

# Report to CCEM on electrical metrology at NIST

March 2025

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## 2 Report

### Digital SI

NIST's efforts on the digital transformation of metrology are presently focused in three areas: digital calibration reports, digital certificates for reference material data, and traceability. Presently, the first two efforts are mostly focused on increasing internal efficiency and preparing for requests for metrology data in a digital format when the need arises from NIST stakeholders. Creating repositories in a FAIR (Findability, Accessibility, Interoperability, and Reuse) data format are important in these efforts. Digital traceability is a key concept in metrology but NIST's efforts are still nascent. In 2024 NIST launched a pilot project in digital traceability to facilitate the use of correlated uncertainty estimates in vector network analyzer (VNA) calibrations by allowing interoperability between existing VNA tools and creating a digital record of the calibration chain.

## DC Josephson Voltage Standard Systems

NIST researchers have developed a new 2 V programmable Josephson voltage standard (PJVS) with dual microwave frequency inputs and multiple output taps. The design provides three main features: (1) output voltages with nanovolt resolution, (2) the ability to perform a microwave frequency self-check based on a null voltage measurement, and (3) additional voltage output taps providing simultaneous 10:1 (or 5:1) divided voltage reference for resistive divider calibration [1,2]. With low heat dissipation, this device is well suited for implementation with a compact cryocooler as a turnkey traveling system to verify the performance of the PJVS systems disseminated through the NIST Standard Reference Instrument (SRI) program.

NIST researchers also tested PJVS implementations on different cryogenic platforms, providing electrical power substitution for cryogenic optical power detectors [3], and quantum current sensing applications with anomalous Quantum Hall resistance devices [4]. NIST researchers hosted a training workshop in 2024 for all U.S. PJVS operators.

[1] A. Rufenacht, A. E. Fox, P. D. Dresselhaus, and S. P. Benz, "Dual-Frequency-Bias Programmable Josephson Voltage Standard Circuit Design," *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10646095.

[2] A. Rufenacht, A. E. Fox, R. L. Johnson-Wilke, B. T. Scheck, P. D. Dresselhaus, and S. P. Benz, "Dual-Frequency-Bias Programmable Josephson Voltage Standard Circuit," *submitted to IEEE transactions on instrumentation and measurement*, 2025.

[3] M. G. White *et al.*, "Direct implementation of a frequency-programmable Josephson voltage standard to provide an SI traceable optical power scale," *Metrologia*, vol. 61, no. 4, p. 045002, Jun. 2024, doi: 10.1088/1681-7575/AD57CA.

[4] J. M. Underwood *et al.*, "Single-cryostat integration of the quantum anomalous Hall and Josephson effects," *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10646010.

## Josephson Arbitrary Waveform Synthesizer

NIST researchers have continued to improve the JAWS system and audio frequency ac measurements based on the JAWS. With the help of a guest researcher from CENAM (Mexico) in 2023, the JAWS based ac/dc measurements were focused on evaluating capacitive leakage current effects and developing methods to measure it [5,6]. Another aspect of the JAWS research was measuring ac voltage sources in collaboration with NRC-Canada [7] and BIPM [8], as well as evaluating the linearity of a commercial digitizer [9]. NIST Boulder performed in 2024 an ac voltage comparison pilot study with BIPM. The JAWS high stability and spectral purity waveform was used as a source to test the BIPM/KRISS PJVS stepwise waveform and differential sampling method [10]. Improvement of the JAWS pulse pattern for low amplitude waveform generation was also reported [11]. A JAWS workshop was held in Boulder, CO immediately after the 2024 Conference on Precision Electromagnetic Measurement (CPEM) with the participation of over 20 international attendees. The audio-frequency JAWS system is available for dissemination to national metrology institutes and primary metrology laboratories through the NIST SRI program.

For frequencies above 1 MHz, diplexer JAWS circuits are used to better match the output impedance to 50  $\Omega$ . NIST researchers performed studies on modulated microwave waveforms, including multitone waveforms around 1 GHz [12] and single-tone very high-frequency band waveforms for power measurements [13,14]. This project benefitted from the visit of a guest researcher from METAS (Switzerland) in 2024.

A summary article about JAWS ac metrology applications [15] and a review article on Johnson noise thermometry [16] were also published in 2024.

