AC Voltage Measurements to 120 V With a Josephson Arbitrary Waveform Synthesizer and an Inductive Voltage Divider

Dimitrios Georgakopoulos, *Senior Member, IEEE*, Ilya Budovsky, *Senior Member, IEEE*, and Samuel P. Benz, *Fellow, IEEE*

***Abstract*—We have developed a system to extend, by a factor of up to 1000, the voltage range over which Josephson arbitrary waveform synthesizers (JAWS) can be used in ac voltage metrology. The system is based on a precision inductive voltage divider, with a lock-in amplifier as the detector. Using a JAWS with a maximum output voltage of 250 mV (root mean square), we have made accurate voltage measurements up to 120 V at 60 Hz with expanded uncertainties ($k = 2$) of no more than 1.5 μV/V and demonstrate that the system can operate up to 1 kHz. We anticipate that our JAWS-based system will improve uncertainties in ac voltage metrology by one order of magnitude compared to techniques based on thermal voltage converters.**

***Index Terms*—Inductive voltage divider, Josephson junction, measurement standards, measurement techniques, quantum voltage standards.**

I. Introduction

THE Josephson arbitrary waveform synthesizer (JAWS) [1] has the potential to replace thermal voltage converters (TVCs) as primary standards for alternating voltage with the ultimate accuracy of a quantum standard. A number of national metrology institutes have established JAWS-based systems for the characterization or replacement of TVCs (see [2]–[5]). The voltage range of JAWS technology is presently limited to 1.5 V [all voltages refer to root-mean-square (rms) values] for a single superconducting integrated circuit, due to challenges in the microwave circuit design for fast pulses. It has been demonstrated that connection of the JAWS chips in series can produce higher voltages [6], but errors such as leakage currents and unequal on-chip and between-JAWS-chips time delays are presently limited the output voltage to 4 V [7]. However, ac voltage metrology requires voltages up to 1000 V to cover the voltage range of precision voltage calibrators and ac voltage standards.

Manuscript received July 4, 2018; revised September 28, 2018; accepted November 16, 2018. Date of publication December 17, 2018; date of current version May 10, 2019. The Associate Editor coordinating the review process was Dr. Sophie Djordjevic. *(Corresponding author: Dimitrios Georgakopoulos.)*

D. Georgakopoulos and I. Budovsky are with the National Measurement Institute Australia, West Lindfield, NSW 2070 Australia (e-mail: dimitrios.georgakopoulos@measurement.gov.au; ilya.budovsky@measurement.gov.au).

S. P. Benz is with the National Institute of Standards and Technology, Boulder, CO 80305 USA (e-mail: samuel.benz@nist.gov).

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Digital Object Identifier 10.1109/TIM.2018.2884063

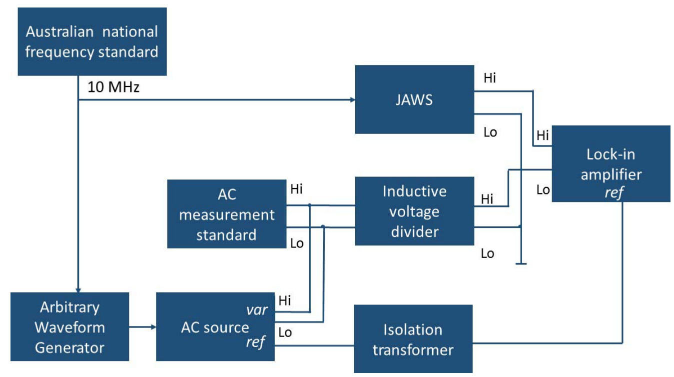

Fig. 1. Block diagram of the measurement system setup.

At the National Measurement Institute Australia (NMIA), we have developed a 1000-V inductive voltage divider (IVD) of excellent ratio accuracy [8] that can potentially extend the voltage range of the JAWS up to a factor of 1000 without an appreciable increase in the uncertainty. In collaboration with the National Institute of Standards and Technology (NIST), NMIA has been developing such a standard [9].

