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 advanced the measurement and automation capabilities of quantum-based dc and ac programmable Josephson voltage standards (PJVS) such that the NIST PJVS is now capable of providing ac voltage measurements through differential sampling at voltages up to 10 V and frequencies up to 400 kHz. New automation software and hardware were implemented. Measurements of leakage resistance were performed and optimized (in collaboration with Solve at BIPM). Two cryocooled PJVS systems were also developed and demonstrated, and their performance was characterized. All results were presented at the CPEM 2014 conference and at the 2014 Applied Superconductivity Conference, and published in Metrologia, IEEE Trans. Inst. Meas. and IEEE Trans. Appl. Superconduct. NIST upgraded existing systems for collaborators at NASA Kennedy Space Center, INMETRO (Brazil), ITRI (Taiwan), NPL (India), KRISS (S. Korea), and CENAM (Mexico). We installed three 10V PJVS systems at NIM (China), two of which will be used with the impedance balance system, a portable version at BIPM, and a partial system at MRL (New Zealand), which MRL customized to operate in a reliquifier-compatible cryostat for use in voltage metrology and with their piston-balance measurement system. The NIST systems are constructed primarily from commercially available electronics, which greatly enhances their reliability. As of August 2014, NIST is providing duplicate versions of both the liquid-helium-cooled and cryocooled PJVS systems through a new NIST Standard Reference Instrument program that is similar to the SRM program.

Over the past two years we also implemented a 2 V PJVS in a (50-400) Hz power calibration system that generates 120 V and 5 A of sinusoidal active and reactive power. A novel differential sampling measurement technique was developed and demonstrated for this system, which proved essential for increasing the measurement accuracy by avoiding the transients between voltage levels in the stepwise-approximated sinewaves. A key component of the system is a voltage amplifier that performs self-calibration and corrections of gain and phase errors. The residual uncertainty of the quantum-based power calibration system at 60 Hz is less than 2 parts in 10^6 (k=1) of applied active and reactive power.

The NIST PJVS based power calibration system was used in 2 comparisons recently. The SIM EM-K5 and a bi-lateral comparison with NRC (Canada). The comparison with NRC used NRC's power bridge with agreement of better than 2 parts in 10^6 for active power. The agreement was excellent given that the two systems are based on different operating principles.

AC Josephson Voltage Standard System (ACJVS)

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NIST improved the ACJVS system dramatically through development of new pulse-bias electronics, bit-coding techniques, and superconducting integrated circuit development such that waveforms with four-fold larger voltage of 1 V rms can now be synthesized with operating current range greater than 1 mA. These 1V rms ACJVS circuits consist of four separately biased, series-connected subarrays on a single 1 cm x 1 cm chip. NIST also demonstrated operation of the ACJVS on the n=2 quantum state, which doubles the output voltage per array while still exhibiting modest margins (0.4 mA at 1 V). An increase in bitstream generator memory now enables waveforms of frequencies down to 1 Hz or multi-tone arbitrary waveforms with tones spaced as close as 1 Hz. These latest 2014 results were presented at the CPEM and the Applied Superconductivity conferences in August. The results were published in IEEE Trans. Appl. Superconduct. NIST installed new two-array ACJVS systems with the new bias electronics and automation software at the Gaithersburg campus, NIM (China) and at the U.S. Army Primary Standards Lab (APSL).

In order to encourage the adoption and dissemination of the ACJVS as a primary standard, NIST has successfully completed early R&D for cryocooler operation of the ACJVS. Operating margins on the cryocooler were comparable to that found with operation of the arrays in a LHe dip probe. Development and automation of cryocooler-based systems is ongoing. AC-DC difference measurements with the new 1 V system have been completed, and an analysis of systematic errors is underway. NIST has also started an ILC with APSL to develop and evaluate a calibration procedure for the Fluke 792A transfer standard with the ACJVS. The ILC encompasses a subset of the ACJVS operating space: rms voltages from 2 mV to 200 mV with two 6400-junction arrays, and frequencies from 100 Hz to 100 kHz. The results of this ILC are being incorporated into a formal uncertainty analysis, to help fulfill calibration quality assurance requirements for both NIST and the U.S. Army.

