An International Intercomparison of Quantum-Based AC Voltage Standards

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***Abstract*—We report the results of a comparison of quantum-based AC Josephson Voltage Standards (ACJVS) between the National Institute of Standards and Technology (NIST), and the National Research Council, Canada (NRC), using a thermal transfer standard as the traveling standard. Excellent agreement was obtained between NIST and NRC from measurements on the lowest voltage ranges of the thermal transfer standard, indicating that the two ACJVS systems are consistent. This work confirms that the use of the ACJVS as a reference for ac voltage measurements is viable, and these systems can form the basis for ac voltage metrology in the future. This intercomparison was performed as part of SIM Bilateral Comparison SIM.EM-S11, AC-DC Voltage Transfer Difference at Low Voltages using an AC Josephson Voltage Standard.**

***Index Terms*—AC-DC Difference; Interlaboratory Comparison; Josephson Voltage Standard; Voltage Measurement**

I. INTRODUCTION

The primary standards for ac voltage and current metrology at National Metrology Institutes, such as NIST and NRC, are multijunction thermal converters (MJTCs) [1,2]. At NIST, MJTCs using thin-film technology and MJTCs using older, wire technology are used to define a primary reference group of MJTCs, with an assigned average value of ac-dc difference of the group of (0 ± 0.4) μV/V from 0.5 V to 2 V over the frequency range from 40 Hz to 10 kHz. The assigned value of (0 ± 0.4) μV/V has been confirmed using both theoretical analyses of the MJTC structure, and using these devices in international intercomparisons of ac-dc difference sponsored by the Consultative Committee for Electricity and Magnetism (CCEM) [3]. Both thin-film MJTCs and calorimetric thermal voltage converters are used at NRC as primary standards of ac-dc difference, and similarly are assigned a group average ac-dc difference of (0 ± 0.4) μV/V at 1 V and 1 kHz [4].

References for voltages outside the operating range of the MJTCs are determined using step-up procedures for voltages greater than a few volts, and step-down procedures for voltages in the region from a few hundred millivolts and below. This scaling process involves measuring a second standard against an MJTC at one voltage, and then using the second standard at a fraction of its full-scale input.

For example, to determine a reference value for 10 mV, a 200 mV thermal converter would be compared to a 500 mV MJTC at 200 mV, then a 100 mV thermal converter would be compared to the 200 mV standard at 100 mV, and so on down to 10 mV. Achieving maximum accuracy at the end of the scaling chain demands that the standards exhibit small changes in ac-dc difference when used at different input voltages, and the uncertainties in this voltage coefficient contribute to each step in the scaling chain, potentially causing significant contributions to the expanded uncertainties at the end of the chain [5].

Over the past five years, advances in pulse-driven AC Josephson Voltage Standards (ACJVS) have provided NIST and NRC with quantum-accurate ac voltage sources that are ideal for determining ac-dc difference at low voltages [6]. The NIST ACJVS was used to provide the first quantum-based data to a commercial calibration customer [7], and the NIST ACJVS currently provides the reference for low-voltage ac-dc difference measurements with uncertainties smaller than can be achieved with the traditional step-down process. However, to have these uncertainties recognized internationally, these uncertainties must be listed in the Calibration and Measurement Capabilities Database maintained by the Bureau International des Poids et Measures (BIPM). This requires an international intercomparison of standards used for these calibrations and has led to SIM.EM-S11, a bilateral comparison between NRC and NIST, under the auspices of the Sistema Interamericano de Metrologia (SIM) the regional metrology organization to which NRC and NIST both belong. The results of this 2008 intercomparison, if accepted by BIPM, will allow calibrations using these quantum-based standards to be recognized around the world.

In this paper we briefly describe the ACJVS, and its limitations and operation. We then describe the SIM.EM-S11 protocol, the measurement process and uncertainty analysis for both NIST and NRC, and give the results of the intercomparison.

