Differential Measurements of an AC Source with a Josephson Arbitrary Waveform Synthesizer

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***Abstract* — This paper describes differential sampling measurements of an ac source and a Josephson arbitrary waveform synthesizer (JAWS). A new iterative approach for aligning the phases of the JAWS and the source waveforms was implemented to minimize the differential voltage at the digitizer. A type-A uncertainty of 45 nV/V after 10 min was measured for a commercial ac source at 1 V rms amplitude and 1 kHz.**

***Index Terms* — Josephson arrays, Measurement techniques, Standards, Superconducting integrated circuits, Voltage measurement.**

I. INTRODUCTION

Josephson arbitrary waveform synthesizers (JAWS) are becoming increasingly implemented for many measurements in ac voltage metrology, including for applications for ac-dc transfer, impedance bridges, and even radio frequency signal generation [1]. The main advantages of JAWS waveforms are high spectral purity, intrinsic voltage accuracy and linearity, and direct traceability to the International System of Units (SI). The recent availability of a low noise and highly stable ac voltage *source* offers an alternative means of ac voltage dissemination, potentially superseding *detector*-based ac-dc thermal transfer standards at voltages below 4 V at audio frequencies. While the main interest of the precision measurement community is presently focused on ac source differential measurements with stepwise-approximated waveforms from a programmable Josephson voltage standard (PJVS), we propose a measurement method of ac sources that is based on JAWS. The JAWS-based differential measurement eliminates adverse effects due to the inherent transients and voltage switching of a PJVS reference. It significantly minimizes the voltage at the input of the digitizer, which reduces gain error effects. This JAWS-based differential measurement method fulfills the requirement of the BIPM comparison protocol for ac voltages [2].

II. SETUP

The schematic of the differential measurement is shown in Fig. 1 (a). The differential voltage between the source and the JAWS is measured by a commercial digitizer (Fluke 8588A[1]), with a 5 MHz sampling rate. The digitizer is placed between the low potential terminals of the source and JAWS to minimize common-mode and leakage effects. All instruments share a common 10 MHz reference and are synchronized with an optical trigger signal from the source at the waveform frequency. The JAWS system consists of a cryopackaged 2 V JAWS circuit mounted on the cold stage of the cryocooler operated at 4.5 K (see [1] for more details). The ac source is a sinewave generator (SWG) developed by the Czech Metrology Institute loaned to NIST from BIPM [2]. The ac source is optically isolated and battery-powered, and a commercial Zener standard provides its external 10 V reference.

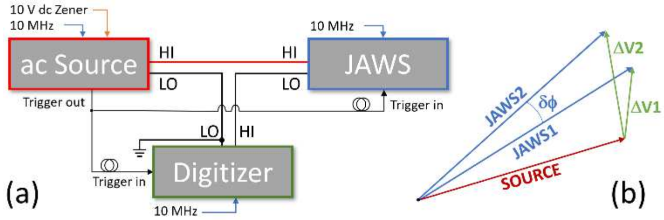

Fig. 1. (a) Schematic of the ac source and JAWS differential measurement and synchronization circuit. (b) Vector representation of the phase and amplitude of the signals. ΔV1 and ΔV2 are the amplitudes and phases measured successively by the digitizer for the Source-JAWS1 and Source-JAWS2 configurations. The JAWS1 and JAWS2 signals are generated from identical Δ–Σ patterns but with a δϕ phase shift implemented by starting the JAWS2 pulse waveform at an integer number cycles of the 28.8 GHz pulse clock.

III. DIFFERENTIAL MEASUREMENT

A. Gain Calibration

The gain calibration measurement consists of setting the source to 0 V (or replacing it with a short) and measuring a small amplitude (≤100 mV) JAWS waveform at the frequency of interest. The correction factor is calculated from the ratio of the JAWS nominal voltage and the digitizer-measured rms voltage at the waveform frequency. The correction includes the gain error and aperture effect and is applied to all subsequent measurements performed at this frequency and digitizer range.

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[1] Certain commercial instruments are identified in this paper to facilitate understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.

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The digitizer linearity results are presented in a separate paper [3]. The sampling

B. Phase Adjustment

The phase of the JAWS waveform must be aligned with the source to minimize the differential voltage at the digitizer input (Fig. 1 (b)). The phase adjustment method starts with a large phase difference (δϕ=10°) between JAWS1 and JAWS2 and with the digitizer set to the 10 V range. The relative phase between the JAWS and source signals is calculated from the two differential measurements (ΔV1 and ΔV2). Next, a new JAWS phase correction is applied to minimize the differential voltage. This procedure is iterated by reducing both the digitizer range and δϕ until the relative phase between the JAWS and source signals is aligned within one millidegree. The digitizer is set to the lowest range (100 mV) if the source and JAWS amplitudes are closely matched.

