Report to CCEM on electrical metrology at NIST
March 2023

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2 Report

Digital SI

In 2022, NIST started a pilot project to produce digital calibration reports and certificates for the analysis of reference materials. This pilot project uses a platform developed at NIST called the configurable data curations system (CDCS). With the CDCS, unstructured data can be transformed into XML for sharing or storing. A large fraction of the effort of the pilot is spent on developing methods to populate the digital calibration report from the XML schema derived from the CDCS. In September 2022, a workshop was held at NIST to discuss the digital calibration reports with stakeholders. The aim of the workshop was to inform the strategy toward a full digital transformation of its measurement services.

DC Josephson Voltage Standard Systems

NIST researchers have improved the reliability and maintainability of the PJVS system by moving from a custom-built to a commercial cryogenic platform to enable dissemination by outsourcing elements that do no need NIST expertise. The new cryocooler has better thermal stability (≈ 1 mK oscillations) and more cooling power for cool-down in < 4 hours from room temperature. In addition, the bias electronics have been updated from the JVS 650 to the JVS 700 by incorporating non-obsolete subsystems and improved performance [9]. Both cryo-packaged chips and PJVS systems continue to be disseminated through the NIST Standard Reference Instrument (SRI) program to external users, with systems going to two US instrument manufacturers and two international NMIs. NIST researchers have continued to improve PJVS designs with the latest design for 15 GHz operation (previously 18 GHz), which allows for more reliable, less expensive microwave synthesizers and amplifiers.

Josephson Arbitrary Waveform Synthesizer System (JAWS)

NIST researchers have continued to improve the JAWS system and ac measurements based on the JAWS. A significant limitation of the JAWS is the loading issue: the output transmission line and attached loads result in a series voltage drop that diminishes the accuracy of the JAWS system. To this end, a buffer amplifier coupled to a multijunction thermal voltage converter (MJTC) was tested to disseminate the JAWS ac voltage (presented at CPEM 2022 in NZ). The buffer amplifier operated up to 2 V rms and was tested from 40 Hz to 20 kHz with uncertainties of a few parts in 106 in the low-frequency limit. NIST also worked with NRC Canada on the development of a compact waveform synthesizer, which could serve as an ac transfer standard alternative to thermal converters (presented at CPEM 2022 in NZ).

To ease microwave control pulse delivery to the cryogenic JAWS chip, NIST demonstrated the use of an optical pulse bias to generate an rms amplitude of 3.3 mV bipolar waveform with 1.2 mA quantum locking range [8]. NIST is working to extend the frequency range of the JAWS system into the microwave range through several recent publications [27, 5, 6, 29] in which gigahertz waveforms are synthesized and calibrated.

Quantum Conductance project

The Quantum Conductance Project is investigating new applications for quantized Hall array resistance standards (QHARS) using epitaxial graphene on insulating SiC with superconducting interconnections. Array standards were used in NIST Kibble balance measurements to provide direct realization of mass at 50 g and 100 g and provided similar or better results than room-temperature resistance references. The $\nu = 6$ resistance plateau was measured using increased carrier concentration, 0.5 K, and magnetic field strength up to 13 T. These conditions, however, were not sufficient to produce full quantization in a 13-device parallel array. For two-terminal QHARS devices, symmetric resistance plateaus are observed for positive and negative field orientation, and a comparison of these plateau resistances is found to be useful as a measure of complete quantization. Under a cooperative arrangement, Graphene Waves, LLC is collaborating with NIST and the University of Maryland on patent-pending technology to develop graphene-based QHARS with a wide range of resistance values. Collaboration with Stanford University is continuing with the goal of developing quantum anomalous Hall effect standards, and 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, with some staff continuing telework several days a week. 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. NIST measurements for the bilateral comparison CCEM-K2.2012.1 of 10 MΩ and 1 GΩ resistance standards between KRISS, NRC, and NIST have been completed and the resistors shipped end of 2022 to NRC in Canada for the closing measurements in 2023. With the quantum conductance project and Graphene Waves, NIST has demonstrated the first measurement combining the wye-delta transformation with quantum Hall array resistance standards (QHARS). The proof of principle measurement reconfigured a 1 MΩ QHARS to 20.6 MΩ , extending the range of QHARS beyond the largest series arrays of 1 MΩ. The technique may be extended to the 100 MΩ to 10 GΩ ranges. The work at NIST in resistance metrology was well represented at CPEM 2022, and we were able to send five people from the two projects and to present six papers at the conference.

