

# Precision Measurements Using a 300 mV Josephson Arbitrary Waveform Synthesizer

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**Abstract**—We have developed a Josephson digital-to-analog converter, otherwise known as a Josephson arbitrary waveform synthesizer, with 300 mV peak output voltage. This is the first system of its kind with demonstrated quantum accuracy. We show precision synthesized waveforms from dc to 100 kHz with measured distortion and harmonic content below  $-115$  dBc (dB below the carrier or fundamental). The heart of the system is a superconducting microwave integrated circuit with two Josephson junction arrays biased in parallel for the microwave drive and connected in series to double the voltage for the audio frequency output waveforms. New superconducting integrated circuits with twice as many stacked junctions and improved microwave circuits have allowed us to more than double the output voltage of our recent system. We also demonstrate that quantum-based synthesized arbitrary waveforms (not just sine waves) can be used for precision measurements of a high-performance commercial analog-to-digital converter.

**Index Terms**—AC measurements, AC voltage standard, digital-to-analog converter, Josephson arrays, Josephson devices.

## I. INTRODUCTION

NIST has been developing a pulse-driven Josephson digital-to-analog converter as an ac Josephson voltage standard (acJVS) and as a Josephson arbitrary waveform synthesizer (JAWS) for over 10 years [1]–[3]. The primary challenge has been to increase the maximum output voltage from tens of microvolts for a single junction to practical and useful values of a few hundred millivolts by use of large, uniform series arrays of coherently operating junctions. The first practical system with 100 mV rms (141 mV peak) ac voltage was recently demonstrated [4], [5] following complete integration of decade-long NIST-developed improvements in superconducting-normal metal-superconducting (SNS) Josephson junction technology [5]–[9], bias techniques [3], [10], [11], and microwave circuits and packaging [12]–[15]. Other significant research toward pulse-driven ac synthesis, which focused on different junction technologies and unique circuit designs, was completed by a European Union-funded collaboration [16]. The first acJVS system is now installed in the NIST voltage calibration service and is expected to have dramatic impact, lowering measurement uncertainties tenfold to a thousandfold, especially at lower voltages of a few millivolts [4], [5]. In this paper, we show further improvement in

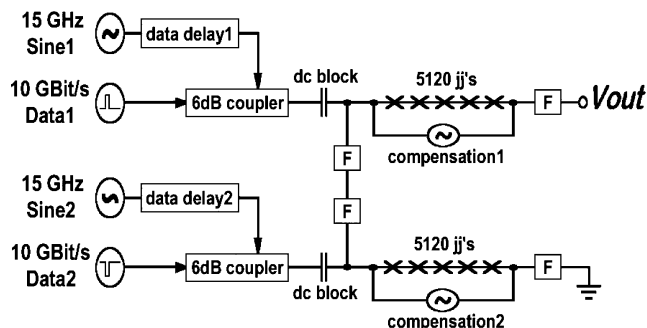


Fig. 1. Schematic of the double-array JAWS/acJVS system and each array's five bias parameters: three amplitudes of and two relative phases between the 15 GHz microwave sine, the 10 Gbit/s digital data signal, and the audio frequency compensation current sources. Each phase shifter is represented as a "data delay", and on-chip inductive filters by "F."

performance, namely more than doubling the previous output voltage to 220 mV rms, and use the precision waveforms to evaluate the performance of a commercial state-of-the-art analog-to-digital converter (ADC).

## II. ACJVS OPERATION

The acJVS system generates arbitrary waveforms with quantum-mechanically accurate voltages that it derives from precise control of the perfectly quantized voltage pulses produced by arrays of Josephson junctions. The acJVS system for the NIST voltage calibration application is designed to produce audio-frequency waveforms up to a few hundred kilohertz by use of a digital-to-analog synthesis technique based on high-speed delta-sigma modulation [17]. To produce the higher voltages for the measurements presented in this paper we increased the number of junctions per array from our previous circuits, so that the circuit uses two independently biased 5120-junction series arrays, as shown in Fig. 1. The arrays use double-stacked junctions with amorphous- $\text{Nb}_x\text{Si}_{1-x}$  ( $x = 0.15$ ) normal-metal barriers and Nb superconducting electrodes [9].

