NIST Report to the 19th meeting of the CCM Mass Realization and Dissemination

Kibble Balance measurements

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

NIST participated in the second key comparison of the unit of mass in October 2021. Two Pt-Ir standards were realized using the US primary mass standard NIST-4 and subsequently sent to the BIPM. The result of this work is published in [1]. For the first time, NIST employed two quantum electrical standards of voltage and resistance in a single current source arrangement directly with the NIST-4 Kibble balance to determine a 50g and 100g mass [2].

The Quantum Electro-Mechanical Metrology Suite (QEMMS) [3-10] is under construction to provide measurements of mass, electrical voltage and electrical resistance traceable to the International System of Units (SI) all within a single metrology scheme. The system is composed of 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 below $2x10^{-8}$ Characterization of mechanical hysteresis in the force mode and error of motion in the velocity mode are underway.

NIST continues its efforts in the development 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 first-generation instrument KIBB-g1 has demonstrated capabilities of realizing gram-level masses on par with OIML Class E2 standards [5]. This endeavor caught the attention of the US Department of Defense and a collaboration was formed for developing the second generation instrument, KIBB-g2 [11]. Efforts continue to push the tabletop Kibble balance project towards commercialization.

In a similar project, NIST has developed a prototype tabletop Kibble-style torque realization device which can realize SI-traceable torque from $1.2x10^{-3}$ Nm to $18x10^{-3}$ Nm with uncertainties of less than one part in 10^3 [12]. The project continues with goals of increasing operational range and pursuing commercialization.

In support of realizing mass using a Kibble balance, the submitted proposal by NIST to pilot the 2023 International Key Comparison of Absolute Gravimeters (ICAG 2023) was approved at the 18th meeting of the CCM. Designated CCM.G-K2.2023, the site 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). The comparison will run from August 21 to September 29, 2023 with a workshop planned for the week of August 28 to September 1, 2023. Presently 19 NMI/DIs have registered with the total of participants at 31. The draft technical protocol will be discussed at the 2023 CCM – WGG meeting.

Publications:

Journals:

1. M Stock, P Conceição, H Fang, F Bielsa, A Kiss, L Nielsen, F Beaudoux, P Espel, M Thomas, D Ziane, H Baumann, A Eichenberger, K Marti, Y Bai, M Hu, Z Li, Y Lu, C Peng, J Wang, Y Wang, D Wu, P Abbott, D Haddad, Z Kubarych, E Mulhern, S Schlamminger, D Newell, K Fujita, H Inaba, K Kano, N Kuramoto, S Mizushima, S Okubo, Y Ota, L Zhang, S Davidson, R G Green, J O Liard, N F

Murnaghan, B M Wood, M Borys, D Eppers, D Knopf, E Kuhn, M Hämpke, M Müller, A Nicolaus, F Scholz, M Spoors and H Ahmedov, Final report on the CCM key comparison of kilogram realizations CCM.M-K8.2021, *Metrologia*, 60, 2023

2. Frank C. Seifert, Alireza R. Panna, I-Fan Hu, Lorenz H. Keck, Leon S. Chao, Shamith U. Payagala, Dean G. Jarrett, Chieh-I Liu, Dipanjan Saha, Randolph E. Elmquist, Stephan Schlamminger, Albert F. Rigosi, David B. Newell & Darine Haddad, A Macroscopic Mass from Quantum Mechanics In An Integrated Approach, *Nature Communication Physics*, 5 (321), December 2022

3. L. Keck, F. Seifert, D. Newell, S. Schlamminger, R. Theska, D. Haddad, Design of an enhanced mechanism for a new Kibble balance directly traceable to the quantum SI, *EPJ Techniques and Instrumentation*, 9, July 2022.

4. R Marangoni, D Haddad, F Seifert, L S Chao, D B Newell, S Schlamminger, Magnet system for the Quantum Electro-Mechanical Metrology Suite, *IEEE Trans. Inst. Meas, 69, 2020*

5. L. Chao, F. Seifert, D. Haddad, J. Pratt, D. Newell, and S. Schlamminger, The performance of the KIBB-g1 tabletop Kibble balance at NIST, *Metrologia*, vol. 57, no. 3, p. 10, 2020

Conferences:

6. L. Keck, F. Seifert, S. Schlamminger, D. Newell, R. Theska, and D. Haddad, A Kibble balance as part of a quantum measurement institute in one room at NIST, SMSI2023

