Status Report to CCEM of Electrical Metrology Developments at NIST

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DC Josephson Voltage Standard Systems and Power Metrology

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NIST researchers have continued to disseminate and improve the performance and usability of the 10V Programmable Josephson Voltage Standard (PJVS) system. Two systems were disseminated to primary standards laboratories: the Air Force Primary Standards Lab (AFMETCAL) and Oak Ridge National Laboratory (DOE). There was also increased functionality in the ability to use the system to produce two independent waveforms – which is presently being used for ac power measurements in the Quantum Watt program. NIST researchers have also dramatically increased the leakage resistance of the system which has allowed a comparison between two PJVS systems, both on cryocoolers, at a combined uncertainty of better than 1 part in 10^{11}. Software improvements also allow the system to track room temperature and pressure for better Zener diode calibrations, including bank measurements of Zener standards.

Josephson Arbitrary Waveform Synthesizer System (JAWS)

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NIST researchers have both significantly simplified and increased the performance [1] of the 1 V rms JAWS system by successfully implementing on-chip splitters which increases the number of arrays that can be driven by a single pulse bias. This has allowed NIST to create a 2 Vrms cryocooled JAWS system with 1.6 mA operating margins on a cryocooler by combining two 1 V rms chips [2]. NIST also implemented this new chip and biasing technology in upgrading the LHe JAWS system at NRC Canada to 1 V rms and in a new cryo-cooled 1 V rms JAWS system installed at APSL, both systems achieving greater than 2 mA operating margins at 1 V rms and automated ac-dc comparison. NIST has also used the JAWS system for two different inter-Josephson comparisons, one as a JAWS-to-JAWS comparison, demonstrating agreement between two 1 V rms cryocooled JAWS systems to better than 100 ppb at frequencies less than 10 kHz [3], and another as a JAWS-to-PJVS comparison, demonstrating agreement to better than 80 ppb for frequencies below 500 Hz and 1 V [4]. NIST, in collaboration with METAS, is developing quantum-based impedance measurements by integrating a METAS-developed impedance bridge with two JAWS sources, and demonstrated its capability to quickly calibrate arbitrary impedances with high precision [5].

Key Publications:

[1] N. E. Flowers-Jacobs, S. B. Waltman, A. E. Fox, P. D. Dresselhaus, and S. P. Benz, "Josephson Arbitrary Waveform Synthesizer With Two Layers of Wilkinson Dividers and an FIR Filter," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 6, pp. 1400307, Sep. 2016.

[2] N. E. Flowers-Jacobs, A. E. Fox, P. D. Dresselhaus, R. E. Schwall, and S. P. Benz, "Two-Volt Josephson Arbitrary Waveform Synthesizer Using Wilkinson Dividers," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 6, pp. 1400207, Sep. 2016.

[3] N. E. Flowers-Jacobs, A. Rufenacht, A. E. Fox, P. D. Dresselhaus, and S. P. Benz, "2 Volt pulse-driven Josephson Arbitrary Waveform Synthesizer," in *2016 Conference on Precision Electromagnetic Measurements (CPEM 2016)*, 2016.

[4] A. Rufenacht, N. E. Flowers-Jacobs, A. E. Fox, C. J. Burroughs, P. D. Dresselhaus, and S. P. Benz, "Direct comparison of a pulse-driven Josephson arbitrary waveform synthesizer and a programmable Josephson voltage standard at 1 volt," in *2016 Conference on Precision Electromagnetic Measurements (CPEM 2016)*, 2016.

[5] F. Overney, N. E. Flowers-Jacobs, B. Jeanneret, A. Rüfenacht, A. E. Fox, J. M. Underwood, A. D. Koffman, and S P Benz, "Josephson-based full digital bridge for high-accuracy impedance comparisons," *Metrologia*, vol. 53, no. 4, pp. 1045–1053, Aug. 2016.

