L)	0.99958	0.99958	0.99958	0.99958	0.99958	0.99958	0.99958	0.99958
T_W (°F)	65.605	65.599	65.589	65.659	65.43	65.608	65.717	66.038
T_d (°F)	64.44	64.43	64.54	64.71	64.56	64.68	65.26	65.19
T_V (°F)	65.39	65.28	65.12	65.32	65.68	65.26	65.53	65.55
P (psig)	10	10	10	10	10	10	10	10
C_{tm}	0.99998549	0.99998488	0.99998399	0.9999851	0.9999871	0.99998477	0.999986267	0.99998638
C_{pl}	1.00005847	1.00005847	1.00005847	1.00005847	1.00005847	1.00005847	1.000058471	1.00005847
C_{ts}	0.9999577	0.9999576	0.99995742	0.99995866	0.99995461	0.99995776	0.999959682	0.99996535
C_{td}	0.99998419	0.99998415	0.99998464	0.99998539	0.99998473	0.99998526	0.999987834	0.99998752
C_{ps}	1.00000529	1.00000529	1.00000529	1.00000529	1.00000529	1.00000529	1.000005294	1.00000529
C_{vs}	1.00010536	1.00015633	1.00022984	1.00016613	0.99987748	1.00017054	1.000091643	1.00023915
C_{su} (p/l)	4607.93533	4608.93575	4607.93533	4608.93575	4607.93533	4608.93575	4607.935333	4607.93533
C_{Ss} (p/l)	4607.54281	4608.31043	4606.97707	4608.27485	4608.5737	4608.2513	4607.628334	4606.97299

Average Constant at Standard Conditions:	4607.8164	pulses/liter
	17442.483	pulses/gallon
Repeatability (Std Error):	0.0048	%

Table 3. Water Draw Performed on Flow Calibrator.

Type A Repeatability of Water Draw

The repeatability of the K factor for the piston prover was taken from the last row of Table 3 by taking the standard error from all the corrected K factor measurements and converting it to a percent of this average.

Where:
Pulses = Number of Pulse Count from the required to fill the 1 Liter Flask [pulses]
V = Volume of Calibrated Flask Used for Volumetric Calibration [L]
T_W = Temperature of Calibrator [°F]
T_d = Temperature of Detector (Encoder) [°F]
T_V = Temperature of Liquid Media in Calibrated Flask [°F]
P = Calibrator Pressure [psig]
C_{tm} = Correction for Thermal Expansion of Water Draw Vessel (Flask) [-]
C_{pl} = Correction for Liquid Compressibility [-]
C_{ts} = Correction for Thermal Expansion of Flow Tube [-]
C_{td} = Correction for Thermal Expansion of Detector (Encoder) [-]
C_{ps} = Correction for Pressure Expansion of Flow Tube [-]
C_{vs} = Correction for Thermal Expansion of Liquid in Calibrated Flask (Vessel) [-]
C_{su} = Apparent Calibrator Constant [pulses/Liter]
C_{Ss} = Corrected Calibrator Constant [pulses/Liter]

And:
Compressibility Factor of Liquid, $Z_{7024\ \&\ Oil} = 5.85\times10^{-6}$ [psi^{-1}]
Flow Tube Inside Diameter, d = 4.625 [in]
Flow Tube Wall Thickness, T = 0.312 [in]
Standard Temperature, $T_{STD} = 68$ [°F]
Standard Pressure, $P_{TSD} = 0$ [psig]
Linear Thermal Expansion Coefficient of Encoder (Detector), $\alpha_{ENC} = 4.44\times10^{-6}$ [$°F^{-1}$]
Area Thermal Expansion Coefficient of Flow Tube, $\alpha_A = 1.766\times10^{-5}$ [$°F^{-1}$],
Volume Thermal Expansion Coefficient of Water Draw Vessel, $\alpha_V = 5.560\times10^{-6}$ [$°F^{-1}$]
Modulus of Elasticity of Flow Tube, $\gamma_{FT} = 2.8\times10^{7}$ [psi]
Volume Thermal Expansion Coefficient of Liquid, $\alpha_{7024\ \&\ Oil} = 4.90\times10^{-4}$ [$°F^{-1}$]

The repeatability was then calculated to be 0.0048% of 4607.8164 pulses.

