Low Frequency Electrical Metrology Programs at NIST

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Abstract: This paper provides a very brief overview of the capabilities and recent accomplishments of many of the low frequency electrical metrology projects at the National Institute of Standards and Technology. The projects presented here include the 5 main electrical measurement services projects (dc voltage, resistance, impedance, ac-dc difference, and electric power) and some electrical metrology related research projects, such as the manipulation of single electrons, redefinition of the SI, and Josephson voltage standards.

1. INTRODUCTION

For over 100 years, the National Institute of Standards and Technology (NIST) has provided the basis for the United States' electrical metrology infrastructure. For low frequency applications, this service is provided by the Quantum Electrical Metrology Division of the Electronics and Electrical Engineering Laboratory of NIST.

The Quantum Electrical Metrology Division consists of approximately 100 employees and guest researchers on both the Gaithersburg, MD and Boulder, CO sites of NIST. These staff provide many of the world's best electrical measurement services and perform significant research related to electrical metrology

This paper and the corresponding presentation are intended to provide a brief overview of the capabilities and activities at NIST related to low frequency electrical metrology. More information is available at http://eeel.nist.gov/817. Research and services related to radio frequency electrical measurements are performed by the Electromagnetic Division of NIST and are discussed at http://eeel.nist.gov/818.

2. MEASUREMENT SERVICES

There are 5 primary measurement services projects in the Quantum Electrical Metrology Division of NIST. Each is briefly presented below showing their measurement capabilities and some recent accomplishments.

2.1 DC Voltage Metrology

The realization of the U.S. volt is achieved using the 3 Josephson voltage standards (JVS) systems available at NIST. These systems are: a 10 V system, a 1 V programmable system, and a 10 V compact, transportable system. Typical customer calibrations for solid-state voltage standards at 10 V have an uncertainty of 0.19 μV/V.

NIST also performs direct JVS-to-JVS comparisons with laboratories that have JVS systems. The most recent comparison with NRC-Canada between 10 V JVS systems resulted in an extraordinary uncertainty of ±1.6 nV [1]. A broader comparison of voltage measurements involving 15 U.S. laboratories was recently completed using the NIST compact JVS. This interlaboratory comparison was accomplished in about 4 months and involved 4 loops of laboratories, with each loop receiving an onsite comparison with the NIST JVS system. Overall, this represented the most efficient dissemination ever of high precision voltage to U.S. industry. Errors at the 2×10^{-8} level were detected and resolved and general uncertainties were lowered by nearly a factor of 10 from previous comparisons [2].

2.2 Resistance Metrology

Resistance measurement services at NIST are based upon a quantum Hall resistance (QHR) standard, and cover about 19 orders of magnitude from 0.01 mΩ to 100 TΩ. NIST recently reduced uncertainties across most of this parameter space (Fig. 1) by improved analysis and measurement techniques.

Another advance in the NIST resistance metrology program is the development of new cryogenic current comparators that allow for direct scaling from the quantum Hall resistance standard to 1 MΩ and 100 MΩ. This enables significant reduction of uncertainties and improved ease of operation. Recent modifications to the NIST precision 1 Ω

