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Voltage Metrology Using a Quantum AC Standard

Thomas E. Lipe, Joseph R. Kinard, Yi-hua Tang, Samuel P. Benz, Charles J. Burroughs, and Paul D. Dresselhaus

Abstract: We report on the use of a quantum-based AC voltage standard for ac-dc difference metrology at the National Institute of Standards and Technology (NIST). The paper describes the characterization of the output transmission line and the methods used to correct for its errors, the use of the quantum standard in voltage scaling to calibration thermal transfer standards, and its use in the NIST calibration services for thermal voltage converters at frequencies up to 100 kHz. Plans for future use are also presented.

1. Introduction

The primary standards for ac voltage at NIST and other national metrology institutes (NMIs) are multijunction thermal converters (MJTCs) [1, 2]. Both measurement and mathematical simulation of these devices indicate that MJTCs can have ac-dc differences of less than 1 μV/V from about 250 mV to 3 V or more at audio frequencies, although they are presently used with good results from 10 Hz to 100 MHz.

Ac-dc differences outside the voltage range of MJTCs are determined using range-to-range scaling techniques [3]. This type of scaling can be difficult to perform accurately, and requires the use of well-made and well-characterized thermal transfer standards (TTS) with small voltage coefficients. The uncertainties assigned to a TTS escalate rapidly with the number of scaling steps, so that the relative uncertainties determined by NIST at 2 mV are several orders of magnitude larger than for the primary standard level. The performance of contemporary ac-dc transfer standards at low voltage is good enough that uncertainties determined by range-to-range scaling are no longer small enough to satisfactorily characterize these instruments.

In addition to the increasing need to reduce uncertainties, other factors are driving the development of non-thermal ac voltage measurements. Most users of thermal transfer standards use them for calibrating voltmeters and calibrators, tasks that could more efficiently be done using an ac voltage source. Unfortunately, no existing conventional voltage source exists that can approach the performance of TTSs. In addition, a philosophical argument can be made that, since ac voltage metrology is based on artifact standards, it is not well referenced to International System (SI) units, a situation that may no longer be tenable given the focus of NMIs on fundamental standards such as watt balances, Josephson voltage standards, and quantum Hall resistors.

To satisfy the requirements for improving ac voltage metrology, NMIs are developing ac standards based on the Josephson effect. Two types of quantum ac standards are being investigated. The first type, and the subject of this paper, generates a sinusoidal output from high-speed pulses applied to the Josephson junctions, and is widely known as an AC Josephson Voltage Standard (ACJVS). The second type uses segments of programmable Josephson junctions to generate a stepped waveform approximating a sinusoid, and is known as a Programmable Josephson Voltage Standard, or PJVS [4].

In this paper we concentrate on the characterization of, and metrology using, an ACJVS at NIST, and describe this method to characterize thermal transfer standards in terms of quantum based ac and dc sources.

2. ACJVS

2.1 ACJVS Chip

An ac source based on the Josephson effect was first described by Hamilton and Benz in 1996 [5], and realized as a useful

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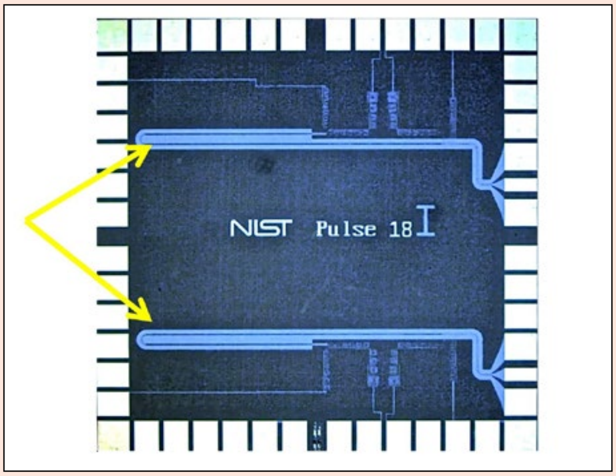

Figure 1. Photograph of an ACJVS chip. The die size is approximately 1 cm^2. The arrays are the two horizontal features shown with arrows.