AC-DC and RF-DC Difference Metrology

Contacts: Thomas Lipe, 301-975-4251

After successfully using a new generation of multijunction thermal converters (MJTCs) fabricated at NIST to reduce calibration uncertainties in the 10 Hz to 1 MHz frequency range, work continues to utilize these devices to reduce the uncertainties for calibrations up to 100 MHz. The latest MJTCs have RF-DC differences at 100 MHz of less than 500 μV/V with very small voltage coefficients and are in routine use for calibration between 10 Hz and 100 MHz. These devices are also offered for purchase through the Standard Reference Instruments Program at NIST (SRI 6002), providing reference standard performance to other organizations. Research into MJTCs intended for ac current metrology has yielded devices capable of measuring input currents of up to 3 A and these are being further developed for use in the ac current calibration services, Work continues on a new generation of 50-Ω devices with tungsten waveguide heaters. In addition, research into MJTCs based on tantalum nitride is beginning, and new packaging methods to reduce ac-dc differences related to the wire bonds in the present generation of MJTCs is being explored.

Capacitance Metrology

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The existing calculable capacitor (CC) at NIST has been used on a regular basis (about twice a year) over the past few years to calibrate the Farad Bank that consists of four 10 pF fused-silica standards maintained in an oil bath at 25 °C. The Farad Bank, which is very stable when undisturbed (drifting only 0.02 µF/F per year), serves to represent the practical units of impedance at NIST.

NIST has made significant progress towards building a new calculable capacitor. The unique approach we adopted has demonstrated some advantages over the conventional design. Diamond-turning technology offers a cost-effective alternative for fabricating the main electrode bars. The interferometer using multiple tunable lasers can measure the absolute cavity length in a continuous fashion. This feature combined with an overall compact capacitor structure has enabled us to realize an automated CC by positioning the movable guard electrode using a linear actuator. The novel translation mechanism of the guard electrodes completely avoids direct contact with the main electrodes, enabling direct use of diamond turned aluminum cylinders. However, extensive testing of the new CC has also revealed some short-comings of our current design, and we have not yet reached our design goal of achieving parts in 10^8 overall uncertainties. Diamond turning has evolved mainly for producing flat optical surfaces; its limiting effect on the aspect ratio that may be achieved when used to manufacture cylinders is not well understood. We are currently exploring the possibilities of increasing the length of the main electrodes in our design, but the maximum length of the cylinders achievable may be limited using this technology, resulting in close-approach errors larger than the conventional design. The non-contact design increases lateral jitters of the guard electrode, which is currently the main error source limiting the overall accuracy of the new CC. The translation mechanism can clearly be further improved. However, the ultimate stability that we can achieve with the non-contact design is hard to predict and is a subject for further study.

NIST has developed a test method for characterizing nonlinearity of capacitance bridges by employing two programmable capacitors. This is important because performance of a bridge is ultimately limited by its nonlinearity which cannot be reduced through data averaging. Nonlinearity tends to differ from one bridge to another, but its pattern for a given bridge is repeatable, at least over short terms. This suggests that it may be possible to develop a calibration method to further correct the bridge nonlinearity. The manufacturer is clearly aware of the bridge nonlinearity that depends on not only the bridge hardware but also its internal software algorithms. The test results for the new model A2700A Option E bridge confirm that the newly implemented internal calibration procedures are effective in reducing the bridge nonlinearity.

