NIST Report to the 18th meeting of the CCM

Mass Realization and Dissemination

Kibble Balance measurements

Fundamental Electrical Metrology Group, Darine El-Haddad, David Newell

NIST participated in the first key comparison of the unit of mass in September 2019. Two Pt-Ir standards were realized on NIST primary realization NIST-4 and were sent to the BIPM. The result of this work is published in [8]. NIST continues its effort in the design of the tabletop-sized Kibble balance operating at the gram-level range with uncertainties on the order of a few parts in 10^6. The design and the uncertainty budget of the first protype KIBB-g1 are published[1]. The next generation KIBB-g2 is under development and the focus will be on: 1) having a more compact and cheaper design, 2) improving the moving and weighing mechanisms, and 3) redesigning the velocity readout. NIST is also developing the Quantum Electro-Mechanical Metrology Suite (QEMMS) to provide measurements of mass, electrical voltage and electrical resistance traceable to the International System of Units (SI). The system is composed by a Kibble balance, a programmable Josephson voltage standard and a graphene-based quantum Hall resistance standard. The QEMMS Kibble balance will be used to measure masses with nominal values up to 100 g with relative uncertainties lower than $2x10^{-8}$

In support of realizing mass using a Kibble balance, NIST has submitted a proposal at the 29 April meeting of the CCM Working Group of Gravity to host the 2023 International Comparison of Absolute Gravimeters (ICAG 2023). The proposed location is the Table Mountain Geophysical Observatory (TMGO) located 20 km North of Boulder, Colorado, USA and operated by the National Oceanic and Atmospheric Administration, National Geodetic Survey (NOAA-NGS). Proposal is pending approval of the CCM.

Publication:

L. Chao, F. Seifert, D. Haddad, J. Stirling, D. Newell, and S. Schlamminger. The design and development of a tabletop Kibble balance at NIST. IEEE Transactions on Instrumentation and Measurement, 68(6):2176{2182, 2019, DOI: 10.1109/TIM.2019.2901550.

Mise-en-pratique

Mass and Force Group, Patrick Abbott, Edward Mulhern, Zeina Kubarych

The NIST pool of mass standards in vacuum and air is complete and fully functioning. Six artifacts, some platinum-iridium and some stainless-steel, are stored in vacuum and six more of both materials are stored in air. The vacuum artifacts have primarily resided in a high vacuum storage chamber but have

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[1] M Stock, P Conceiao, H Fang, F Bielsa, A Kiss, L Nielsen, D Kim, M Kim, K C Lee, S Lee, M Seo, B C Woo, Z Li, J Wang, Y Bai, J Xu, D Wu, Y Lu, Z Zhang, Q He, D Haddad, S Schlamminger, D Newell, E Mulhern, P Abbott, Z Kubarych,N Kuramoto, S Mizushima, L Zhang, K Fujita, S Davidson, R G Green, J O Liard, N F Murnaghan, C A Sanchez, B M Wood, H Bettin, M Borys, M Mecke, A Nicolaus, A Peter, M Mu¨ller, F Scholz, and A Schofeld. Report on the CCM key comparison of kilogram realizations CCM.m-k8.2019. *Metrologia*, 57(1A):07030–07030, Jan 2020,
DOI: 10.1088/0026-1394/57/1a/07030.

been transferred to NIST's high resolution vacuum mass comparator via the evacuated Mass Transfer Vehicle for occasional mass measurements. Our data indicate a systematic mass drift of the artifacts in vacuum between 0.002 mg and 0.005 mg over the course of the past 18 months (2020-mid 2021). Mass changes of the air-stored artifacts are more random, and systematic changes can be attributed to a small drift rate (~ 0.001 mg/year) in the platinum-iridium prototypes.

Dissemination

Mass and Force Group, Patrick Abbott, Zeina Kubarych

As of February 1, 2021, he NIST mass scale is traceable to the SI through the Consensus Value of the kilogram (CV) as determined by the results of the first key comparison CCM.M-K8.2019. The uncertainties of K20, K4, and K79 are now 0.020 mg as prescribed by the CCM Task Group on the Phases for the Dissemination of the kilogram following redefinition (CCM-TGPfD-kg). This uncertainty has been propagated throughout the NIST mass scale, and where appropriate, CMCs are being revised.