This paper, which is an extension of [10], presents a continuation of this paper. We have combined a 250-mV NIST JAWS system [11] with the NMIA IVD and a lock-in amplifier and demonstrate agreement with TVCs at voltages up to 120 V at 60 Hz, within the uncertainties of the TVCs. The system can operate up to 1 kHz. The target uncertainties for our system are from 0.1 to 2 μV/V, depending on voltage and frequency. We describe the measurement system, present the results of its evaluation, and discuss relevant uncertainty components.

II. Measurement System Description

Fig. 1 shows a simplified diagram of the system. The ac voltage from a semiconductor-based source is applied to an ac measurement standard (the instrument under test) and to the input of the IVD. The ac source is synchronized with the JAWS using an arbitrary waveform generator referenced to the same 10 MHz signal as the JAWS. This 10-MHz signal is derived from the cesium clock that is designated as the Australian national frequency standard. The phase difference between the output voltage of the IVD and the JAWS can be adjusted within 0.001°. The difference between these voltages is applied to a lock-in amplifier, which is set to measure the in-phase component of the difference.

The difference voltage is formed using coaxial cables and a modified tee connector and is applied to a single input of the lock-in amplifier. This is the main improvement from [9], where a differential summation function of the lock-in amplifier was relied upon. This improvement reduces the uncertainty component introduced by the lock-in amplifier to the measurement, since the lock-in amplifier measures the difference of two signals (less than 10 μV) rather than two large signals (e.g., 120 mV) and forming their difference in firmware. The tee connector joins the low potential terminal of the JAWS to the low potential terminal of the IVD output.

The ratio uncertainties of the IVD range from 1×10^{-9} to 7×10^{-9}V/V at frequencies from 40 Hz to 1 kHz. The ac source is a Clarke-Hess[§] 5500 phase standard modified to accept an external reference signal whose frequency can be adjusted within a small range to enable synchronization.

Two essential factors for achieving quantized operation of the JAWS are carefully laid out connections and an absence of ground loops. The circuit measurement ground is connected to the mains safety conductor (earth) at the low potential output of the IVD only. The cases of the ac source and the lock-in amplifier are disconnected from the mains safety conductor to mitigate the effects of common-mode input voltage with respect to the mains safety conductor. The low potential terminal of the ac source (which is connected to its case) and the low potential terminal of the lock-in amplifier (which is internally connected to its case through a 10-kΩ resistor) are connected to the measurement ground using a "star" connection. The guard of the ac measurement standard is connected to the measurement ground but disconnected from its internal ground terminal. To avoid ground loops through the GPIB computer interface, the lock-in amplifier is connected to the control computer through an optically isolated GPIB extender. To ensure electrical safety, the ac source and the lock-in amplifier should be connected to the mains through isolation transformers.

The system operation requires two phase adjustments—the phase difference between the ac source and the JAWS, and the reference phase setting of the lock-in amplifier with respect to its input. To make these adjustments, we use the following procedure. First, the cable is disconnected from the output of the IVD and shorted. Then, the reference phase of the lock-in amplifier is adjusted to minimize the quadrature component of the lock-in amplifier reading. Finally, the cable is reconnected to the output of the IVD, and the phase of the ac source is adjusted by, again, minimizing the quadrature component of the lock-in amplifier reading and monitoring that the in-phase component of the lock-in amplifier is minimum.

III. System Evaluation

The voltages generated by the JAWS must be: 1) insensitive to the specific JAWS circuit and bias electronics used in the particular experimental realization: 2) insensitive to the JAWS bias parameters (i.e., RF power and compensation current); 3) of high spectral purity, limited by the modulation scheme used; and 4) independent of the repetition frequency and of the RF pattern of pulses used to produce a particular voltage level (i.e., if a particular voltage level can be obtained using more than one pattern of pulses and repetition frequencies, then the resulting voltage should be the same). Furthermore, the measurements must agree with the conventional ac voltage standards for any chosen combination of the IVD ratio and the JAWS voltage. Any deviation from the above conditions indicates that the JAWS voltage is not quantized or an unwanted voltage is superimposed on the quantized JAWS voltage introducing an error in the measurement.