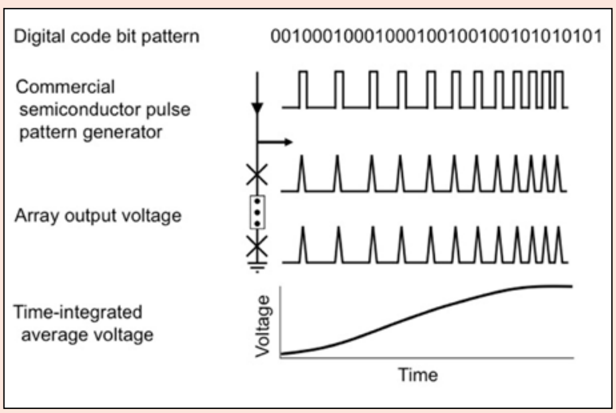

Figure 2. Operation of ACJVS, showing the digital code pattern produced by the code generator, the output voltage pulses of a Josephson array, and the time-average output sinusoid.

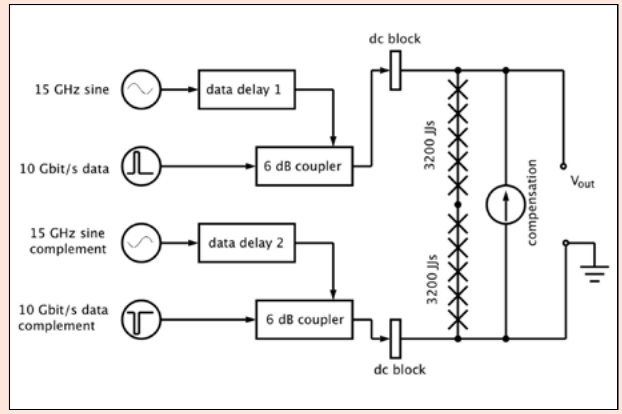

Figure 3. Schematic of ACJVS system showing microwave drives and pulse generators for both channels.

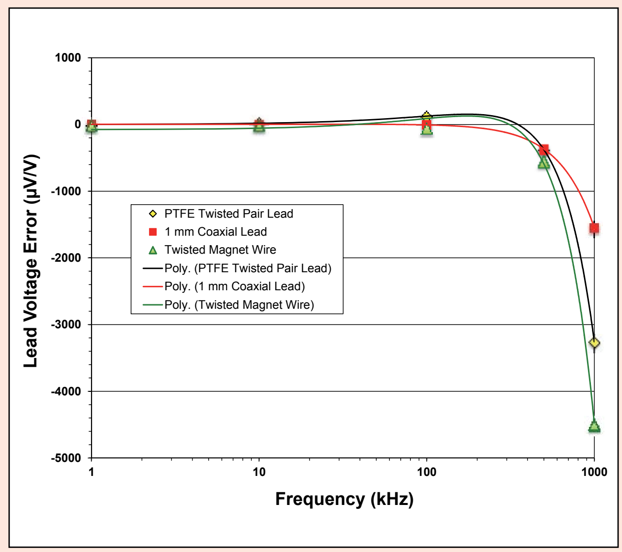

Figure 4. Comparison of the various types of wire used for the ACJVS output transmission line.

metrological tool some ten years later [6]. The ACJVS produces ac waveforms via digital-to-analog synthesis using high-speed sigma-delta modulation. The perfect quantization of the Josephson voltage pulses makes the ACJVS intrinsically accurate. The precise control of the quantized pulses allows arbitrary waveforms with accurate, calculable voltages.

Presently, ACJVS systems based on the technology developed by Benz, et al., at NIST in Boulder, Colorado, are used at NMIs in the U.S., Canada, the Netherlands, Australia, and South Korea. The ACJVS chip used at NIST, shown in Fig. 1, features two arrays of 6400 junctions each. If the arrays are used in series, a maximum output voltage of about 300 mV is possible.

A bipolar pulse train supplied by a commercial bitstream generator excites the Josephson arrays; this causes the junctions to produce a series of voltage pulses, the time integral of which is perfectly quantized. The input current pulses are modulated with a low-frequency sinusoidal waveform, which appears in the spectrum of the output voltage pulses, as shown in Fig. 2. The magnitude of this low-frequency component can be calculated from the number of junctions in the array, the known area of a single pulse, and the pulse modulation pattern.