Collaborative Study

The Sistema Interamericano de Metrologia (SIM) Kilogram Dissemination Project (SKDP) co-piloted by NIST and NRC-Canada continues, though scheduling has been delayed due to COVID-19 pandemic shutdowns and travel restrictions. Since November 2018, participating SIM countries have been making regular mass measurements of the stainless steel one-kilogram mass artifacts that they were given at the beginning of the study, against their own standards. Each country is preparing send their artifact to either NIST or NRC-Canada for recalibration in June of 2021. These arrangements were discussed between the participants at a closed session of the online meeting "KCDB 2.0 at the service of the SIM region in Mass and Related Quantities" held in March 2021.

Participation in relevant comparisons

NIST participated in the CCM.M.K8 key comparison for realization of the kilogram.

Publications, conferences, Training

- P. Abbott, "The Revised SI, Mass Metrology, and the Cost of Freedom", NCSLI International Workshop and Symposium, 2019
- P. Abbott, E. Benck, E. Mulhern, and Z. Kubarych, "Mass Standards at NIST for 2020 and Beyond", NCSLI Virtual Symposium, 2020.
- Abbott, Patrick J., Redefined but not perfected: the ongoing saga of the kilogram, *Cal Lab*, 27, (2), 28-33 (2020).
- P. Abbott, "Metrology and the Updated SI: The IPK Strikes Back!", *NCSLI 2020 Metrology in Motion Webinar Series*, April 28, 2020.
- P. Abbott participated in a Peer Review of NRC-Canada Mass and Related Quantities calibration services (December 2018).
- P. Abbott was one of three panelists for NRC-Canada METRO Mass and Related Quantities facility review (March 2021).
- P. Abbott, "The New Kilogram Definition in the Revised SI", Measurement Science Conference training course, 2019.

Small Mass and Force Metrology

Mass and Force Group, Gordon Shaw

<u>Main research and development activities related to CCM activities:</u>

<u>Milligram Mass Metrology</u>

The NIST Electrostatic Force Balance (EFB) is an electromechanical balance using SI electrical metrology to measure mass and force. It has begun operating as a primary reference for mass at the milligram level and below after demonstrating equivalence to conventional subdivision methods in 2016 [1]. Subsequent to the SI redefinition, the EFB now realizes mass for NIST in the range from 30 milligrams to 50 micrograms [2]. These calibrations have been made available as a special test.

<u>Photon Pressure Force Metrology for Laser Power Measurement</u>

The NIST Electrostatic Force Balance (EFB) was used in a comparison to establish the traceability of laser power calibration using photon pressure force. The NIST Sources and Detectors Group provided a calibrated detector that measured the power of a 3-watt laser reflected from a mirror on the EFB. The measured photon pressure force was compared to that expected from the calibrated detector, and a detailed uncertainty analysis was carried out [3]. Methods for use of masses calibrated by the EFB (see above) were developed allowing calibration of the NIST Radiation Pressure Power Meter (RPPM), Standard Reference Instrument 6009, reducing calibration uncertainty [4], and extending the range of SI traceable laser power calibrations [5].

<u>Mass, Force and Laser Power on a Chip</u>

As part of the NIST-on-a-Chip program, a portable electrostatic force reference was developed for distributed realization of mass, force and laser power [6]. The balance is designed to provide laser power realization using photon pressure force in the range of 500 micronewtons with a relative standard uncertainty of approximately 10^{-4}.

<u>Publications:</u>

- Gordon A. Shaw, Julian Stirling, John Kramar, Paul Williams, Matthew Spidell, Richard Mirin, “Comparison of electrostatic and photon pressure force references at the nanonewton level” *Metrologia* **56** 025002 (2018) DOI: 10.1088/1681-7575/aaf9c2
- K. A. Rogers, P. A. Williams, G. A. Shaw, “Simplified kilogram traceability for high-power laser measurement using photon momentum radiometers” *Applied Optics*, 59, 8719-8723 (2020) DOI: 10.1364/AO.399989

- P. Williams, M. Spidell, J. Hadler, T. Gerrits, A. Koepke, D. Livigni, M. Stephens, N. Tomlin, G. A. Shaw, J. Splett, I. Vayshenker, M. White, C. Yung, J. Lehman, “Meta-study of laser power calibrations ranging 20 orders of magnitude with traceability to the kilogram” *Metrologia*, 57, 015001 (2020) DOI: 10.1088/1681-7575/ab4641
- L. Keck, G.A. Shaw, R. Theska, S. Schlamminger, “Design of an Electrostatic Balance Mechanism to Measure Optical Power of 100 kW” *IEEE Trans. Instrum. Meas.*, 70, 7002909 (2021) DOI: 10.1109/TIM.2021.3060575