[5] R. L. Johnson-Wilke et al., "Leakage Current Pathways in Josephson Arbitrary Waveform Synthesizer Standards," in *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, Institute of Electrical and Electronics Engineers Inc., 2024. doi: 10.1109/CPEM61406.2024.10646083.

[6] R. L. Johnson-Wilke et al., "Impact of Leakage Currents on Voltage Accuracy in the Josephson Arbitrary Waveform Synthesizer," in *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, submitted to *IEEE transactions on instrumentation and measurement*, 2025.

[7] G. Granger et al., "Stability Study of ac Voltage Source using Josephson Voltage Standards," *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10646131.

[8] A. Rufenacht et al., "Differential Measurements of an AC Source with a Josephson Arbitrary Waveform Synthesizer," *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10646054.

[9] J. M. Mejia et al., "Digitizer Linearity Measurement with a Josephson Arbitrary Waveform Synthesizer," *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10646120.

[10] <https://www.bipm.org/en/-/2024-10-24-pilot-study-ac-voltage>

[11] N. E. Flowers-Jacobs et al., "Pulse Patterns for the Josephson Arbitrary Waveform Synthesizer," *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10646074.

[12] A. A. Babenko, N. E. Flowers-Jacobs, A. E. Fox, P. D. Dresselhaus, Z. Popović, and S. P. Benz, "Quantum-Based Modulated Microwave Waveforms," *IEEE Transactions on Microwave Theory and Techniques*, vol. 72, no. 4, pp. 2047–2056, Apr. 2024, doi: 10.1109/TMTT.2023.3297364.

[13] J. N. Thomas, N. E. Flowers-Jacobs, A. E. Fox, A. A. Babenko, S. P. Benz, and P. D. Dresselhaus, "VHF Josephson Arbitrary Waveform Synthesizer," *2024 United States National Committee of URSI National Radio Science Meeting, USNC-URSI NRSM 2024 - Proceedings*, p. 44, 2024, doi: 10.23919/USNC-URSINRSM60317.2024.10464474.

[14] J. N. Thomas, N. E. Flowers-Jacobs, A. E. Fox, A. Rufenacht, and P. D. Dresselhaus, "Measuring VHF Detector Linearity using a Quantum-Based Source," *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10646166.

[15] S. P. Benz *et al.*, “AC metrology applications of the Josephson effect,” *Applied Physics Letters*, vol. 125, no. 5, p. 50501, Jul. 2024, doi: 10.1063/5.0219991/20086877/050501\_1\_5.0219991.AM.PDF.

[16] S. P. Benz *et al.*, “Practical realisation of the kelvin by Johnson noise thermometry,” *Metrologia*, vol. 61, no. 2, p. 022001, Feb. 2024, doi: 10.1088/1681-7575/AD2273.

### Quantum Conductance Project

The Quantum Conductance Project continues to develop graphene-based wye-delta and star-mesh quantized Hall array resistance standards (QHARS) with optimized networks. This technique significantly reduces the number of Hall bars integrated in 1 M $\Omega$ , 100 M $\Omega$ , and 1 G $\Omega$  devices and, therefore, increases the performance and yield of QHARS using epitaxial graphene on insulating SiC with superconducting interconnections. Array standards are used in NIST Kibble balance measurements to provide direct realization of mass at 100 g and with similar or better results than room-temperature resistance references. A dedicated 9T cryocooler system has been brought online for the Kibble balance using graphene QHARS array standards at 1 k $\Omega$  at this time. A 100  $\Omega$  QHARS is planned for the Kibble balance, and an internal array development task is planned, along with partnering with other NMIs. We are continuing with our in-house growth of graphene for device and array fabrication. A quantum current realization was demonstrated in a cryostat with a quantum anomalous Hall device and a Josephson voltage source. The Quantum Conductance Project is developing AC-QHRS for the capacitance/impedance metrology project to modernize the capabilities for dissemination of the ohm and farad. A 14 T cryocooler with a Variable Temperature Insert and a 25 mK dilution probe has been acquired and will be delivered by the end of 2025. Our project continues to sponsor Guest Researchers from universities and other national measurement institutes.