7. L. Keck, F. Seifert, D. Newell, R. Theska, and D. Haddad, The Quantum Electro-Mechanical Metrology Suite – a new Kibble balance in an NMI in one laboratory,"ICW2023

8. L. Keck, F. Seifert, D. Newell, R. Theska, S. Schlamminger, and D. Haddad, Proof of performance of the new flexure-based mechanism for a Kibble balance at NIST, CPEM2022

9. L. Keck, F. Seifert, S. Schlamminger, D. Newell, R. Theska, and D. Haddad, An enhanced mechanism for a Kibble balance at the National Institute of Standards and Technology, EUSPEN 2022

10. L. Keck, S. Schlamminger, F. Seifert, D. Newell, R. Theska, and D. Haddad, Design of the mechanical system for the quantum electro-mechanical metrology suite, ASPE 2021

11. Y. Cao, S. Schlamminger, D. Newell, J. Hendricks, B. Goldstein, L. Chao, The design and development of the second generation tabletop Kibble balance at NIST, Euspen's 22nd International Conference Proceedings, Geneva, Switzerland, June 2022

12. Z. Comden, J. Draganov, S. Schlamminger, F. Seifert, C. Perera, D. Newell, L. Chao, Refining Measurements of a n SI-Traceable Self-Calibrating Electronic Torque Standard, American Society for Precision Engineering, 2022

Mass Dissemination

Mass and Force Group, Zeina Kubarych, Patrick Abbott, Kevin Chesnutwood, Eric Benck, Edward Mulhern, Joshua Graybill

As of March 1, 2023, the 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-K8.2021. As prescribed by the CCM Task Group on the Phases for the Dissemination of the kilogram following redefinition (CCM-TGPfD-kg) the correction has been propagated throughout the NIST mass scale.

Mass Automation Software

Work with the NIST Office of Information Systems and Management continues with integration of mass comparators, database, data analysis, report generation, and application of digital calibration certificate requirements to enable interfacing with the NIST Storefront and the generation of machine-readable reports.

Digital Calibration Certificate (DCC) Pilot Project

Participated in NIST-wide Digital Calibration Certificate (DCC) pilot program. Provided calibration data and reports, input on information required for DCC, standardization of reports, and using the mass calibration automation software and database as a source for successfully generating machine-readable XML reports and human-readable reports.

SIM Project

Completed Phase 2 of the SIM Kilogram Dissemination Project in collaboration with NRC Canada. The stability of mass standards was monitored using standards kept at NIST by completing multiple measurement campaigns. Mass standards distributed to SIM participants were returned to NIST and NRC, they were measured, new reports were generated and sent back to the participating NMIs. Analysis of the results is ongoing in collaboration with NRC.

Participation in relevant comparisons and collaborations

NIST participated in the second round of CCM.M.K8 key comparison for realization of the kilogram and is participating in the third round taking place in late 2023.

NIST is participating in the NIST/PTB cooperation to measure the mass of a silicon sphere.

Publications, Conferences, Training

- Abbott, P. J., Kubarych, Z. J., Mulhern, E.C., co-authors on Metrologia publication on results of CCM.M.K8 Key Comparison of the realization of the kilogram:
  M Stock *et al* 2023 *Metrologia* **60** 07003**DOI** 10.1088/0026-1394/60/1A/07003
- Abbott, P.J. Presentation at A2LA Tech Forum on the status of redefinition of the kilogram, Aug 2021
- Abbott, P.J. Presentation at SIM Metrology for Digital Transformation M4DT Symposium on "Automation of Mass Calibrations", September 2021.
- Abbott, P.J. Presentation at training event organized by Mettler Toledo for World Metrology Day in May 2022.
- Mulhern, E.C. One-day tutorial on mass metrology at the NCSLI Conference in August 2022.

Small Mass and Force Metrology

Mass and Force Group, Gordon Shaw

Milligram Mass Metrology

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.

Subsequent to the SI redefinition, the EFB now realizes mass for NIST in the range from 30 milligrams down to 50 micrograms. These calibrations have been made available as a special test.

A new EFB capable of SI mass realization for liquid samples was developed for the True Becquerel Innovation In Measurement Science (IMS) program at NIST. This balance will aid in the preparation of samples of radionuclide SRMs in a new paradigm for realizing the becquerel using superconducting Transition Edge Sensors (TESs).

Photon Pressure Force Metrology for Laser Power Measurement

A portable EFB was designed, constructed and implemented in a comparison to establish the traceability of laser power calibration using photon pressure force. The protype balance uses the same traceability path used for mass calibration as described above, and is capable of resolving watt-level laser power (10 nanonewtons of force) with a measurement uncertainty of less than 0.1 % for laser power up to 100 kW.