Resistance Metrology and Graphene QHE Research

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Optimization of scaling from the quantum Hall resistance (QHR) I = 2 plateau to 100 Ω standard resistors used to support the NIST-4 Watt Balance provided traceability $<10 \times 10^{-9}$. Direct calibration in terms of the QHR is done by cryogenic current comparator (CCC) and a more recently installed binary cryogenic current comparator (BCCC) of commercial design. Direct current comparator (DCC) room temperature bridges have been used to monitor the 100 Ω resistance standards between QHR measurements and provide current dependence characterization to the 100 Ω resistance standards from 3.5 mA to 13.8 mA which correspond to masses of 500 g to 2000 g. Characterization of 10 Ω and 1 kΩ standard resistors that are used to transfer from the NIST 100 Ω reference bank to 100 Ω Watt Balance resistors using a two-step process with the DCC has also been done. Additional high resistance standards of nominal values 100 MΩ, 1 GΩ, 10 GΩ, and 100 GΩ have been constructed in a collaborative effort with Instituto Costarricense de Electricidad (ICE) and are being monitored for long-term drift. NIST and the National Institute of Advanced Industrial Science and Technology (AIST) are in the process of comparing high resistance measurements at six-decade resistance values from 100 MΩ to 10 TΩ.

NIST continues to pursue better epitaxial graphene quantum Hall effect (QHE) standards, to allow wider access for measurement traceability. Quantized magnetotransport was observed in 5.6×5.6 mm^2 epitaxial graphene devices, grown using highly constrained sublimation on the Si-face of SiC(0001) at high temperature (1900 °C). The precise quantized Hall resistance of $R_{xy} = \frac{h}{2e^2} \times (1 \pm 5\times10^{-9})$ is maintained for a critical current $I_{xx} = 0.72$ mA at $T = 3.1$ K and 9 T. Our devices are based on large-area homogeneous EG layers with low strain, which allows high mobility and charge carrier homogeneity at carrier density as low as $n \approx 1 \times 10^{10}$ cm^{-2}, and thus may support QHE devices that operate at very low magnetic field. In other news, we have supported development of a microwave cavity non-contact surface conductance measurement of epitaxial graphene samples and correlated these results with dc measurements, seeking to provide traceable standards of microwave conductivity for thin film materials. Finally, NIST is cooperating with Stanford University physicists to study magnetic-layer topological insulator devices that support the quantum anomalous Hall effect in zero magnetic field. The QH plateau value of $R_{xy} = \frac{h}{e^2} \times (1 \pm 1.5\times10^{-6})$ was measured in such devices with quantization maintained for current levels up to 100 nA. Further advances in the understanding of these materials are required for practical measurement traceability.

Key Publications:

"Epitaxial graphene homogeneity and quantum Hall effect in millimeter-scale devices" Carbon 215, 229–236 (2017).

D. G. Jarrett, R. E. Elmquist, M. E. Kraft, G. R. Jones, S. U. Payagala, F. Seifert, D. Haddad, S. Schlamminger, "Quantum Hall Resistance Traceability for the NIST-4 Watt Balance," CPEM 2016 Conference Digest, July 10-15, 2016, Ottawa, Ontario, Canada.

B. I. Castro, D. G. Jarrett, M. E. Kraft, "Fabrication of High Value Standard Resistors for ICE-LMVE," CPEM 2016 Conference Digest, July 10-15, 2016, Ottawa, Ontario, Canada.

Electronic Kilogram

Contact: Jon Pratt, 301-975-5470 and Stephan Schlamminger, 301-975-3069

Work on the NIST-3 Kibble balance has stopped completely. Researchers have been working on the new generation Kibble balance, NIST-4, which is now fully functional. In 2016 a first result of a measurement of *h* with a relative standard uncertainty of 34×10^{-9} was published (Haddad *et al. Rev. Sci Instrum.* **87**, 061301). The largest entries in the uncertainty budget were the statistical uncertainty and an uncertainty due to magnet nonlinearity, with the former contributing 24.9 x 10^{-9} and the latter 15.4 x 10^{-9} to the relative standard uncertainty.

In the spring of 2016, the watt balance team took part in the pilot study and assigned mass values to two masses (one made from platinum-iridium the other from stainless steel) using the 2014 CODATA adjusted value of the Planck constant as input.