### Metrology of the Ohm

The Metrology of the Ohm project closely collaborates with other projects within the Fundamental Electrical Measurements group, such as quantum conductance, the NIST-4 Kibble Balance, and capacitance/impedance metrology. Delivery of measurement services to our other internal and external customers has returned to near normal operations when laboratory conditions allow. The development of a digital impedance bridge for capacitance and resistance measurement and the development of resistance-to-frequency conversion are impedance projects supported by the metrology of the ohm. Support for low current measurements, SI traceable to resistance, in the nA, pA, and fA ranges continues for photodetectors, aerosol electrometers, ionizing radiation chambers, and novel devices. Measurements for the bilateral comparison CCEM-K2.2012.1 of 10 M $\Omega$  and 1G $\Omega$  resistance standards between KRISS, NRC, and NIST have been completed. With the quantum conductance project, NIST has realized wye-delta type quantum Hall array resistance standards (QHARS) of 1 M $\Omega$  and 100 M $\Omega$ , as well as a star-mesh QHARS at 1G $\Omega$ . The 1 G $\Omega$  star-mesh has been used as a quantum resistance standard to measure 100 M $\Omega$ , 1 G $\Omega$ , and 10 G $\Omega$  standard resistors with an updated version of the dual-source bridge. NIST work in resistance metrology was well represented at CPEM 2024, we were able to send four people from the two projects and presented three papers at the conference.

The Quantum Conductance Project and Metrology of the Ohm Project share permanent staff, and there has been a significant change in personnel over the past two years. Shamith Payagala left NIST in July 2023 to pursue other opportunities. Albert Rigosi took a temporary assignment elsewhere in NIST starting Dec. 2023, expected to return April 2025. Long-term NIST associate Yanfei Yang started Nov. 2023 as a permanent NIST employee. After 38 years of service, Rand Elmquist retired in June 2024. Other permanent staff are Alireza Panna and Dean Jarrett.

- [1] Y. Wang *et al.*, "New Method for Determining Time Constant of Resistors," *Review of Scientific Instruments* **94**, 034711 (2023); <https://doi.org/10.1063/5.0143225>, published 3/21/23
- [2] D.G. Jarrett, *et al.*, "Graphene-Based Star-Mesh Resistance Networks", *IEEE Trans. on Instrum. Meas.*, **72**, (2023), DOI: 10.1109/TIM.2023.3290290
- [3] D. Saha *et al.*, "Current Distribution Near Hot Spots in Graphene QHR Devices", *IEEE Trans. on Instrum. Meas.*, Submitted Jan 2023.
- [4] D. S. Scaletta *et al.*, "Mathematical optimization of graphene-based quantized Hall arrays for recursive star-mesh transformations," *Applied Physics Letters* **123** (2023), <https://doi.org/10.1063/5.0164735>
- [5] L. K. Rodenbach *et al.*, "Realization of the quantum ampere using the quantum anomalous Hall and Josephson effects," submitted to *Nature Electronics.*, Aug. 1, 2023., resubmitted Dec. 3, 2024, <https://arxiv.org/abs/2308.00200>
- [6] D.G. Jarrett *et al.*, "Recursive Star-Mesh Transformations for Resistance Standards," CPEM 2024 Conference Digest, Denver, CO, USA, July 6-11, 2024. DOI: 10.1109/CPEM61406.2024.10646049
- [7] Y. Yang *et al.*, "Optimization of Wye-Delta-Type Quantum Hall Resistance Standard", CPEM 2024 Conference Digest, Denver, CO, USA, July 6-11, 2024. DOI: 10.1109/CPEM61406.2024.10646005
- [8] N. T. M. Tran *et al.*, "Development of a Topological-Insulator-Based Quantum Resistance Standard," CPEM 2024 Conference Digest, Denver, CO, USA, July 6-11, 2024. DOI: 10.1109/CPEM61406.2024.10646119
- [9] J. Underwood *et al.*, "Single-cryostat integration of the quantum anomalous Hall and Josephson effects," CPEM 2024 Conference Digest, Denver, CO, USA, July 6-11, 2024. DOI: 10.1109/CPEM61406.2024.10646010

## Kibble balances

NIST is currently participating in the third key comparison of the unit of mass. Mass determinations of two Pt-Ir kilogram standards are being conducted on the US primary mass standard, NIST-4, and subsequently will be sent to the BIPM at the end of February 2025. NIST has also started a collaboration with two NMIs: (1) with PTB/Germany to measure a 1kg silicon sphere directly on NIST-4 to understand the dispersion in values from XRCD and Kibble balance primary realizations, and (2) with RISE/Sweden to compare both institutes 100  $\Omega$ , and 1 k $\Omega$  quantum Hall array standards, and to implement those primary resistance standards directly in the circuit of the NIST Kibble balance.