Uncertainty Summary for Repeatability:

Type of Uncertainty: Relative Type A

Sensitivity Coefficient: K^{-1}

Distribution: Normal

One Standard Uncertainty: $(4607\ pulses) \cdot (0.0048\%/100) = 0.2213\ pulses$

Combine Uncertainty

The combine uncertainty is calculated below using the following equation:

$$u = \sqrt{u_{M_E}^2 + u_p^2 + u_V^2 + \left(u_{T_W} + u_{T_d} + u_{T_V}\right)^2 + u_{P_{CAL}}^2 + u_{Z_{7024}}^2 + u_{\alpha_{7024}}^2 + u_d^2 + u_T^2 + u_{\alpha_{ENC}}^2 + u_{\alpha_A}^2 + u_{\alpha_V}^2 + u_{\gamma_{FT}}^2 + u_K^2} \tag{47}$$

$$u = (0.000122603) \cdot (100\%) = 0.0122603\%.$$

Expanded Uncertainty

Expanding the above combine uncertainty for a 95% level of confidence a coverage factor of k=2 is used. Therefore the total combine uncertainty for the Flow Calibrator used for this Uncertainty Analysis is given as

$$U_E = k \cdot u = 2 \cdot (0.0122603\%) = 0.02452\%. \tag{48}$$

See Table 4 on the following page for a summary of the Uncertainty Analysis.

