Progress Toward a 1 V Pulse-Driven AC Josephson Voltage Standard

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***Abstract*—We present a new record root mean square (rms) output voltage of 275 mV, which is a 25% improvement over the maximum that is achieved with previous ac Josephson voltage standard (ACJVS) circuits. We demonstrate the operating margins for these circuits and use them to measure the harmonic distortion of a commercial digitizer. Having exceeded the threshold of 125 mV rms for a single array of Josephson junctions, we propose and discuss the features of an eight-array circuit that is capable of achieving 1 V rms. We investigate the use of a resistive divider to extend the ACJVS voltage accuracy to higher voltages. By the use of a switched-input measurement technique, an integrating sampling digital voltmeter, a resistive voltage divider, and ACJVS synthesized sine waves as reference voltages, we characterize the stability of a commercial calibration source for a few voltages up to 2.7 V.**

***Index Terms*—Digital–analog conversion, Josephson arrays, quantization, signal synthesis, standards, superconductor–normal–superconductor devices, voltage measurement.**

I. Introduction

SINCE the invention of the pulse-driven Josephson digital-to-analog converter in 1995 [1], an important goal has been to increase the root mean square (rms) output of the quantum-accurate synthesized waveforms to 1 V. Most audio-frequency voltage calibrations that are performed with thermal voltage converters use this amplitude. This large output voltage is also important for increasing the signal-to-noise ratio of other precision measurement applications. Ten years of continual research and development was required to increase the output voltage from a few microvolts for a single junction to 100 mV for dual-array circuits [2], [3]. The first practical ac Josephson voltage standard (ACJVS) system was implemented in the National Institute of Standards and Technology (NIST) ac voltage calibration service in 2006 [4].

During the past two years, further improvements have been made, particularly to the microwave design of the superconducting Josephson circuits, which have enabled circuits with two arrays to generate rms amplitudes up to 220 mV [5], [6]. In this paper, we present a new record output voltage of 275 mV rms. Although it is an incremental improvement, the result is particularly important because the circuit exceeds the threshold of 125 mV rms for a single array. This allows us to propose a practically achievable eight-array circuit that will enable the direct synthesis of 1 V rms quantum-accurate waveforms. We describe the proposed 1 V circuit and present the measured results at 275 mV, including fast Fourier transform (FFT) measurements using a commercial digitizer at 1 kHz and 100 kHz frequencies. We also use these circuits to investigate a measurement technique, based on a resistive divider, that might be used to extend the ACJVS accuracy to higher voltages.

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II. Higher Voltage Arrays and Circuits

Because the output voltage of a single Josephson junction is only 30 μV for a typical 15 GHz bias signal, series arrays of junctions are required to achieve useful voltages in the millivolt range. Unfortunately, the voltage that can be produced by a single array is also limited because only a finite number of junctions can be placed in series before junction dissipation detrimentally attenuates the microwave bias signal along the array [7]. The maximum rms voltage of a single distributed array (with negligible capacitance) is independent of frequency and is typically around 50 mV.

To further increase the voltage, two techniques have been implemented: 1) an ac-coupled bias technique that allows multiple arrays to be connected in series [8] and 2) improved microwave designs that counteract the dissipation and allow more junctions in a single array [5], [6]. In this paper, further improvements were made to the microwave design that allowed the number of junctions to be increased from 5120 to 6400 so that the rms voltage per array increased from 110 mV to 137.5 mV. More junctions were possible because the array transmission line impedance was tapered even further (from 50 Ω at the input to 22 Ω at the termination), whereas the previous circuits were tapered to only 32 Ω [6]. The mean critical current and the mean resistance of the junctions are 8.1 mA and 4.3 mΩ, which are similar to previous circuits.