NIST researchers are building the Quantum Electro-Mechanical Metrology Suite (QEMMS), a metrology institute in a single room, to provide three mechanical standards of time, length, and mass, and three electrical standards of voltage, resistance, and current traceable to the

International System of Units (SI). The system is comprised of a Kibble balance, a programmable Josephson voltage standard (PJVS), and a graphene-based quantum Hall resistance array standard (QHARS). The first prototype of mechanical, optical and electrical parts of the Kibble balance were built and characterized [1-2]. A new mechanical assembly was designed to implement additional alignment features and was assembled [3].

Testing is in progress. Dr Frank Bielsa from BIPM visited NIST from April to August 2024 where we collaborated on different aspects of the QEMMS Kibble balance.

NIST continues developing tabletop Kibble balances with a 0.001 g to 20 g dynamic range and uncertainties of a few parts in  $10^6$ . In 2020, the first-generation KIBB-g1 was inducted into the NIST on a Chip (NOAC) program. Soon after, NIST began developing KIBB-g2, focusing on robustness, usability, and commercialization, supported by a 3-year US Army metrology grant. In 2024, NIST partnered with Rice Lake Weighing Systems through a Cooperative Research and Development Agreement (CRADA) to commercialize the technology, while the US Army extended funding for 4 more years to develop a novel instrument reaching up to 1 kg after NIST successfully deployed KIBB-g2 to their primary calibrations laboratory at Redstone Arsenal, Alabama.

Simultaneously, in 2020, NIST applied the Kibble principle to a rotational frame for torque realization, enabling direct SI-traceable torque calibrations. Supported by a 3-year Air Force metrology grant, NIST developed the Electronic NIST Torque Realizer (ENTR) with a 0.007 Nm –1 Nm dynamic range and 0.1% uncertainty. In 2024, NIST formed a CRADA with Snap-On Industrial to commercialize ENTR, while the US Air Force extended funding for 4 years to expand the range to 340 Nm. In early 2025, NIST successfully deployed ENTR to Nellis Air Force Base, Nevada.

- [1] L. Keck et al., “Flexures for Kibble balances: minimizing the effects of anelastic relaxation,” *Metrologia* **61**, 045006 (2024) doi: 10.1088/1681-7575/ad57cb
- [2] L. Keck et al., “Applications and limitations of the Kibble-Robinson theory,” *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10645979.
- [3] Keck, L., 2025. Flexure-based mechanism for a Kibble Balance. Berichte aus dem Institut für Maschinen- und Gerätekonstruktion (IMGK). Universitätsverlag Ilmenau, Ilmenau. doi:10.22032/dbt.63554
- [4] Z. Comden et al., “The design and performance of an electronic torque standard directly traceable to the revised SI,” *IEEE Trans. Instrum. Meas.* **72**, 1-6 (2023) doi: 10.1109/TIM.2023.3279911
- [5] K. Arumugam et al., “Honey I shrank the Kibble balance: A second generation NIST table top balance,” *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 2024, doi: 10.1109/CPEM61406.2024.10646050.

## Capacitance Metrology

NIST has recently demonstrated a digital four-arm bridge for the comparison of resistance with capacitance. The NIST digital four-arm bridge is an extension of the six-arm bridge developed at NMIA 20 years ago. The NMIA six-arm bridge uses an analog combining network to produce an appropriately weighted sum of three detector currents; the NIST four-arm bridge replaced the analog combining network with digital operations after simultaneously digitizing the detector current signals. Another added feature of the NIST bridge is that it implemented a digital correction mechanism when the bridge's main loop deviates slightly from balance. Both bridges retain the key feature of the classical quad bridge with the source balance, the detector balance, and the

main balance, where the required precision of the source voltages is only of the order of the square root of the ultimate bridge precision.