A schematic of the ACJVS is shown in Fig. 3. Presently, the ACJVS is limited to a normal lower frequency limit of 2.5 kHz due to memory limitations in the code generator, and an upper voltage limit of about 300 mV because of the limited number of junctions. A new code generator is under development, which should allow measurements at 50 Hz and below.

2.2 Output Transmission Line

The plane of reference for the ACJVS is at the output of the on-chip Josephson arrays. In normal operation, the voltage supplied by the ACJVS chip is applied to the unit under test (UUT) via leads about 1 m long inside a cryoprobe. The ACJVS chip is placed inside a mumetal shield at the cold end of the probe, at the bottom of the dewar, and the output signal routed up through the cryoprobe to the probe head, and then through a 30.5 cm RG-58 lead to the UUT. Several types of leads

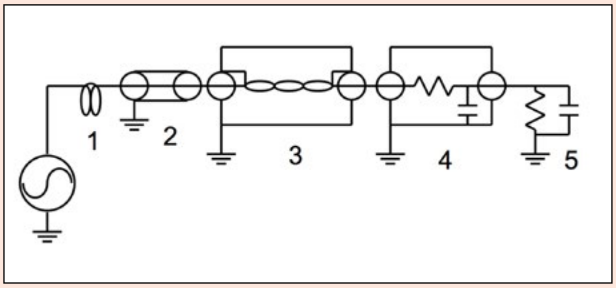

Figure 5. Equivalent circuit of ACJVS transmission line and TTS input showing on-chip inductances (1), 30.5 cm RG-58 cable (2), coaxial choke (3), RC filter (4) and TTS input (5).

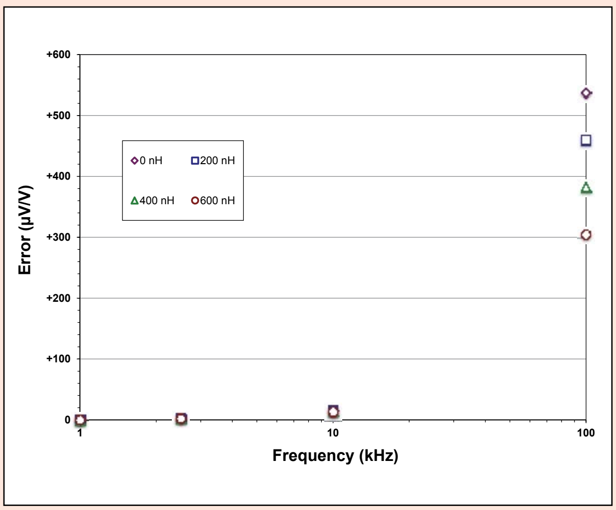

Figure 6. Effect of various on-chip inductances on transmission line error. The markers cover the uncertainty bars.

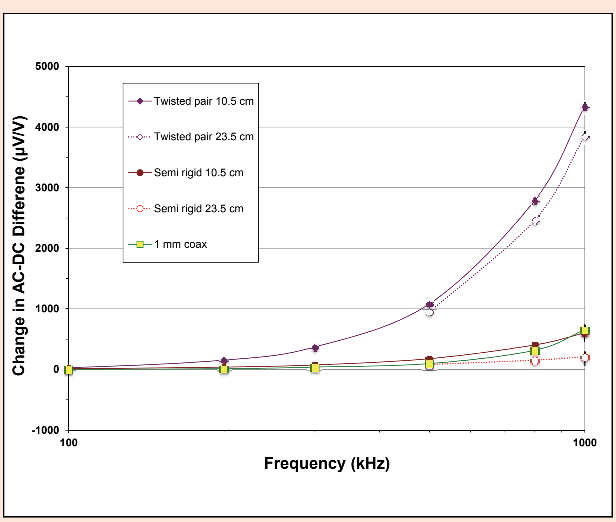

Figure 7. Effect of liquid helium level on transmission line error. The error bars are smaller than the markers. The errors at frequencies less than 100 kHz are negligible. The 1 mm coaxial line was measured only at the 10.5 cm level.

have been evaluated, included magnet wire with varnish insulation, twisted-pair wire with polytetrafluoroethylene (PTFE) insulation, and low-temperature 1 mm coaxial cable. Systematic, frequency-dependent errors associated with this output network must be taken into account before the ACJVS can be used as a metrological system, especially at frequencies exceeding about 100 kHz.