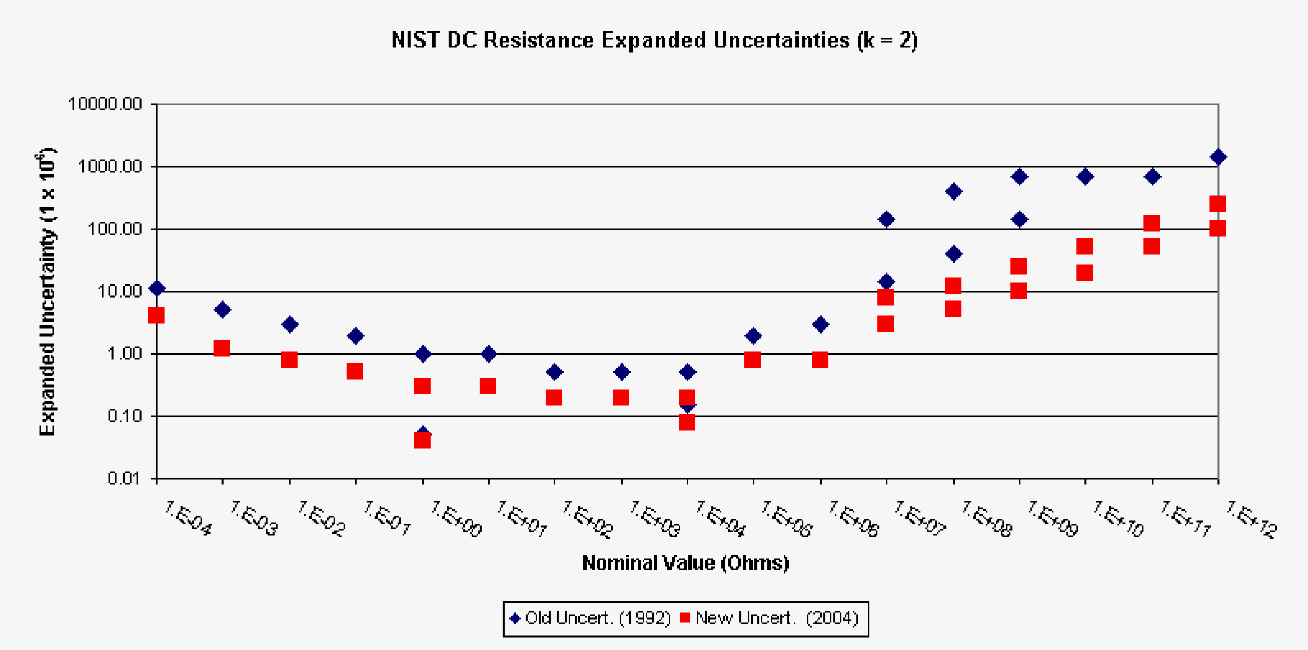

Fig. 1 *Recent improvements in uncertainties of dc resistance calibrations. Nominal values at which there are two uncertainties indicate 2 types of available tests.*

current comparator system have also allowed for improved characterization of 1 Ω standards as a function of pressure and temperature [3]. This clarifies the limits of the reliability of these resistors for precision interlaboratory comparisons.

NIST is serving a the pilot lab for a SIM international resistance comparison for 1 Ω, 1 MΩ, and 1 GΩ values. NMIs from 6 SIM countries are participating. The comparison was started in 2006 and is anticipated to be completed by March 2007 when it will then be linked to the relevant CCEM Key Comparisons.

2.3 Impedance Metrology

At NIST, impedance is realized by the calculable capacitor which is then linked to a bank of precision capacitors that maintains the U.S. Farad. Calibration services are available from <1 pF to 1μF for frequencies from 20 Hz to 1 MHz. Uncertainties at cardinal points (such as 10 pF at 1 kHz) are approximately 0.2 ppm. The NIST capacitance chain and its links to resistance and other projects is shown in Fig. 2.

In addition to expansion of frequency-dependent calibrations from 20 Hz to 1 MHz, another recent advancement is the capability to measure dissipation factors in fused-silica capacitance standards. This capability has been developed for 10 pF capacitors in response to industry need and will be extended to other capacitance values in 2007. The uncertainty for this calibration is 0.16 ppm at 1 kHz [4]

NIST is also piloting a SIM international comparison for capacitance at 1 pF, 10 pF, and 100 pF. All six participants in the comparison have completed their measurements, and the draft report is scheduled to be distributed in 2007.

