Report to CCEM on electrical metrology at NIST
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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. Three cryocooled PJVS systems were disseminated to primary standards laboratories: the Navy Primary Standards Lab (NPSL), the Army Primary Standards Lab (APSL) and Sandia National Laboratory (DOE). All these systems have been qualified with an on-site direct PJVS comparison with a liquid cooled travel standard, as part of the NIST measurement service (performed by Stefan Cular). Following the study of a comparison between two PJVS systems, both on cryocoolers, and with a combined uncertainty of better than 1 part in 10^{11} [?], NIST researchers have focused their work on improving the leakage resistance of the PJVS. The leakage resistance to ground was increased by 10-fold with the implementation of custom built low-leakage current bias cable. NIST has demonstrated a new automated method to measure both leakage current to ground and leakage resistance to ground of the PJVS system. An upgrade of the bias electronics module will soon be made available to all currently disseminated PJVS systems to perform this important task. The BIPM PJVS system, on loan from NIST, has taken part into on-site comparisons with the NMIJ/AIST PJVS [?]. A review article, focusing on the best practices with PJVS (and JAWS) as well as their impact with the new SI redefinition has been published in Metrologia [**?**].

Quantum conductance project

The quantum conductance project introduced efficient and highly repeatable processes for growing large-area, single-layer graphene on insulating SiC wafers and used this material to fabricate devices superior in electrical performance to the QHR standards previously in use at NIST. This work has resulted in graphene devices that are compatible with low-cost cryogen-free magnet systems, operating at 4 K or above, which can be compared to conventional standard resistors using room temperature equipment. Moreover, this innovation may soon allow the creation of practical standards with a broad range of values for realization of the ohm at convenient levels using multi-terminal graphene device arrays that are superior to devices operating at only one level of resistance. The new NIST graphene-based resistance standards have been used to provide calibration traceability in the DC resistance laboratory, and when used with commercial, room temperature measurements can offer similar precision and resolution in competition with expensive custom cryogenic equipment.

Metrology of the ohm

The metrology of the ohm project continues to provide ongoing support for experiments such as the NIST-4 Kibble balance at the 100 Ω level of resistance provided traceability $< 10 \times 10^{-9}$ as well as delivery of measurement services to our other internal and external customers. Support for low current measurements, SI traceable to resistance, in the nA, pA, and fA ranges continues for photodetectors and aerosol electrometers with new emphasis on ionizing radiation chambers. The installation of a table top cryocooler (4 K) with 5 T magnet with a graphene quantum Hall resistance standard has provide traceability in the primary resistance lab based on graphene. Preliminary AC measurements with graphene have taken place in collaboration with the capacitance/impedance project. Collaborations with and the National Institute of Advanced Industrial Science and Technology (AIST) are continuing with comparison of NIST Graphene with AIST GaAs devices (2017, 2018) as well as a high resistance comparison at 10 TΩ and 100 TΩ (2017). A high resistance comparison with Instituto Costarricense de Electricidad (ICE) at 100 MΩ and 100 GΩ took place during 2018 using high resistance standards constructed previously at NIST with an guest researcher from ICE.

Kibble balances

In July 2017, researchers working on the fourth generation Kibble balance (NIST-4) published the last determination of the Planck constant h with a relative standard uncertainty of 13×10^{-9}. This value was part of 2017 CODATA least square adjustment. Due to a mechanical failure in a rotational decoupler supporting the coil suspension, the Kibble balance was taken apart in February 2018 and re-assembled by May 2018. Upgrades were made to the interferometer plates to reduce vibration coupling in the interferometer and to the flexures supporting the main coil by increasing the stiffness of the suspension and hence reducing the difference in the vertical position of the coil between mass on and off.

The tabletop-sized Kibble balance (KIBB-g1) designed to operate at the gram-level range with uncertainties on the order of a few parts in 10^6 is currently under development. Recent data indicates the precision of KIBB-g1 has uncertainties of about 1.7×10^{-6} on a nominally 10 g mass.

Smart grid standards and metrology

NIST continues to support electric grid modernization efforts known as the smart grid (SG). Working with industry, the US Department of Energy, and other key partners, NIST has provided leadership through the development and publication of the overall NIST roadmap and framework to achieve interoperability of SG devices and systems. NIST has renovated a suite of laboratories known as the NIST SG Testbed that is dedicated to research supporting grid modernization efforts. A series of SG workshops is being launched in April to support the next revision of the NIST Framework and Roadmap for SG Interoperability Standards, expected to be published in 2019.