[§]Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the NIST and the National Measurement Institute, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

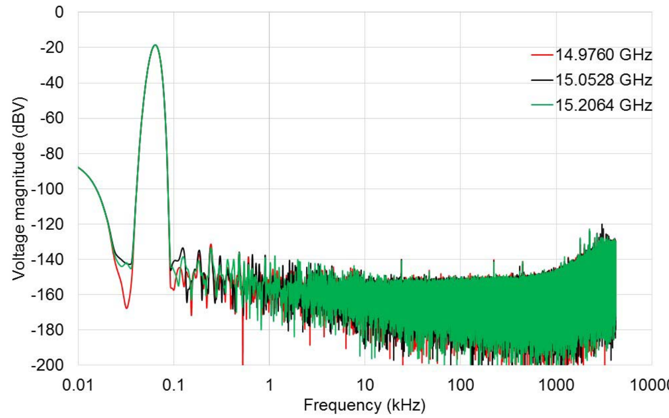

Fig. 2. Spectrum of three JAWS voltages generated by three different patterns of RF pulses and different repetition frequencies using the same single superconducting integrated circuit. The sampling rate was 15 MS/s. The measured signal-to-noise ratio is greater than 110 dBV, and the measurement is limited by the signal-to-quantization noise ratio of the digitizer. The results show that the JAWS output voltage is essentially the same for all the three difference patterns of RF pulses and repetition frequencies.

In this section, we describe how conditions (2)–(4) are met by investigating the quantization of the JAWS, and comparing the JAWS-based system with the conventional ac voltage standards of NMIA based on TVCs. The investigation for condition (1) is described in [12].

A. Quantization of the JAWS

To investigate conditions (3) and (4) on the JAWS voltage, we used a National Instruments PXI 5922 to measure the spectrum of three JAWS voltages, each being 120 mV at 60 Hz but generated by different patterns of RF pulses and repetition frequencies (14.976, 15.0528, and 15.2064 GHz) using the same Josephson junction array having 12 800 junctions and driven by the same output of the pattern generator. Fig. 2 shows the results. For frequencies up to 5 MHz, the noise floor and the high frequency individual harmonics are less than 1 μV, so even if an unwanted harmonic folds into and is in phase with the signal frequency of the JAWS its effect in the rms value of the fundamental will be less than 0.02 nV/V.

We also measured the correction of a Keysight 3458A configured as a digital sampling voltmeter (DSVM) [13] at 4 V and 60 Hz by using the same three JAWS voltages and the same IVD ratio of 0.03 V/V, see Fig. 3. The measured

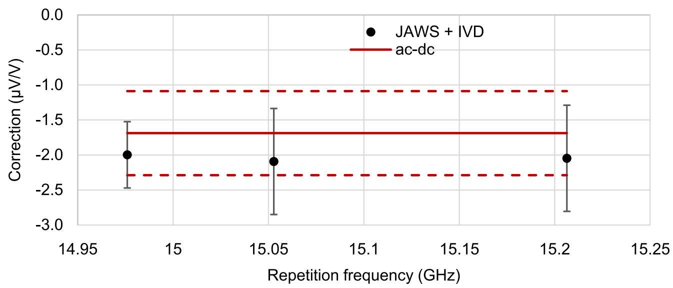

Fig. 3. Correction of the 3458A at 4 V, 60 Hz, measured using the JAWS producing 120 mV. The JAWS voltage was generated by using three different patterns of RF pulses at three repetition frequencies. The results are compared with the conventional ac–dc voltage standards of NMIA. The error bars show the standard deviation of the measurements. The broken lines show the standard deviation of the conventional ac–dc voltage measurement.

