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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1109/I2MTC.2012.6229229>

2012 IEEE International Instrumentation and Measurement Technology Conference, pp. 98-102, 2012-07-02

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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) [1-4]. 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 $(0 \pm 0.4) \mu\text{V/V}$ from 0.5 V to 2 V over the frequency range from 40 Hz to 10 kHz. The assigned value of $(0 \pm 0.4) \mu\text{V/V}$ has been confirmed using both theoretical analyses of the MJTC structure, and by using these devices in international intercomparisons of ac-dc difference sponsored by the Consultative Committee for Electricity and Magnetism (CCEM) [5]. 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 $(0 \pm 0.4) \mu\text{V/V}$ at 1 V and 1 kHz [6].

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.

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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 only 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 scaling chain.

Over the past five years, advances in pulse-driven AC Josephson Voltage Standards (ACJVS) have provided NIST and NRC with ac voltage sources based on quantum effects that are ideal for determining ac-dc difference at low voltages [7,8]. The NIST ACJVS was used to provide the first quantum-based data to a commercial calibration customer [9], 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 Mesures (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 [10]. AC waveforms are produced using a digital-to-analog synthesis method based on sigma-delta modulation and oversampling.

The precise control and timing of these quantized pulses allows the synthesis of ac waveforms with calculable, accurate voltages (Fig. 1).

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-average output sinusoid.

The ACJVS chip (Fig. 2) 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. 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. 2. Photograph of NIST ACJVS chip. The microwave launches for the 20 GHz drive signal are at right, and the voltage outputs at left.

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 [11,12]. 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 simple circuit model of the output transmission line is shown in Fig. 3.

Fig. 3. Schematic of ACJVS output transmission line.

In Fig. 3, inductances L_0 , L_2 , and capacitance C_3 , are located on the chip, and resistance R_2 and part of C_2 represent the twisted pair leads in the cryoprobe. The combination of C_2 - L_1 - R_3 - C_1 is the added physical components of the output filter. "Cable" represents the coaxial connection to the TTS, and R_1 - C_4 represents the input impedances of the transfer standard.

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); the TTS is calibrated by using the micropotentiometer (μ pot) at both full-scale input and at

reduced input to fully characterize the TTS, as shown in Fig. 4.

Fig. 4. 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 MJTC is generally 1 $\mu\text{V/V}$ 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 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 $\mu\text{V/V}$.

For this comparison, NRC reported for the ACJVS results uncertainties consistent with those provided for the key comparison CCEM-K11 [13], including 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 [14]. A summary of the NRC uncertainties is shown in Table 2.

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. We assume that the uncertainty of the

ACJVS is dominated by the characteristics of the transmission line. The Type A uncertainty contributions include the standard deviations of the measured data and the stability of the transfer standard. Simulations of the transmission line shown in Fig. 2 indicate that the uncertainty of the transmission line depends critically on the circuit elements comprising the line between the ACJVS chip and input connector of the TTS. Table 3 lists the Type B uncertainties, calculated using [9], associated with the circuit elements, as well as the final Type B uncertainty of the NIST ACJVS. 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, as indicated in Table 3. These uncertainties were used by NIST for SIM.EM-S11 at the points specified in the comparison.

Table 1. Type B uncertainties associated with the circuit elements comprising the output transmission line, in $\mu\text{V/V}$.

Parameter	2.5 kHz	5 kHz	10 kHz	20 kHz
R_2	0.5	0.5	2.0	3.5
C_1	0.0	0.5	0.5	0.7
C_2	0.3	0.7	2.3	4.0
L_1	0.3	0.7	2.7	4.0
L_2	0.0	0.0	1.0	1.5
C_3	0.0	0.0	0.0	0.0
L_0	0.0	0.0	0.0	0.0
Cable length	0.5	0.5	2.0	3.0
Expanded Uncertainty ($k = 2$)	0.7	1.5	4.9	12.0