Kibble balances

NIST participated in the second key comparison of the unit of mass in October 2021. Mass determinations of two Pt-Ir kilogram standards were conducted on the US primary mass standard, NIST-4, and subsequently sent to the BIPM. The result of this work is published in [36]. NIST has recently employed two quantum electrical standards in a single current source arrangement with the NIST-4 electromagnet to levitate a mass [22], i.e, the current used to levitate a mass passes through a graphene quantum Hall resistance array standard (QHARS) [26]. The Josephson effect voltage is then compared directly to the resulting quantum Hall effect voltage. After accomplishing these two measurements, the NIST-4 lab went under construction for a year to repair the damage that resulted from the flood in 2018. Researchers are currently reassembling different parts of NIST-4 in preparation for the next key comparison in the fall of 2023. Researchers at NIST 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 [15], a programmable Josephson voltage standard (PJVS), and a graphene-based quantum Hall resistance array standard (QHARS). The QEMMS Kibble balance will measure masses with nominal values up to 100 g with relative uncertainties lower than 2×10^{-8}. All different mechanical, optical and electrical parts of the Kibble balance were built and are undergoing tests at present. The superconducting magnet for the QHARS has been delivered and is currently being assembled.

NIST continues its effort in the design of the tabletop-sized Kibble balances operating at the gram-level range with uncertainties on the order of a few parts in 10^6. In early 2020, KIBB-g1 was inducted into the NIST on a Chip (NOAC) program. Soon after, NIST started developing the next generation KIBB-g2 with a deeper focus on mechanism robustness, usability, and general commercialization after having received 3-year funding from the US Army metrology division. Using the linear Kibble principle in a rotating frame, NIST applies these ideas to a rotational frame for usage in torque standards instead of mass standards. NIST received 3-year funding from the Air Force metrology division to build the Electronic NIST Torque Realizer (ENTR) having a dynamic range of 0.007 N·m– 1 N·m with 0.1 % uncertainty.

Capacitance Metrology

NIST has recently demonstrated a hybrid impedance bridge for comparison of a capacitor with a resistor where the impedance ratio was measured in two separate parts. The modulus of the impedance ratio was matched arbitrarily close to the input-to-output ratio, in magnitude, of a two-stage IVD by adjusting the operating frequency of the bridge; the residual deviation between the two together with the phase factor of the impedance ratio was measured using a custom detection system based on a four-channel 24-bit digitizer. The IVD was calibrated, in situ, using a four-arm bridge with two known capacitors. In contrast to the conventional approach of emphasizing precision and stability of the voltage sources driving the bridge, we adopted an approach that focused on the resolution and stability of the detectors. Fluctuations of the source voltages were largely removed through postprocessing of the digitized data, and the measurement results were limited by the digitizer error. While we have achieved a low Type A uncertainty of 0.02 μF/F in 2 hours for determining the capacitance of a 100 pF capacitor relative to a 12906 Ω resistor at 1233 Hz, the combined relative standard uncertainty is 0.13 μF/F. In the future, we plan to focus our research on reducing the digitizer error for the hybrid impedance bridge to serve as an alternative system at NIST for realizing the capacitance unit [12].

NIST has also developed a new method for determining the time constant of ac resistors with values around 10 kΩ, using a digital impedance bridge for the comparison of two nominally equal resistors. The method involves adding a probing capacitor in parallel to one of the resistors to induce a quadratic frequency dependence in the real component of the admittance ratio between the two resistors. The magnitude of this quadratic effect is proportional to the self-capacitance of the unperturbed resistor, enabling us to determine its value and the associated time constant with an estimated standard uncertainty ($k = 1$) of 0.02 pF and 0.2 ns, respectively. An archival paper describing the new method in detail has been submitted to the Review of Scientific Instruments.

Antenna Metrology

As of April 2022 the NIST Antenna Calibration Service SKU63100 was re-instated (shop.nist.gov). NIST completed significant facilities renovations and upgrades that have modernized NIST's old legacy facilities in order to address modern antenna calibration needs across a wide range of frequencies from 1 GHz to 500 GHz. This new state-of-the-art Antenna Measurement Facility (AMF) consists of an anechoic shielded chamber that provides a radio-quiet environment for antenna metrology within which resides two antenna ranges that together cover the 1 GHz to 500 GHz frequency range.

One antenna range, the Large Antenna Positioning System (LAPS), designed for larger antennas covers the 1 GHz – 50 GHz frequency range and is based on a thirteen-axis dual robotic positioning system. The second antenna range the Configurable Robotic Millimeter Wave Antenna system (CROMMA) is designed with smaller high-frequency antennas in mind which operate from 50 GHz to 500 GHz and supports very high accuracy antenna position through the use of laser-guided and aligned robotic positioners and high-frequency radio frequency sources. Testing to validate the new AMF supporting the NIST Calibrations Service SKU63100S for On-Axis Gain and Polarization. Multiple measurements were conducted on check-standard antennas to provide an end-to-end test of the new NIST antenna facility. Three pairs of antennas spanning a varied range of frequencies which included WR-90 (X-Band), 8.2 GHz – 12.4 GHz, WR-62 (Ku-Band), 12.4 GHz – 18 GHz, WR-10 (W-Band) 75 GHz – 110 GHz were used which were part of previous documented comparisons were used for this validation including antennas used in the Ku-Band CCEM Key Comparison CCEM.RF-K23.F (2015) at 12 GHz -18 GHz, and WR-10, from 75 GHz — 110 GHz, (2010) comparison. Results showed agreement within stated uncertainties providing equivalence to 17 and congruency to data dating back to 1980. Measurements and research are also being conducted related to advancing robotic antenna range approaches and technologies for the next generation of antenna testing and development of broad band antenna check standards for 1 GHz to 18 GHz operation. Other activities that are under way include addressing Action 3 of the previous GTRF meeting where NIST has been working to coordinate efforts with other NMI's for conducting a key comparison of antenna on-axis gain and secondary parameters of polarization ratio and polarization sense of rotation around the WR-05 (140 GHz – 220 GHz).

