# PROGRESS TOWARD A 1 V PULSE-DRIVEN AC JOSEPHSON VOLTAGE STANDARD

S.P. Benz, P.D. Dresselhaus, N.F. Bergren, and R.P. Landim[1]
National Institute of Standards and Technology
Boulder, CO, USA

## Abstract

We present a new record output voltage of 275 mV rms, which is a 25 % improvement over the maximum achieved with previous ac Josephson voltage standard circuits. We demonstrate 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 an eight-array circuit capable of achieving 1 V rms.

## Introduction

Since the invention of the pulse-driven Josephson digital-to-analog converter in 1995 [1], an important goal has been to increase the 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 were 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 NIST ac voltage calibration service in 2006 [4].

During the past two years, further improvements have been made, especially 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 for the first time to propose a practically achievable eight-array circuit that will enable direct synthesis of 1 V rms quantum-accurate waveforms. We describe the proposed 1 V circuit and present measured results at 275 mV, including FFT measurements using a commercial digitizer at 1 kHz and 100 kHz frequencies.

## 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 in order 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.

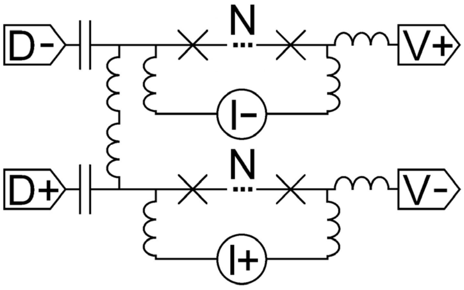

**Figure 1.** Simplified schematic of ac-coupled circuit showing differential voltage output, capacitive dc blocks, compensation current (I), Data (D+) and Data complement (D–), inductive low-pass filters, and "N" number of series junctions per array.

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 work, 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, while the previous circuits were tapered to only 32 Ω.

We also 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 purpose produces an analog waveform of inverted polarity. DC blocking capacitors (acting as broadband high-pass filters) remove 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, in order 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.

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[1] R. P. Landim is with the National Institute of Metrology, Standardization and Industrial Quality (INMETRO), AV. Nossa Senhora das Gracas, 50, Xerém, Duque de Caxias , RJ 25250-020, Brasil (e-mail: rplandim@inmetro.gov.br)

We propose to construct 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 on a 1 cm-square chip for eight arrays. The challenge of this approach is to simultaneously create and synchronize the output waveforms of the eight digital and eight compensation bias signals. Implementation of this approach is currently limited by the inability to synchronize the digital bitstreams.

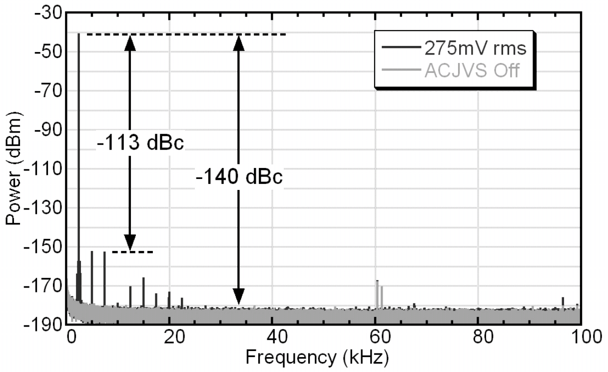

**Fig. 2.** Digitally sampled spectral measurement showing –113 dBc [dB below the fundamental (carrier)] low distortion of the ACJVS output. Two series-connected Josephson arrays are generating a precision 275 mV (rms) sinewave at 2.5 kHz. The digitizer used 1 MΩ input impedance, the 10 V input range,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

## Measurements

The arrays are biased with a 15 GHz microwave drive and a 4 Mbit digital pattern clocked at 10 Gbit/s. Waveforms with a minimum frequency of 2.5 kHz can be synthesized with this configuration, as well as harmonics 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 PXI-5922 Digitizer with low harmonic distortion [9]. 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 that 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 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 working properly for these longer arrays.

The larger precision 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 ADC, 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 of the digitizer. It is easy to confirm that the digitizer produces the distortion, because for single arrays we can exactly reproduce the distortion using each array independently. For larger voltages with both arrays active, we confirm this by attenuating the ACJVS signal and look for changes in the distortion. Even for the 100 kHz waveforms, the digitizer distortion is excellent, and is better than -108 dBc for all voltages and input ranges.

**Table I. Measurements of the digitizer distortion for different ACJVS precision voltages at 2.5 kHz and 100 kHz.**

| Frequency (kHz) | Array Circuit | Voltage (mV rms) | Distortion (dBc) Meter Range | |
|---|---|---|---|---|
| | | | 10V | 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 |

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.

## Acknowledgements

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## References

[1] S.P. Benz and C.A. Hamilton, “A pulse-driven programmable Josephson voltage standard,” *Appl. Phys. Lett.*, vol. 68, pp. 3171-3173, May 1996.

[2] S.P. Benz and C.A. Hamilton, “Application of the Josephson effect to voltage metrology,” *Proc. of the IEEE*, vol. 92, pp. 1617-1629, Oct. 2004.

[3] S. P. Benz, C. J. Burroughs, P. D. Dresselhaus, N. F. Bergren, T. E. Lipe, J. R. Kinard, and Yi-Hua Tang, “An AC Josephson Voltage Standard for AC-DC Transfer Standard Measurements,” *IEEE Trans. Inst. Meas.*, vol. 56, no. 2, pp. 239-243, April 2007.

[4] J. Kinard, T. Lipe, Y. Tang, S. Benz, C. Burroughs, and P. Dresselhaus, “Calibration of Thermal Converters using a Quantum AC Source,” paper 1E-1 in (CD) Proceedings of the 2007 NCSLI Workshop and Symposium, July 29-Aug. 2, 2007, St. Paul, MN.

[5] P. D. Dresselhaus, S. P. Benz, C. J. Burroughs, N. F. Bergren, and Y. Chong, “Design of SNS Josephson arrays for high voltage applications,” *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 173-176, June 2007.

[6] S. P. Benz, P. D. Dresselhaus, C. J. Burroughs, and N. F. Bergren, “Precision measurements using a 300 mV Josephson arbitrary waveform synthesizer,” *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 864-869, June 2007.

[7] S. P. Benz, P. D. Dresselhaus, and C. J. Burroughs, “Nanotechnology for next generation Josephson voltage standards,” *IEEE Trans. Inst. Meas.*, vol. 50, no. 6, pp. 1513-1518, Dec. 2001.

[8] S. P. Benz, C. J. Burroughs, and P. D. Dresselhaus, “AC coupling technique for Josephson waveform synthesis,” *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 612-616, March 2001.

[9] This commercial instrument is identified in this paper only in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified are necessarily the best available for the purpose.