DC Comparison of a Programmable Josephson Voltage Standard and a Josephson Arbitrary Waveform Synthesizer

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***Abstract* — We present the first dc comparison of a programmable Josephson voltage standards and a pulse-driven Josephson arbitrary waveform synthesizer (JAWS) at 3 V. Both circuits are mounted side-by-side on the cold stage of a cryocooler. The relative agreement achieved was better than 1 part in 10^8. This measurement allowed us to identify systematic errors of the JAWS system. An undesired current injection from the JAWS isolation amplifier into the measurement circuit was responsible for an error voltage of a few nanovolts.**

***Index Terms* — Digital-analog conversion, Josephson arrays, standards, superconducting integrated circuits, voltage measurement.**

I. Introduction

The Josephson Arbitrary Waveform Synthesizer (JAWS) was developed to generate quantum-accurate waveforms with low harmonic distortion for voltage metrology applications [1]. The programmable Josephson voltage standard (PJVS), with an output voltage of 10 V, is currently used by primary standard laboratories for dc calibrations [2]. PJVS systems are also capable of generating stepwise-approximated waveforms at frequencies up to ~1 kHz. Direct comparison of JAWS and PJVS waveforms at 1 V rms and 250 Hz agree to 1 part in 10^8 [3]. Recent JAWS development at NIST has increased the rms output voltage of a single chip to 2 V, enlarging the voltage overlap domain with the PJVS. Combining JAWS and PJVS for the first time in the same cryostat allows us to test the performance of each system. We compared both systems at 3 V dc, without the additional complications associated with ac waveforms. With the new redefinition of the SI, such a dc comparison is an important step to verify the agreement of JAWS systems with the well-established dc primary voltage standards.

II. Measurement Setup

The measurement setup, shown in Fig. 1, consists of a 10 V PJVS circuit and a “1 V + 1 V” JAWS circuit mounted side-by-side on the cold plate of a cryocooler operated at 4.2 K. The measured cooling capacity of the system at this temperature is about 550 mW [4]. The PJVS circuit has a total of 265 156 Josephson junctions (JJs) and is biased at 15 GHz. Details about the PJVS circuit, system, and the 24-channel current source can be found in Ref. [2]. The JAWS circuit has eight arrays, each with 12 810 JJs, capable of generating a dc voltage of 3.051 V

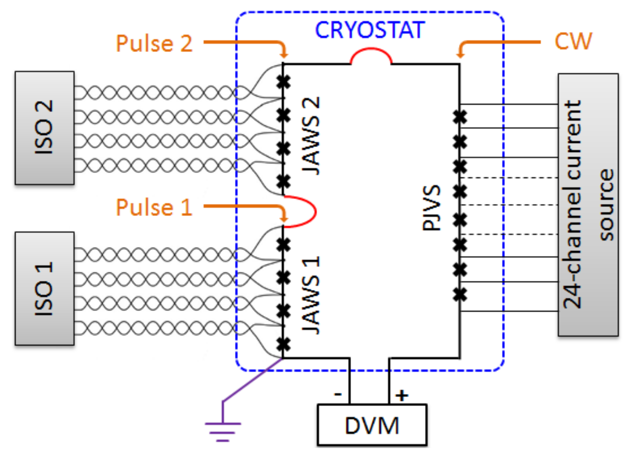

Fig. 1. Schematic of the PJVS and JAWS comparison measurement circuit.

in total when all the JJs are biased with a continuous pulse train generated by a commercial high-speed arbitrary waveform generator clocked at 14.4 GHz. With the “1 V + 1 V” configuration, the two halves of the JAWS circuit (JAWS 1 and JAWS 2) are independent. Each half has a separate pulse bias line (labeled Pulse 1 and Pulse 2 in Fig. 1) connected to two stages of Wilkinson dividers to distribute the pulses among the four arrays [1].

Two short copper wires (red wires in Fig. 1) are soldered between the two JAWS circuits and between the JAWS and PJVS packages, so that all three circuits (JAWS 1, JAWS 2, and PJVS) are connected in series. The JAWS compensation current bias is provided by two custom battery-powered isolation amplifiers (ISO 1 and ISO 2), connected respectively to JAWS 1 and JAWS 2. The voltage difference between the two systems $\Delta V = V_{\mathrm{JAWS}} - V_{\mathrm{PJVS}}$ is measured by a digital nanovoltmeter (DVM). Copper twisted-pair wires connect the bottom of JAWS 1 array and the bottom of the PJVS array to the DVM at room temperature. The Earth ground potential in the measurement circuit is connected to the bottom of the JAWS 1 array. The fast pulse generator (JAWS) and the PJVS continuous waveform generator (CW) are locked to the 10 MHz frequency from the NIST atomic clock.