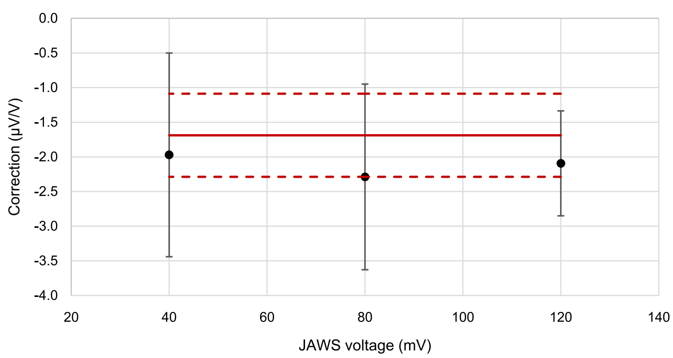

Fig. 4. Correction of the 3458A at 4 V, 60 Hz measured using three JAWS voltages 120, 80, and 40 mV and IVD ratios of 0.03, 0.02, and 0.01 V/V, respectively. The results are compared with the conventional ac–dc voltage standards of NMIA. The error bars show the standard deviation of the JAWS-based measurements. The broken lines show the standard deviation of the conventional ac–dc voltage measurement.

corrections agree within the standard deviation of the measurement. Fig. 3 also shows the correction of the DSVM at the same voltage and frequency measured with the conventional ac–dc voltage standards of NMIA.

Further, the correction of the DSVM was measured at 4 V, 60 Hz using three JAWS voltages; 120, 80, and 40 mV with corresponding IVD ratios 0.03, 0.02, and 0.01 V/V (Fig. 4). The results agree within the standard deviation of the measurement. The results also agree well with the DSVM correction measured with the conventional ac–dc voltage standards.

The dc blocks and the attenuators at the output of the RF amplifier driving the RF pulses to the Josephson array can introduce a systematic error on the measurement [14]. To evaluate the adequacy of the dc blocks and attenuators, we measured the corrections of the DSVM at 120 mV at 60 Hz using one, two, and three cascades of dc block plus 1-dB attenuators (Fig. 5). The error bars represent the standard deviation of the measurements. The results with different numbers of cascades agree with each other within the expanded uncertainty of the measurements. For our system, more than one cascade of dc block plus 1-dB attenuator is required to reduce the systematic errors from this source. This is an active area for our research at NMIA. For the results reported in this section, two dc blocks plus 1-dB attenuators were used.

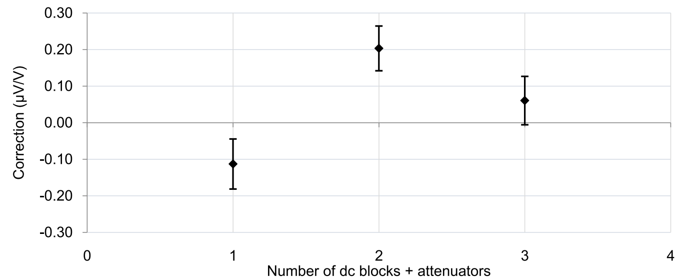

Fig. 5. Corrections of a DSVM measured using the JAWS at 120 mV, 60 Hz with a cascade of one, two, and three dc block/attenuator networks at the output of the RF amplifiers driving the Josephson junction array.

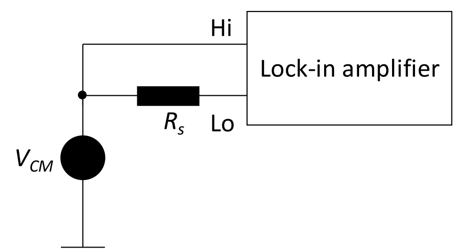

Fig. 6. Block diagram of the experimental setup used to measure the CMRR.