We used the ac coupling technique to double the output voltage by summing the voltage from two arrays. A simplified circuit schematic for the ac-coupling technique is shown in Fig. 1. Commercial bitstream generators typically have a second complementary data output (D−) that produces a bit sequence that is the ones-complement of the data output (D+), which, for our purposes, produces an analog waveform of inverted polarity. DC blocking capacitors (acting as broadband high-pass filters and audio-frequency stop-band attenuators) remove

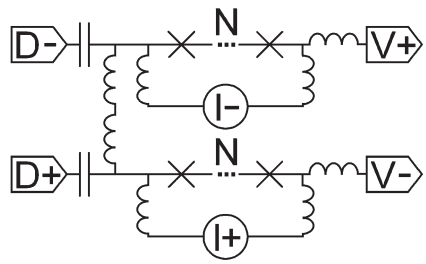

Fig. 1. Simplified schematic of an ac-coupled circuit showing the differential voltage output, the capacitive dc blocks, the compensation current (I), the data (D+) and data complement (D−), the inductive low-pass filters, and the "N" number of series junctions per array.

the low-speed (in this case, audio frequency) component of the digital bias signal. This prevents common-mode signals from appearing on the microwave terminations (not shown) and allows the low-speed inductively filtered output-voltage leads to float so that the two arrays can be connected in series. However, to achieve operating margins, the audio-frequency bias (of appropriate polarity I±) must be reapplied across each array (except for low-voltage signals, where it is not necessary). This "compensation" bias is provided through floating differential amplifiers and commercial arbitrary waveform generators with adjustable gain that are synchronized with the digital waveform.

III. ACJVS Design for the 1 V Output

We propose constructing a 1 V rms ACJVS system using this same ac-coupled bias technique. In this design, the circuit of Fig. 1 would be quadrupled so that eight arrays are connected in series. There is enough room for eight arrays of stacked junctions on a chip that is 1 cm^2. The challenge of this approach is to simultaneously create and synchronize the output waveforms of the eight digital and eight compensation bias signals. Currently, such a system cannot be implemented because there are no commercially available high-speed (greater than 10 Gb/s) digital bitstream generators that have eight synchronized output channels. We are currently collaborating with high-frequency instrument experts to create an instrument with such multiple channels, as well as a larger memory that will enable lower frequencies to be synthesized.

IV. Digitizer Measurements

The arrays are biased with a 15 GHz microwave drive and a 4 Mb digital pattern that is clocked at 10 Gb/s. Waveforms with a minimum frequency of 2.5 kHz can be synthesized with this configuration, as well as integer multiples of this pattern repetition frequency. We performed FFT measurements at a number of different voltages using these higher voltage circuits. Various waveforms were synthesized at different frequencies and amplitudes, and with either one or both arrays. ACJVS synthesized sine waves were measured with a National Instruments (NI) PXI-5922 digitizer with low harmonic distortion, as shown in Figs. 2 and 3.[1]

[1]Commercial instruments are identified in this paper only to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the NIST, nor does it imply that the equipment identified is necessarily the best available for the purpose.

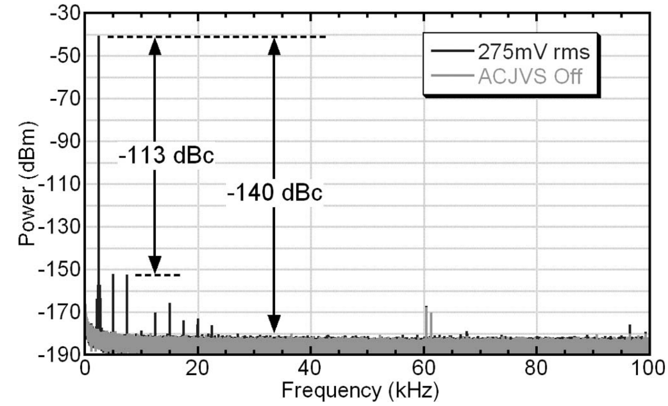

Fig. 2. Digitally sampled spectral measurement showing the −113 dBc low-distortion measurement of the ACJVS output. Two series-connected Josephson arrays are generating a precision 2.5 kHz, 275 mV (rms) sine wave. The digitizer used a 1 MΩ input impedance, a 10 V input range, a 2 Hz resolution bandwidth, 10 averages, and a 500 kS/s sampling rate. Gray-shaded data show the digitizer noise floor and spurious signals with the ACJVS pulses off.