For the comparison of a 100 k $\Omega$  resistor with a 1 nF capacitor near 1592 Hz, the combined standard uncertainty ( $k=1$ ) is 5 parts per billion, which is comparable to the uncertainty of the conventional quad bridge at NIST. The impedance ratio determined by the digital four-arm bridge will provide an independent check for the two-arm digital bridges that rely on the digitizers to provide the one-to-one ratio [1,2].

NIST has developed a simple method to measure the frequency dependence of four terminal-pair air capacitors using a four-channel network analyzer. With a calibrated network analyzer, the measurement of one standard takes less than 45 min and can be made in one hook-up, i.e., no change in connection is required. NIST is currently analyzing the uncertainty budget [3].

- [1] Y. Wang and S. Schlamminger, "A digital four-arm bridge for the comparison of resistance with capacitance," *Metrologia* **61**, 055009 (2014) doi: 10.1088/1681-7575/ad7590
- [2] M. Feige *et al.*, "Comparison of a 100-pF Capacitor With a 12 906- $\Omega$  Resistor Using a Digital Impedance Bridge", *IEEE Trans. Instrum. Meas.* **71**, 1-7 (2021) doi: 10.1109/TIM.2021.3139709
- [3] S. Schlamminger *et al.*, "Measurement of the Frequency Dependence of Four Terminal-Pair Air Capacitors With a Vector Network Analyzer", *IEEE Trans. Instrum. Meas.* **72**, 1-10 (2023) doi: 10.1109/TIM.2023.3322503

## Antenna Metrology

NIST is piloting a GT-RF antenna gain comparison at the WR-05 (140-220 GHz) band. Coordination continues for this key comparison for antenna gain and polarization to address Action 3 from the 2019 GT-RF meeting. There is broad agreement for the WR-05 (140 GHz-220 GHz) band which is very important for the upcoming 6G millimeter-wave operation at 140 GHz. The technical protocol has been drafted and disseminated to other NMIs and is awaiting final input from them. It is expected that the GT-RF will make the next actions for this comparison during the 2025 meeting and solidify engagement from NMI representatives so that the protocol can be finalized, and the comparison can continue to move forward.

A new advanced antenna alignment algorithm [1] to improve calibrations by simultaneously reducing alignment time during measurement setup with increased antenna alignment accuracy has been developed and implemented on the NIST antenna range. Leveraging the unique robotics capability of the NIST Robotically Enhanced Antenna Lab for metrology (REALM) this new antenna alignment algorithm allows the antenna-positioning-robots to learn and implement the required antenna alignment to around 10 microns accuracy by incorporating reverse kinematics and laser tracker metrology. This was fully integrated to the REALM and completed in June of 2024. This gives NIST the unique capability for performing large (many square meters) apertures while mainlining fractions of a wavelength alignment accuracy that is needed well above 100 GHz.

Development of new broad-band antenna check standards for addressing customer requests for these antennas is continues. A shift in customer calibration needs from standard gain horn antennas that operate at individual frequency bands to broad band antennas that operate over multiple bands is happening. For many applications

used by DOD, law enforcement, and Over The Air (OTA) testing for communications, broad band antennas are becoming more ubiquitous due to the fact that a single broad band antenna can replace as many as ten standard gain antennas over the 600MHz to 18 GHz range. However, calibrating broad band antennas properly is challenging due to the broad frequency range. In particular, it would take around 30 individual calibrations done using the current standard gain antenna approach to calibrate just one broad band antenna properly. This is both time and cost prohibitive and is one of the reasons broad band antennas are specified with large uncertainties. The antenna project is leading the development of a new set of broad band check standard antennas, which will allow NIST to calibrate broad band antennas with only three antennas as opposed to 30 antennas. This will significantly reduce the calibration time for broad band antennas and give NIST new capability, expanding the antenna calibration services to broad band.

As part of this broadband antenna effort an exploratory bi-lateral comparison of antenna gain for broad band dual ridge horn antennas from 750 MHz to 18 GHz is planned to be performed between NIST and NMII/AIST Japan beginning in FY25. The hope is that if this comparison works out it can be discussed as future larger scaler multi-NMI comparison.