The error contribution of the transmission line was estimated using a combination of measurements and extensive simulation of the circuit. Experimental verification of the transmission line errors involved the measurement of a thermal transfer standard with and without the probe and the enclosed transmission line connected between the plane of reference and its input terminal. The variation in ac-dc difference with and without the probe provides an estimate of the effect of the probe and transmission line. Of the three transmission line types, the 1 mm coaxial cable shows the least variation with length, as shown in Fig. 4. The 1 mm coaxial cable was used for the data shown in Figs. 7, 8, and 9.

To reduce the digital noise produced by the high-speed pulses supplied to the Josephson junctions, a simple RC filter was inserted in the transmission line, along with a coaxial choke to eliminate common-mode voltages in the output signal, as shown in Fig. 5. Results of electrical simulation of the transmission line with various values of on-chip inductance are shown in Fig. 6; as can be seen, the transmission line error is critically dependent upon the on-chip inductance. From geometrical considerations, we calculate this inductance to be about 36 nH. The measured error of the probe at 100 kHz is (+538 ± 20) µV/V, indicating that the on-chip inductance is less than 50 nH.

2.3 Effect of Liquid Helium Level

In operation, the ACJVS probe is inserted into a 100 L storage Dewar of liquid helium until the shielded enclosure for the chip is nearly at the bottom of the Dewar. During the course of the measurements, it was noticed that the day-to-day variation in the ac-dc difference of the ACJVS seemed to correlate with the level of liquid helium (LHe) in the storage Dewar. To check for this effect, a series of controlled measurements were made at defined probe-head heights above the Dewar collar, and compared to measurements on the probe at room temperature. The results are shown in Fig 7. To magnify the effect of the LHe level, a loop of transmission line of twice the probe length was installed inside the probe, and measurements made with the probe all the way in the dewar, and partially retracted from the dewar. The twisted-pair wire exhibited both the largest absolute error and the largest change with helium level, while a semi-rigid microwave cable showed the least. The 1-mm coaxial cable showed a relatively small error. It is important to note that this effect seems to be important only at frequencies above 100 kHz [7].

3. Measurement Results

The first use of the ACJVS as a calibration tool was reported in 2007 [6]. Since then, NIST has disseminated ac-dc difference data using a TTS traceable to the ACJVS at frequencies from 2.5 kHz (the lower frequency limit of the ACJVS) to 20 kHz. More recent work has validated the ACJVS at frequencies up to 100 kHz. Figures 7 and 8 show new measurements at 50 kHz and 100 kHz with 100 mV applied to the 220 mV range of the TTS. The data include the stability of the two ACJVS arrays over several days, and the agreement between values measured for the TTS and values

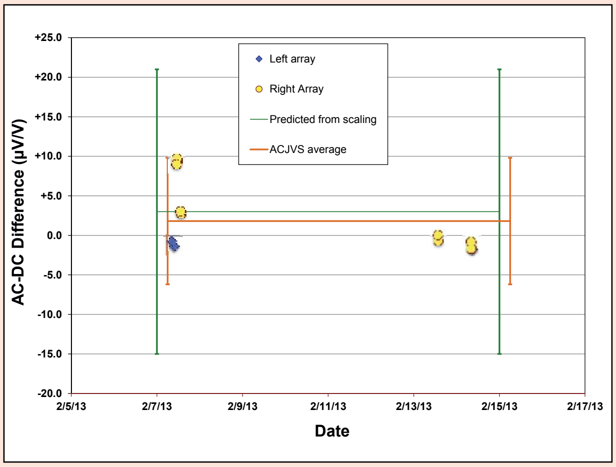

Figure 8. Performance of ACJVS, showing data for the right and left arrays on different dates, relative to the values predicted for the TTS from traditional scaling techniques at 50 kHz with 100 mV applied to the 220 mV range of the TTS.