Mass, Force and Laser Power on a Chip

As part of the NIST-on-a-Chip program, a chip-scale force reference was developed for distributed realization of mass, force, and laser power. The device is designed to provide laser power realization in a miniaturized form factor at the Watt level with percent-level uncertainty.

Publications:

- 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.

- Sven Schulze, Lorenz Keck, Kyle Rogers, Brian Simonds, Alexandra Artusio-Glimpse, Paul Williams, John Lehman, Frank Seifert, David Newell, René Theska, Stephan Schlamminger, Gordon Shaw, An electrostatic balance as a primary standard to measure high laser power by a multiple reflection system, *Proc. ASPE*, October 10-14, Bellevue, WA, (2021).

- Sven Schulze, Kumar Arumugam, René Theska, Gordon Shaw, Development of a high precision balance for measuring quantity of dispensed fluid as a new calibration reference for the becquerel, *Proc. EUSPEN*, Geneva, CH, May/June (2022).

- Kumar Arumugam, Gordon A. Shaw, A miniature electrostatic force balance for laser power measurement, *Proc. ASPE*, September 19-20, Indianapolis, IN (2022).

- G. A. Shaw, Milligram mass metrology for quantitative deposition of liquid samples, *Measurement: Sensors*, 22, 100380, DOI: 10.1016/j.measen.2022.100380 (2022), invited.
- Ryan P. Fitzgerald, Bradley K. Alpert, Daniel T. Becker, Denis E. Bergeron, Richard M. Essex, Kelsey Morgan, Svetlana Nour, Galen O'Neil, Dan R. Schmidt, Gordon A. Shaw, Daniel Swetz, R. Michael Verkouteren, and Daikang Yan, Toward a New Primary Standardization of Radionuclide Massic Activity Using Microcalorimetry and Quantitative Milligram-Scale Samples, *NIST J. Res*., 126, 126048 (2021).
- Richard M. Essex, Jacqueline Mann, Denis E. Bergeron, Ryan P. Fitzgerald, Svetlana Nour, Gordon A. Shaw, R. Michael Verkouteren, Isotope dilution mass spectrometry as an independent assessment method for mass measurements of milligram quantities of aqueous solution, *Intl. J. Mass Spec*., 483, 116969 (2023).10.1109/TIM.2021.3060575

Static and Dynamic Force

Mass and Force Group, Akobuije Chijioke, Jared Strait, Kevin Chesnutwood, Joshua Graybill, Samuel Ho

<u>Participation in relevant comparisons</u>

Participated in the key comparison CCM.FK23 in Force at 200 N and 500 N (piloted by METAS). NIST showed equivalence to the reference value established by the pilot and the 8 participants. Final report issued in April 2023.

NIST will pilot the upcoming key comparison CCM-F-K4 Force at 2 MN and 4 MN tentatively scheduled to begin in 2024.

Finalized the technical protocol of the "Supplementary Comparison, Measurand Force in the scope of 200 kN-1000 kN" within SIM (likely to have 8 participants with NIST establishing the reference value and the pilot being the Instituto Nacional de Tecnología Industrial (INTI) – Argentina. The comparison should start in the next few months.

<u>Dynamic Force Calibration</u>

After some interruption by the COVID-19 pandemic, collaborative work with NIST staff engaged in Charpy impact testing of materials has progressed, with advancement of impact calibration methodology, data acquisition arrangement, and data processing & analysis.

In concert with the NIST Manufacturing Extension Partnership (MEP), custom dynamic force measurements were provided.

<u>Kibble-Principle-Based Dynamic Force Standard</u>

A revised prototype Kibble-principle traceable dynamic force source that is optimized for testing design tradeoffs has been developed and is being tested.

Collaborations:

Attended the IMEKO 2021 World Congress (virtual), August 27 – September 30, 2021.

Participated in the CCM Working Group on Force and Torque meeting (virtual), September 23, 2021.

Attended the IMEKO 24th TC3, 14th TC5, 6th TC16 and 5th TC22 International Conference, 11 – 13 October 2022, Cavtat-Dubrovnik, Croatia.

Publications:

- Burns, D. E., Vlajic, N., Chijioke, A. and P. A. Parker, (2022). An Aerodynamic Metrologist's Guide to Dynamic Force Measurement, *AIAA Journal of Aircraft*, 59.