A new Enhanced Gain Extrapolation method has also been developed. The new method allows antenna gain to be measured using less data points per antenna pair than the traditional three antenna gain extrapolation method. This new method recently published in IEEE [2] purposely uses third order antenna-to-antenna scattering to reduce the number of data points from many thousands down to around 10. This new method also reduces the measurement distance of gain extrapolation by up to a factor of six which is a significant reduction in necessary size of measurement facilities [3].

[1] "Rapid Automated Antenna Alignment on Robotic Antenna Ranges", B. Moser, J. Gordon, European Conference on Antennas and Propagation (EuCAP) (March 2024)

[2] J. A. Gordon and B. L. Moser, "Enhanced Gain Extrapolation Technique: A Third-Order Scattering Approach for High-Accuracy Antenna Gain With Sparse Sampling, at Fresnel Distances," in IEEE Transactions on Antennas and Propagation, vol. 72, no. 12, pp. 9035-9049, Dec. 2024, doi: 10.1109/TAP.2024.3478330

[3] "Compact Homodyne Extrapolation System (CHEXS)", J. Gordon, B. Moser, Proc. 46th Ant. Meas. Tech. Assoc. (AMTA)(October 2024)

## RF Scattering-parameters

At NIST, an updated uncertainty analysis based on a combination of dimensional measurements, instrument effects, and environmental effects has been deployed in the WR-42 rectangular waveguide band. The analysis was designed to preserve correlations in uncertainties and to support both a conventional sensitivity analysis and a Monte-Carlo analysis of uncertainties. Preserving information about correlations in uncertainties is expected to facilitate improved uncertainties for measurements that involve transformations between the frequency domain and the time domain, as well as tighter comparisons between check standards that are characterized with the same primary standards. In comparison to a sensitivity analysis, the Monte-Carlo analysis may be able to reveal and correct some sources of bias, as well as offer more accurate confidence intervals for unusual uncertainty distributions. This uncertainty analysis is being utilized in the WR-42 international intercomparison for microcalorimetry to assess the uncertainties in S-parameter measurements [3].

A parallel uncertainty analysis is currently under development for coaxial devices, beginning with 2.4 mm, slated for deployment in the current international intercomparison (CCEM.RF-K5d.CL). This analysis will also include models of the connector effects of the calibration artifacts to account for systematic contributions in S-parameter measurements from airline standards.

Additionally, we are doing research to characterize the additional uncertainty mechanisms associated with electronic calibration units (ECal units). These include drift from the calibration unit, as well as internal switch repeatability. We are developing this uncertainty analysis in the 2.4 mm coaxial connector type.

### RF Power

NIST is continuing its work to develop a new twin-load microcalorimeter for 2.4 mm coaxial power sensors and evaluate commercially-available 2.4 mm coaxial thermoelectric power transfer standards that are compatible with microcalorimetry. The new microcalorimeter will operate with both legacy thin-film sensors and new thermoelectric sensors. The new thermoelectric sensors are dc coupled, making them suitable for power measurements from dc to 50 GHz. The uncertainty analysis for these thermoelectric sensors is underway, and some preliminary results on power metering have been published [1]. Additionally, while NIST is still using thermistor sensors in the type N connector type (dc to 18 GHz), NIST is also exploring thermoelectric sensors due to their commercial availability and their ability measure power at lower frequencies than thermistor sensors. NIST is also pursuing microcalorimetry to establish traceable power measurements for devices with WR-6 connectors that operate in the frequency range from 110 GHz to 170 GHz.

In our direct-comparison services for power, NIST has historically operated several sixport network analyzer systems to perform S-parameter measurements and to transfer calibrations from rectangular waveguide power sensors characterized in microcalorimeters to other power sensors. We have retired these and replaced with a combination of commercial network analyzers for scattering-parameter measurements and direct comparison systems for power-transfer measurements. We are continuing our work to migrate the software for these measurements from HP Basic to Python.

NIST is also participating in the CIPM key comparison CCEM.RF-K28.W, "RF power from 18 GHz to 26.5 GHz in rectangular waveguide". NIST recently migrated its WR-42 power measurements from sixport network analyzers to direct comparison, and so the direct comparison system was used for these measurements. The direct comparison system was calibrated with a transfer standard that was characterized in a microcalorimeter. The measurements are complete, and the report is in progress.