II. ACJVS

The intrinsic accuracy of the ACJVS is derived from the perfect quantization of voltage pulses generated by each Josephson junction in an array of identical junctions [8]. AC waveforms are produced using a digital-to-analog synthesis method based on sigma-delta modulation and oversampling.

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The precise control and timing of these quantized pulses allows the synthesis of ac waveforms with calculable, accurate voltages.

The ACJVS consists of two arrays of 5120 Josephson junctions each, which may be used individually or in series. The most recent chip is capable of supplying 275 mV rms using both arrays in series. The junctions are made to pulse by impressing a digitally generated pulse train on the microwave feed to the arrays (Fig. 1). Producing an accurate sine wave, especially at low frequencies, demands significant memory in the code generator, and this memory length restriction determines the lower frequency limit in the ACJVS. In normal operation, half the total available memory of 8 Mbit is devoted to a dc code and half to an ac code. Splitting of memory in this fashion restricts the lower frequency limit to 2.5 kHz.

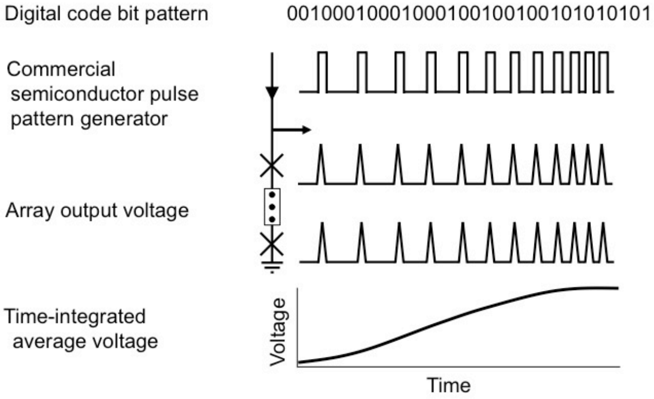

Fig.1. Operation of ACJVS, showing the digital code pattern produced by the code generator, the output voltage pulses of a Josephson array, and the time-averaged output sinusoid.

The output ac waveform is referenced at the end of a 1 m long transmission line connecting the ACJVS chip to the top of a cryoprobe inserted in a liquid helium dewar, plus any additional transmission line connecting the probe to the instrument under test. The transmission line inside the cryoprobe was originally insulated twisted-pair copper wire that introduced large errors in the waveform at frequencies greater than about 20 kHz [9]. The most recent cryoprobe features coaxial cables for the waveform output leads, and preliminary tests have shown that these leads significantly reduce the errors associated with the output transmission lines. A coaxial choke is placed in the output transmission line between the probe head and instrument under test to both reduce common-mode voltages in the leads and to prevent errors arising from circulating currents. At the frequencies reported here (2.5 kHz to 20 kHz) the transmission line makes a negligible contribution to the output voltage error. A schematic of the transmission line is shown in Fig. 2. In Fig. 2, inductances L0, L2, and capacitance C3, are located on the chip, and resistance R2 and part of C2 represent the twisted pair leads in the cryoprobe. The combination of C2-L1-R3-C1are the added physical components of the output filter. “Cable” represents the coaxial connection to the TTS, and R1-C4 represents the input impedances of the transfer standard.

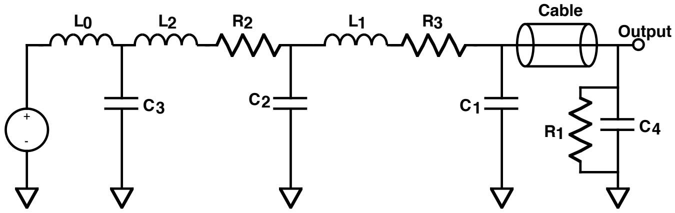

Fig. 2. Schematic of ACJVS transmission line.