AC-DC and RF-DC Difference Metrology

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Multijunction Thermal Converters (MJTCs) fabricated at NIST have been implemented in the calibration service for thermal transfer standards and facilitated the reduction of uncertainties by as much as 75 % over the voltage range from 200 mV to 1000 V, at frequencies from 10 Hz to 1 MHz. The large dynamic range of the MJTCs results in fewer steps in the voltage scaling procedure, while the extremely flat frequency response permits a single MJTC to be used from 10 Hz to well over 1 MHz. Taken together, these properties have enabled the substantial reductions of uncertainty. MJTCs are now used for all ac-dc difference measurements of thermal voltage converters, and as the standard for thermal current converters on selected ranges. Research is underway to develop MJTCs with 50-Ω input impedances for use at frequencies up to 1 GHz, as well as devices useful for ac current measurements up to 1 A.

DC Voltage Metrology

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In 2014, the 10th Josephson Voltage Standard (JVS) Interlaboratory Comparison coordinated by the National Conference of Standards Laboratories International (NCSLI JVS ILC) was organized to perform JVS comparisons. In addition to a typical protocol of using a set of Zener standards as transfer standards for the comparison, NIST and the NASA Metrology and Calibration (MetCal) Program Office, located at the Kennedy Space Center (KSC) collaborated to use a programmable Josephson voltage standard (PJVS) as a transfer standard for direct comparisons with Conventional JVSs (CJVS) of several participating laboratories.

An automated direct-comparison protocol has been developed to compare a CJVS and the PJVS using a Local Area Network (LAN) to establish communications between the two systems. The automated protocol improves the efficiency of the comparison by reducing the amount of human interaction necessary during the comparison. It also allows the collection of a large number of measurements, which is useful for investigations of Type A uncertainty through Allan variance analysis that determines the $1/f$ noise floor of the comparison data.

This is the first time that a PJVS has been used as a transfer standard in the NSCLI JVS ILC. Comparisons with CJVSs at NIST and the other laboratories' CJVS allowed us to determine that the degree of equivalence between these JVS at 10 V is a few parts in 10^{10}. It also provided guidance for some laboratories to further improve their JVS operation and reduce their measurement uncertainty by reducing the EMI of their systems.

Capacitance Metrology

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The existing calculable capacitor 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. NIST staff have successfully completed the design, fabrication, and testing of prototype mechanical, optical, and electrical subsystems representing the core elements of a new calculable capacitor. These elements all appeared individually executed in a fashion consistent with an assembled performance at the level of a few parts in 10^8. However, preliminary testing of the final assembly of a complete system in vacuum has revealed some technical issues related to translation control of the top blocking electrode that limit the overall accuracy. We are currently in the process of reworking the blocking electrode system. We plan to re-assemble and re-align the capacitor, and re-evaluate its overall performance this year.

NIST has produced several variable capacitors that are digitally programmable capacitance standards based on a modification of a fixed commercial fused-silica capacitance standard. The commercial device consists of 23 capacitors of roughly binary values that have been configured to combine via computer control to produce any capacitance value in the range from about 0.1 fF to 110 pF, with sub-femtofarad resolution. Upon placing the device in a custom enclosure inside an air bath, the short-term capacitance stability achieved using a commercial capacitance bridge is on the order of a few parts in 10^8 over the full capacitance range.

Resistance Metrology and Graphene QHE Research

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In DC Resistance, NIST, CENAM, and INTI completed the SIM.EM-S9 high resistance cryogenic current comparator scaling comparison and published a description of the measurement systems along with the positive results (Review of Scientific Instruments 85, 044701, 2014). The comparison will help to support revised and improved measurement capabilities over four decades, from 1 MΩ to 1 GΩ. NIST has developed high resistance standards including Hamon scaling networks up to 100 TΩ and Wye-delta networks for 1 PΩ and 10 PΩ. Low current (10 µA to 20 fA) measurement techniques have provided SI traceable measurements from high resistance for photo detectors and aerosol electrometers. Systems have been installed for remote calibration of 100 Ω standard resistors in the laboratory housing the newly installed Electronic Kilogram experiment in the underground Advanced Measurement Laboratory.