The latter part of 2016 was devoted to reducing the largest uncertainties in the uncertainty budget. The statistical uncertainty was reduced a factor of two by stiffening the support of the three main interferometers. The team has started to measure the magnet nonlinearity with greater care and it is expected that this contribution to the uncertainty budget can be reduced, too. Besides the improvements in uncertainty, the team has taken some data for a last high precision determination of the Planck constant. It is expected that this number will make it into the final CODATA adjustment of *h*.

NIST has started to explore the possibility of building a table top Kibble balance with the aim to realize gram level masses with relative uncertainties of a few parts in 10^6. Guest researchers from CENAM (Mexico) and NPLI (India) were involved in these experiments. These experiments are ongoing and we hope to have working balances by the time of the redefinition.
The following articles were published in the reporting period:

1. H. Bettin and S. Schlamminger, “Realization, maintenance and dissemination of the kilogram in the revised SI”, *Metrologia* **53** A1 (2016).
2. I.A. Robinson and S. Schlamminger, “The watt or Kibble balance: a technique for implementing the new SI definition of the unit of mass”, *Metrologia* **53** A46 (2016).
3. D. Haddad, F. Seifert, L. Chao, S. Li, D.B. Newell, C. Williams, S. Schlamminger, “Bridging classical and quantum mechanics”, *Metrologia* **53** A83 (2016).
4. D. Haddad, F. Seifert, L. Chao, S. Li, D.B. Newell, C. Williams, S. Schlamminger, “Invited Article: A precise instrument to determine the Planck constant, and the future kilogram”, *Rev. Sci. Instrum.* **87** 061301 (2016).
5. S. Li, S. Schlamminger, D. Haddad, F. Seifert, L. Chao, J.R. Pratt, “Coil motion effects in watt balances: a theoretical check”, *Metrologia* **53** 817 (2016).A. Cao, G. Sineriz, J. Pratt, D. Newell, S. Schlamminger, “First measurements of the flux integral with the NIST-4 watt balance,” submitted for publication in *IEEE Trans. Instr. Meas.*.
6. L. S. Chao, S. Schlamminger, D.B. Newell, J.R. Pratt, G. Sineriz, A. Cao, D. Haddad, X. Zhang, *Am. J. Phys.* **83** 913 (2015).
7. E.J. Leaman, D. Haddad, F. Seifert, L.S. Chao, A. Cao, J.R. Pratt, S. Schlamminger, and D.B. Newell, “A determination of the local acceleration of gravity for the NIST-4 watt balance”, *IEEE Trans. Instr.* **64** 1663 (2015).
8. S. Schlamminger, R.L. Steiner, D. Haddad, D. B. Newell, F. Seifert, L.S. Chao, R. Liu, E.R. Williams, J. R. Pratt, “A summary of the Planck constant measurements using a watt balance with a superconducting solenoid at NIST”, *Metrologia* **52** L5 (2015).

Outreach

The NIST team was actively involved in communicating the concepts of the revised SI to students and the general public. So far, NIST has built five LEGO watt balance and they have been demonstrated at several conferences, science shows, and universities. The Lego watt balances are being shown between six and ten times a year. Several students around the world have successfully built LEGO watt balances. The NIST team has provided guidance to several other LEGO watt balance builders.

Jenifer Lauren Lee of NIST made a YouTube video about the NIST LEGO watt balance containing a playful explanation of the real watt balance. This video won the 2016 American Institute of Physics award for best science writing in the broadcast category.

Jon Pratt was featured in a nationally aired radio show "science Friday" on June 13th 2014.

RF Scattering-parameters and Power Characterization

Contact: Ron Ginley, 303-497-3634

We continue to improve the software that we are using with our new Vector Network Analyzer (VNA) systems. Of particular importance is the software that manages our data including our check standard database. We are also updating several of the data manipulation routines to modern programming languages and environments.

