Report to CCEM on electrical metrology at NIST
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2 Report

DC Josephson Voltage Standard Systems

NIST researchers have continued to disseminate and improve the performance and usability of the 10 V Programmable Josephson Voltage Standard (PJVS) system. A 2 V cryocooled PJVS systems was disseminated to NIST Gaithersburg for implementation with the Kibble balance and multiple 10 V and 2 V PJVS circuits (assembled in a cryopackage) were disseminated to national metrology institutes around the globe [13, 46]. Both cryopackaged chips and PJVS systems continue to be disseminated through the NIST Standard Reference Instrument (SRI) program to external users. NIST researchers have developed and built a prototype of compact (bench-top) cryocooled dc Josephson voltage standard at 1 V (BJVS). The prototype was presented and demonstrated at the 2019 NCSLI Workshop and Symposium in Cleveland (OH, USA). The results of BJVS to PJVS comparison (agreement of 5 parts in 10^{10} at 1 V) was presented at the virtual CPEM 2020 conference [41]. NIST researchers have continued to improve the automated leakage current measurement with the PJVS, including the measurement of the isolation resistance between the voltage leads, which is a critical component of the PJVS uncertainty budget [12].

Quantum Conductance project

The Quantum Conductance project introduced precise QHR arrays consisting of 13 QHR elements in parallel, providing SI resistance $R_K/26 \approx 992.800287\,\Omega$. These arrays consist of single-layer graphene on insulating SiC with superconducting interconnections, providing a two-terminal resistance standard, and with highly symmetric plateaus for both directions of magnetic field. The arrays can operate with precision of a few parts in 10^9 for source-drain current up to 1.2 mA at 1.6 K. This work has resulted in graphene devices that are compatible with low-cost cryogen-free magnet systems and have been used as the resistance standard for weighing measurements in Kibble balance with 50 g and 100 g mass standards. A chip with two such standards has been provided to the PTB for DC and AC QHR measurements in support of the Graphene Impedance Quantum Standard - EMPIR 2019 Joint Research Project. NIST has plans to provide similar QHR array standards to collaborating NMIs within the SIM region. Other research includes characterization of graphene p–n junction arrays and development of standards for quantum Wheatstone and Kelvin bridges in collaboration with AIST and INRIM.

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 continued during the pandemic with minimal staff onsite. 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. As part of a collaborative research project with Measurements International, graphene and GaAs devices were compared in the same cryostat with a dual probe system. Most recently, a new 9 T cryocooler for graphene quantum Hall resistance standards has been installed in the resistance laboratory. Collaboration with and the National Institute of Advanced Industrial Science and Technology (AIST) continued with NIST hosting a guest researcher from AIST from 2019 through 2020. Activities focused on an onsite high resistance comparison from $1\,\mathrm{M}\Omega$ to $10\,\mathrm{T}\Omega$ of AIST and NIST dual source bridges and evaluation of GaAs arrays for a quantum Wheatstone bridge.

Kibble balances

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 106. The design and the uncertainty budget of the first protype KIBB-g1 are published in [52]. 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 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 2×10^{-8}.

Determination of Absolute Phase of Digitizers

Absolute Phase is a term of art in use since the mid 1800's. The term describes the phase shift through a process recently it has been used in power systems to mean phase referenced to a theoretical signal synchronous with UTC/TAI time. The NIST Synchrometrology lab, in collaboration with METAS are working to improve the determination of absolute phase through the digitization process. This work builds on and refines work published by NIST, IMRIM, METAS, and EPFL by using an equivalent time sampling technique to determine the phase shift due to the digitizers anti-aliasing filter.

Smart Grid Standards and Metrology

The NIST Synchrometrology lab, with Allen Goldstein as its principal investigator, continues to support the traceability of the IEEE Synchrophasor Conformity Assessment Program (ICAP) by providing a calibration service for labs applying to become ICAP certified to test Phasor Measurement Units (PMUs). NIST is collaborating with METAS and INMETRO to transfer this capability to those labs. NIST Synchrometrology lab is participating in IEC efforts to standardize frequency measurement devices in bulk power distribution systems via IEC 62786-41, the first committee draft (CD) of that document is currently out for comment by the national committees. Allen Goldstein has also been leading the effort to revise the IEEE C37.242 Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs)... This is a major overhaul of the 2013 document based on innumerable lessons learned in the field and in testing. The guide has passed sponsor ballot and is being approved for publication this year. The NIST Smart Grid Testbed is in pre-commissioning phases. A safety compliance inspection has been completed and hazards are being mitigated. The Smart Grid Program has published the fourth edition of the NIST Framework and Roadmap of Smart Grid Interoperability Standards. In addition NIST Smart Grid has published the Summary Report on the NIST Smart Grid TestBeds and Collaborations Workshops in NIST SP-1900-102.