Static and Dynamic Force

Mass and Force Group, Akobuije Chijioke, Kevin Chesnutwood

Main research and development activities related to CCM activities:

Dynamic Force Impact Calibration

Work on a laboratory impact standard has continued, with application to calibration of impact transfer standards up to 10 kHz. Collaboration with NIST staff engaged in Charpy impact testing of materials has yielded progress in SI-traceable calibration of instrumented Charpy impacts, including construction and successful demonstration of a new instrumented striker design. Investigation of the effects of nonlinearity in dynamic calibration has been carried out, along with work to provide full uncertainty estimates for deconvolved dynamic measurements.

Optomechanical Force Sensing

Research on optomechanical sensors based on electro-optic comb readout of optical cavity response has been carried out, as part of a team involving other NIST groups. Recent work has focused on application of the method to optomechanical accelerometers, but the technique directly applies to optomechanical force sensors as well.

Participation in relevant comparisons

CCM.F-K23: key comparison of Measurand Force 200 N and 500 N. Initial measurements completed at NIST in September 2020. Pilot lab METAS completed measurements in February 2021. Final NIST measurements are underway in April 2021.

Collaborations:

NIST participated in the SIM-IADB collaborative project Industrial Dynamic Measurements, from 2017-2020.

Participated in the "KCDB 2.0 at the service of the SIM region in Mass and Related Magnitudes" virtual event. The events goal was to provide tools to the Working Group on Mass and Related Magnitudes of the Inter-American Metrology System (SIM) on how to properly interact with the KCDB 2.0 platform. The 5-day event took place from March 22-26 and ended the week with a WG7 working group meeting in Force and Torque.

Participated in the CCM Working Group on Force and Torque virtual meeting in April 2021.

Kevin Chesnutwood was elected Technical Secretary of the SIM MWG7 Force and Torque at the April 2021 virtual meeting

List of relevant publications:

- Burns, D. E., Vlajic, N., Chijioke, A. and P. A. Parker, (2021). An Aerodynamic Metrologists Guide to Dynamic Force Measurement, *submitted to AIAA Journal of Aircraft*.
- Chijioke, A. and N. Vlajic (2021). High-Bandwidth Impact Force Calibration Standard, *submitted to XXIII IMEKO World Congress.*
- Savarin, A. and A. Chijioke (2021). Measurement of Dynamic Rocking in Sinusoidal Calibration with an Electrodynamic Shaker, *submitted to XXIII IMEKO World Congress.*

- Long, D., Reschovsky, B. J., Zhou, F., Bao, Y., LeBrun, T. W., and J. Gorman (2021). Electro-optic Frequency Combs for Rapid Interrogation in Cavity Optomechanics. Optics Letters, 46(3), 645-648.
- Vlajic, N., Chijioke, A., and E. Lucon, (2020). Design Considerations to Improve Charpy Instrumented Strikers, Journal of Research of the National Institute of Standards and Technology, 125, 1-17.
- Cilenti, L.D., Chijioke, A., and B. Balachandran (2020). Error Quantification in Dynamic Application of Weakly Nonlinear Transducers. In *ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 2: 16th International Conference on Multibody Systems, Nonlinear Dynamics, and Control (MSNDC)*. American Society of Mechanical Engineers.
- N. A. Vlajic, A. D. Chijioke, E. Lucon and L. Einfeld, *NIST Technical Note 2081*, Investigations of SI-Traceable Dynamic Calibration of Instrumented Charpy Strikers: Activities Performed at NIST in FY2019 Investigations on SI-Traceable Dynamic Calibration of Instrumented Charpy Strikers, (2020).
- Long, D. A., and B. J. Reschovsky, (2019). Electro-optic Frequency Combs Generated via Direct Digital Synthesis Applied to Sub-Doppler Spectroscopy, OSA Continuum, 2(12), 3576-3583.
- Rezac, J. D., Dienstfrey, A. M., Vlajic, N., Chijioke, A. D, and P. D. Hale, (2018). Generalized Source-Conditions and Uncertainty Bounds for Deconvolution Problems. In *XXII World Congress of the International Measurement Confederation (IMEKO 2018)*.