NIST is also exploring on-chip methods for power calibration at both room temperature and cryogenic temperatures down to the mK range. On-wafer power standards will be validated up to the bandwidth of the calibration kit, initially scoped up to 110 GHz.

[1] Z. C. Roberts, D. C. Gray, V. Neylon, A. C. Stelson, A. M. Hagerstrom and C. J. Long, "Traceable RF Power Metering Procedures With Thermoelectric Sensors," 2024 103rd ARFTG Microwave Measurement Conference (ARFTG), Washington, DC, USA, 2024, pp. 1-4, doi: 10.1109/ARFTG61196.2024.10661070.

### Thermal Noise Metrology

NIST's Thermal Noise project has extended its digital radiometry capability by completing a comprehensive study of quantifying uncertainty for spectrum measurements. The digital radiometer work was published in a special issue of Microwave Magazine [1]. Since then, we collaborated with a mathematician in the RF Technology

Division to develop uncertainty analysis of digital noise measurements in the time domain. A rigorous uncertainty analysis is applicable not only to the digital radiometry work but also to commercial instruments that are used for general spectral power measurements [2].

We have completed a research project funded by NASA measuring over-the-air (OTA) noise standards for remote-sensing satellites, in particular for small satellites (CubeSats). It was a collaborative effort among four institutions: Colorado State University, Duke University, NIST, and Northrup Grumman. We have demonstrated a lightweight and compact OTA calibration device that is suited for CubeSats operating at multiple radiometric frequencies [3, 4].

In response to the congressional push to strengthen the US semiconductor industry, we have secured four-year funding to develop a new measurement technique for measuring noise characteristics of amplifiers and transistors. These amplifiers and transistors are made by semiconductor chips for ultra-sensitive receiver frontends, which are critical components in communication, military and space applications. Existing commercial scientific equipment has encountered significant challenges for keeping up with the performance needed to qualify of the latest ultra-low-noise transistors. The new technique in development by NIST holds promises of improved precision and versatility. We have completed the first year of the project by demonstrating the feasibility of measuring the base-band noise of connectorized devices with the new technique [5]. Next, we will extend the frequency range beyond the base band and expand to measurements on on-wafer transistors by implementing the new approach in a probe station.

On the fundamental metrology front, we are in the process of modernizing the radiometer by consolidating the 1 GHz to 40 GHz measurement systems. The consolidated radiometer has a 2.4-mm interface, which will replace the existing 7-mm, WR62, WR42 and WR28 systems. The development of such a system will greatly streamline the measurement process and reduce the calibration cost. A recent departure of a team member presented the challenges to timely complete the fabrication and characterization of the new radiometer.

[1] X. Lu, D. Kuester and D. Gu, "A Prototype Digital Radiometer for Noise Metrology Applications: A Metrology-Grade Digital Radiometer," in IEEE Microwave Magazine, vol. 23, no. 5, pp. 57-66, May 2022.

[2] D. Gu, J. Rezac, X. Lu and D. Kuester, "On Digital Signal Processing of Time Series for Spectrum Estimation," in IEEE Transactions on Instrumentation and Measurement, vol. 73, pp. 1-11, 2024, Art no. 1008211.

[3] O. Khatib, D. Gu, J. Smith, W. R. Deal, W. J. Padilla and S. C. Reising, "Planar Metamaterial Absorbers for Calibration of Microwave Radiometers for Atmospheric Remote Sensing," IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, Kuala Lumpur, Malaysia, 2022, pp. 7214-7217.

[4] D. Gu et al., "Characterization of Microwave Blackbody with Monostatic Measurement," IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium, Athens, Greece, 2024, pp. 6262-6267.

[5] D. Gu, X. Lu, and D. Kuester, "A Digital Correlator for Noise-Parameter Measurements on Amplifiers and Transistors," 2025 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Chemnitz, Germany, 2025, Accepted.

## Waveform Metrology

NIST has been using electro-optic sampling (EOS) as the primary source of waveform traceability since 2006. Photodiodes calibrated with this technique are the basis for traceable calibrations of lightwave component

analyzers, oscilloscopes, pulse/comb generators, modulated signals, and vector signal analyzers. Much of our work involves developing methods to traceably characterize these instruments and waveforms with application to wireless communications.