The work to incorporate the NIST Microwave Uncertainty Framework (MUF) continues. The MUF gives us VNA error corrections, device under test responses and 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. One and two-port capabilities have been tested. The difference between the responses are far smaller than the uncertainties from the established NIST technique. Details of one of the comparisons can be seen in reference [1]. We are still working on the comparison of the uncertainties from the different techniques. This is more complicated than the response comparison as we want to make sure that the different techniques are utilizing equivalent uncertainty components. We are starting to use the MUF to provide traceability for lower level error correction techniques such as the open-short-load and automatic calibration methods.

We are now making s-parameter measurements in the WR-08, 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 those areas.

The biggest change in the power measurement area has been the departure of the primary scientist who was responsible for the area. His responsibilities have been divided amongst several different people. The broad breakdown of responsibilities is: power measurement services – no substantial change except investigating the use of the MUF for power measurements, micro-calorimeter operation/research – the micro-calorimeters are operating nominally and we are starting to develop calorimeter capability above 110 GHz, and advanced power topics – here we are developing a new sensor design for use above 110 GHz and we are still pursuing a new power traceability path through quantum phenomenon.

[1] R. A. Ginley, "Kicking the tires of the NIST Microwave Uncertainty Framework, Part 1", *88th ARFTG Microwave Measurement Symposium*, Austin, Texas, Dec. 2016.

Field Strength Parameter Characterization (2017)

Contacts: Chris Holloway, 303-497-6184 or Josh Gordon, 303-497-4312

The quantum based electric (E) field strength (V/m) probe based on Rydberg atoms is now operating. Measurements have been made in the range 1 – 300 GHz demonstrating linearity and good agreement with analytical predictions. Example results can be found in publications listed below. Results of interest include:

- The probe can measure E-fields with a physical resolution that depends on the wavelength of the of the laser frequencies exciting the vapor cell atoms to the Rydberg state. These laser wavelengths are much smaller than the RF wavelength. Thus, E-fields may be mapped with sub-RF wavelength resolution. For example, this allows us to map the standing waves inside a low-reflectance glass vapor cell which is important to the uncertainties associated with this approach.
- Vapor cells can be filled with two different atoms; we used both Cs and Rb. We demonstrated that such a cell gives the same result whether Cs is excited, Rb is excited, or both are excited simultaneously. This constitutes a natural intercomaprison.
- Measurements to date have been done on an optical table with the vapor cell fixed in position and excited by optically guided laser beams, and then exposed to an RF field via a nearby horn antenna. More recently, a vapor cell was constructed with optical fiber guiding the laser excitation into the cell. This allows the vapor cell to be removed from the optical table and introduced into other RF environments. Planned are measurements in a TEM cell and a small reverberation chamber, where comparisons to dipole probes can be made.

[1] H. Fan, S. Kumar, J. Sheng, J.P. Shaffer, C.L. Holloway and J.A. Gordon, "Effects of vapor cell geometry on Rydberg atom-based radio-frequency electric field measurements", *Physical Review Applied*, Vol. 4, 044015, November, 2015.

[2] D. A. Anderson, S. A. Miller, G. Raithel, J. A. Gordon, M.L. Butler, and C. L. Holloway, "Optical measurements of strong microwave fields with Rydberg atoms in a vapor cell", *Physical Review Applied*, 5, 034003, 2016.

[3] Holloway, C. L., Simons, M. T., Gordon, J. A., Wilson, P. F., Cooke, C. M., Anderson, D. A., Raithel, G. "Atom-Based RF Electric Field Metrology: From Self-Calibrated Measurements to Subwavelength and Near-Field Imaging," accepted for publication in IEEE Trans. Electromagn. Compat.2017.

Antenna Parameter Characterization

Contacts: Jeff Guerrieri, 303-497-3863, Josh Gordon, 303-497-4312, or David Novotny, 303-497-3168

The NIST CROMMA (Configurable RObotic MilliMeter-wave Antenna) antenna range facility reported on at the last CCEM meeting is in operation. Improvements to the positioning control have been made so that real time corrections can be made as the robot warms or otherwise changes. As examples of recent applications, pattern and extrapolation measurements have been made on standard gain horns at 183 GHz, on 3D printed horns at 118 GHz, and on a CubeSat feed horn at 118 GHz.