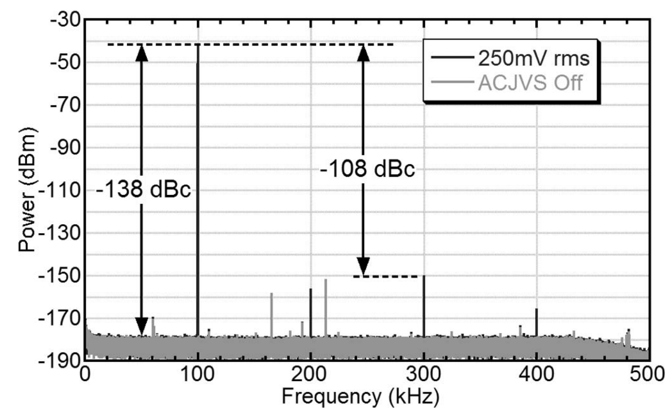

Fig. 3. Digitally sampled spectral measurement showing the −108 dBc low-distortion measurement of the ACJVS output. Two series-connected Josephson arrays are generating a precision 100 kHz, 250 mV (rms) sine wave. The digitizer used a 1 MΩ input impedance, a 10 V input range, a 4 Hz resolution bandwidth, 10 averages, and a 1 MS/s sampling rate. Gray-shaded data show the digitizer noise floor and spurious signals with the ACJVS pulses off.

The operating margins were determined for six different arrays on three different chips. Margins of all bias parameters for each of the six arrays were similar to those of the circuits with fewer junctions and are, thus, sufficient for all applications. For comparison with other circuits, we usually quote the dc operating margin, which is the dc current range over which no distortion is measured above that of the digitizer and its noise floor. The dc operating margin for each array in these new circuits was about 2 mA peak-to-peak, which is similar to that of previous circuits. Since the operating margins are similar to those of previous circuits, we conclude that the tapered design is properly working for these longer arrays.

The larger output voltage of these new circuits allows us to explore a larger dynamic range of the NI digitizer. This instrument has a front-end amplifier and a sigma–delta sampling analog-to-digital converter, both of which have low, yet measurable, intrinsic nonlinearities. Table I shows the measured distortion of the largest amplitude harmonic for different voltages, frequencies, and input ranges of the digitizer. The distortion values provide a characterization of the nonlinearities

TABLE I
MEASUREMENTS OF THE DIGITIZER DISTORTION FOR DIFFERENT ACJVS PRECISION VOLTAGES AT 2.5 kHz AND 100 kHz

Frequency (kHz)	Array Circuit	RMS Voltage (mV)	Distortion (dBc) Meter Range 10V	Distortion (dBc) Meter Range 2V
2.5	Both	275	-113	-122
2.5	Both	250	-114	-120
2.5	Single	125	-122	-114
100	Both	250	-108	-110
100	Single	125	-112	-108

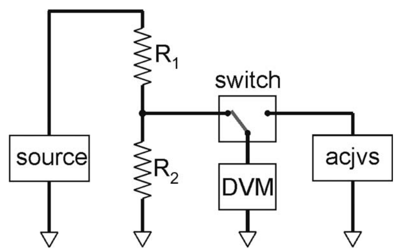

Fig. 4. Measurement configuration involving the switching unit and the resistive voltage divider that has resistor values $R_1 = 801\ \Omega$ and $R_2 = 90\ \Omega$.

of the digitizer. We use a number of techniques to confirm that the digitizer produces the distortion and not the arrays [6]. The measured distortion changes with different digitizer ranges, attenuated input, and after digitizer self-calibrations. The distortion remains identical for different arrays (including different chips and circuits) and for different array biases, provided that they are within the array operating margins. Even for the 100 kHz waveforms, the digitizer distortion is excellent, i.e., better than –108 dBc (decibels below the carrier or fundamental) for all voltages and input ranges.

The low measured harmonic distortion and excellent operating margins of these higher voltage circuits are more than adequate for use in ACJVS applications. We expect that additional measurements of operating margins, as well as precision voltage measurements using a thermal transfer standard, will confirm optimum operation of these 275 mV circuits.

V. MEASUREMENTS OF A COMMERCIAL AC SOURCE

One approach to extend the ACJVS accuracy to a higher voltage is by using a resistive voltage divider, as shown in the simplified circuit schematic of Fig. 4. The accuracy that is attributed to the higher voltage source will depend on the measurement technique, the stability and the uncertainty of the divider ratio, and the intrinsic stability of the source. Compared with other measurement techniques, such as differential sampling and differential or transformer-bridge lock-in detection, the switched-input direct-sampling approach, which we used in these measurements, has the advantage that the phase alignment of the two signals is not required. A major challenge of the resistive divider approach is that, in addition to a precise divider calibration, the value of the divided voltage is also dependent on the finite resistance of the input and output leads of the divider, including those of the switching circuit. The impedance of the source, load (measurement input), and transmission lines also affect the measurement accuracy. A precise calibration of the source amplitude requires these more detailed measurements.