Allen Goldstein led a joint IEEE-IEC working group in developing a dual-logo standard for PMUs based on IEEE PMU standards, IEC/IEEE 60255-118-1:2018. NIST developments have led to the IEEE Conformity Assessment Program – ICAP for PMU certification, and staff have performed two special tests of PMU calibration systems onsite at the customers' locations.

Research on the effects of harmonics present in electric power systems on the uncertainties of electric energy metering of the fundamental component has been performed and publications are in process. A suite of laboratories in the SG Testbed has been equipped to simulate a microgrid with variable power sources, inverters, battery storage, and electronic loads, and is at present undergoing testing. Performance and interoperability of microgrid controllers and sensors will be investigated.

Capacitance metrology

NIST has recently completed reexamination [?] of the nonlinearity of the NIST CC which was designed by Cutkosky. The nonlinearity can be caused by nonuniformity of the capacitor's main electrodes and misalignment of its components. These mechanical error sources have been grouped together and classified as "geometrical imperfections" in the overall uncertainty budget. The relative standard uncertainty due to this combined source was increased in 1997 from the earlier reported value of 7×10^{-9} to 1.5×10^{-8} when a series of linearity tests measuring 0.1 pF increments along the length of the calculable capacitor from 0.2 pF to 0.7 pF revealed larger than expected differential nonlinearity. After a thorough reexamination of the geometrical imperfections, we have concluded that the dominant nonlinearity error originates from the electrode nonuniformity. Improved accuracy can be achieved by avoiding the end-effect near the 0.7 pF position and operating the calculable capacitor in a shortened range from 0.2 pF to 0.6 pF. The combined relative standard uncertainty due to the geometrical imperfections is then 1×10^{-8}.

Josephson arbitrary waveform synthesizer system (JAWS)

NIST researchers have developed new 2 V rms JAWS chips and new bias electronics [?] which have been packaged into a new NIST Standard Reference Instrument that has two independent 1 V rms outputs. We anticipate delivering systems to Sandia and NIST-Gaithersburg this year, in addition to upgrading the system at the U.S. Army Primary Standards Lab. By combining two of the new chips, we have created a 3 V rms JAWS system and demonstrated agreement between the two halves of the system to better than 100 ppm at 1 kHz. We have also started a JAWS-PJVS comparison and demonstrated agreement better than 1 ppb at DC and, with NRC Canada, continued to test the performance of the JAWS system versus thermal transfer standards. Finally, we have continued a collaboration with METAS on JAWS-based impedance measurements by loaning a JAWS system to METAS and started making quantum-Hall traceable measurements. We have also published in Metrologia a detailed uncertainty analysis [?] and a review article [?] which focused on the best practices for using JAWS (and PJVS) systems as well as their status as primary realizations of the volt after the new SI redefinition.

AC-DC and RF-DC difference metrology

With the success of the last generation of NIST multijunction thermal converters (MJTCs) up to 100 MHz, AC-DC research has shifted to the improvement of high current MJTCs ($> 100\,\mathrm{mA}$) and low frequency low voltage MJTCs($< 20\,\mathrm{kHz}$). The current designs, AC-DC difference results, and packaging effects will be presented during the next CPEM. A study of the most commonly used voltmeters for AC-DC difference was conducted to measure the linearity and noise as a function of MJTC output resistance to include in our measurement services calibration uncertainty budgets. These results will be presented at an upcoming conference. December of 2018, NIST MJTCs standards were shipped to the first laboratory in the CCEM K6a/K9 and K6c comparison. The comparisons will be done by 15 NMIs over the next 2 years with NIST acting as the pivot lab.

Thermal noise metrology

NIST's Thermal Noise project focused research efforts on the development of a remote-sensing standard (also known as brightness-temperature standard). The work was internally funded by the NIST Green House Gas Initiative Program and culminated in the successful demonstration of a microwave brightness-temperature standard that is traceable to NIST's primary noise standards. This constituted the first traceable microwave based over-the-air thermal noise artifact designed towards improving upon accuracies in remote sensing of weather and climate. This standard is based on conical-type blackbodies with multi-layer coatings that were designed, fabricated and characterized. NIST is looking to transfer the traceable brightness-temperature standards to the stakeholder community.

Recent research focus has shifted towards investigating noise properties in wireless communications. On-going efforts include traceable spectrum sensing and monitoring, noise performance evaluation of integrated receivers, and wireless forensic with calibrated sensor networks. To that end, NIST developed a new radiometer architecture that allows noise measurements traceable to time, frequency, and physical temperature. A prototype system was demonstrated in the frequency band of 2 GHz to 4 GHz touting improvements in operational efficiency by 33 % and improvements in measurement uncertainty of more than 30 % over conventional radiometer architectures. This work holds promise of a precise, efficient and compact radiometer for a variety of practical applications.