NIST is further upgrading its antenna metrology facilities with the installation of a large fully anechoic chamber (approx. 18 m x 7.5 m x 7.5 m) that will house a pair of articulated robotic arm positioners, one on rails to give variable separation on the order of 9 m. This facility will be used to develop test methods for active array 5G and MIMO antennas, in addition to standard extrapolation and spherical near-field scans. CROMMA will also be moved into one end of this chamber. The new facility should be installed in late 2017.

High-speed Waveform Metrology

Contacts: Paul Hale, 303-498-5367, Jeffrey Jargon, 303-497-4961, or Ari Feldman, 303-497-4969

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 2017, 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.

We also started a comparison of photodiode response measurements with PTB in 2015. Although initial results of the comparison looked promising, the comparison is currently on hold due to equipment issues. We hope to resume the comparison as resources at both institutions allow.

Selected publications:

[1] NIST Microwave Uncertainty Framework, available at https://www.nist.gov/services-resources/software/wafer-calibration-software.

[2] S. Eichstädt, V. Wilkens, A. Dienstfrey, P. Hale, B. Hughs, and C. Jarvis, "On challenges in the uncertainty evaluation for time-dependent measurements," *Metrologia*, vol. 53, S125-S135, 2016.

[3] C. Y. Cho, J.-G. Lee, P. D. Hale, J. A. Jargon, P. Jeavons, J. Schlager, and A. Dienstfrey, "Calibration of time-interleaved errors in real-time oscilloscopes", *IEEE Trans. Microwave Theory Tech*., vol. 64, no. 11, pp. 4017-4079, Nov. 2016.

[4] J. A. Jargon, D. F. Williams, P. D. Hale, and M. D. Janezic, "Characterizing a Noninsertable Directional Device Using the NIST Uncertainty Framework," 83rd ARFTG Microwave Measurement Conference, Tampa Bay, FL, Jun. 2014.

[5] K. A. Remley, D. F. Williams, P. D. Hale, C.M. Wang, J.A. Jargon, and Y.C. Park, "Modulated-Signal Measurements and Uncertainty in Error Vector Magnitude at Millimeter-Wave Frequencies," *IEEE Trans. Microwave Theory Tech*., vol. 63, no. 5, pp. 1710-1720, May 2015.

[6] J. A. Jargon, C. Y. Cho, D. F. Williams, and P. D. Hale, "Developing Physical Models of 2.4 mm and 3.5 mm Coaxial VNA Calibration Kits for Use with the NIST Uncertainty Framework," *85th ARFTG Conference*, May 2015.

[7] P. D. Hale, K. A. Remley, D. F. Williams, J. A. Jargon, and C. M Jack Wang, "A Compact Millimeter-wave Comb Generator for Calibrating Broadband Vector Receivers," *85th ARFTG Conference*, May 2015.

[8] D. F. Williams, J. A. Jargon, U. Arz, and P. D. Hale "Rectangular-Waveguide Impedance," *85th ARFTG Conference*, May 2015.

[9] A. Dienstfrey and P. D. Hale, "Analysis for dynamic metrology," *Meas. Sci. Technol.,* **25** **(**2014) 035001.

[10] A. Dienstfrey and P. D. Hale, "Colored noise and regularization parameter selection for waveform metrology," *IEEE Trans. Instrum. Meas.,* vol. 63, no. 7, pp. 1769-1778, July 2014.

