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Comparison of Sandia's JAWS system to conventional AC-DC difference measurements

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Abstract:
Late in 2019, the Primary Standards Laboratory (PSL) at Sandia National Laboratories procured a Josephson Arbitrary Waveform Synthesizer (JAWS) that was designed and built by the National Institute of Standards and Technology (part of the Standard Reference Instrument program). JAWS is an intrinsic, quantum-based standard for alternating voltage and is analogous to the Programmable Josephson Voltage Standard for direct voltage. Though JAWS is limited in voltage and frequency ranges, there is suitable overlap with conventional AC-DC thermal transfer measurements that appropriate comparisons can be made. The PSL performed initial measurements using the JAWS as an intrinsic alternating voltage source to measure AC-DC differences on Fluke 792A devices. These initial measurements show that JAWS results fall within the error bars of traditional AC-DC difference measurements using a thermal transfer standard. This paper will highlight optimization of the JAWS system and provide pertinent comparisons between JAWS and more conventional AC-DC difference measurements.

Introduction:
Josephson junction arrays have been used in voltage metrology as a primary standard for well over 30 years [1] [2]. Two comparable types of Josephson voltage standards used today are the Programmable Josephson Voltage Standard (PJVS) and the Josephson Arbitrary Waveform Synthesizer (JAWS; also known as the AC Josephson Voltage Standard or ACJVS). In both cases, the Josephson standard utilizes the inverse Josephson effect [3] in which the Josephson junction functions as an ideal frequency-to-voltage converter [1].

On the direct voltage side, the PJVS is primarily used for direct voltage metrology and is often used as an intrinsic standard to calibrate direct voltage standards such as Fluke 732A/B/C devices. To generate a direct voltage output, the Josephson junctions are driven by an applied microwave bias. The output voltage is expressed as

$$V_{DC} = \frac{nNhf}{2e} \tag{1}$$

where n is the quantum step, N is the number of junctions, h is the Planck constant, e is the charge of an electron and f is the frequency of the applied microwave bias. In other words,

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the output voltage is dependent on two fundamental constants (h and e) and the frequency of the microwave bias.

On the alternating voltage side, JAWS is an intrinsic standard for alternating voltage and can be used to calibrate thermal transfer standards. JAWS uses a current *pulse* bias to drive the Josephson junctions, and the pulse area quantization behavior of the junction yields a practical alternating voltage. With an appropriate current pulse applied to the junction, the output voltage can be expressed as:

$$\int v(t)dt = \frac{h}{2e} \tag{2}$$

and thus the integrated area of the output pulse is given by fundamental constants - h and e . To synthesize a sinusoid, a sequence of current pulses is generated in which the spacing of the pulses is proportional to the voltage of the sine wave. When the pulse timing is controlled, the JAWS can produce spectrally pure low-frequency sine waves for alternating voltage metrology [1].

One common application for JAWS is the AC-DC difference calibration of thermal transfer standards. While JAWS presents challenges beyond audio frequencies [4], JAWS AC-DC difference measurements can be performed with significant overlap compared to conventional AC-DC difference calibrations. In this paper, initial AC-DC difference measurements on Sandia's JAWS system are compared to results using a more conventional AC-DC measurement setup.

Experimental Methods:

JAWS:

Sandia's Primary Standards Lab (PSL) procured and installed a National Institute of Standards and Technology (NIST) standard reference instrument (SRI) JAWS system in the fall of 2019. This JAWS system was the first of its kind built for customers interested in owning a quantum standard for alternating voltage metrology. The purchased system was a NIST SRI cryocooled 2 V JAWS system [5] with two 1 V chips on a cryocooler [6]. The two chips, designed and fabricated at NIST, collectively account for 102,480 Josephson junctions and are summed to create waveforms with an rms output voltage of 2 V [6] [1]. Details of the chip design can be found elsewhere [6] but will be described very briefly here. The NIST JAWS chip utilizes on-chip Wilkinson dividers so that each pulse generator channel and microwave line can bias multiple Josephson junction arrays. This reduces system expense and complexity, but also introduces limitations which have been mitigated with finite-impulse-response (FIR) filters and inside-outside DC blocks [6] [7] [1] [6].