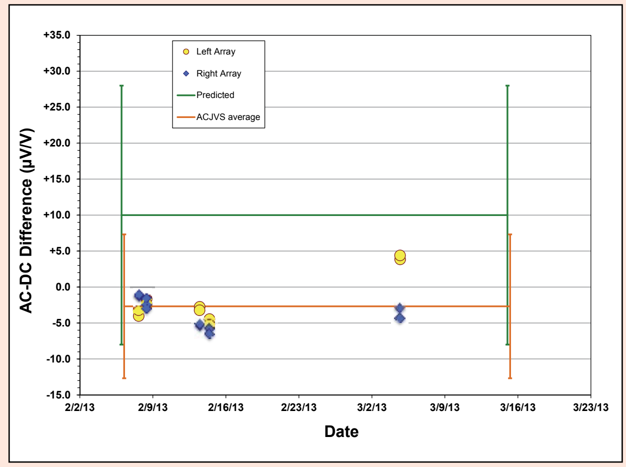

Figure 10. Performance of ACJVS, showing data for the right and left arrays on different dates, relative to the values predicted for the TTS from traditional scaling techniques at 50 kHz with 60 mV applied to the 220 mV range of the TTS.

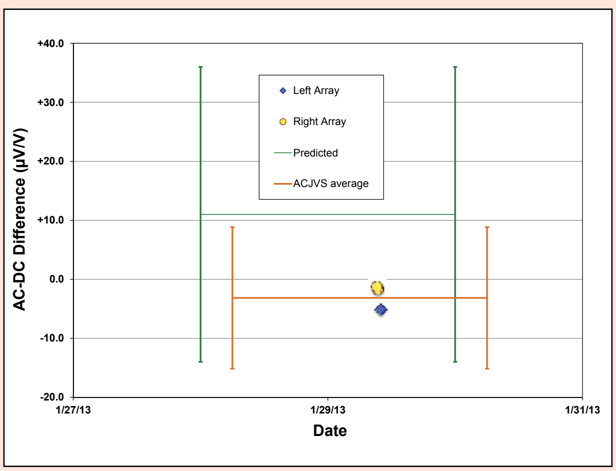

Figure 9. Performance of ACJVS, showing data for the right and left arrays on different dates, relative to the values predicted for the TTS from traditional scaling techniques at 100 kHz with 100 mV applied to the 220 mV range of the TTS.

	100 KHZ	300 KHZ	500 KHZ	1 MHZ
Present (100 mV)	35	70	100	170
Anticipated (100 mV)	12	20	30	50
Present (10 mV)	135	200	270	335
Anticipated (10 mV)	50	80	130	160

Table 1. Present expanded relative uncertainties (k = 2) for internal NIST calibrations and anticipated uncertainties using ACJVS, in μV/V of applied voltage.

predicted from the traditional scaling techniques. The uncertainties shown for the TTS are expanded uncertainties (k = 2) determined from the range-to-range scaling. Uncertainties for the ACJVS at these points are based on the variation of the system (Type A) the change in ac-dc difference caused by varying the parameters of the circuit model of Fig. 5, and the characteristics of the TTS.

4. Summary of Results

The most recent measurement cycle was designed to test the ACJVS at extended voltage and frequency ranges, including the characterization of the transmission line at frequencies up to 100 kHz. Using a combination of coaxial choke and RC filter, we determined the on-chip inductance to be less than 50 nH, consistent with the value of about 36 nH estimated from geometrical considerations. We also determined that the effect of liquid helium level is significant only at frequencies above 100 kHz, and can be largely ignored in the present work. Characterization of the TTS, shown in Figs. 8, 9, and 10 indicates that, at least at higher voltages, the measured ac-dc differences are consistent with those predicted using traditional range-to-range scaling. Corrections for the transmission line based on measurements of the frequency-dependent effects and simulations described above are included in the ACJVS data.

5. Conclusions

The NIST ACJVS has been used for several years to provide calibration customers with ac-dc difference data referenced directly to a quantum standard at frequencies from 2.5 kHz to 20 kHz. The work described in this paper will allow us to expand the calibration frequency range to 100 kHz, and provides an excellent basis to extend it to 1 MHz. The successful determination of the on-chip inductance, the intra-array variation, day-to-day variations, and variation with cryogen level will allow us to calculate uncertainties for ac-dc differences provided by the ACJVS that are significantly smaller than those provided by range-to-range scaling techniques, as shown in Table 1. Combined with the PJVS, this system will provide a quantum basis for ac voltage metrology at NIST well into the future.

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