Capacitance Metrology

NIST has recently demonstrated a detector-limited digital impedance bridge, using two nominally equal resistors to form a 1:1 ratio. Fluctuations of source voltages are largely removed through post-processing of the digitized data, and the measurement results are limited mainly by the detector noise. This detector-limited operating condition was first demonstrated using three modified Keysight 3458A multimeters for measurements of the voltage ratios, achieving 1 part in 10^8 Type A uncertainty in less than 15 min at 1 kHz. It has also been demonstrated that by using three lock-in detectors for measuring small deviations from the perfect ac ratio of unity magnitude, a few parts in 10^7 Type A uncertainty can be achieved in a few hours for each point from 1 kHz to 5 kHz.

In order to take advantage of the excellent phase control and stability of the digital bridge and extend the newly demonstrated measurement capability for comparing a capacitor with a resistor, NIST plans to explore two different approaches. For an impedance ratio with the nominal value of one in magnitude, NIST plans to adopt a proven technique of BIPM by allowing slight frequency adjustment so that the impedance ratio of the capacitor to the resistor is arbitrarily close to one in magnitude with its phase close to 90^o. For other impedance ratios, application of ac voltage scaling and calibration functions in the bridge need to be further investigated by adding an inductive voltage divider between one of the high potential ports and the voltage measurement system so that the apparent magnitude of the main voltage ratio stays near unity

Josephson Arbitrary Waveform Synthesizer System (JAWS)

NIST researchers have continued to disseminate and improve the performance and usability of the JAWS system with rms output voltages up to 4 V. Dissemination efforts continue through the NIST Standard Reference Instrument (SRI) program include the delivery of JAWS chips with liquid helium probes to both NIM and METAS and ongoing support of JAWS systems at Sandia, Army, and VSL. We are also working to expand the applications for these JAWS sources. We used this 4 V JAWS system to measure the 4 V 1 kHz output of a calibrator with a type A uncertainty of 0.01 µV/V [20]. Achieving the highest output voltage requires low-frequency compensation bias currents which introduce voltage errors, however lower output voltages can also be generated without compensation; by improving the microwave biases, the maximum demonstrated rms output voltage was increased in this "zero-compensation" mode to 1.33 V [19]. We have continued a collaboration with METAS on JAWS-based impedance measurements using the "zero-compensation" mode for improved precision. The JAWS sources allow a single bridge to compare impedances with arbitrary ratios and phase angles in the complex plane. The recently published uncertainty budget shows that the traditional METAS calibration chain and the JAWS-based calibration have comparable uncertainties in the kilohertz range [33, 32]. The NIST Power group has integrated a JAWS system as a reference for active power meter calibrations, showing agreement to with 1 part in 10^6 [43, 4]. We are also working to expand precision JAWS measurements to DUTS with low input impedances by using a negative impedance convertor [42].

AC-DC and RF-DC Difference Metrology

In December of 2018, NIST MJTCs standards were shipped to the first laboratory in the CCEM K6a/K9 and K6c comparison. Over the past two years, one standard was damaged beyond repair and was replaced. A second standard was repaired twice. NIST has done two pivot measurements and will do one more pivot measurement and a closeout measurement. Due to pandemic and shipping issues, the comparison measurements are now scheduled to finish mid-2022.

Ac-dc difference metrology suffered numerous standard and equipment failures partly from pandemic related building shutdowns. Most equipment was repaired August-October 2020. The calibration control software was updated to facilitate the use of new computers and combine ac-dc difference with thermistor mount calibration capabilities. Current efforts to improve the control software include increased data collection and incorporation of new equipment. Building on the success of NIST multijunction thermal converters (MJTCs), a variation of the technology was implemented with 50 Ω devices for RF applications. New research within ac-dc difference metrology is focusing on evaluation of photonic technology as a replacement for thermocouples to surpass limitations of current MJTCs. Active circuits are being developed to improve input and output characteristics of MJTCs.