The JAWS system is based on a Josephson array that is biased with high-speed current *pulses*. Because the maximum, sinusoidal output voltage is proportional to the pulse repetition rate, a fast pulse rate of $15 \, x \, 10^9$ pulses per second is required for generating voltages up to 1 V per chip [7]. To synthesize a pulse pattern for a desired waveform, a delta-sigma modulator converts the mathematically defined waveform into a corresponding pulse pattern. The delta-sigma algorithm for JAWS steps through the desired waveform as a function of time. At each step, a decision is made whether the agreement between the desired waveform and the programmed waveform is better with a positive pulse, negative pulse or no pulse [1]. Once the pulse pattern is created, it is uploaded to a pattern generator that delivers the microwave pulse sequence to the JAWS chips. The Josephson junction arrays then transform the incoming "digital" pulse pattern into a sinusoidal waveform [4]. Figure 1 demonstrates the sequence of steps required to generate a quantize waveform with the JAWS.

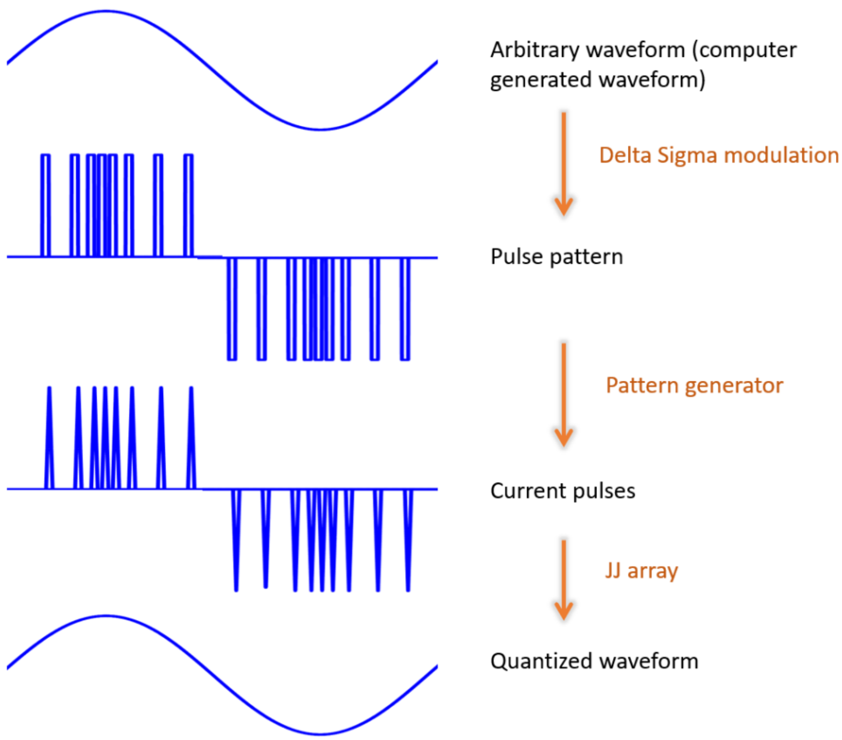

Figure 1 Sequence of steps required to generate a quantized waveform with JAWS.

When every Josephson junction produces a single voltage pulse per input bias pulse, the system is said to be operating within its quantum locking range (QLR) [1]. When operating within the QLR, the output voltage generated by the Josephson junctions is precisely known [1]. If the system does not have a QLR, then the output voltage is undefined and the system cannot serve as a quantum standard. To determine if a system has a viable QLR, the bias current is dithered to determine the limits of the operating range (known as operating margin). If the output voltage remains constant as a function of dithered bias parameter, then the operating conditions are valid [6]. NIST has developed a graphical method for displaying QLR for the JAWS. In this method, the ideal synthesized waveform is subtracted from the measured signal and only the residuals are shown in a surface density plot [6] [1]. An example of NIST's QLR visualization is shown in Figure 2. Here, the vertical axis shows the magnitude of DC offset current (dither magnitude) and the horizontal axis represents one period of the JAWS signal [6]. The central speckled band shows the QLR where the residuals are minimal. The bright colored bands at the top and the bottom of the plot represent bias current values outside the QLR. This visual representation of QLR can be used to monitor the size and quality of the QLR band as a function of bias parameters.