Influence Quantities	Variable	Value	Units	Distribution							
				Normal	Rectangular	One Standard Uncertainty	$\frac{1}{K}\cdot\frac{\partial K}{\partial x}$ Sensitivity Coefficient	Sensitivity Value	Std Unc (1σ)	Variance (σ^2)	Std Unc 2σ%
Meniscus Reading Uncertainty	M_E	0.999580	L		0.000105403	6.08546E-05	M_E^{-1}	1.000420176	6.088E-05	3.706E-09	0.01218
Pulses	p	4607.816	(counts)	0.252348217	0.5	0.315044821	p^{-1}	0.000217023	6.837E-05	4.675E-09	0.01367
Volume (liters)	V	0.999580	l		0.00011	6.35085E-05	V^{-1}	1.000420176	6.354E-05	4.037E-09	0.01271
Temperature Calibrator, T_W (°F) (Correlated)	T_W	65.66	°F	0.0144		0.0072	$\frac{\alpha_A[1-\alpha_{7024}\cdot(T_V-T_W)]-\alpha_{7024}\cdot[1+\alpha_A\cdot(T_W-T_S)]}{[1-\alpha_{7024}\cdot(T_V-T_W)]\cdot[1+\alpha_A\cdot(T_W-T_S)]}$	4.723-04	3.401E-06	1.156E-11	0.00068
Temperature Detector, Td (°F) (Correlated)	T_d	64.73	°F	0.018		0.009	$\frac{\alpha_{ENC}}{1+(T_d-T_{STD})\cdot\alpha_{ENC}}$	4.44E-06	3.9961E-08	1.5975E-15	0.00001
Temperature Vessel, T_V (°F) (Correlated)	T_V	65.39	°F	0.0144		0.0072	$\frac{[1-\alpha_{7024}\cdot(T_V-T_W)][-\alpha_{7024}\cdot(1+\alpha_V\cdot(T_V-T_S))-\alpha_V\cdot(1-\alpha_{7024}\cdot(T_V-T_W))]}{[1+\alpha_V\cdot(T_V-T_S)]}$	4.96E-04	3.5690E-06	1.274E-11	0.00071
StandardTemperature (°F)	T_{STD}	68.00	°F	-	-	-	-	-	-	-	-
Standard Pressure (spig)	P_{STD}	0.0	psi	-	-	-	-	-	-	-	-
Calibrator Pressure, P (psig)	P_{CAL}	10.000	psi	4.800		2.4	$\frac{d+\gamma_{FT}\cdot T\cdot Z_{7024}}{\gamma_{FT}\cdot T(1-P_{CAL}\cdot Z_{7024})\cdot(1+(P_{CAL}\cdot d/\gamma_{FT}\cdot T))}$	6.38E-06	1.5304E-05	2.342E-10	0.00306
Compressibility Factor (MIL-C-7024)	Z_{7024} & oil	5.85E-06	in²/lbf		5.85E-09	3.37562E-00	$\frac{P_{CAL}}{1-P_{CAL}\cdot Z_{7024}}$	1.0001E+01	3.3758E-08	1.140E-15	0.00001
Volume Thermal Expansion Coefficient of Fluid (7024)	α_{7024} & oil	4.90E-04	°F⁻¹	3.485E-05		1.74263E-05	$\frac{(T_V-T_W)}{(1+\alpha_{7024}\cdot(T_V-T_W))}$	-2.6434E-01	-4.6065E-06	2.122E-11	0.00092
Flow Tube Inside Diameter (inches)	d	4.63E+00	in		0.0001	5.7735E-05	$\frac{P_{CAL}}{\gamma_{FT}\cdot T+P_{CAL}\cdot d}$	1.14E-06	6.6088E-11	4.368-21	0.00000
Flow Tube Wall Thickness (inches)	T	3.12E-01	in		0.0001	5.7735E-05	$\frac{P_{CAL}\cdot d}{T(T\cdot\gamma_{FT}+P_{CAL}\cdot d)}$	1.70E-05	9.7967E-10	9.598E-19	0.00000
Linear Thermal Expansion Coefficient, ad (encoder)	α_{ENC}	4.44E-06	°F⁻¹		5.56E-07	3.21E-07	$\frac{(T_d-T_{STD})}{1+(T_d-T_{STD})\cdot\alpha_{ENC}}$	3.27E+00	1.0501E-06	1.103E-12	1.00021
Area Thermal Expansion Coefficient, bp (flow tube)	α_A	1.766E-05	°F⁻¹		6.244E-07	3.60483E-07	$\frac{(T_W-T_{STD})}{1+(T_W-T_{STD})\cdot\alpha_A}$	2.344E+00	8.4514E-07	7.143E-13	0.00017
Volume Thermal Expansion Coefficient, vm (draw vessel)	α_V	5.56E-06	°F⁻¹		3.89E-07	2.24526E-07	$\frac{(T_V-T_{STD})}{1+(T_V-T_{STD})\cdot\alpha_V}$	2.61E+00	5.8574E-07	3.431E-13	0.00012
Modulus of Elasticity, E (flow tube)	γ_{FT}	2.800E+07	psi	5.600E+05		280000	$\frac{P_{CAL}\cdot d}{\gamma_{FT}(\gamma_{FT}\cdot T+P_{CAL}\cdot d)}$	1.89E-13	5.2942E-08	2.803E-15	0.00001
Repeatability of Water Draw (Type A)	K	4607.816	Pulses/l	4.426E-01		0.221315412	K^{-1}	0.000217023	4.8030E-05	2.307E-09	0.00961
									Combined Variance	1.50E-08	
									Combined Uncertainty (k=1)	0.000122603	
									Expanded Uncertainty for Cps (k=2)	**0.02452%**	

Table 4. Volumetric Water Draw Uncertainty.

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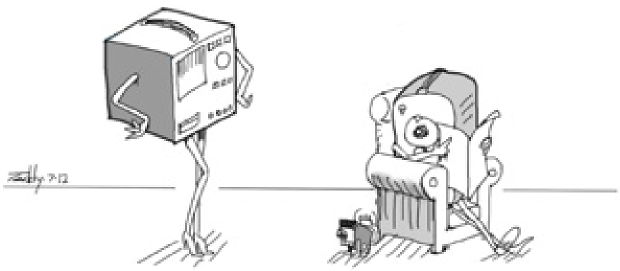

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