The effect of the compensation current flowing through the parasitic impedances of the Josephson array was estimated by generating waveforms with small amplitudes (10 and 20 mV) that do not require compensation current, and then measuring the change in the voltage when the compensation current was turned on and off. To increase the sensitivity of the experiment, we used two waveforms at 100 kHz [14]. The measured inductance was less than 9 nH with an estimated uncertainty of 12 nH. Hence, the effect of the inductance to the measurement has small contribution to the uncertainty for frequencies up to 1 kHz (Section IV). Changes of the RF power by 5% do not have any statistically significant effect on the measurements.

To investigate the effect of the potential ground loops and common-mode voltages on the quantized operation of the JAWS, we exploit the two isolated outputs of the IVD: unlike the grounded outputs of the IVD, the low terminals of the isolated outputs are not connected to the input low. We calibrated the DSVM at 4 V, 60 Hz using both the grounded and the isolated outputs of the IVD with the 0.01 V/V ratio. The corresponding corrections agreed within the standard deviation of the measurements.

In our setup, the combination of the IVD output impedance and the impedance of the connecting cable is less than 100 mΩ (estimated), and the impedance of the line at the output of the Josephson array is less than 1 Ω (measured) for frequencies up to 1 kHz. These impedances can reduce the effectiveness of the common-mode rejection ratio (CMRR) of the lock-in amplifier in the measurement circuit. We separately investigated the CMRR of the lock-in amplifier using the setup of Fig. 6, where resistor R_s represents the output resistance of the IVD, the Josephson array, and their leads. Measurements were performed with a common-mode voltage V_{CM} of 4 V in the frequency range 60 Hz to 10 kHz, with various values

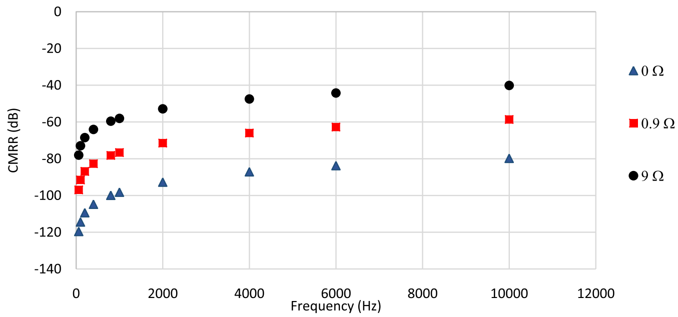

Fig. 7. CMRR for different resistance values of the experimental setup of Fig. 6 between the "hi" and "low" terminals of the lock-in amplifier.

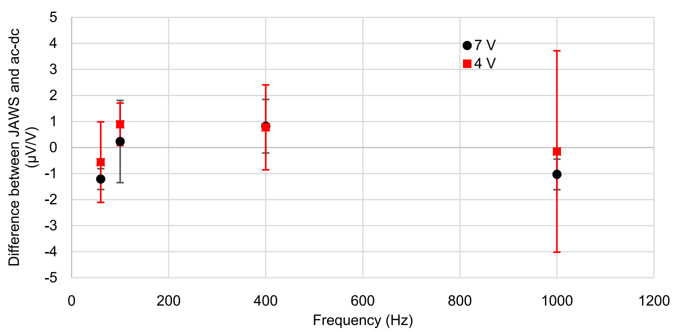

Fig. 8. Difference between the ac–dc differences of a DSVM measured using the TVC and the JAWS system at 4 and 7 V. The error bars show the standard deviation of the JAWS measurements.

of R_s (Fig. 7). The value of the resistor was varied from 0 (ideal case) to 9 Ω (about four times the corresponding impedance in the circuit). As can be seen from Fig. 7, the CMRR of the lock-amplifier depends on the frequency and on R_s.