Researchers have produced epitaxial graphene with large-area homogeneity, and are characterizing standards-quality quantum Hall effect devices. NIST has developed techniques to control the doping level (Small 11, 90 – 95, 2015) so that QHR comparisons can be made at low magnetic field, below 9 T. Recently, electronic devices were patterned to make use of nearly the entire 50 mm^2 surface area of monolayer epitaxial graphene (EG) chips grown at NIST on SiC wafers. Electronic transport measurements show complete quantization of the lowest QH state, as demonstrated by vanishing longitudinal resistance and a QH plateau at 12 906.4035 Ω. The study of large device formats may lead to a better understanding of fundamental size-dependent scaling in the QH state, as well as useful QH standards that operate at higher current.

Electronic Kilogram

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NIST has had two efforts on the electronic kilogram. The existing watt balance, named NIST-3 and a watt balance in construction, NIST-4. The objective of NIST-3 was to determine the precise value of the Planck constant; by contrast the objective of NIST-4 is to realize the kilogram, once the redefinition of the SI has been adopted. Technically the biggest difference between the two watt balances is the source of the magnetic field: a superconducting solenoid on NIST-3 vs. a permanent magnet system on NIST-4.

NIST-3 has been used to measure the Planck constant h at NIST for over ten years. However, two recently published values using the instrument disagree by more than one standard uncertainty. For example, in April, 2014 NIST published a new value of the Planck constant, determined using NIST-3 (Schlamminger *et al* 2014 *Metrologia* **51** S15). The result aimed to establish a new data point from the instrument largely independent from previous determinations. Towards this end, a new team was installed and the measurement was performed blindly, i.e. the team did not know the precise value of the mass used in the experiment. This published value, relative to the conventional value fixed in 1990, or h_{90}, was fractionally higher than the value determined in 2007 by 130 parts in 10^9.

A recent manuscript examines all the NIST-3 data and arrives at a single value. The value published in 2014 is corrected to take into account a recently discovered systematic error in mass dissemination at the Bureau International des Poids et Mesures (BIPM). Furthermore, we provide guidance on how to combine the 2007 and 2014 numbers into one final result. In order to adequately reflect the observed inconsistency of the instrument and measurement procedures, we concluded that an additional systematic uncertainty be added to the published uncertainty budgets. The final value of h measured with NIST-3 is $h = 6.626\ 069\ 36(37)\times10^{-34}$ J s. This result is $77(57) \times 10^{-9}$ fractionally higher than h_{90}. Each number in parentheses gives the value of the standard uncertainty in the last two digits of the respective value and h_{90} is the conventional value of the Planck constant given by h_{90} as determined using the conventional values of the Josephson and von Klitzing constants. The manuscript has been accepted by *Metrologia*.

NIST-4 and its' facility are nearing completion, as described in a number of recent papers listed at the end of this section. The balance has demonstrated both weighing and velocity mode functions, and work at present is focused on further integration and control aspects required to directly incorporate the quantum electrical standards in the measurement. The project schedule aims to measure and report a value of the Planck constant before the close of 2015. The project will then transition to executing the *mise en pratique* of the kg to participate in the pilot study organized by the CCM for completion in 2016.

1. D. Haddad, F. Seifert, L. Chao, 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.*.
2. 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," accepted for publication in *IEEE Trans. Instr. Meas.*, http://arxiv.org/abs/1412.4143.
3. F. Seifert, A. Panna, S. Li, B. Han, L. Chao, A. Cao, D. Haddad, H. Choi, L. Haley, S. Schlamminger, "Construction, Measurement, Shimming, and Performance of the NIST-4 Magnet System," *IEEE Trans. Instr. Meas.* **63**, 3027-3038 (2014).
4. S. Li, S. Schlamminger, J. Pratt, "A nonlinearity in permanent-magnet systems used in watt balances," *Metrologia* **51,** 394-401 (2014).