Additionally, NIST presented preliminary work (CPEM 2016) on a WR10 radiometer operating in the frequency range of 75 GHz to 110 GHz to expand measurement capability in thermal noise metrology beyond 100 GHz.

RF scattering-parameters and power characterization

Our control, acquisition and analysis software continue to be updated and improved. We are moving from older platforms to newer, modern ones, such as labview and python.

This software update includes all of the scattering-parameter and power systems. Our check standard database, and software for check standard analysis and quality control is also being updated.

Efforts continue to apply the NIST Microwave Uncertainty Framework (MUF) in order to improve the characterization of measurement uncertainty. The MUF provides vector network analyzer (VNA) error corrections, device under test responses, as well as fully correlated uncertainties. Several comparisons have been made between the established NIST process and the results from the MUF. For responses, there is good agreement between the resultant scattering-parameters from the two different techniques, for both one and two-port devices. The difference between the responses calculated from the MUF and the established NIST technique are far smaller than the uncertainties from the established NIST technique. Details of one of the comparisons can be found in references [1] and [2]. We have established the process for achieving fully traceable evaluations of lower-level VNA calibration artifacts, such as the short-open-load (SOLx) family of calibration techniques, and automatic calibration units, based on thru-reflect-line (TRL) VNA calibrations with fully correlated uncertainties [3]. Testing has shown that this process works very well and is stable over a long period of time. We have developed capabilities within the MUF for adapter evaluation and measuring the equivalent source mismatch factor of a power splitter, and we are also developing the algorithms for the direct comparison power measurement process. We are also investigating the use of machine learning applied to the verification and quality control processes [4], [5], [6].

We are now performing s-parameter measurements in the following waveguide bands: WR-08, WR-06, WR-05, WR-03, WR-2.2, and WR-1.5 (90-140 GHz, 140-220 GHz, 220-325 GHz, 325-500 GHz, and 500-750 GHz respectively). At the present time we are not offering outside measurement services in these frequency bands.

With the recent departure of the primary scientist who was responsible for research and measurements in the microwave power area, we have divided the responsibilities in power into two areas. One is the forward-looking research area, here we are developing new power detectors and measurement systems and techniques. The latest output from this area is the addition of WR-06 power measurement capabilities. We can now provide traceable effective efficiency measurements in the 110 GHz -170 GHz range. This service is not yet available to the public but should be in the near future. The other branch of power measurement responsibilities involves the improvements to our microwave calorimeters, the calorimeter-based measurement services, and the direct comparison measurement services. For power measurements, we are investigating use of the MUF for processing and analyzing data while continuing calorimeter operation and research, and are implementing improvements to the calorimeter software for operation and analysis. We continue to pursue a new power traceability path through quantum phenomenon.

Field strength metrology

NIST field strength measurement facility is currently undergoing refurbishment. NIST previously had the capability to establish a reference CW electric field in both TEM cells (100 kHz to 200 MHz) and the fully anechoic chamber (250 MHz to 40 GHz). After 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, 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.

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.

In 2019, 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 replacing the ball-screw translation stage with a modern direct drive translation stage.

We also started a comparison of photodiode response measurements with PTB, NIM, and KRISS, in 2018. Measurements among the NMIs are nearly complete and comparison of the data and techniques will occur in 2019.

Antenna metrology

To address the metrology challenges of OTA measurements, NIST has created a new state-of-the-art Antenna Measurement Facility (AMF) that is part of the Antenna and Communications Metrology Laboratory (ACML). Metrology capability in complex electromagnetic environments is critical to the successful design and evaluation of existing and future 5G communication systems, and OTA test methods for multiple-input multiple-output (MIMO) technologies from UHF to millimeter-wave. The AMF consists of a fully anechoic shielded chamber that provides a radio quiet environment for antenna metrology. Two antenna positioning systems are installed that together cover the 1 GHz to 500 GHz frequency range. One is a newly conceived Large Antenna Positioning System (LAPS) that will cover the 1-50 GHz frequency range. The LAPS can track and measure multiple beams from Electrically Steerable Array (ESA) antennas, simulate Doppler effects using dynamic antenna positioning, and scan entire systems consisting of multiple antennas with improved accuracy and repeatability. A phase Coherent Receiver System (CRS) will be used to acquire the OTA RF measurements on the LAPS. The other is the Configurable Robotic MilliMeter-wave Antenna (CROMMA) system that is centered around a compact, high accuracy, six-axis antenna positioning robot that can cover millimeter-wave frequencies from 50 GHz to 500 GHz. CROMMA is used for the development of high frequency (mmWave) antenna OTA test methods.

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