TABLE II
VOLTAGE DEPENDENCE OF THE DC RATIO AND THE AC–DC DIFFERENCE AT 2.5 kHz FOR THE RESISTIVE VOLTAGE DIVIDER

Input Voltage	DC Measurement Ratio	DC Measurement Difference from 1 V ratio	2.5 kHz AC-DC Difference Difference	2.5 kHz AC-DC Difference Uncertainty
1V	0.10105299	-	1 μV/V	5 μV/V
2V	0.10105416	11.6×10^{-6}	2 μV/V	4 μV/V
3V	0.10105475	17.4×10^{-6}	2 μV/V	5 μV/V

The ratio at 2.5 kHz has the same ratio as at DC, within the measurement uncertainty. The uncertainty is k=2.

For the switched-input measurements described below, we compared the commercial source voltage with the ACJVS reference voltage by alternately measuring their signals with an Agilent 3458 time-integrating sampling (digital) voltmeter (DVM). The voltage source was a Fluke 5720A multifunction calibrator. All the measured signals were at a frequency of 2.5 kHz. The ACJVS waveforms were all synthesized by the use of one of the 275 mV ACJVS chips described above. Different rms voltages were produced with different waveforms and with either one (137.5 mV) or both arrays (200 mV and 275 mV). The switching network contained latching relays with contact resistances that are smaller than 50 mΩ. This NIST-built switch circuit board is battery operated and optically decoupled from the computer.

The divider that we used had a total resistance of 891 Ω, and its ratio was nominally 9.9 : 1. The first two columns of Table II show the dc ratio that was measured with a DVM and a precision current source at three voltages. The ratio has voltage dependence, which is probably a thermal response, such that the ratio increases by 17.4×10^{-6} from 1 V to 3 V. The ratio values at 2.5 kHz were inferred from the dc ratios through ac–dc difference measurements using thermal converter comparisons. The 2.5 kHz ratios at the same voltages appear to agree with the dc ratios, within the nominal 5 μV/V measurement uncertainty $(k = 2)$.

As a preliminary step toward a voltage accuracy comparison, in the measurements below, we investigated the stability of the source and characterized the measurement noise (which is one contribution to the type A uncertainty $k = 1$) of the sampled-switched-input comparison technique. For the 2.5 kHz waveform measurements presented here, the DVM aperture time is set at 20 μs. The measured signal and reference amplitudes are first determined by use of a fitting calculation based on 8000 sampled voltages (1000 periods of 2.5 kHz) [9]. The signal is then reconstructed or "calibrated" by the reference amplitude. The commercial DVM was modified to operate with an external time reference. All the measurements were performed on the 1 V range of the DVM.

To evaluate the switched-input measurement technique, we first determined the measurement noise and the gain stability of the DVM and the switching circuit. The same ACJVS signal was applied to both switch inputs (via a BNC tee), which were then alternately measured with the DVM. One of these signals was used as the "reference." The series of ACJVS reference signal measurements allows the gain variation and the first-order drift of the DVM to be calculated and removed

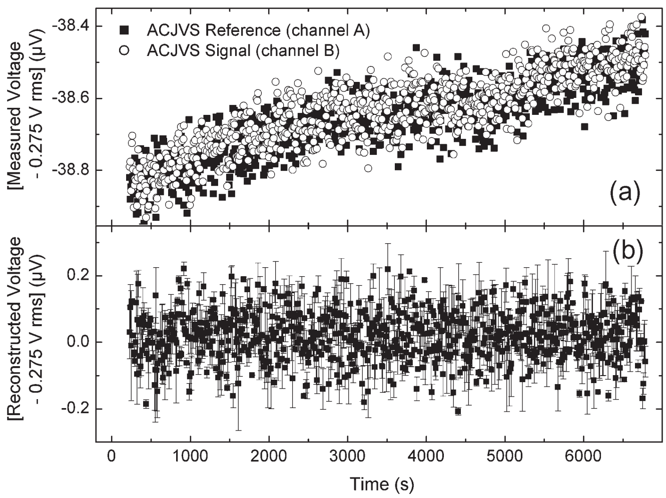

Fig. 5. (a) Time-dependent measurements of the ACJVS 275 mV, 2.5 kHz signal. The same signal was supplied to both inputs of the switch circuit. (b) Reconstructed amplitude shows the minimum noise level that is achievable for the DVM and the switch circuit.