Smart Grid Standards and Metrology

Contacts: Jerry FitzPatrick 301-975-8922, Tom Nelson 301-975-2986, Al Hefner 301-975-2071, Paul Boynton 301-975-3014, and David Wollman 301-975-2433

NIST has an ongoing effort to support the development of an improved electric power grid, known as the smart grid, using distributed computing, two-way communications and sensors to enable increased use of distributed and renewable energy sources. The research also supports new products and systems with improved smart grid functionality, including microgrids, energy management systems and plug-in electric vehicles. 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 Smart Grid devices and systems and establishment of the Smart Grid Interoperability Panel (SGIP). The next revision of the NIST smart grid roadmap is expected to be published in 2018.

As part of the electrical metrology support for the Smart Grid, NIST offers a special test measurement service for Phasor Measurement Units (PMUs) used to measure the power system voltage and current signals and report their phasor information with Coordinated Universal Time (UTC) timestamps. There are now over 1800 PMUs in the North American power grid, most of them co-funded by the U.S. Department of Energy and electric utilities. NIST research in the dynamic performance of PMUs has led to an amended version of the IEEE PMU standard, and NIST is leading a joint IEEE-IEC working group developing a dual-logo standard for PMUs based on the IEEE standards. NIST technical developments and support also have led to a conformity assessment program established by the IEEE (IEEE Conformity Assessment Program – ICAP) for PMU certification, and its accreditation of a commercial test lab. IEEE has adopted the NIST-developed Test Suite Specification (TSS) for testing conformity with the synchrophasor standards. Additionally, results of a study to establish baseline performance of PMUs and a study of PMU response to the coordinated Universal Time (UTC) leap second were published.

Construction of a NIST testbed for research projects related to the smart grid continues. A Smart Sensors project is the first to be stood up in this smart grid laboratory. Research in and testing of performance of advanced smart current and voltage sensors, PMUs, and merging units (analog-to-digital processors that interface between the pervasive conventional grid instrument transformers and digital substation equipment) has begun. Future work is planned to study PMUs for local electric power distribution systems, where requirements for dynamic measurement accuracy are far more challenging than those used to date in long-distance transmission systems. Additional projects to be rolled out in the near future in this testbed include those to develop measurement methods for Power Conditioning Systems (PCSs), smart meters, time synchronization, cybersecurity, and advanced networks. The PCSs and their associated high power inverter electronics are critical for the efficient integration of variable renewable generation, electric energy storage, and microgrids into today's electrical grid. The PCS grid applications supported include smart grid interfaces for individual renewable/clean energy and storage systems, as well as microgrids, and DC circuits. Research in smart meters is planned to study the effects of wireless communications packages embedded in the meters on their measurement accuracy; harmonic power measurements; new industrial smart meters having advanced functionality for wide bandwidth power quality measurements and synchrophasor measurements; and the use of smart power/energy meters as voltage sensors.

Selected publications:

NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0, NIST Special Publication 1108r3, available at http://dx.doi.org/10.6028/NIST.SP.1108r3, Gaithersburg, MD September 2014

IEEE Standard for Synchrophasors for Power Systems, IEEE Std C37.118.1a-2014, Apr. 2014

Investigation of PMU Response to Leap Second: 2015, A. Goldstein, D. Anand, Y-S. Li-Baboud, NISTIR 8077, available at publication is available at http://dx.doi.org/10.6028/NIST.IR.8077, Gaithersburg, MD August 2015

2014 NIST Assessment of Phasor Measurement Unit Performance, A. Goldstein, NISTIR 8106 available at http://dx.doi.org/10.6028/NIST.IR.8106, Gaithersburg MD February 2016

IEEE Synchrophasor Measurement Test Suite Specification (TSS), available at http://standards.ieee.org/email/2014_12_synchrophasor_tss_web.html, IEEE, Piscataway, NJ December 2014

E.Y. Song and G.J FitzPatrick, "Interoperability Test for IEEE C37.118 Standard-based Phasor Measurement Units (PMUs)," *2016 IEEE Innovative Smart Grid Technologies Conference,* September 2016