Hardness

Mechanical Performance Group, Materials Science and Engineering Division, Samuel Low

Main research and development activities related to CCM activities:

- Sam Low (NIST) has served as Chair of the CCM-Working Group (CCM-WGH) on Hardness since 2014. There have been two CCM-WGH meetings since the last CCM meeting (May 2019):
  - 19th Meeting — 27th September 2019 in Ulm, Germany
  - 20th Meeting — 30th April 2021 as a 2-hour virtual meeting hosted by the CCM
- NIST is leading the CCM-WGH task to develop measurement parameter definitions for the Rockwell B (HRBW) hardness scale and the Rockwell N (HR15N, HR30N, HR45N) hardness scales and a revision of the definition for the Rockwell C (HRC) hardness scale to be used by NMIs that standardize these measurements.
- NIST commissioned the new Primary (PHSM) machine to be used for the realization of the Rockwell hardness scales and is working on the replenishment of inventory of the low and middle hardness level of Rockwell C hardness scale reference blocks.

Key Comparisons and Pilot Studies:

- NIST participated in a CCM Pilot Study [CCM.H-P1] of Geometrical Measurements of Rockwell Diamond Indenter. NIST participated in the data analyses and preparation of the Report. The final Report is completed and approved by the CCM.

Relevant Publications:

- R. R. Machado, S. Low, A. Germak, CCM pilot study overview: geometrical measurement of the Rockwell diamond indenter, Special Issue of Acta IMEKO, Vol 9, No 5 (2020), https://acta.imeko.org/index.php/acta-imeko
- S. Low, A. Germak, A. Knott, R. Machado, J. Song, "Developing Definitions of Conventional Hardness Tests for Use by National Metrology Institutes", in process, to be published in the proceedings of the IMEKO2021 World Congress on Elsevier open access Journal: Measurement: Sensors.

Pressure and Vacuum

Thermodynamic Metrology Group, Julia Scherschligt

Main Research and Development Activities:

The NIST Thermodynamic Metrology Group has been working next generation pressure and vacuum primary standards with active programs to redefine how pressure and vacuum is realized and disseminated. The NIST program and progress in these areas: 1) development of photonic based pressure standards based on Fixed Length Optical Cavities (FLOCs). 2) Development of a Cold -Atom Vacuum Standards (CAVS) for extreme vacuum measurements (XHV). 3) Development of dynamic pressure measurement standards based on spectroscopic methods.

1.Photonic based Pressure Standards:

Significant progress has been made in a program intended to eliminate the need of mercury manometers as primary pressure standards, and to replace them with an optical technology based on direct measurements of density by measuring the refractive index of a gas. Traceability is achieved through quantum chemistry calculations of helium's refractive index. The technique enables a new route to the SI unit of pressure, the pascal. This is in contrast to the traditional methods of measuring column heights of mercury or force per area Impacts: Replacement of mercury manometer primary pressure standards, field deployable primary standards for national labs and for international key comparisons. Status: Fixed Length Optical Cavities have been built and have demonstrated measurement performance that meets or exceeds mercury manometers in terms of precision and range. Several techniques to determine refractive index of nitrogen through an independent method are underway including: two color fixed length interferometry and monolithic interferometer for refractometry (MIRE). These experiments should enable the FLOC measurement accuracy to surpass that of the NIST ultrasonic interferometer mercury manometers.

2. Cold Atom Vacuum Standard:

NIST has started a program to develop the world's first primary pressure standard based on trapped cold atoms. The Cold Atom Vacuum Standard (CAVS) will measure gas pressure in the UHV and XHV ranges through atom loss from a shallow trap, which is traceable to fundamental physics. Impacts: First SI traceable XHV vacuum standard. Status: A large-scale prototype system has been demonstrated, and *a priori* quantum-collision calculations that establish traceability are complete for a variety of different collision partners. An apparatus to experimentally verify these calculations is nearly finished, and a portable version of the CAVS has been designed. Impacts: Next generation semiconductors and molecular electronics requiring pure XHV production environments.

3. Transient Pressure Standard:

NIST is conducting research to enable traceability for transient pressure measurements. Ultimately, traceability will be achieved via spectroscopic interrogation of gas molecules. The project is also developing photonic transient pressure sensors that are drop in replacements for current sensors. Status: A highly reproducible shock tube has been built and characterized and with initial tests of photonic sensors. The spectroscopic method has been evaluated under static conditions. Impacts: Traumatic brain injury, gas turbines, industrial processing and energy production.