III. TRAVELING STANDARD

A. Characterization

The artifact used as the traveling standard for this intercomparison was a commercially-available thermal transfer standard (TTS) with switch-selectable 220 mV and 22 mV ranges. The TTS uses a thermally-isolated transistor as the sensor, with a series of amplifiers to boost the input voltage on these ranges to the 2 V level required by the sensor. The ac-dc differences of the TTS therefore depend largely on the characteristics of the input amplifiers, and are not necessarily independent of frequency, even over the limited part of the audio frequency range reported in this intercomparison. Standards of this type have traditionally been characterized using a step-down technique to scale from the higher voltage of the primary standards to lower voltages. This type of scaling relies upon the independence of the ac-dc difference with voltage level of a second standard (usually a micropotentiometer, or µpot); the TTS is calibrated by using the micropotentiometer at both full-scale input and at reduced input to fully characterize the TTS, as shown in Fig. 2.

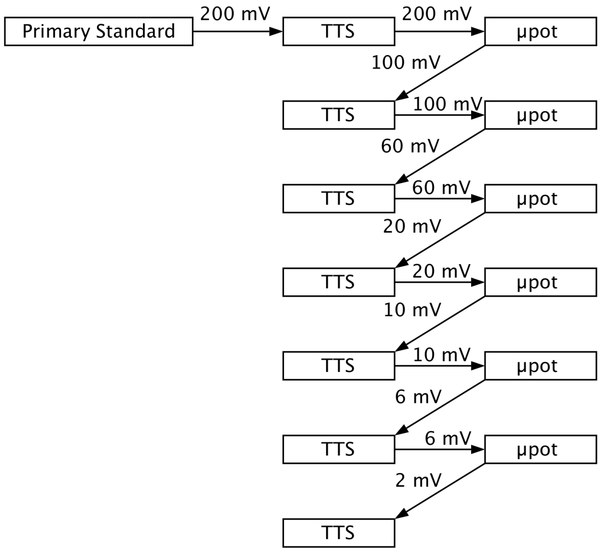

Fig. 3. Step-down path from the primary standards at 200 mV to 2 mV on the 22 mV range of the TTS.

B. Uncertainties

The uncertainty of the primary standard is generally 1 µV/V or less at 200 mV and audio frequencies; however, the ac-dc difference of the micropotentiometer cannot be assumed to be independent of input voltage, so an uncertainty component must be assigned to each step in the scaling process to account for the dependence of ac-dc difference upon input voltage. Taken together with other uncertainty components, the uncertainty assigned to the TTS at each input voltage increases rapidly, so that at 2 mV the uncertainties at audio frequency can be greater than 250 µV/V.

For this comparison, NRC reported for the ACJVS results uncertainties consistent with those provided for the key comparison CCEM-K11 [9], which include contributions from:

- The reference standard at 200 mV
- The step-down process
- Uncertainties associated with the measurement system
- Voltage and frequency effects
- Uncertainties associated with connectors
- Temperature-related effects
- Reproducibility

A more detailed presentation of the NRC uncertainty analysis may be found in [10].

At NIST the ACJVS is used solely as a source supplying voltage directly to the TTS at the desired level; therefore, scaling from a higher voltage to a lower one is unnecessary. The uncertainties determined for the TTS measurements at any level depend only on the uncertainty of the ACJVS and the stability of the TTS. The uncertainties assigned by NIST to the TTS at millivolt levels using the ACJVS can be significantly smaller than those assigned using the traditional scaling technique.

IV. PROTOCOL

An international intercomparison using a TTS such as the one used here might normally concentrate on voltages and frequencies near the extremes, the better to test both the performance of the TTS and of the systems used to measure it. However, owing to the frequency and voltage limitations of the ACJVS, we selected the points shown in Table 1.

Table 1. Points measured in the ACJVS intercomparison

	2.5 kHz	5 kHz	10 kHz	20 kHz
200 mV	X	X	X	
100 mV	X	X	X	X
10 mV	X	X	X	X
6 mV	X	X	X	X

NRC measured additional frequencies at all voltage levels; since these points were not part of the comparison, they are not reported here.