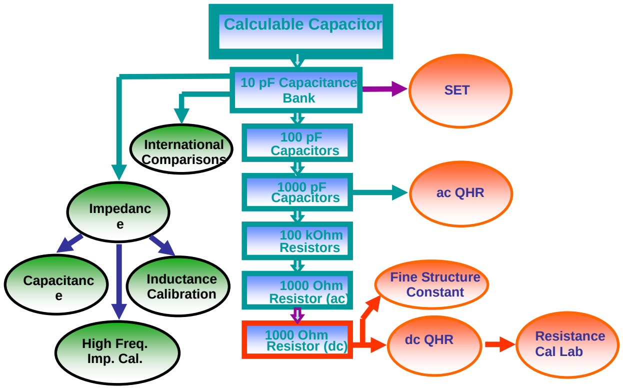

Fig. 2. *Traceability chain for impedance calibrations and linkage to other NIST electrical metrology experiments.*

2.4 AC-DC Difference Metrology

Ac-dc calibration services cover a very broad parameter space. The voltage calibration service runs from 2 mV to 1 kV from 10 Hz to 1 GHz. For ac-dc current calibrations, the parameter space covers 100 µA to 100 A from 10 Hz to 100 kHz. Uncertainties vary considerably over the parameter space for both current and voltage calibrations. This is shown in Fig. 3 for ac-dc voltage measurements.

Recent advances to the ac-dc difference measurement services at NIST include the extension of the service up to 1 GHz in Gaithersburg with reduced uncertainties [5] and lower calibration fees. Additional information may be found at http://www.acdc.nist.gov.

A new ac-JVS system developed by the Quantum Voltage project (see below) has been set up in the voltage laboratory. This system will serve as the quantum standard for ac voltage measurements for voltages from 2 mV to 100 mV for frequencies from 1 kHz to 1 MHz. With the realization of a stepped-waveform quantum ac voltage standard, NIST also will have quantum standards from 2 mV to 2 V over the frequency range from 10 Hz to 1 MHz. Combined with the NIST multijunction thermal converter primary standards, this work will result in significant improvements in the uncertainties of our calibrations for thermal transfer standards [6].

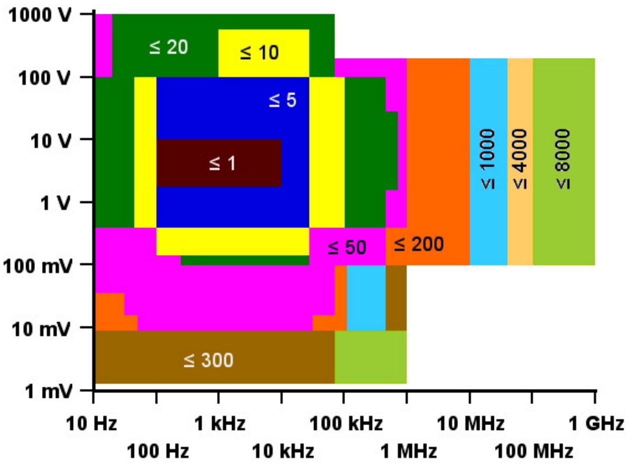

Fig. 3 *Parameter space and uncertainties (ppm) for ac-dc voltage measurements.*

2.5 Electrical Power Metrology

The electrical power measurement service offers calibrations of watts, watthours, vars, and varhours for devices up to 600 V and 100 A primarily at power frequencies. Uncertainties at cardinal points (e.g., 120 V, 5 A, 60 Hz) approach 15 ppm.

In the area of electric power, NIST has recently implemented two new special services. The first is for electric power calibrations of non-sinusoidal waveforms containing power frequency harmonics up to 3 kHz. This service will help in efforts to evaluate the performance of power meters in the presence of "polluted" electrical power signals. The second new service is related to the testing and calibration of Phasor Measurement Units (Fig. 4). These devices are used to perform measurements of system conditions (voltage and current amplitude, phase, and frequency) synchronized to the universal coordinate time in order to improve electric grid reliability.