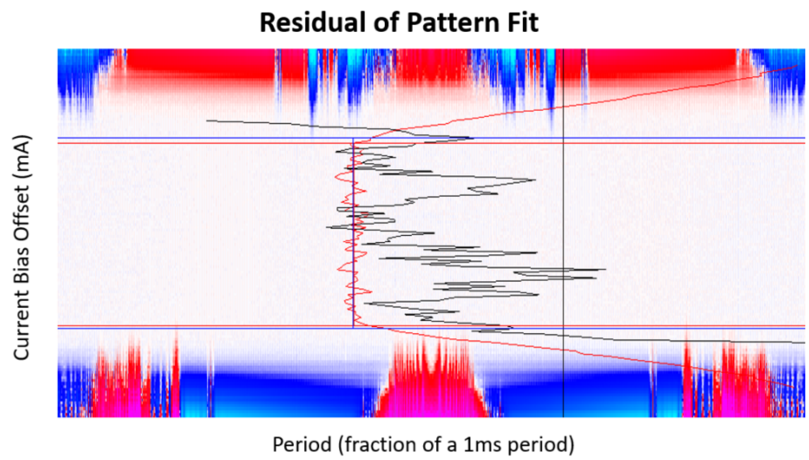

Figure 2 Graphical method for displaying QLR in the JAWS. The residuals of the ideal versus measured waveforms is plotted as a function of DC current offset and period. The light area represented the region where the residuals are a minimum (desired state). The black, red and blue curves represent the total harmonic distortion of the pattern.

For Sandia's JAWS system, pattern generation and QLR margin visualization was performed using software developed by NIST. Optimization of the QLR was required for the desired output voltages and frequencies. For each voltage and frequency, a pulse pattern was generated using the delta-sigma algorithm described above. Then, this pattern was loaded into the JAWS specific software and various bias parameters were manually adjusted to maximize the QLR margin. This process was repeated for each voltage and frequency step. Optimization of the QLR was required for all of the desired output voltages and frequencies.

Once the QLR margins were optimized for each voltage and frequency, AC-DC difference measurement were performed on a Fluke 792A. AC-DC difference measurements were performed using NIST-developed software for the JAWS. JAWS was used as a source and a Fluke 792A as the device under test (DUT); in other words, JAWS AC and DC voltage outputs were directly fed into the DUT. The AC-DC difference, δ, was calculated as

$$\delta = \frac{(AC_{DUT} - DC_{DUT})}{DC_{DUT}} \quad (3)$$

where AC_{DUT} is the DUT's output voltage when an AC voltage is applied and $DC_{DUT}$is the DUT's output voltage when a DC voltage input is applied.

Each AC-DC difference measurement was the average of six consecutive difference measurements of the triple-voltage sequence of V_{+DC}, V_{AC}, and V_{-DC}. A 30 s delay was programmed between each voltage measurement to ensure that all biases switched properly and that the Fluke 792A stabilized. For each of the voltage measurements, the output of the DUT was measured on a DVM. The software internally calculated the AC-DC difference using the equation shown above. The software also applied a small dither offset current bias to select points to allow the user to provide a quick verification that the system was operating within the QLR.

Conventional AC-DC measurements:

At Sandia's PSL, conventional AC-DC measurements involved a comparison method in which the DUT was measured in parallel with a standard thermal transfer device. AC and DC voltages are applied to both units and the output voltages of the devices were measured. The AC-DC difference equation above was used with a correction to account for any difference between the measured value and the calibrated value of the standard. In other words,

$$\delta_{DUT} = \left(\frac{(AC_{DUT} - DC_{DUT})}{n_{DUT}DC_{DUT}}\right) - \left(\frac{(AC_{STD} - DC_{STD})}{n_{STD}DC_{STD}}\right) + \ \delta_{STD} \qquad (4)$$

where δ_{DUT} is the AC-DC difference of the DUT, δ_{STD} is the AC-DC difference of the standard, and n is a sensitivity coefficient.