B. Comparison With Conventional AC–DC Transfer Standards

Our system takes advantage of the JAWS to perform ac voltage measurements without the need of ac–dc transfer. It is not intended and cannot be used for ac–dc transfer since most of its components cannot operate at dc. Hence, it cannot be directly compared with the conventional ac voltage standards based on ac–dc transfer.

For this reason, we used two ac voltage measuring instruments as transfer standards to compare the voltages produced by the JAWS with the conventional ac voltage standards of NMIA. For voltages less than 10 V, we used the DSVM, and at higher voltages a Fluke 5790A ac voltage standard.

Precision evaluation of the JAWS system at voltages greater than 10 V is limited by the increasing uncertainties of the thermal ac–dc transfer standard. For this reason, we first evaluated our system at 4 and 7 V using two TVCs with a low uncertainty (better than 2 μV/V), and then proceeded to 70 and 120 V using TVCs with uncertainties better than 14 μV/V. We used the same IVD for both experiments, which, given the very high voltage linearity of the IVD [8], gives us confidence that the Type B uncertainty of the system is independent of the voltage.

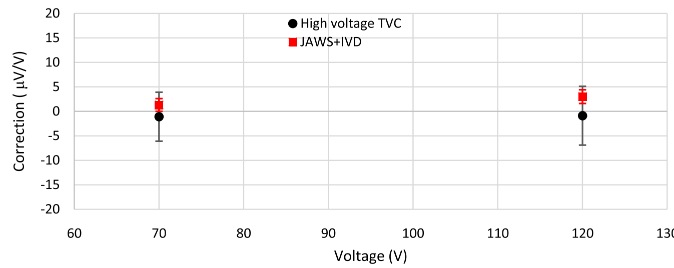

Fig. 9. AC–DC difference of an ac measurement standard (Fluke 5790A) at 70 and 120 V at 60 Hz measured with a high-voltage TVC and the JAWS-based system. The error bars show the standard deviation of the measurement.

TABLE I

NORMALIZED ERROR, E_n, BETWEEN THE CONVENTIONAL AC–DC STANDARDS AND THE JAWS-IVD SYSTEM

Transfer standard	Voltage (V)	Frequency (Hz)	En ratio
DSVM	4	60	-0.25
DSVM		100	+0.39
DSVM		400	+0.29
DSVM		1000	-0.04
DSVM	7	60	-0.55
DSVM		100	+0.11
DSVM		400	+0.31
DSVM		1000	-0.26
5790A	70	60	-0.18
5790A	120	60	-0.27

For the low-voltage test, we measured the corrections of the DSVM at 4 and at 7 V and frequencies from 60 Hz to 1 kHz using the JAWS and the NMIA conventional ac voltage standards. The ratio of the IVD was 0.01 V/V so the output voltages of the JAWS and the IVD were 40 mV for 4 V and 70 mV for 7 V. The results are shown in Fig. 8.

For the high-voltage test, we measured the corrections of a Fluke 5790A ac measurement standard at 70 and at 120 V and 60 Hz using the JAWS and the TVC-based ac–dc calibration system (Fig. 9). The IVD ratio in these measurements was 0.001 V/V.

Table I shows the normalized error, E_n, between the conventional ac voltage standards and the JAWS-IVD system, based on the uncertainty analysis of Section IV.

IV. UNCERTAINTY ANALYSIS

Our system employs a JAWS, an IVD, a semiconductor source, and a lock-in amplifier. Each of these components introduces an uncertainty to the measurement.

Typical uncertainty statements for the calibration of voltages of 4 V at 60 Hz and 1 kHz and 120 V at 60 Hz, are shown in Tables II–IV, respectively. In each case, the JAWS voltage is 120 mV, and the IVD ratio is set accordingly. At 4 V, the estimated expanded uncertainty is less than 1 μV/V, while that at 120 V is 1.3 μV/V.