The ac-dc voltage transfer difference for this intercomparison is defined as

$$\delta = \frac{V_{ac}-V_{dc}}{nV_{dc}} \tag{1}$$

where:

V_{ac} is the rms value of the input voltage

V_{dc} is the dc voltage which when reversed produces the same mean output voltage of the transfer standard as V_{ac}.

n is the response characteristic of the TTS (n = 1 for this particular model.)

For both laboratories, the ambient temperature was reported to be (23 ± 1) ºC at a relative humidity of (45 ± 10) %. The plane of reference for the NRC tests was at the center of a Type N tee, with the low of the input connector and guard and ground terminals on the front panel connected to a common ground. The TTS was operated from its external battery pack. From extensive experience in the use of this instrument by both laboratories, we believe that contributions to the uncertainties from battery pack voltage, ambient temperature and humidity fluctuations, and transportation are negligible. At NIST, the output from the ACJVS was supplied directly to the input of the TTS; in this case the plane of reference was at the output of the ACJVS chip.

V. RESULTS

The results of the intercomparison are presented in Figs. 3-6. The error bars reflect the reported expanded (k = 2) uncertainties of each laboratory.

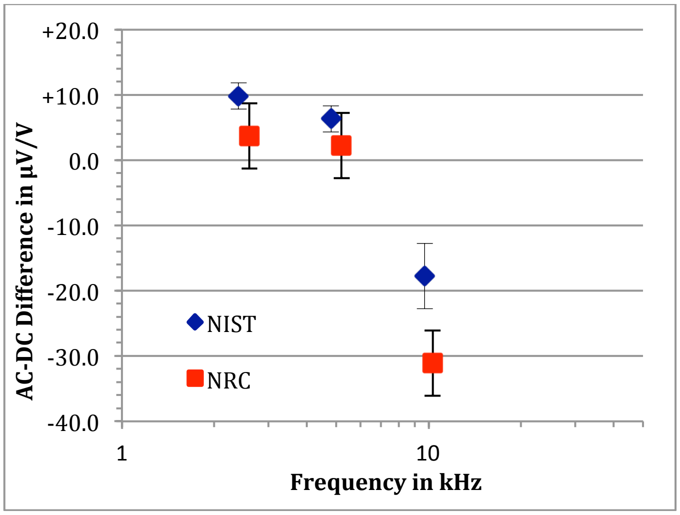

Fig. 4. Agreement between NIST and NRC ACJVS systems with 200 mV applied to the 220 mV range.

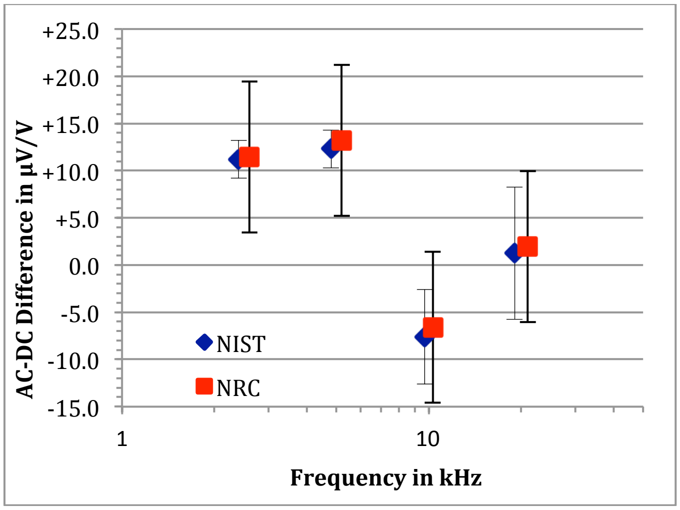

Fig. 5. Agreement between NIST and NRC ACJVS systems with 100 mV applied to the 220 mV range.