The data obtained on the JAWS system was compared to AC-DC difference data collected using conventional methods both at Sandia and at Fluke Corporation. The same device was used for all measurements shown here. AC-DC difference measurements were performed on the Fluke 792A 22 mV, 220 mV and 700 mV ranges for frequencies from 20 Hz up to 100 kHz.

Results and Discussion:

To provide an adequate comparison of AC-DC measurements between the JAWS and conventional measurements, similar voltages and frequencies were chosen when performing measurements on the JAWS. A set of 3-4 voltages were chosen for three different ranges of the Fluke 792A.

The results of the JAWS AC-DC difference measurements on a Fluke 792A are shown in Figure 3, Figure 4, Figure 5. In the plots, the raw JAWS data is shown and plotted against conventional measurements performed at Sandia's PSL and Fluke Corporation. In the plots, the error bars on the Fluke Corporation and PSL data reflect combined uncertainties at $k = 2$. At this point, the error bars on the JAWS datapoints represent measurement repeatability only. A full uncertainty analysis on the JAWS data will be calculated at a future date and will follow the guidelines presented in Ref. [4].

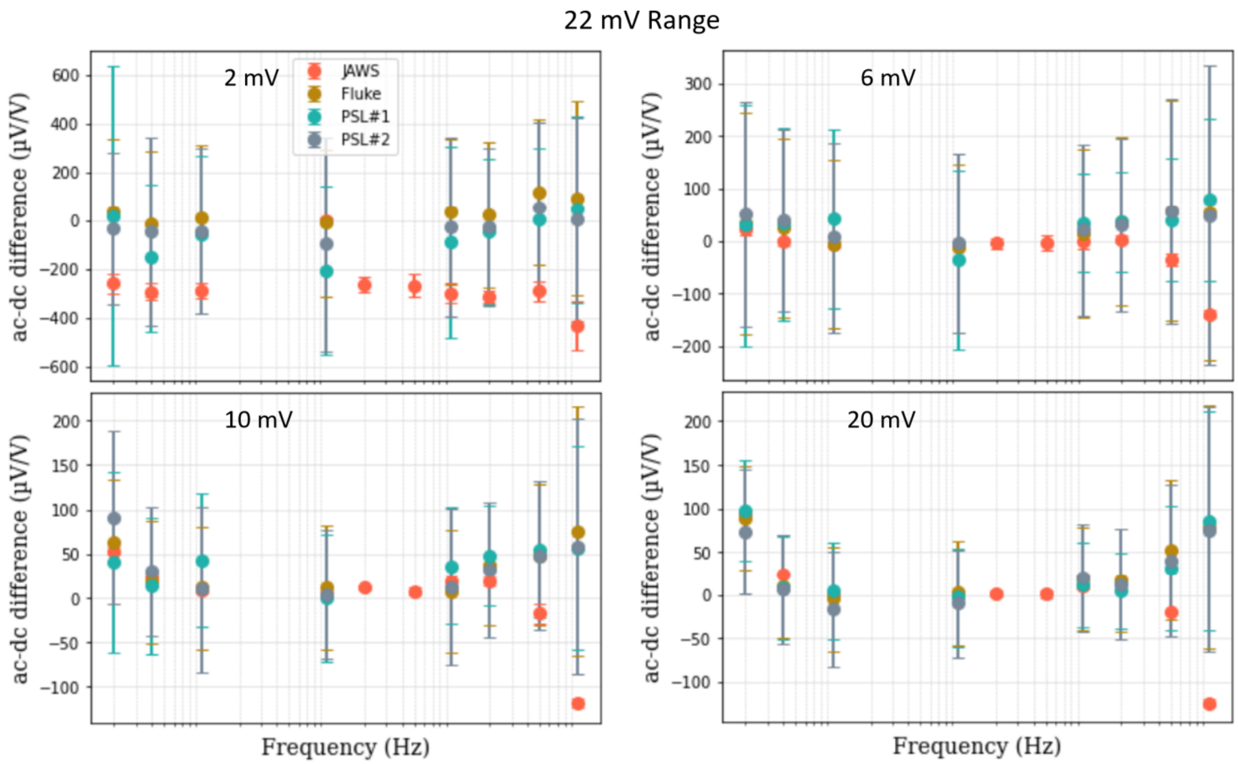

Figure 3 AC-DC difference data on Sandia PSL's JAWS system as compared to conventional AC-DC difference measurements. Data is shown for the 22 mV range on a Fluke 792A.