Outreach Finally, the Electronic Kilogram project has also been working on communication and outreach to disseminate the concepts of the new SI prior to its adoption. Following the example set by Terry Quinn and colleagues, we have developed a version of a watt balance constructed of Lego building blocks to illustrate the concepts surrounding the redefinition of the kilogram. Details of the construction and operation of this instrument have been published with the aim of stimulating educators to incorporate the topic in science curricula. We have also donated a working Lego watt balance to the BIPM. We have given over 30 conference and invited presentations on the topic in the last two years. Selected papers related to our outreach activities include:

1. L.S. Chao, S. Schlamminger, D.B. Newell, and J.R. Pratt, G. Sineriz, F. Seifert, A. Cao, and D. Haddad, X. Zhang, "A LEGO Watt Balance: An apparatus to demonstrate the definition of mass based on the new SI," accepted for publication in *Am. J. Phys.*, http://arxiv.org/abs/1412.1699.
2. D.B. Newell, "A more fundamental International System of Units," *Physics Today* **67**, 35-41 (2014).
3. J.R. Pratt, "How to Weigh Everything from Atoms to Apples Using the Revised SI," *NCLSI Measure J. Meas. Sci.* **9**, 26-38 (2014).

RF Scattering-parameters and Power Characterization

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We have upgraded the commercially made Vector Network Analyzer (VNA) systems that we use for scattering parameter measurements to the latest generation of instruments. In addition we have upgraded our proprietary control and analysis software. We are continuing to develop vector network analyzer calibration/measurement techniques for WR-08, WR-05, WR-03, WR-2.2, WR-1.5, and WR-1.0 waveguide sizes (90-140 GHz, 140-220 GHz, 220-325 GHz, 325-500 GHz, 500-750 GHz, and 750-1100 GHz respectively). For power we have completed the evaluation of the calorimeter correction factor for both the new Type-N and the new WR-15 calorimeters. Uncertainties have improved slightly, but not significantly. A recent lab move from an area with controlled humidity to an area of uncontrolled humidity caused changes in the values being measured for several of our waveguide power standards (note that the normal humidity uncontrolled level at our labs in the winter is about 10% relative and 30% in the summer). We discovered that the power standards were much more dependent on humidity level than we initially thought. We devised a method of "pre-charging" the units in a high humidity environment and then measuring the units in the low humidity area within a short time period, three days. With this new method, the changed values reverted to the values obtained before the move. For the power area, we have started to investigate a method of tracing the power measurements to quantum phenomena, this work in is an early stage, but shows promise. The work to incorporate the NIST uncertainty framework into our measurement process is continuing. The work is initially being done in the scattering parameter area, but will soon be added to the power and thermal noise areas. The uncertainty framework is very modular and utilizes both single value error propagation and Monte Carlo analysis techniques. The most important aspect of the uncertainty framework is that it provides correlation of uncertainty values between frequency points which allows the results and uncertainties from the frequency domain to be transformed to and from the time domain. Once we have established the process with the uncertainty framework, we will be doing a complete comparison to the results from our present established technique.

Antenna Parameter Characterization

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The demand for millimeter Wave (mmWave) antenna measurements (> 100 GHz) has increased due to the practical realizations of many mmWave systems and applications. Point-to-point communication links from 92 – 95 GHz and 120 GHz are now commercially available, and 220 – 650 GHz systems are being researched for medical and security applications. New developments in climate monitoring require traceability in radiometric and remote sensing equipment from 100 – 850 GHz, including calibrated power, emissivity and antenna gain. NIST has as goals extending current antenna parameter calibrations to these higher frequencies and facilitating the ability of users to make similar measurements.

Toward these goals, the National Institute of Standards and Technology (NIST) recently developed a new robotic arm scanning system for performing near-field antenna measurements at mmWave frequencies above 100 GHz, the Configurable RObotic MilliMeter-wave Antenna (CROMMA) Facility, shown in Figure 1. This system is capable of planar, spherical, cylindrical, or mixed-geometry scanning. The position and orientation information provided by the laser tracker system is used to assess the quality of the alignment and allows for the implementation of position and orientation correction algorithms.

The CROMMA facility uses two robotic positioners and one rotary positioner. First, an industrial robotic arm that consists of six rotation joints connected in series by ridged linkages. This allows for six degrees of freedom (6DoF), x, y, z and roll, pitch and yaw, positioning of the probe. After initial setup, alignment using the laser tracker, and applying position correction tables, the robotic arm provides probe positioning within 25 µm. Second, a hexapod that uses a parallel network of six prismatic actuators allows for 6DoF positioning and alignment of the test antenna to the measurement azimuthal rotation axis. Individually the actuators have an accuracy of 500 nm giving a combined accuracy of 1 µm for the hexapod system. Finally, a precision rotary stage is used to rotate the hexapod over a range of 360 degrees. This rotary stage is used for the measurement azimuthal rotation axis for the test antenna when performing spherical near-field antenna measurements. The angular resolution of the rotator is 0.36 arc-sec and has an accuracy of 20 arc-sec.