Development of new broad-band antenna check standards for addressing customer requests for these antennas is underway. 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 600 MHz 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.

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-15 rectangular waveguide band [23, 13]. 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 was utilized in the WR-15 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. NIST is also building a similar uncertainty analysis for Type N connectors simultaneously.

RF Power

NIST is currently developing a new twin-load microcalorimeter for 2.4 mm coaxial power sensors and evaluating 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. 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 six-port network analyzer systems to perform S-parameter measurements and to transfer calibrations from rectangular waveguide power sensors characterized in microcalorimeters to other power sensors. These systems are being retired and replaced with a combination of commercial network analyzers for scattering-parameter measurements and direct comparison systems for power-transfer measurements. This process is complete for devices with WR-10 and WR-15 connector types. The remaining six-port systems – those operating in the WR-90, WR-62, WR-42, WR-28, and WR-22 bands – are expected to make similar transitions within the next two years. The software for these systems is also migrating from HP Basic to Python [32].

NIST is also exploring on-chip methods for power calibration at both room temperature and cryogenic temperatures down to the mK range.

Thermal Noise Metrology

NIST's Thermal Noise project has completed the prototype digital radiometer that achieves unprecedented spectral resolution and efficiency for communication sensing applications. The digital radiometer operates in the frequency band of 1 GHz to 2 GHz and is reconfigurable for different frequency ranges. Using the side-band separation scheme, signals occupying lower and higher side bands can be distinguished. The high-speed digitizing backend enables the detection of drastically varying communication signals. In addition, the radiometer is calibrated by NIST SI-traceable primary standards, which allows high-fidelity measurements of signal strength. This work is published in a special issue of Microwave Magazine in May 2022 [16].

Extending the digital radiometry work, we are collaborating with a mathematician on quantifying uncertainty for spectral analysis. Different from conventional analog radiometry, the spectrum measurements with digital samplers are conducted on data series in the time domain. The resultant spectrum in the frequency domain by digital signal processing is, at best, an approximation. The development of rigorous uncertainty analysis is significant not only to the digital radiometry work but also for many commercial instruments involving spectral power measurements.

On the fundamental metrology front, we are modernizing the radiometer by consolidating the 1 GHz to 40 GHz measurement systems. We have identified and acquired the necessary parts and will start integration and testing in the first half of 2023. 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 US DoD primary standards lab has expressed interest to fund the project.

In response to the congressional efforts to strengthen the US semiconductor industry, we have engaged with semiconductor chip makers to identify measurement challenges. Existing commercial instruments and methods are inadequate to address the qualification requirements of highly sensitive transistors. These transistors determine the high-performance state of the art in wireless receivers for satellite communications, quantum technology, global navigation services, and remote sensing for weather and climate, among others. A more precise and versatile measurement technique is called for to provide a better tool for the semiconductor industry to qualify the transistor performance. We believe that the success of this research effort will significantly improve the performance of commercial metrology instruments and transistor design models.

High-speed 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 due to the coaxial 1 mm connectors available on photodiodes. The EOS system itself has a bandwidth above 1 THz based on the electrooptic response of the LiTaO3 crystal and the interaction between electric field penetration into the substrate and the pulse propagation through this field. In 2023, we plan to characterize a photodiode with a 0.8 mm adapter, which will increase our bandwidth to 140 GHz. This will require new characterizations of the photodiodes, probes, and on-wafer devices utilizing 0.8 mm connectors. So far, we have purchased the required hardware and developed physical models for a 0.8 mm coaxial vector network analyzer (VNA) calibration kit that will be used to make the necessary impedance mismatch corrections.

We are also working toward developing a novel spatially resolved electro-optic sampling system to enable real-time visualization of the electric field as it propagates down a coplanar waveguide. In 2022 we started developing this system which uses a custom polarization-sensitive microscope and the inherent parallelism of a high-speed near-infrared camera to acquire up to several hundred spatially distributed EO signals simultaneously. In 2023, we are optimizing the resolution and field of view for measurements from approximately 10 GHz to 1 THz on several electro-optic substrates. A further innovation is the development of a tunable separation-balanced photodetector with better noise performance and much higher optical power handling than any commercial balanced photodetector.

The fiber delay service completed the intercomparison with LAMETRO and published a report on the results. However, due to the lack of interest in the service, with the last calibration in 2015, we have opted to discontinue this as a measurement service. A notice of final offering went out in the fall of 2022, and no one has expressed interest, validating our course of action.

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