Table 2. Expanded ($k = 2$) NRC uncertainties for SIM.EM-S11

Voltage Range mV	Applied Voltage mV	Uncertainty ($\mu\text{V/V}$ of applied voltage)			
		2.5 kHz	5 kHz	10 kHz	20 kHz
22	6	37	37	37	37
22	10	25	25	25	25
220	100	8	8	8	8

Table 3. Expanded ($k = 2$) NIST uncertainties for SIM.EM-S11

Voltage Range mV	Applied Voltage mV	Uncertainty ($\mu\text{V/V}$ of applied voltage)			
		2.5 kHz	5 kHz	10 kHz	20 kHz
22	6	12	12	12	15
22	10	4	4	7	12
220	100	2	2	5	12

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 4.

Table 4. 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

$$\delta = \frac{V_{ac} - V_{dc}}{nV_{dc}} \quad (1)$$

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.)

Except for the 200 mV measurements, the reported results are averages of data obtained using the left and right arrays individually, and the disagreement between the arrays is accounted for as a Type A contribution in the uncertainty analysis. The 200 mV output is obtained by using the arrays in series; the Type A contribution for these points is the standard deviation of a large number of measurements. For both laboratories, the ambient temperature was reported to be $(23 \pm 1)^\circ\text{C}$ at a relative humidity of $(45 \pm 10)\%$. The low terminal of the input connector on the TTS and guard and ground terminals on the front panel were 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.

The results from ACJVS measurements on the TTS depend critically upon the selection of the plane of reference for the applied voltage. In general, for AC-DC transfer difference measurements with two TTSs, the plane of reference is at the center of a tee structure connecting the two devices. For AC voltage measurements, the TTS and the source are connected as closely as possible to each other to minimize the length of the transmission line between the devices. In the case of the ACJVS, the plane of reference is at the output pads of the Josephson chip, with the TTS connected to the plane of reference using the transmission line in the cryoprobe, and additional coaxial cable from the cryoprobe head to the TTS (a distance of about 1.5 m.) The length of the transmission line introduces frequency-dependent errors; however, we assume that the NRC and NIST ACJVS systems are sufficient similar to neglect differences in the output transmission lines.

V. RESULTS

The results of the intercomparison are presented in Figs. 5-8 as the differences in the NIST and NRC data. The error bars reflect the expanded ($k = 2$) uncertainties of the laboratories combined using RSS.

Fig. 5. Agreement between NIST and NRC ACJVS systems with 200 mV applied to the 220 mV range.

Fig. 6. Agreement between NIST and NRC ACJVS systems with 100 mV applied to the 220 mV range.

Fig. 7. Agreement between NIST and NRC ACJVS systems with 10 mV applied to the 22 mV range.

Fig. 8. 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 extremely 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 interesting to note that the largest inter-laboratory discrepancies are seen at 200 mV, the only point requiring the two arrays to be used in series. The output signals from the ACJVS chip are brought up the probe using dedicated transmission lines for each array. Although the NIST and NRC systems are substantially identical, the output voltage leads differ; twisted pair magnet wire with PFTE insulation over varnish is used in the NIST ACJVS, while twisted, stranded wire with PFTE insulation is used in the NRC system. While it is unlikely that the transmission lines are contributing large errors at 10 kHz, we have recorded differences of several $\mu\text{V/V}$ in the outputs of individual arrays and it is possible that the inter-laboratory discrepancies seen at 200 mV are the result of differences in the NIST and NRC ACJVS output stages.

VII. CONCLUSIONS

As reported earlier in [15], we have performed the first international intercomparison of quantum ac voltage standards, using as a traveling standard a thermal transfer standard shipped between NIST and NRC. Over the limited frequency range available with these systems, we found excellent agreement between the laboratories at applied voltages from 200 mV down to 6 mV, including differences of 1 $\mu\text{V/V}$ or less at all frequencies at 100 mV applied. This superb agreement provides confidence in both the quantum systems and the traditional step-down techniques, and also provides a solid basis for the low-level calibration services of the participants.

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