A laser tracker augmented with an infrared photogrammetry system is used to measure, track, and record the position and orientation of the probe in all 6DoF. The x, y, and z position data is measured with an accuracy of 20 µm, while the roll, pitch and yaw orientation data is measured to within 0.01 degrees. The 6DoF data are combined into a “coordinate frame” that describes the position and orientation of the 6DoF laser tracker target. A machine vision technique using the synergy of three cameras linked to the laser tracker is used to determine the “coordinate frames” of the probe and the test antenna. Spatial analyzing software that is integrated with the laser tracker, robotic arm and hexapod allows for the relative alignment of the "coordinate frames" to the measurement coordinate system.

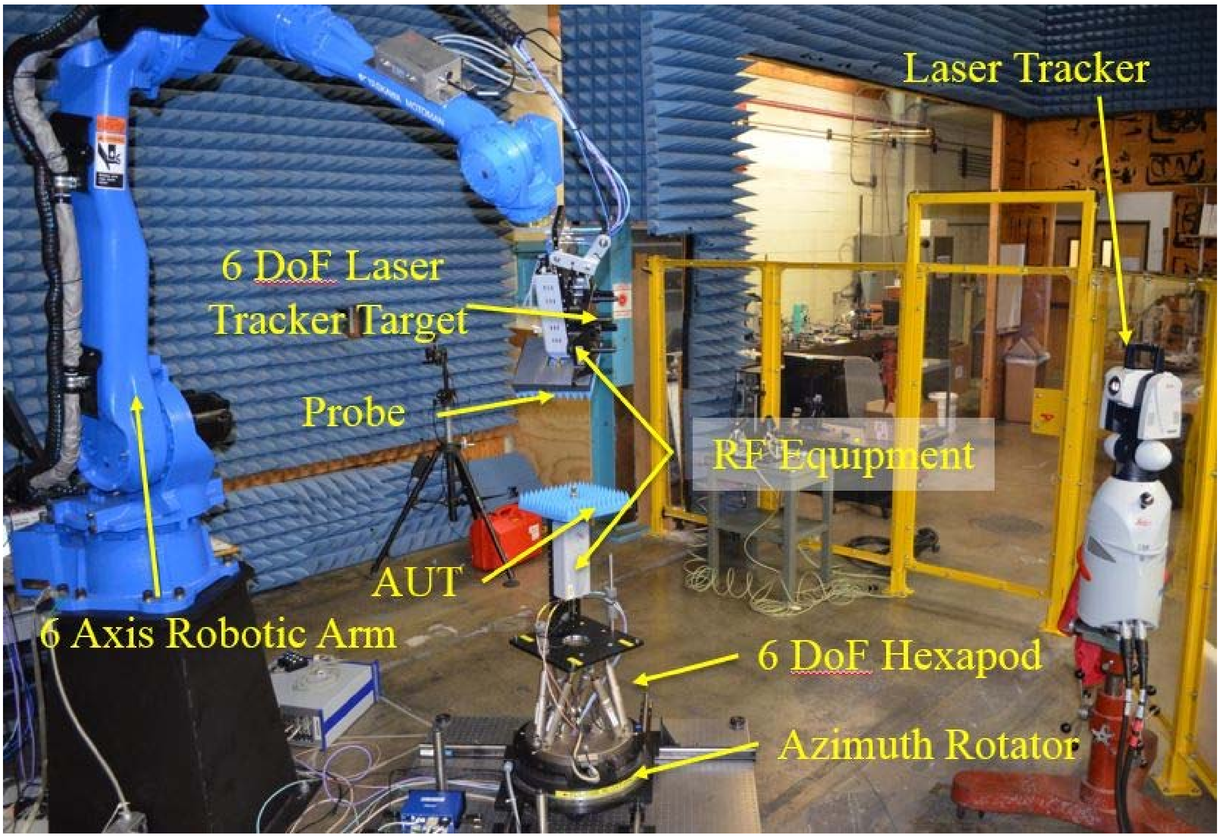

Figure 1. CROMMA facility positioners. Serial 6DoF robotic arm, parallel 6DoF hexapod, precision rotary stage, probe and test antenna.