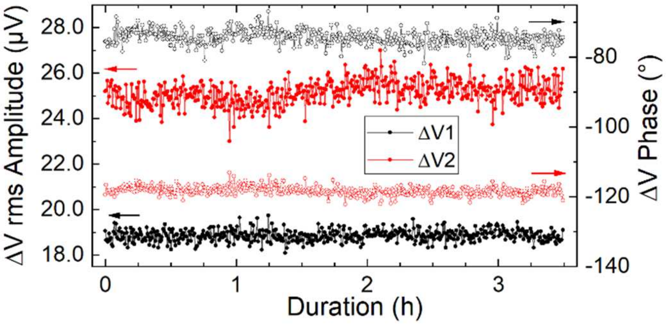

Fig. 2. 1 kHz component of the FFT of the digitizer signal (amplitude and phase) for ΔV1=Source-JAWS1 and ΔV2=Source-JAWS2 over 3.5 hours. The JAWS1 and JAWS2 rms amplitude at 1 kHz is exactly 1 V. JAWS1 and JAWS2 relative phase difference is δϕ=0.001°.

C. Data Acquisition

The data acquisition consists of repeating the differential measurement with successive JAWS1 and JAWS2 signals. The switch from one pattern to the other happens quickly since both JAWS waveforms are preloaded in the memory of the pulse bias electronics. The source synchronization signal triggers the start of the JAWS waveform. A "mini" quantum locking range measurement is performed by applying a dc offset current on the JAWS1 and JAWS2 signals at every repetition (offset iteratively switching between 0 mA, +0.2 mA, and −0.2 mA) [1]. For every measurement, the digitizer acquires multiple periods of the differential voltage, and a fast Fourier transform (FFT) extracts the amplitude and phase at the frequency of interest. The result of 500 measurements of ΔV1 and ΔV2 (at JAWS=1 V rms and 1 kHz) is shown in Fig. 2.

IV. RESULTS

The rms amplitude of the source is reconstructed (Fig. 3) from the two sets of differential measurements shown in Fig. 2. The room's temperature, atmospheric pressure, and relative humidity were recorded during the source measurement. The source output voltage is stable within the typical laboratory environmental conditions and over the full measurement duration. The Allan deviation calculation (Fig. 4) performed on the Fig. 3 data shows a 1/f noise floor of 45 nV.

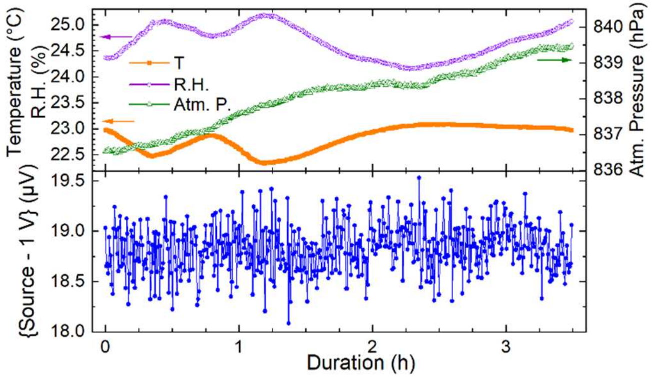

Fig. 3. (Top) Room environment conditions recorded (temperature, atmospheric pressure, and relative humidity). (Bottom) Reconstructed rms amplitude for the source at 1 kHz.

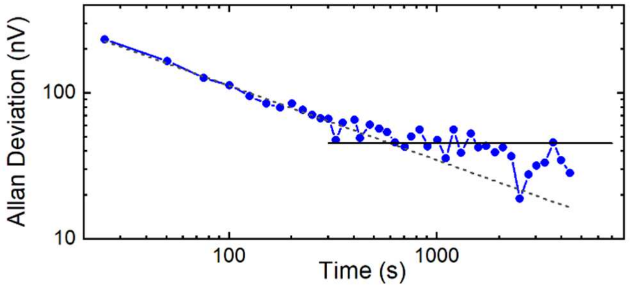

Fig. 4. Allan deviation of the source amplitude measured at 1 V and 1 kHz. The horizontal solid line represents the 1/f noise floor (45 nV) reached after 10 min of measurement.

V. CONCLUSION

The data reported here show that the JAWS-based differential sampling method is applicable to the measurement of high-performance ac sources. We will next use this method to directly compare two independent JAWS systems or two JAWS arrays on the same circuit [4]. The use of two JAWS-based waveforms enables the evaluation of the limits of the digitizer and potential systematic errors of the JAWS-based differential sampling method.

REFERENCES

[1] A. Rüfenacht, N. E. Flowers-Jacobs, and S. P. Benz, "Impact of the latest generation of Josephson voltage standards in ac and dc electric metrology," *Metrologia*, vol. 55, no. 5, pp. S152–S173, Oct 2018.

[2] BIPM.EM-K10.b. Protocol, "On-site comparison of dc and ac voltages from Josephson arrays," *https://www.bipm.org/kcdb/comparison/doc/download/1779/BIPM.EM-K10_Technical_Protocol.pdf*, 2023.

[3] J. Medina Mejia, R. Johnson-Wilke, A. Rüfenacht, A. Fox, N. E. Flowers-Jacobs, and P. Dresselhaus, "Digitizer Linearity Measurement with a Josephson Arbitrary Waveform Synthesizer," Submitted to CPEM 2024 conference digest.

[4] O. F. Kieler, R. Behr, D. Schleussner, L. Palafox, and J. Kohlmann, "Precision Comparison of Sine Waveforms with Pulse-Driven Josephson Arrays," *IEEE Trans. On Appl. Superconductivity*, vol. 23, no. 3, pp. 1301404 (1-4), Jun 2013.