III. DC Comparison Results

Before starting the comparison measurement, the leakage current to Earth ground (LCG) from the PJVS and JAWS systems was evaluated with the method described in Ref. [5]. At 3.051 V the LCG measured on the PJVS system was less than 25 pA and the corresponding voltage error on the comparison result was negligible. However, the LCG measured on the JAWS system for the same voltage was much larger (~1.5 μA). The JAWS-PJVS comparison was performed at three different voltages, 3.051 V, 1.526 V, and 0 V, with a total of six different bias configurations of the JAWS system (labeled "A" to "F" in Table 1).

#	PJVS (V)	JAWS 1 (V)	JAWS 2 (V)	*ΔV* (nV)	***ΔV meas.*** **(nV)**	*σ* (nV)
A	3.051526899	1.525…	1.525…	**−0.3**	**0.9**	1.0
B	1.525763449	1.525…	0	**0.3**	**−5.0**	1.0
C	1.525763449	1.525…	N.C.	**0.3**	**0.5**	1.0
D	1.525763449	0	1.525…	**0.3**	**7.8**	1.0
E	1.525763449	N.C.	1.525…	**0.3**	**7.8**	1.1
F	0	0	0	**0**	**0.2**	0.8

Table 1. DC voltage comparison results as a function of the JAWS bias configuration. The voltage produced by JAWS 1 and JAWS 2 was 1.525 763 449 35 V @ 14.4 GHz or 0 V. The columns "*ΔV*" and "*ΔV* meas." are the expected (calculated) and measured voltage differences between the two systems. The Type-A uncertainty reported is the standard deviation σ with $k = 1$. The abbreviation N.C. indicates that the compensation module (ISO) was disconnected from the array (0 V).

The CW frequency of the PJVS was adjusted to match the voltage of the JAWS system to the 9th decimal place. Small voltage differences, $|\Delta V| < 0.4$ nV, remained. Each value reported for the voltage difference was calculated with a linear fit based on four polarity reversal sets "+−+− ", to remove the contributions of the thermal electromotive forces. A polarity set consisted of 15 DVM readings on the 1 mV range at 10 power line cycles each. To test the quantum locking range of both systems during the comparison measurements, a dither current of ±0.25 mA was sequentially applied to the PJVS and the JAWS arrays. None of the measurement results reported in Table 1 were affected by the applied dither current.

At 3.051 V, the difference between the measured and expected values *ΔV* was 1.2 nV (Fig. 2). However, a larger spread in the results was obtained at 1.526 V when one of the JAWS array was set to 0 V (with or without the corresponding ISO connected). This effect cannot be explained solely by the JAWS LCG. An independent measurement showed the presence of a significant current injection (CI) from both isolation amplifiers (several microamperes, depending on the potential difference with Earth ground). Any current flowing in the resistive wire connecting the JAWS 1 and JAWS 2 arrays will lead to a voltage error in the measurement circuit. However, when the ISO 2 was disconnected (bias configuration "C") or when the voltages of all the arrays was set to zero ("F"), no current was flowing in the resistive wire. Connecting or disconnecting the ISO 1 ("D" and "E") results in the same voltage error (7.5 nV), which showed that the CI from the ISO 1 unit, when its low side was referenced to the Earth ground potential, did not contribute to the voltage error. Replacing the

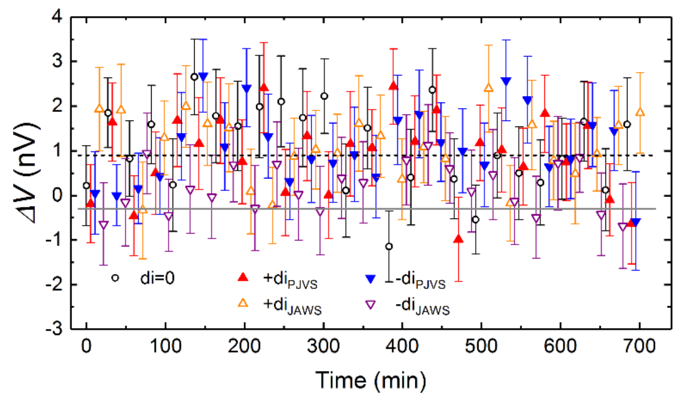

Fig. 2. Measured voltage difference versus time for the comparison at 3.051 526 899 V. The dashed line shows the mean value measured (0.9 nV) while the solid line represents the expected voltage difference (−0.3 nV). Error bars are calculated from the residuals of the fit to remove the thermal electromotive forces (k=1).

"1 V + 1 V" JAWS wiring configuration with the "2 V" configuration that has an on-chip superconducting series connection should eliminate this source of voltage error in future comparisons.

IV. Conclusion

These dc comparison measurements revealed the presence of undesired CI generated by the present ISO. Our present priority is to reduce the LCG and CI caused by the ISO units. After we remove the undesired voltage error due to the CI, the agreement between the JAWS and PJVS systems is expected to improve from 1 part in 10^8 to 1 part in 10^9. Our measurement noise was only σ ≅ 1 nV, which demonstrates that the two very different types of voltages standards can operate side-by-side on a single cryocooler without interference. The next measurements performed with this setup will compare PJVS stepwise-approximated waveforms with spectrally-pure low-frequency JAWS sine waves using the differential sampling method.

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