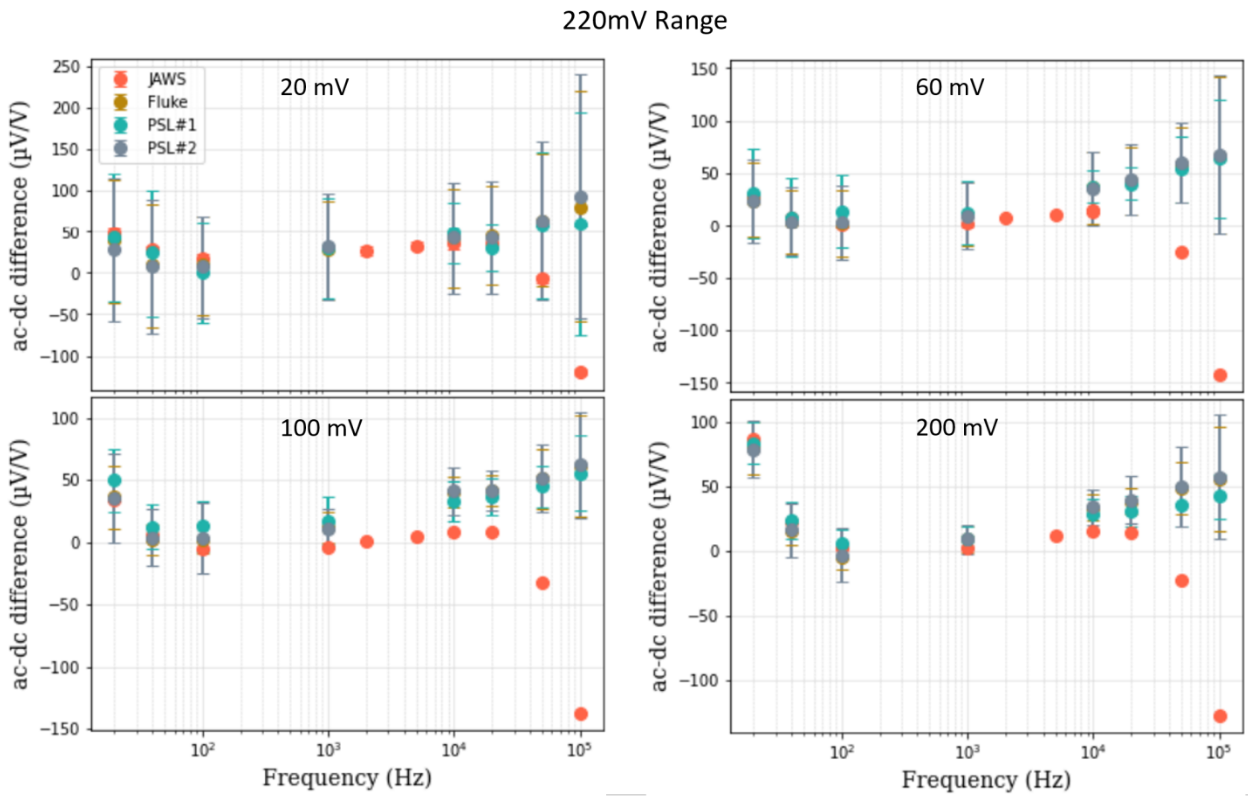

Figure 4 AC-DC difference data on Sandia PSL's JAWS system as compared to conventional AC-DC difference measurements. Data is shown for the 220 mV range on a Fluke 792A.