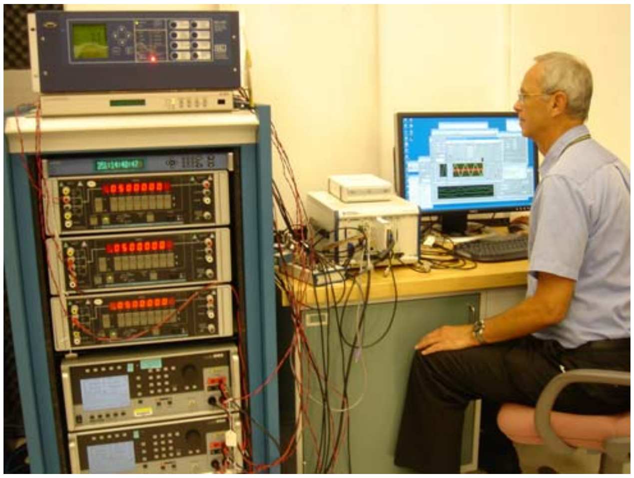

Fig. 4 *J. Stenbakken with the phasor measurement unit testbed.*

NIST is also developing a quantum power standard based upon two programmable Josephson voltage standards. This "quantum watt" will serve as the basis for the new primary standard for our electric power calibrations and should result in uncertainties of less than 10 ppm.

3. QUANTUM ELECTRICAL METROLOGY RESEARCH

3.1. Single Electron Tunneling

Single electron tunneling (SET) refers to the ability to move and/or count single electrons. Previously, NIST has demonstrated the ability to move single electrons on and off a capacitor with an error rate of approximately 0.01 ppm. This suggested the possibility of using this capability to pump a known number of electrons onto an extremely low loss capacitor (Fig. 5), and thereby produce a quantum capacitance standard via $C=q/V$ where q is the known charge on the capacitor (ne) and V is the measured resulting voltage. This has been demonstrated [7].

More recently, the concept of using SET to "close the metrology triangle" has been proposed. By using quantum standards (JVS for voltage, QHR for resistance, and SET for current) it should be possible to validate Ohm's Law ($V=IR$). Interestingly, this can be nearly equivalently accomplished via the capacitance experiment discussed in the previous paragraph. By careful analysis of the capacitance data, NIST presented results at CPEM2006 that "closed the metrology triangle" to approximately 1 ppm. Future work is aimed at improving these results to approximately 0.1 ppm. At this level of uncertainty, the results of this experiment begin to have implications for the redefinition of the SI units discussed below.

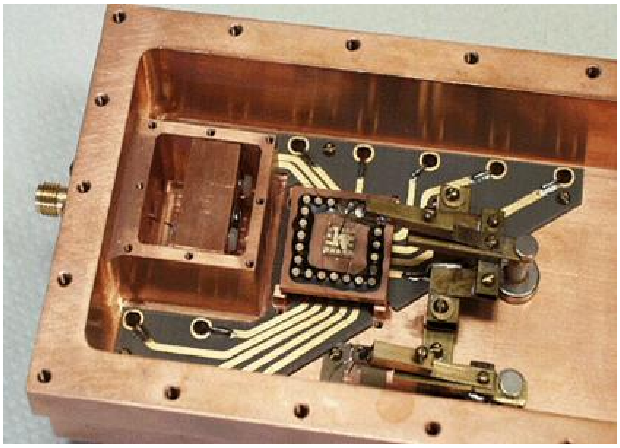

Fig. 5 *Electron counting capacitance standard with single electron tunneling pump on the chip.*

3.2. Electronic Kilogram

The kilogram is the one remaining SI unit that is still realized by a physical artifact. By using a "watt balance" to precisely equate physical force to electrical force, the kilogram artifact standard may be replaced by a reproducible experiment – the "electronic kilogram" or watt balance. In practice, the watt balance experiment determines a value for Planck's constant (h). Defining the exact value h is equivalent to redefining the kilogram.

The NIST watt balance (Fig. 6) has recently published the lowest uncertainty determination of h in the world [8] with an uncertainty of 36 ppb. We anticipate reducing this uncertainty to approximately 20 ppb by the end of 2007.