(in these measurements as well as those of the commercial source). The results in Fig. 5(a) show a -38.8 μV mean gain offset of the DVM that monotonically increases with time. Other measurements on different days had much smaller drift. The measurement emphasizes the usefulness of the ACJVS reference for calibrating the measurement instrument. Continuously measuring the ACJVS reference voltage is also important for verifying that the Josephson system remains on operating margins for the duration of the measurement.

Fig. 5(b) shows the reconstructed amplitude of the second ACJVS "source" signal after correcting for the DVM gain and drift via the ACJVS reference measurements. The standard deviation of these data is 74 nV. This measurement, which was the longest one that we performed, was completed over 1 h 52 min. Compared with the 275 mV signal, these data (Fig. 5) have a relative standard deviation of 0.3 μV/V, which represents the lowest achievable noise on this range of the DVM. Interestingly, we measured a small 20 nV offset in the reconstructed amplitude, which indicates a systematic difference between the two input channels of the switching circuit. This may be caused by an additional resistance in one of the switches or from additional line lengths. Although it is only a small error, it demonstrates the challenge of using this method to make an absolute voltage determination of a source, even when a quantum standard is used as a reference.

Next, we made *direct* measurements of the commercial source signal without the resistive divider. These measurements provided information about the source stability for different voltage amplitudes. Results of these direct-source measurements are shown in the first three rows of Table III. Standard deviations are tabulated for the ACJVS reference signals σ_{REF} and the reconstructed source amplitudes σ_{MEAS}. For the two lowest voltages, σ_{MEAS} is more than twice as large as σ_{REF}. For the largest 275 mV measurement, σ_{MEAS} is about eight times larger than σ_{REF} and about ten times larger than σ_{MEAS} for the lower voltages. For these direct measurements, source stability σ_{SRC} is equivalent to σ_{MEAS}.

TABLE III
MEASURED STANDARD DEVIATIONS OF ACJVS REFERENCE σ_{REF}, SOURCE VOLTAGE σ_{MEAS}, AND THE INFERRED STANDARD DEVIATION OF SOURCE σ_{SRC}

ACJVS Ampli. (V)	σ_{REF} (µV)	Source Ampli. (V)	σ_{MEAS} (µV)	σ_{SRC} (µV)	Source range (V)	Relat. σ_{SRC} *(µV/V)*
0.1375	0.05	0.13750	0.10	0.10	0.22	*0.8*
0.2000	0.05	0.20000	0.14	0.14	0.22	*0.7*
0.2750	0.13	0.27500	1.01	1.01	2.20	*3.7*
0.1375	0.04	1.36086	0.14	1.37	2.20	*1.0*
0.2000	0.05	1.97973	0.14	1.36	2.20	*0.7*
0.2750	0.09	2.72146	1.09	10.80	22.00	*4.0*

All measurements were performed at 2.5 kHz. For the 137.5 mV ACJVS voltages, only one array was used. The first three rows describe direct comparisons, while the second three are with the resistively divided source (Fig. 4). The inferred standard deviation of the source scales with the source range. The right-most column is the relative standard deviation of the source (σ_{SRC} divided by the source voltage).

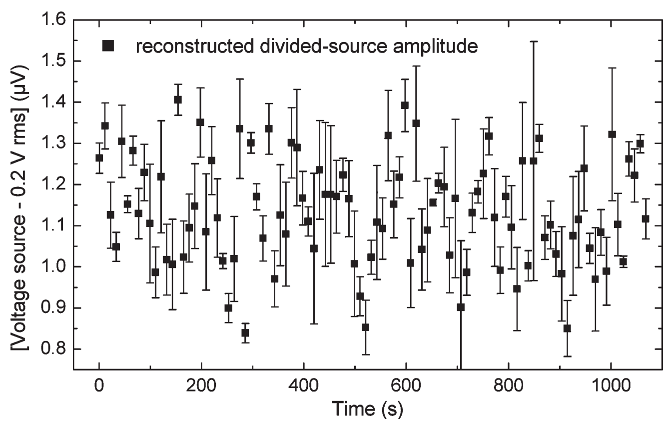

Fig. 6. The 9.9×-divided 2 V source voltage versus time measured with a 200 mV ACJVS reference voltage at a 2.5 kHz frequency. The standard deviation is 0.14 μV.