- A. Savarin & A. Chijioke , Measurement of Dynamic Rocking in Sinusoidal Calibration with an Electrodynamic Shaker, *Proceedings of the IMEKO 24th TC3, 14th TC5, 6th TC16 and 5th TC22 International Conference*, DOI 10.21014/tc22-2022.141

Hardness

Mechanical Performance Group, Materials Science and Engineering Division, Carlos R. Beauchamp

Main research and development activities related to CCM activities**:**

- Carlos R. Beauchamp, serving as NIST delegate to the CCM-Working Group (CCM-WGH) on Hardness since December 2021. There have been two CCM-WGH meetings since the 18th meeting of the CCM (May 2021), both 2-hour virtual meetings each:
  − 21st Meeting — 10 November 2021
  − 22nd Meeting — 27 October 2022
  Upcoming hybrid meeting: 28 September 2023
- NIST is participating in the CCM-WGH task to develop measurement parameter definitions for the Rockwell B (HRBW) and Rockwell N (HR15N, HR30N, HR45N) hardness scales and a revision of the definition for the Rockwell C (HRC) hardness scale
- NIST is upgrading its decommissioned Hardness Standardizing Machine (former Primary Hardness Standardizing Machine until 2019). When the work is completed, the machine will be used for the provision of a new NIST measurement service: a Measurement Assurance Program for hardness scales for which no certified reference materials are offered by the Institution

Key Comparisons and Pilot Studies**:**

- NIST will participate on the CCM Key Comparison for Hardness Rockwell C (HRC) scale [CCM.H-K3] to start Fall 2023, status: Protocol Complete

- NIST will serve as Pilot Laboratory for a new Key Comparison set to follow the 2019 CCM Study on the Geometrical Measurements of the Rockwell Diamond Indenter [CCM.H-P1], to be discussed at the upcoming CCM-WGH meeting to be held 28 September 2023 at the ASTM Headquarters in Conshohocken, Pennsylvania

Publications:

- C. R. Beauchamp, J. E. Camara, J. Carney, S. J. Choquette, K. D. Cole, P. C. DeRose, D. L. Duewer, M. S. Epstein, M. C. Kline, K. A. Lippa, E. Lucon, J. Molloy, M. A. Nelson, K. W. Phinney, M. Polakoski, A. Possolo, L. C. Sander, J. E. Schiel , K. E. Sharpless, B. Toman, M. R. Winchester, D. Windover, NIST Special Publication 260-136 2021 Ed., Metrological Tools for the Reference Materials and Reference Instruments of the NIST Material Measurement Laboratory, https://doi.org/10.6028/NIST.SP.260-136-2021
- S. Low, A. Germak, A. Knott, R. Machado, J. Song, Developing definitions of conventional hardness tests for use by National Metrology Institutes, *Measurement: Sensors*, Vol 18, Dec 2021, 100096, Elsevier, https://doi.org/10.1016/j.measen.2021.100096
  Video Presented, IMEKO2021 Online Virtual Conference, August 30 to September 3, 2021
- S. R. Low III, E. A. Ruth, Strategy for estimating uncertainty using reference materials, a proposed section for ISO/AWI TR 8463 Strategy for a Common Framework to Determine Measurement Uncertainty in Mechanical Testing, ISO Stage 20.00
- J. Song, T.B. Renegar, C.R. Beauchamp, Calibration Reproducibility of Microform Geometry for NIST Standard Rockwell Hardness Diamond Indenters, submission to the *Journal of Testing and Evaluation*

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).

Photonic based Pressure Standards:

Significant progress continues to be 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 include the replacement of mercury manometer primary pressure standards, field deployable primary standards for national labs and for international key comparisons. Fixed Length Optical Cavities (FLOCS) 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. NIST's CRADA partner is working on commercialization and there are ongoing research projects to use the device in an "air data tester" for avionics, as well as to extend the range into the vacuum.

Cold Atom Vacuum Standard (CAVS):

NIST has 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 ultra-high vacuum (UHV) and extreme-high vacuum (XHV) ranges through atom loss from a shallow trap, which is traceable to fundamental physics. Impacts: First SI traceable XHV vacuum standard. Status: Both a lab-based standard (l-CAVS) and a portable sensor (p-CAVS) have both been demonstrated. A priori quantum-collision calculations that establish traceability are complete for a variety of different collision partners, which has been recently experimentally verified by comparing the two CAVSs against a continuous expansions standard operating in the ultra-high vacuum (UHV). Impacts: Next generation semiconductors, accelerator and accelerator-type facilities, and molecular electronics requiring pure XHV environments.