Antenna Metrology

NIST is currently working diligently to bring the Antenna Calibration Service SKU63100 online. NIST is finalizing 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 1-50 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 is underway in support of the NIST Calibrations Service SKU63100S for On-Axis Gain and Polarization. Multiple measurements, both planned and in progress, will be used to validate the AMF facility across a range of frequencies. Antennas previously part of comparisons will be 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. Measurements are also being conducted related to 5G antenna metrology use cases such as channel sounding and characterization of standard gain reference antennas. 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) or WR-03 (220 GHz - 325 GHz) frequency bands.

Field Strength Metrology

NIST field strength measurement facility is finalizing a refurbishment of their anechoic chamber. NIST now has the capability to establish a reference CW electric field in both TEM cells (100 kHz to 250 MHz) and the fully anechoic chamber (250 MHz to 40 GHz). NIST is currently working with another NMI in order to do a probe intercomparing in NIST's new chamber. This year NIST, will also be performing inter-comparisons of several commercial probes. Now that the CW reference field capability is re-established, we plan to extend reference field capability to fast, modulated signals representative of existing and future communication signals. Currently, a traceability chain for such radiated signals does not exist. The goal is to develop a traceability chain, investigate current modulated signal probes for accuracy and uncertainties, make recommendations on improvements, and assess low cost versus precision probes. This project has also made significant progress in the use of Rydberg-atom based probes that not only provide SI-traceable field strength measurements but also show promise for direct field strength measurement of modulated signals.

RF Scattering-parameters and Power Characterization

In our calibration services for scattering-parameters, one of the most important measurements in the traceability path is the dimensional characterization of coaxial and waveguide transmission lines with air dielectrics. These dimensional measurements were historically performed at the NIST Boulder campus, but the dimensional measurement facilities in Boulder were closed several years ago. In the last two years, these dimensional measurements were taken up by NIST's Dimensional Metrology group under NIST Service ID 11050S. The Dimensional Metrology group developed the capability to perform traceable dimensional measurements of both rectangular waveguide and coaxial air-line standards. In comparison to the historical measurements performed at the Boulder campus, these measurements offer improved accuracy, precision, and a more direct traceability path to the SI. This capability will be deployed one connector type at a time, with measurements of WR-15 rectangular waveguide standards already completed and measurements of 2.4 mm coaxial standards underway. An updated uncertainty analysis based on a combination of dimensional measurements, instrument effects, and environmental effects is also currently under development. The analysis is 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.

In our microcalorimetry services for power, we recharacterized our WR-15 microcalorimeter and updated our uncertainty analysis to incorporate an updated uncertainty model for scattering-parameters in the WR-15 band, a non-linear model of the thermopile output voltage, and the reproducibility of the microcalorimeter characterization process. The updated uncertainty analysis was employed for NIST's measurements in the CIPM key comparison CCEM.RF-K27.W. The data acquisition software for all microcalorimeters was also migrated from Visual Basic to LabView. In the near future NIST will also be developing a twin-load microcalorimeter for 2.4 mm coaxial sensors. The new microcalorimeter is expected to operate with both thin-film sensors and thermoelectric sensors.

In our direct-comparison services for power, NIST has historically operated several six-port network analyzer systems to transfer calibrations from rectangular waveguide power sensors characterized in microcalorimeters to other power sensors. We began the process of retiring these six-port systems and migrating all calibration services that relied on six-port systems to a combination of commercial network analyzers for scattering-parameter measurements and direct comparison systems for power-transfer measurements. In the last year, we completed the transition for a six-port system that operated in the WR-15 rectangular waveguide band. The new system is based on a commercial network analyzer with WR-15 extender heads. The extender heads are also employed as sources for the direct comparison measurements, though a coupler with a thermistor mount on the side arm is still employed as a monitor mount in lieu of the network analyzer's receiver. The remaining six-port systems – those operating in the WR-90, WR-62, WR-42, WR-28, WR-22, and WR-10 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. Finally, NIST issued an updated technical note on the theoretical basis of direct-comparison systems.