TABLE II

TYPICAL UNCERTAINTY BUDGET FOR A VOLTAGE OF 4 V AT 60 HZ, USING A JAWS VOLTAGE OF 0.12 V AND IVD RATIO 0.03 V/V

Source		Type	Distribution	U_i (μV/V)
JAWS	Compensation current	B	Normal	0.0039
	Dc block	B	Normal	0.3434
	Transmission line	B	Normal	0.0001
	Potential clock folding	B	Normal	0.0001
IVD	Ratio	B	Normal	0.0034
	Loading	B	Normal	0.0009
Source	Total harmonic distortion	B	Normal	0.0938
Source-JAWS	Phase alignment	B	Normal	0.0009
Lock-in amplifier	Gain	B	Normal	0.107
	Common-mode rejection ratio	B	Normal	0.1260
Other	Estimated standard deviation of the mean (ESDM)	A	Normal	0.3163
	IUT resolution	B	Rectangular	0.0100
Combined standard uncertainty (μV/V)			0.51	
v_{eff}			25.7	
k			2.06	
Expanded uncertainty (μV/V)			1.05	

TABLE III

TYPICAL UNCERTAINTY BUDGET FOR A VOLTAGE OF 4 V AT 1 KHZ, USING A JAWS VOLTAGE OF 0.12 V AND IVD RATIO 0.03 V/V

Source		Type	Distribution	U_i (μV/V)
JAWS	Compensation current	B	Normal	0.5386
	Dc block	B	Rectangular	0.3434
	Transmission line	B	Normal	0.1568
	Potential clock folding	B	Normal	0.0001
IVD	Ratio	B	Normal	0.0234
	Loading	B	Normal	0.0009
Source	Total harmonic distortion	B	Normal	0.0938
Source-JAWS	Phase alignment	B	Normal	0.0009
Lock-in amplifier	Gain	B	Normal	0.1074
	Common-mode rejection ratio	B	Normal	1.4724
Other	Estimated standard deviation of the mean (ESDM)	A	Normal	0.3163
	IUT resolution	B	Rectangular	0.0100
Combined standard uncertainty (μV/V)			1.65	
v_{eff}			15.4	
k			2.13	
Expanded uncertainty (μV/V)			3.52	

At 60 Hz, the largest uncertainty components are the Type A uncertainty, which is mainly due to the noise coupled into the low-voltage JAWS–IVD part of the measurement system, and the Type B due to the dc block plus attenuator networks at the output of the RF amplifier and the CMRR of the lock-in amplifier. The Type B uncertainty component due to the dc block plus attenuator networks was estimated from measurements of the difference between two and three cascades of dc block plus attenuator networks [15]. Improving these uncertainty components is an active area of our research.

TABLE IV

TYPICAL UNCERTAINTY BUDGET FOR A VOLTAGE OF 120 V AT 60 HZ, USING A JAWS VOLTAGE OF 0.12 V AND IVD RATIO 0.001 V/V

Source		Type	Distribution	U_i (μV/V)
JAWS	Compensation current	B	Normal	0.0324
	Dc block	B	Rectangular	0.3434
	Transmission line	B	Normal	0.0006
	Potential clock folding	B	Normal	0.0001
IVD	Ratio	B	Normal	0.1000
	Loading	B	Normal	0.0009
Source	Total harmonic distortion	B	Normal	0.0938
Source-JAWS	Phase alignment	B	Normal	0.0009
Lock-in amplifier	Gain	B	Normal	0.1074
	Common-mode rejection ratio	B	Normal	0.1260
Other	Estimated standard deviation of the mean (ESDM)	A	Normal	0.4744
	IUT resolution	B	Rectangular	0.0100
Combined standard uncertainty (μV/V)			0.62	
v_{eff}			21	
k			2.09	
Expanded uncertainty (μV/V)			1.3	

V. CONCLUSION

The experimental results from the evaluation of our system show that the application of the JAWS can be extended to high voltages with uncertainties of a few microvolts per volt or less, depending on the voltage amplitude and frequency. The use of the IVD and the lock-in amplifier to extend the voltage range of the JAWS is limited to 1 kHz due to the frequency response limitations of the IVD, and the CMRR of the lock-in amplifier.