As an example of a CROMMA pattern measurement above 100 GHz, a WR-5 standard gain horn was measured at 183 GHz using the spherical near-field method at a radius of 10 cm. 183 GHz represents an important water vapor line measured by microwave radiometers. The results were compared to a theoretical model and to a direct far-field measurement at 100 cm. The 100 cm data were also transformed to the 'true' far field for comparison.

Figures 2 and 3 are the comparison of the E- and H-plane far fields, respectively, for: (1) measured at 100 cm, (2) transforming the 100 cm data to the 'true' far field, (3) theoretical, and (4) transforming the 10 cm near-field data. For the E-plane, the theoretical, and calculated far fields from the 100 cm data and 10 cm data nominally agree out to the -20 dB side lobe level (approx. 30°). The directly measured field at 100 cm agrees out to 50° where the data have more noise. The H-plane results agree for the main lobe, again out to the -20 dB side lobe level. A high level of noise is apparent in the 100 cm data due to limitations on transmit power (about -12 dBm). The received power at 100 cm is about 20 dB less than that measured in the near-field at 10 cm, which is consistent with the expected spatial attenuation. Improvements to the CROMMA system and a full uncertainty analysis are ongoing.

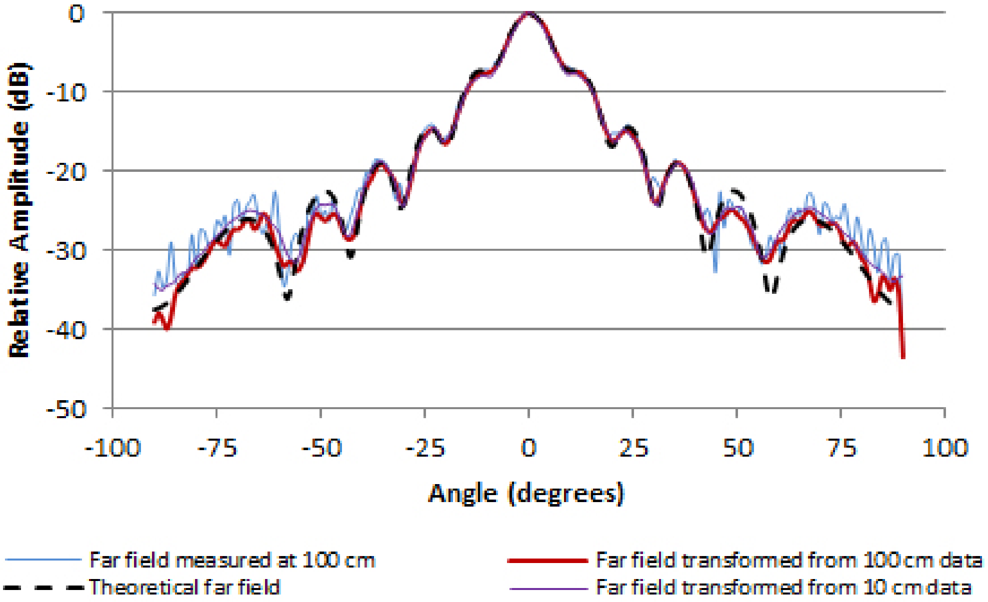

Figure 2. E-plane far field comparison.