Key Comparisons and Pilot Studies:

CCM.P-K4.2012	Comparison of absolute pressure in the range, 1 Pa to 10 kPa	Completed.
CCM.P-K14	Comparison of absolute pressure in the range, 1 mPa to 1 Pa	Completed.
SIM.M.P-K1	Effective area of piston gauges, 600 kPa to 7 MPa.	Report B in review.
SIM.M.P-K2	Absolute pressure comparison from 10 kPa to 120 kPa (NIST is pivot lab)	Measurement phase.
SIM.M.P-K6	Effective area of piston gauges, 10 kPa to 120 kPa.	Draft A complete.
SIM.M.P-K6.1	Positive gauge pressure comparison from 10 kPa to 100 kPa (NIST is pivot lab)	Measurement phase.
CCM.P-K4.2012.1	NIST – PTB Bilateral comparison in absolute pressure from 0.1 Pa to 10000 Pa	Protocol accepted. Measurement phase.
CCM.P-K1.b.2020	Key Comparisons on Gas Pressure 25 kPa – 350 kPa, Gauge Mode	Measurement Phase
CCM.P-K1.c.2020	Key Comparisons on Gas Pressure 0.7 MPa – 7 MPa, Gauge Mode	Measurement Phase

Relevant Publications:

"Transient heating in fixed length optical cavities for use as temperature and pressure standards," Ricker, Jacob, et al, Metrologia 58 (2021) 035003.

"Outgassing rate comparison of seven geometrically similar vacuum chambers of different materials and heat treatments", J.A. Fedchak, *et. al.*, *Journal of Vacuum Science & Technology B* **39**, 024201 (2021).

"A Bitter-type electromagnet for complex atomic trapping and manipulation," J.L. Siegel, *et. al., Review of Scientific Instruments* **92**, 033201 (2021).

"An integrated and automated calibration system for pneumatic piston gauges", Yang, Yuanchao, et al, Measurement, Volume 134, February 2019, Pages 1-5.

"Measured relationship between thermodynamic pressure and refractivity for six candidate gases in laser barometry," Egan, Patrick et al, J. Vac. Sci. Technol. A 37 (2019) 031603

"Collisions of room-temperature helium with ultracold lithium and the van der Waals bound state of HeLi." C. Makrides, et. al*., Physical Review A* **101**, 012702 (2020).

"Elastic rate coefficients for Li+H_2 collisions in the calibration of a cold-atom vacuum standard," C. Makrides, *et. al.*, *Physical Review A* **99**, 42704 (2019).

"Towards traceable transient pressure metrology," Hanson, E. et. al., Metrologia 2018.

"Quantum-based vacuum metrology at the National Institute of Standards Technology", Scherschligt, Julia, et al, , J. Vac. Sci. Technol. A. 36 (2018) 040801. doi:10.1116/1.5033568.

"Recommended practice for calibrating vacuum gauges of the ionization type", J.A. Fedchak, et. al., Vac. Sci. Technol. A Vacuum, Surfaces, Film. 36 (2018) 030802.

"Recent Developments in Surface Science and Engineering, Thin Films, Nanoscience, Biomaterials, Plasma Science, and Vacuum Technology", M.Mozetič, et al, Thin Solid Films, Volume 660, 30 August 2018, Pages 120-160.

"Challenges to miniaturizing cold atom technology for deployable vacuum metrology" Eckel, Stephen et. al. Metrologia 55 (5), S182 (2018).

"Quantum for Pressure" J. Hendricks, *Nature Phys* **14,** 100 (2018). https://doi.org/10.1038

"Perspectives for a new realization of the pascal by optical methods", Karl Jousten, Jay Hendricks, et al, Metrologia, Volume 54, no.6, November 2017.

"Cell-based refractometer for pascal realization "Egan, Patrick, et al, Optics Letters Vol. 42, Issue 15, pp. 2944-2947 (2017) https://doi.org/10.1364/OL.42.002944.

"Stuck in a moment: A view from the MIRE", Egan, Patrick, et al ASPE Precision Engineering and Optics, April 2017.

"Report on the Key Comparison CCM.P-K4.2012 in Absolute Pressure from 1 Pa to 10 kPa", Ricker. Jacob, et al, Metrologia. 2017, 54(Technical Suppl). pii: 07002. doi: 10.1088/0026-1394/54/1A/07002.

US Patent No. 9,719,878, "PHOTONIC ARTICLE, PROCESS FOR MAKING AND USING SAME" Patent issued: Aug 1st, 2017.