In this paper, we extended the range of a single superconducting integrated circuit from 250 mV to 120 V However, by using the same IVD and an amplifier at the output of the ac source, the output voltage of a 1-V JAWS chip could be extended to 1000 V without a compromise in the uncertainty.

ACKNOWLEDGMENT

The authors would like to thank their colleagues at NMIA, R. Xie for calibrating the IVD, and V. Balakrishnan for calibrating the DSVM and the 5790A with the conventional ac–dc measurements standards of NMIA.

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Dimitrios Georgakopoulos (A'11–M'12–SM'12) was born in Athens, Greece, in 1972. He received the B.Eng. degree in electrical engineering from the Technological Educational Institution of Piraeus, Egaleo, Greece, in 1996, the M.Sc. degree in electronic instrumentation systems from the University of Manchester, Manchester, U.K., in 1999, and the Ph.D. degree in electrical engineering and electronics from the University of Manchester Institute of Science and Technology, Manchester, in 2002.

From 2002 to 2007, he was a Research Scientist at the National Physical Laboratory, Teddington, U.K. In 2007, he joined the National Measurement Institute Australia, West Lindfield, NSW, Australia, as a Research Scientist, where he has been focused on the development of quantum voltage standards and low-frequency electromagnetic compatibility standards.

Dr. Georgakopoulos is a member of the Measurements in Power Systems IEEE committee (TC-39) and the American Association for the Advancement of Science, USA.

Ilya Budovsky (M'00–SM'03) was born in 1964. He received the B.E. degree in electrical engineering from the Technical University of St. Petersburg, St. Petersburg, Russia, in 1987, and the Ph.D. degree from the D. I. Mendeleyev Research Institute for Metrology, St. Petersburg, in 1995.

Since 1991, he has been with the National Measurement Institute Australia, West Lindfield, NSW, Australia, formerly the National Measurement Laboratory of CSIRO. He became the Leader of the Low-Frequency Standards Group in 1997 and the manager of the Electricity Section in 2009. He is responsible for the development and dissemination of Australian measurement standards for electricity, magnetism, and time.

Dr. Budovsky is a fellow of the Engineers Australia and the Australian representative to the Consultative Committee for Electricity and Magnetism, where he chairs the working group on inter-regional coordination.

Samuel P. Benz (M'01–SM'01–F'10) was born in Dubuque, IA, USA, in 1962. He received the B.A. degree (*summa cum laude*) in physics and math from Luther College, Decorah, IA, USA, in 1985, and the M.A. and Ph.D. degrees in physics from Harvard University, Cambridge, MA, USA, in 1987 and 1990, respectively.

In 1990, he joined the National Institute of Standards and Technology (NIST), Boulder, CO, USA, as a NIST/NRC Postdoctoral Fellow and became a permanent Staff Member in 1992. He has been the Project Leader of the Quantum Voltage Project at NIST since 1999, and a Group Leader of the Superconductive Electronics Group since 2015. He has focused on a broad range of topics within the field of superconducting electronics, including Josephson junction array oscillators, single flux quantum logic, ac and dc Josephson voltage standards, Josephson waveform synthesis, and noise thermometry. He has authored over 250 publications and holds three patents in the field of superconducting electronics.

Dr. Benz is a fellow of NIST and the American Physical Society. He is a member of Phi Beta Kappa and Sigma Pi Sigma. He has received three U.S. Department of Commerce Gold Medals for Distinguished Achievement, the 2016 IEEE Joseph F. Keithley Award, and twice the IEEE Council on Superconductivity Van Duzer Prize. He was awarded an R.J. McElroy Fellowship to work toward the Ph.D. degree from 1985 to 1988.