The main difference between this higher voltage measurement and the two lower voltage measurements is that the source is at a higher output range. The 0.22 V range is used for the 200 mV signal, whereas the 2.2 V range is used for the 275 mV signal. The stability of the source is, therefore, linked with its range, as one might expect. This effect is not caused by differences in the ACJVS waveforms because the same waveform was used to generate the reference voltage at 137.5 mV (with only one array) as was used at 275 mV (synthesized with both arrays), and different waveforms were used for the two lowest voltages. The last column in Table III shows the relative standard deviation of the source (the sigma source divided by the source voltage), which is five times larger (3.7 μV/V) for the 275 mV source signal, from the higher range, than that for the two lower voltage signals (less than 0.8 μV/V).[2]

For the final three measurements shown in Table III, we measured higher voltages of the commercial source signal by the use of the resistive *divider*. As an example, Fig. 6 shows the time-dependent data that were measured when the source

[2]We note that this measurement standard deviation, which is primarily dominated by the source noise floor of the calibrated source on the 2.2 V range, agrees with that determined by the use of a completely different differential measurement technique that was performed at 60 Hz with quantum-accurate stepwise approximated sine waves [9].

voltage was 2 V. The source voltages were increased 9.9-fold, so that their 9.9-fold-divided voltages could be compared with the ACJVS reference voltage, as shown in Fig. 4. The amplitude of the divided source signal was always comparable to that of the ACJVS reference. The corresponding stability of the source output signal σ_{SRC}, namely, that provided to the divider input, is calculated as the product of the measured stability and the divider ratio. The source stability for these higher voltages (and higher output ranges) follows the same behavior as the previous direct measurements without the divider, namely, that the standard deviation increases about tenfold for the next higher source range. The relative standard deviation is 4 μV/V for the 2.7 V signal from the 22 V range, as measured with the divider, and the 275 mV ACJVS voltage reference. The relative standard deviations of the lower voltages (on the 2.2 V range), as measured with the divider, are less than 1 μV/V.

We observed another interesting feature of the resistive voltage divider approach that has implications for measuring the voltage accuracy and stability of voltage sources. For sufficiently long measurement times (at least 20 min), we observed a drift in the measured source voltage that was caused by the divider. We believe that the drift probably resulted from a thermal response of the divider because it was particularly prominent for higher source voltages. To minimize the thermal response of the divider, we waited for at least 20 min before measuring the source with the divider. For future divider measurements, we will likely construct an improved divider with better thermal stability.

As mentioned above, there are many issues that require resolution before the resistive-divider switched-input approach can be used to improve the accuracy of high-voltage source signals using the ACJVS. For example, the integrating sampling DVM may not be the best measurement instrument for higher frequencies because the measurement noise will increase for shorter aperture times [10]. The sampling FFT digitizer, which was measured in Section III, is a potential alternative measurement instrument.

Summarizing the results of the switched-input measurement, we found that the relative standard deviation of the measurement setup is 0.3 μV/V, which was determined by measurements with the DVM without the divider, and the ACJVS was used as the source and the reference. For the commercial source measurements, the measurement noise was three to ten times higher (depending on the source range) and was dominated by the source stability.

VI. Conclusion

In Section V, we have described detailed measurements using a resistive voltage divider with a switched-input measurement technique to characterize the stability of a commercial source. We have concluded that the measurement noise can be made sufficiently low so that resistive dividers are a useful approach to extending the accuracy of the ACJVS to higher voltages. However, we reiterate that to fully determine a source's voltage accuracy, many systematic errors must be measured and characterized, such as those from lead resistances as well as source and load impedances. Other approaches, such as the use of amplifiers with highly stable gain, should also be investigated. Different approaches may be better suited for different applications, such as those requiring a high voltage or a high frequency. In any case, the best solution to achieve accurate higher voltage waveforms is to increase the output voltage of the ACJVS system. Until the necessary bias electronics are available that will allow the operation of the eight-array 1 V ACJVS, there are a number of useful measurement techniques that can be explored and improved with the present ACJVS system, which will have a positive impact on ac voltage metrology.

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