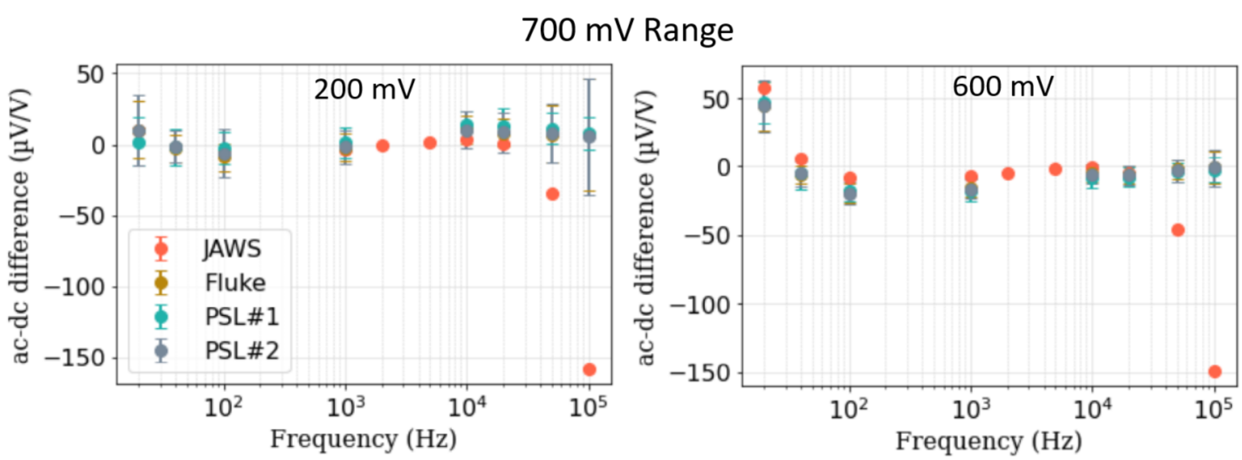

Figure 5 AC-DC difference data on Sandia PSL's JAWS system as compared to conventional AC-DC difference measurements. Data is shown for the 700 mV range on a Fluke 792A.

For nearly all voltages and ranges, the JAWS data falls within the conventional measurement error bars up to ~20 kHz. Above these frequencies, transmission line effects play a more significant role and a correction is necessary to remove these effects and bring the AC-DC difference data back in line with conventional measurements. Reference [4] discusses the transmission line effects in detail and outlines the steps necessary for performing corrections to the data. This will be performed on the Sandia PSL's JAWS measurements in the near future.

This initial data shows good agreement between the conventional measurements and the JAWS measurements using a Fluke 792A as a DUT. As mentioned, moving forward, a correction method will need to be applied to the higher frequencies to remove transmission line effects. Additionally, an interlaboratory comparison on a DUT, such as a Fluke 792A, will need to be performed. In this case, the DUT will be first measured at NIST-Gaithersburg which has two JAWS systems: one earlier model AC-JVS and an SRI JAWS which is identical to the JAWS system at Sandia. Measurements will be performed on both NIST systems and also performed on the Sandia JAWS system to complete the interlaboratory comparison. These measurements will be performed within the next 6-12 months. Lastly, a complete uncertainty analysis will need to be performed on the Sandia PSL JAWS system. To do this, a method similar to that outlined in Ref. [4] will be performed.

Conclusion:

In conclusion, the Sandia PSL recently procured an SRI JAWS system from NIST. The JAWS is a quantum, intrinsic standard for alternating voltage and, in Sandia's case, will be used to calibrate DUTs such as Fluke 792A. As discussed in the paper, the JAWS posseses some limitations in frequency and voltage, however, there is enough overlap with conventional AC-DC difference measurements on the Fluke 792A that a reasonable comparison can be performed between the two methods. The PSL recently completed a full set of data to perform a comparison of AC-DC difference measurements between JAWS and conventional measurements. The data shows reasonable agreement (JAWS data within the error bars of the conventional measurements) for data up to 20 kHz. Above this frequency, known transmission line effects inflate the AC-DC difference values for the JAWS data. These effects can, and will, be corrected in the upcoming months. These initial data sets are a promising step towards having an in-house intrinsic standard for alternating voltage at Sandia.

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