"Final report on the key comparison, CCM.P-K15 in the pressure range from 1.0 × 10 -4 Pa to 1.0 Pa", C. Wuethrich et. al. Metrologia. 54 (2017) 07003–07003.

"Development of a new UHV/XHV pressure standard (cold atom vacuum standard)" Scherschligt, Julia et. al. Metrologia 54 (6), S125 (2017).

"Automated Piston Gauge Calibration System" Scherschligt, Julia et. al. NCSLI Measure 12 (1), 42-45 (2017).

Flow

Fluid Metrology Group, John Wright

<u>Research and development activities of the NIST Fluid Metrology Group (FMG) related to the CCM</u>:

- The FMG is working to establish traceable, lower uncertainty measurements of pollutants from smokestacks. This work facilitates accurate accounting of carbon emissions from electric power plants. The NIST Wind Tunnel was modified to perform automated calibrations of air speed sensors over ranges of yaw angle ±180°, pitch angle ±45°, airspeed 1 m/s to 30 m/s, and turbulence intensity 0.07 % to 25 %. New multiport Pitot sensors and non-nulling velocity profiling methods were developed. (Pitot tubes are normally used for in situ calibrations of ultrasonic stack flow meters.) NIST developed methods are 4 times faster and reduce uncertainty for CO2 and other emissions from 20 % or more to 2 % or less. These results are based on measurements made in the NIST Smokestack Simulator and during field tests at four coal-fired electric power plants. We have also demonstrated that ultrasonic flow meters using a crossed pair of paths instead of one path reduce errors due to swirl from 17 % to 1 %.

- The FMG is researching temperature corrections to Coriolis flow meter measurements by developing a physical model that connects material properties to the meter factor. The model was validated using data from water flows over a range of temperatures and cryogenic flow data. The goal is to extrapolate coriolis meter calibrations performed using room temperature water to cryogenic applications (like liquified natural gas) with well known, low uncertainty.

- The FMG is applying acoustic and microwave resonator methods to measure the average temperature and volume of gas in a pressurized vessel. This effort will enable accurate and lower cost measurements of large gas flows via blow-down gas flow standards.

See the publications listed below for more information on these and other projects.

<u>Recent flow comparisons with NIST participation:</u>

Identifier	Description
CCM.FF-K1.2015	Water flow
CCM.FF-K2.1.2011	Hydrocarbon liquid flow
CCM.FF-K6.2017	Low Pressure Gas Flow
SIM.M.FF-K4.2017	Liquid volume
SIM.M.FF-K6.2017	Low Pressure Gas Flow

<u>Recent papers relevant to the CCM activities</u>:

"Faster, More Accurate, Stack Flow Measurements", Johnson, Shinder, Filla, Boyd, Bryant, Moldover, Martz, and Gentry, Journal of Air and Waste Management Association, Vol. 70, 2020.

“Blow-Down Calibration of a Lage Ultrasonic Flow Meter”, Johnson, A. N., Harman, E., and Boyd, J. T., Flow Meas. Instrum., 77, 2021.

“Non Nulling Measurements of Flue Gas Flows in a Coal-Fired Power Plant Stack”, Johnson, A. N., Shinder, I. I., Filla, J. B., Boyd, J. T., Bryant, R., Moldover, M. R., FLOMEKO 2019, Lisbon, Portugal, June 26 to 28, 2019.

“Improving Measurements of Smokestack Emissions – Workshop Summary”, Bryant, Johnson, Wright, Wong, Whetstone, Moldover, Shinder, Swiggard, Gunning, Elam, Martz, Harman, Nuckols, Zhang, Kang, Vigil, NIST Special Publication 1228, 2018.

“Modeling Temperature Effects on a Coriolis Mass Flow Meter”, Costa, Pope, and Gillis, Flow Measurement and Instrumentation, Vol. 76, 2020.

“Progress towards a Gas-Flow Standard Using Acoustic and Microwave Resonances”, Pope, J. G., Gillis, K. A., Moldover, M. R., Harman, E., and Mehl, J. B., Flow Measurement and Instrumentation, July, 2019.

“Reproducibility of Liquid Micro-Flow Measurements”, Wright, J. D. and Schmidt, J. W., FLOMEKO 2019, Lisbon, Portugal, June 26 to 28, 2019.

“Automated Substitution Weighing Apparatus for Liquid Volume Measurement”, Wright, Sheckels, and Boyd, 18th FLOMEKO, Lisbon, Portugal, June 26 to 28, 2019.