The calibration of photodiodes using EOS system is currently limited to frequencies below 110 GHz as our measurement setup, workflow and analysis targets photodiodes with a 1 mm coaxial connector. However, the EOS system itself has a bandwidth above 1 THz based on the electrooptic response of the LiTaO<sub>3</sub> crystal and the interaction between electric field penetration into the substrate and the pulse propagation through this field. Over the last couple of years we have focused on extending the frequency of this service through characterizations of higher frequency photodiodes. We are examining the use of photodiodes with a 0.8 mm adapter increasing our bandwidth to 145 GHz and working with an industry collaborator on rectangular waveguide WR6 photodiodes that support higher frequencies (110 GHz – 170 GHz). One of the limitations to our research, and a primary obstacle to overcome, is that the on-wafer characterization and subsequent de-embedding of the wafer probes has been very noisy due to the high permittivity of the LiTaO<sub>3</sub> crystal. We are actively working to redesign the on-wafer calibration artifacts to provide high frequency traceability.

We are also working towards upgrading the electro-optic sampling to use advancements in dual-comb THz and optical spectroscopy to simplify the mechanical scanning challenges of traditional time-domain electro-optic sampling. One frequency comb generates impulse responses on a photodetector while the second comb with samples the electro-optic effect on wafer. Dual frequency comb EOS offers not only mechanical simplicity, but better frequency resolution without the need for mechanical time delays with >10 ns range [1]. The coherence of the comb also allows for improvement of the signal to noise by employing coherent averaging or real-time phase correction methods. This year we will perform a comparison between the dual-comb EOS and the standard mechanical delay stage EOS. A prototype spatially resolved EOS was also developed that can image the electric field as it propagates down the coplanar waveguide. This technique has a bandwidth around 1 THz and projects approximately 70 spots used for imaging of the waveform [2].

We demonstrated a technique for traceable calibration of a vector signal analyzer (VSA) for the measurement of modulated communications signals at millimeter-wave frequencies. In this method, a multisine waveform is generated using an arbitrary waveform generator (AWG) and upconverter. The multisine signal output of the AWG is characterized using a sampling oscilloscope, which itself has been calibrated using a photodiode pulse source, providing traceability to the fundamental units of the meter and second by means of electrooptic sampling system (EOS). By comparing the multisine signal measurements of the VSA and sampling oscilloscope, and accounting for oscilloscope impulse response and impedance mismatch, we determine the band-limited impulse response of the VSA. The technique has been demonstrated at 28 GHz, and the calibrated VSA was used to measure error vector magnitude (EVM) of a quadrature amplitude modulated (QAM) communications waveform [3].

Several staff have also been working on a new standard for sample-by-sample waveform uncertainty documentary standard through the International Electrotechnical Commission (IEC). Although this effort began with researchers at the German NMI The Physikalisch-Technische Bundesanstalt (PTB), NIST staff now leads this collaborative effort that includes representatives from several industrial partners (e.g. Anritsu, Rohde and Schwarz, Textronix) as well as several national metrology institutes (e.g. PTB, METAS, KRISS, NIM, CMI). This work builds upon our deep experience and expertise in full waveform metrology.

Due to staffing changes, we re-envisioned the traceability path for the low-level radiometry service and transferred all measurement capabilities to the US Navy. A notice of final offering went out during the summer of 2023 and after transfer of the capabilities in the spring of 2024 the service was discontinued.

[1] D. Barot, A. D. Feldman and B. R. Washburn, "Dual-Comb Asynchronous Electro-Optic Sampling Technique for High-speed Optoelectronic Devices," 2023 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, USA, 2023, pp. 1-2.

[2] Bryan Bosworth, Nick Jungwirth, Jerome Cheron, Franklyn Quinlan, Nathan Orloff, Christian Long, Ari Feldman, "Imaging mmWave propagation on wafer," Proc. SPIE PC12885, Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XVII, PC128850C (12 March 2024).

[3] P. Manurkar, J. M. Kast, D. F. Williams, R. D. Horansky, D. G. Kuester and K. A. Remley, "Recommended Practices for Calibrated Millimeter-Wave Modulated-Signal Measurements," 2023 100th ARFTG Microwave Measurement Conference (ARFTG), Las Vegas, NV, USA, 2023, pp. 1-4, doi: 10.1109/ARFTG56062.2023.10148875.