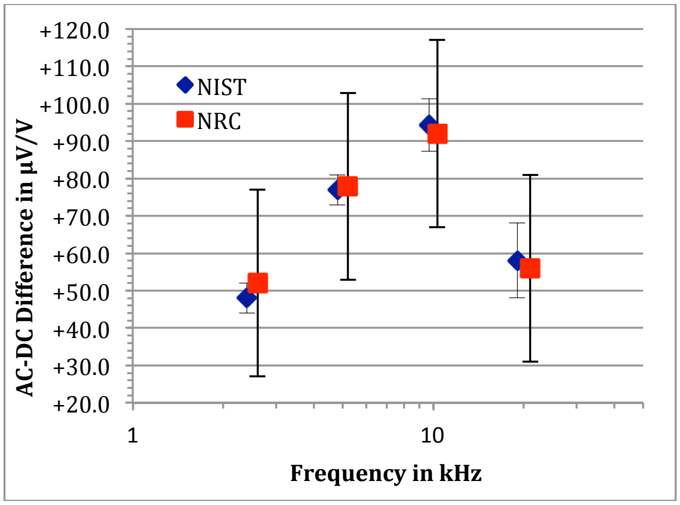

Fig. 6. Agreement between NIST and NRC ACJVS systems with 10 mV applied to the 22 mV range.

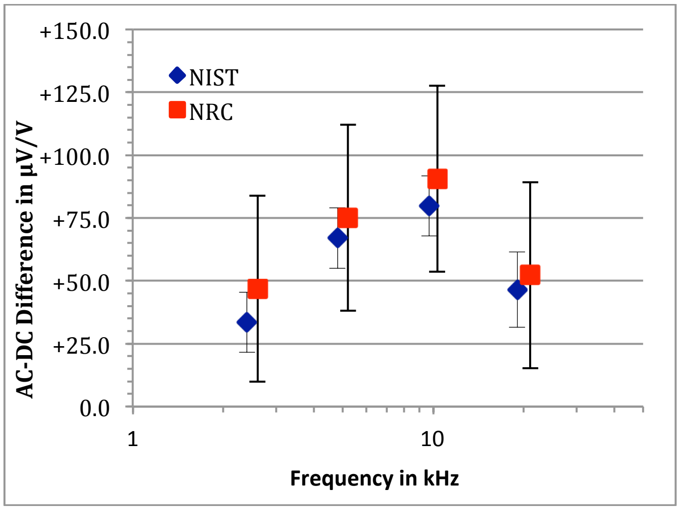

Fig. 7. Agreement between NIST and NRC ACJVS systems with 6 mV applied to the 22 mV range.

VI. Discussion

As shown in the figures, NRC and NIST generally agree very well at all points measured in this intercomparison. This excellent agreement provides assurance both that the traditional scaling techniques are valid and are performed in an effective manner, and that the performance of the ACJVS is well within expectations.

It is worth noting that only the 200 mV point requires the arrays to be operated in series; at the lower applied voltages the arrays are used individually, and the measurement results using each array averaged, with the intra-array difference used as a Type A component of the assigned uncertainty for that point. Both NIST and NRC have noticed variations in the array outputs when used in series, probably due to differences in the output transmission lines or variations in on-chip characteristics. The discrepancy at 10 kHz with 200 mV applied to the 220 mV range may be due to these variations, but is still within the normal calibration uncertainties given by NIST and NRC for this point.

VII. Conclusions

We have performed the first international intercomparison of quantum ac voltage standards, using a TTS shipped between NIST and NRC. Over the limited frequency range of this system, we found excellent agreement between the laboratories at applied voltages from 200 mV down to 6 mV. This excellent agreement provides confidence in both the quantum systems and the traditional step-down techniques, and also provides a solid basis to the low-level calibration services of the participants.

The results of this intercomparison will be summarized in a report to the CIPM, and if accepted, will be included in the Calibration and Measurement Capabilities Database maintained by the (BIPM), indicating international recognition of these measurement capabilities.

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