Thermal Noise Metrology

NIST's Thermal Noise project has devoted recent research in support of digital wireless communications. A digital radiometer is under development in order to provide precision measurements of digital interference signals with unprecedented spectral resolution and efficiency. We aim to build reconfigurable RF frontends in combination with the NIST SI-traceable primary standards and optimize digital signal processing algorithms tailored for spectrum sensing applications. This flexible and robust instrument will provide a unique capability for sensing slow changes in low-noise frequency allocations such as global navigation satellite systems and weather satellite radiometry. By implementing rigorous uncertainty analysis and new instrumentation, we plan to develop a metrological standard for noise and interference measurements in the digital world along an unbroken traceability path. A preliminary report on the digital radiometer development was presented at the CPEM 2020. On the fundamental metrology front, we collaborated with Scattering (S)-Parameter Metrology project to investigate the noise influence in S-parameter measurements. A comprehensive model along with a rigorous statistical analysis is developed to include noise effects in S-parameter measurements by a vector network analyzer. For the first time, the uncertainty due to stationary noise ubiquitously existing in S-parameter measurements can be accounted for systematically. This study has laid a solid foundation for improving accuracy of a variety of microwave measurements impacted by noise, including joint signal and noise metrology, high-selectivity antenna development for 5G-and-beyond and high extinction-ratio antenna polarization metrology. In light of the global pandemic, NIST staff has embarked on a measurement campaign to better understand the spectrum environment in teleworking sites and healthcare facilities. By use of the off-the-shelf software-defined radios (SDRs), spectral occupancies are studied in a number of WLAN and LTE frequency bands. In addition, best practices of characterizing and calibrating commercial SDRs are under development so as to improve the homogeneity of a sensor network. These efforts and the resultant data are critical to regulatory and industrial stakeholders in making judicious decisions in disaster and emergency responses.

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. A gradual upgrade of the EOS system was started in 2012. These upgrades include: 1. Move to a modern temperature-controlled laboratory and a larger optical table in 2012. 2. Acousto-optic chopper to increase chopping frequency and reduce noise floor in 2012. 3. Replace aging equipment, including control computer, chopper driver, and volt meters in 2015 - 2016. 4. Install precision environmental monitoring equipment and a laser interferometer for traceable measurement of the stage position in 2015 - 2016. 5. Replace control software with Windows 7/10 compatible software in 2016. This software gives more real-time feedback on the measurement status, allowing user intervention when problems with the measurement occur. 6. A new $LiTaO_3$ wafer was fabricated and characterized in 2018 to enable future measurements 7. The ball-screw translation stage with a modern direct drive translation stage was installed 2019 providing a more reliable relative delay.

In 2021, we plan to upgrade the EOS data analysis software to be more fully integrated into the NIST Microwave Uncertainty Framework. This will allow us to more accurately quantify errors in the measurement and give a more general, sustainable approach to calibrating measurements. Further improvements of the system include implementing controllable XYZ positioners to the wafer stage and wafer probes to enable remote management of the calibrations.

From the spring of 2018 to the summer of 2019, PTB, NIST, NIM, and BIRMM (Beijing Institute of Radio Metrology and Measurement) performed the first international comparison in ultrafast waveform metrology, where the frequency response of a photodiode with a nominal bandwidth of 100 GHz was measured. The NMIs used different measurement procedures, all based on electro-optic sampling (EOS) techniques employing ultrafast lasers with a center wavelength of 1550 nm and an optical pulse duration ranging between 100 and 250 fs. The frequency-domain amplitude responses exhibited good agreement with an increased spread among the results below 20 GHz and above 90 GHz. The frequency-domain phase responses also showed good agreement with minor differences starting to become noticeable above 70 GHz. A detailed report of the comparison and results was presented at the 2020 Conference on Precision Electromagnetic Measurements (CPEM). Additional studies and comparisons could incorporate a more detailed statistical analysis of results and uncertainties, the inclusion of additional NMIs, and a comparison of time-domain responses from all participants.

During this same time frame (2018 - 2019), NIST compared the magnitude responses of photodiodes as measured by our heterodyne and EOS systems up to 75 GHz. The two methods compared favorably describing the roll-off of the photodiode response with most points agreeing within their uncertainties. The few points that do not agree could be attributed to on-wafer and coaxial connections and calibrations. This result is the best comparison of these methods to date and offers a couple of areas for improvements.

NIST (USA) and designated institute LAMETRO (Costa Rica) performed a bi-lateral comparison of fiber delay measurements to support optical time domain reflectometer metrology. Using a 10 km singlemode fiber spool artifact, the results of measurement by the two IEC-61746-1:2009-12 methods of modulation phase shift (NIST) and recirculating delay line transfer standard (LAMETRO) were favorably compared to within their uncertainties.

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