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

Publications:

L. Ehinger, B. Acharya, D. Barker, d, J. Fedchak, J. Scherschligt, , E. Tiesinga and S. Eckel. Comparison of two multiplexed portable cold atom vacuum standards, *AVS Quantum Science* **4** 034403 (2022).
DOI: 10.1116/5.0095011

D. Barker, B. Acharya, J. Fedchak, N. Klimov, E. Norrgard, J. Scherschligt, E. Tiesinga and S. Eckel, Precise Quantum Measurement of Vacuum with Cold Atoms, *Review of Scientific Instruments* **93** 121101 (2022).
DOI: 10.1063/5.0120500

Jacek Kłos and Eite Tiesinga, Elastic and glancing-angle rate coefficients for heating of ultracold Li and Rb atoms by collisions with room-temperature noble gases, H2, and N2, *J. Chem. Phys*. **158**, 014308 (2023).
DOI:10.1063/5.0124062

Daniel S. Barker, James A. Fedchak, Jacek Kłos, Julia Scherschligt, Abrar A. Sheikh, Eite Tiesinga, and Stephen P. Eckel, Accurate measurement of the loss rate of cold atoms due to background gas collisions for the quantum-based cold atom vacuum standard, arXiv:2302.12143 (2023).
DOI:10.48550/arXiv.2302.12143

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. Si. 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

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 designing and building gas flow standards based on the rate of rise method to support gas flows between, 0.1 cm^3/min and 1000 cm^3/min. When complete, the gas flow standard will be used to improve the physical models for laminar and thermal gas flow meters and facilitate extrapolation of calibrations in gases like nitrogen to other gases for which the properties (*e.g.* viscosity, density, thermal conductivity) are well known.

- The FMG has largely completed our effort to lower the uncertainty of measurements of flow (and hence pollutants) from smokestacks. The NIST non-nulling hemispherical sensor and associated methods reduce the uncertainty for CO_2 and other emissions from 20 % or more to 2 % or less and the method is 4 times faster than other 3D methods. The FMG was granted a patent on the method in 2023 and a committee of the American Society of Mechanical Engineers is drafting a documentary standard.

- In collaboration with PTB, the FMG has published a follow up article on comparison criteria that are more complete than the $E_n \leq 1$ approach and that include the possibility of inconclusive comparison results. A spreadsheet that applies the Cox uncertainty weighted approach and probability-based comparison criteria was shared within the Working Group for Fluid Flow and other working groups are encouraged to try it out too.

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

CCM.FF-K1.2022	Liquid Micro-Flow

Recent papers relevant to the CCM activities:

Non-Nulling Gas Velocity Measurement Apparatus and Performing Non-Nulling Measurement of Gas Velocity Parameter, Shinder, I. I., Johnson, A. N., and Filla, B. J., U.S. Patent Number 11,525,840, December 13, 2022.

Non-nulling Protocols for Fast Accurate, 3-D Velocity Measurements in Stacks, Shinder, I. I., Johnson, A. N., Filla, B. J., Khromchenko, V. B., Moldover, M. R., Boyd, J., Wright, J. D., and Stoup, J., *Journal of Air and Waste Management*, 2023.

Evaluating Inter-laboratory Comparison Data, Frahm, E. and Wright, J. D., *FLOMEKO,* Chongqing, China, November 1 to 4, 2022.

Dynamic Measurement of Gas Flow Using Acoustic Resonance Tracking, Pope, J. G., Schmidt, J. W., and Gillis, K. A., *Review of Scientific Instruments*, 94, 034904, (2023)

Gas Flow Standards and Their Uncertainty, Wright, J. D., Nakao, S.-I., Johnson, A. N., and Moldover, M. R., *Metrologia*, 2022. https://doi.org/10.1088/1681-7575/ac8c99.

Thermal Boundary Layers in Critical Flow Venturis, Wright, Kang, Johnson, Khromchenko, Moldover, Zhang, and Mickan, *Flow Measurement and Instrumentation*, 81, July, 2021.

Flow Meter Calibrations with NIST's 15 kg/s Water Flow Standard, NIST Pope, Johnson, Filla, Bean, Moldover, Boyd, Cowley, Shinder, Gillis, and Wright, Liquid Special Publication 250-98, June, 2021, https://doi.org/10.6028/NIST.SP.250-98.

Facility for calibrating anemometers as a function of air velocity vector and turbulence, Shinder, Moldover, Filla, Johnson, and Khromchenko, *Metrologia*, July 19, 2021.