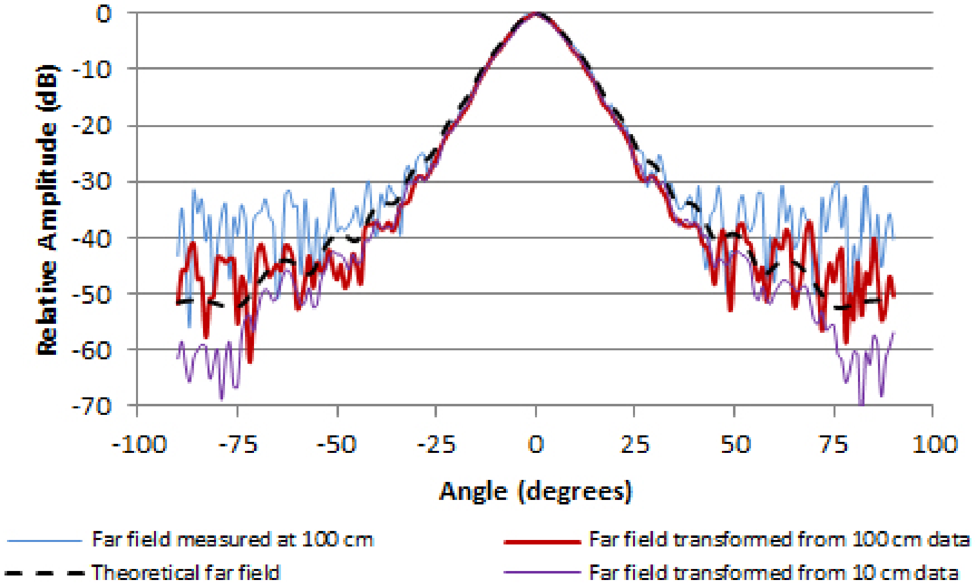

Figure 3. H-plane far field comparison.

Field Strength Parameter Characterization

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NIST continues work on a quantum based electric (E) field strength probe. The E-field probe is based on the interaction of RF-fields with Rydberg atoms, where alkali atoms are excited optically to Rydberg states and the applied RF-field alters the resonant state of the atoms. For this probe, the Rydberg atoms are placed in a glass vapor cell (MEMS and/or fiber based). This vapor cell acts like an RF-to-optical transducer, converting an RF E-field to an optical frequency response. The probe utilizes the concept of electromagnetic induced transition (EIT), where the RF transition in the four-level atomic system causes a split of the transition spectrum for the pump laser. This splitting is easily measured and is directly proportional to the applied RF field amplitude. Therefore, by measuring this splitting we get a direct measurement of the RF E-field strength. The significant dipole response of Rydberg atoms over the GHz regime suggests this technique could allow traceable measurements over a large frequency band including 1-500 GHz. This new approach for RF E-field measurements has the following benefits: 1) it will allow direct SI units linked RF *E*-field measurements, 2) it is self-calibrating due to atomic resonances, 3) it will provide RF field measurements independent of current techniques, 4) the probe will not perturb the field during the measurement, since no metal is present in the probe, 5) it will have vastly improved sensitivity and dynamic range over current E-field probes (<0.01 mV/m, *two orders of magnitude improvement over current approaches)*, and 6) it will be a very small and compact probe based on optical fiber. We have successful performed proof-of-concept measurements at George Tech and have just finished setting up a lab at NIST to continue the developed of the probe.

Smart Grid Standards and Metrology

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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 latest revision of the NIST smart grid roadmap was published in September 2014. The SGIP has now transitioned to a private-public partnership with greater private sector funding. This legal non-profit entity, known as SGIP 2.0, Inc., has been established and four meetings have been held since its inception in December, 2013. NIST will continue to engage, lead and provide technical resources within the SGIP, which provides many mechanisms to address standards gaps, such as committees and working groups, as well as Priority Action Plans led by NIST staff.

As part of the electrical metrology support for the Smart Grid, NIST has developed measurements and 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. The U.S. Department of Energy has co-funded with electric utilities the installation of nearly 1000 PMUs in the North American power grid under a Smart Grid Investment Grant program. NIST has updated its test systems to meet the requirements of recent IEEE and IEC standards, and the testing has been automated using a commercial PMU calibrator developed by Fluke Corporation, Inc. under a NIST grant. NIST efforts are now focused on calibrating PMU calibration systems.

Construction of a NIST testbed for research projects related to the smart grid is now underway. The first phase of the testbed laboratories, which is planned to be operational in the first quarter of 2015, will have projects to develop measurement methods for Power Conditioning Systems (PCSs) and associated high megawatt power electronics technologies needed 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 including plug-in electric vehicles used as storage, as well as microgrids, and DC circuits. Additionally, research in performance and interoperability, and the development of tests for smart voltage and current sensors for the power grid will be conducted in the new laboratories.