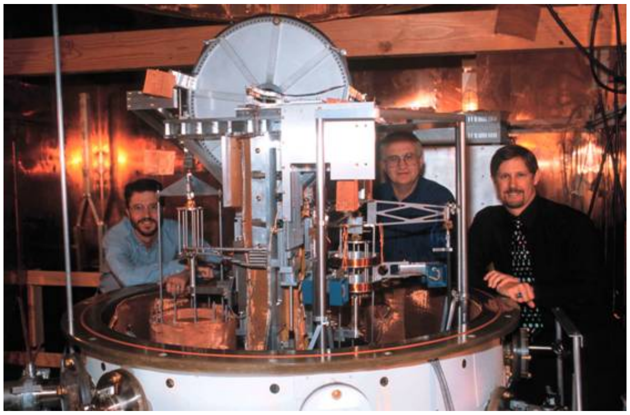

Fig. 6 *D. Newell, E. Williams, and R. Steiner with the balance portion of the NIST watt balance experiment.*

It has been proposed [9] that the definition of the SI kilogram be redefined in 2011 by linking the definition to an exactly defined value of h. A measured uncertainty of 20 ppb for h prior to 2010 has been set as one of the requirements for this redefinition. The NIST watt balance is anticipated to be the first experiment to achieve this goal. It also has been proposed that at the same time the Kelvin, ampere, and mole be linked to defined values of the Boltzmann's constant, the electron charge, and Avogado's constant, respectively.

3.3 Quantum Voltage

As discussed previously, the volt is realized by the quantum Josephson effect. NIST has an active program in developing and advancing quantum voltage standards so as to improve the dissemination of electrical standards. In addition to the ac-JVS and the quantum watt work discussed earlier, the NIST Quantum Voltage project is striving to demonstrate a 10 V programmable JVS that does not require an expert operator. This challenging task requires significant development of array technology, microwave integrated circuits, electronic instrumentation, and cryogenic packaging. Using newly fabricated stacked junctions (Fig. 7), the NIST team has recently demonstrated circuits with output voltages of 5 V.

This project is also leading the world in utilizing Josephson voltage circuits to construct a quantum voltage noise source. This unique source provides the capability to develop a quantum-based Johnson noise thermometry (JNT) system. This system could be used to provide precision measurements of high temperatures in extreme environments. It could also provide a novel route to a redetermination of the Boltzmann constant that may be part of the proposed 2011 redefinition of the SI units.

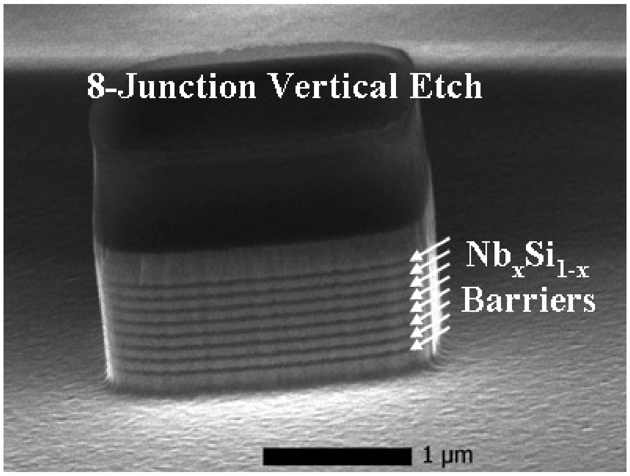

Fig. 7 *Scanning electron microscope image of an 8-junction stack that enables increased voltage output from a Josephson voltage array.*

4. SUMMARY

The Quantum Electrical Metrology Division strives to provide the world's best electrically-based measurements and standards. The services, projects, experiments, and achievements discussed in this brief overview reflect only a portion of the research being performed in the Division. For example, the QEM Division has active programs in precision cryogenic sensors, quantum computing, magnetic sensors, fuel cells, arbitrary waveform analysis, and digital signal processing.

All of the projects in the QEM Division benefit from interactions with scientists from other institutions and we are constantly looking for excellent visiting guest scientists and collaborators. Please contact us for more information on any of the work mentioned here.

ACKNOWLEDGEMENTS

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