In order to synthesize bipolar waveforms, the arrays are biased with both a 15 GHz microwave drive and a 4 Mbit digital pattern clocked at 10 Gbit/s use of a digital code generator [10]. Note that the two digital data streams have opposite polarity (one is the complement of the other) and produce opposite-polarity voltage waveforms across each array. These two high-speed signals are combined with a (reverse-biased) microwave coupler. Following the ac coupling method described in [11] for removing common mode signals on the microwave transmission line termination resistors (not shown), 10 MHz dc

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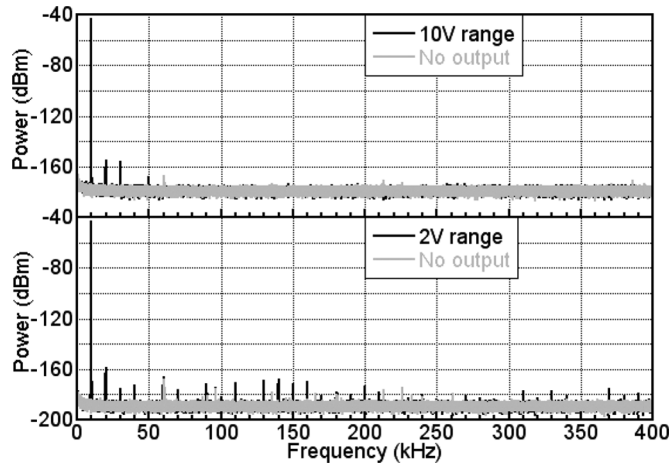


Fig. 2. Spectra of a 220 mV, 10 kHz waveform (with both arrays operating) measured on both input ranges (2 V and 10 V) of the digitizer (10 averages, 10 Hz resolution bandwidth, and 2 MHz sampling rate). The noise floor and pick-up tones shown overlaid in grey were measured with the acJVS biases turned off (no output) in order to help to highlight the synthesized tone and the different distortion tones (black) for both ranges.

blocks are used to remove the audio-frequency harmonic content of the digital signals. This audio-frequency signal is necessary for biasing the array on operating margins, so it is re-applied as the “compensation” signal across each array using separate programmable arbitrary waveform generators (AWG). The two AWGs have independent amplitude and phase adjustments. The AWG phases are synchronized to the digital waveform by the trigger output of the digital code generator. For waveforms with amplitude less than about 20% of the maximum output voltage, adequate operating margins can usually be obtained without compensation; for low voltage waveforms, the compensation current is small and the high-frequency digitization harmonics (provided by the ac-coupled digital waveform) contain the majority of the waveform energy and are sufficient to drive the array. Four on-chip inductive low-pass filters [14] are used to make four-point measurements of each array: two for the voltage output leads and two (not shown) for the compensation/current bias leads.

By use of the above techniques, the voltage waveforms generated by the two arrays can be summed, and arbitrary waveforms with any desired peak voltage up to 311.127 mV (220.000 mV rms) can be accurately synthesized by choosing an appropriate bit pattern. This voltage is 28.6% higher than our previous record 242 mV peak output voltage [12]. The maximum dc voltage that can be generated is 317.6 mV, which is determined by the total number of junctions  $N$  and the drive frequency  $f$  from the Josephson equation  $V = Nf/K_{J-90}$ , where  $K_{J-90} = 0.4835979 \text{ GHz}/\mu\text{V}$ . Unfortunately, the maximum ac signal that can be reliably synthesized is only 98% of this value, due to limitations of the single-pole delta-sigma modulator algorithm [17]. A 10 kHz synthesized sine wave at the maximum voltage is shown in Fig. 2.

In addition to simple, single-tone sinewaves, we also synthesize and demonstrate arbitrary waveforms, which can be created by choosing appropriate amplitudes and phases of harmonics of the 2.5 kHz pattern repetition frequency and summing them to

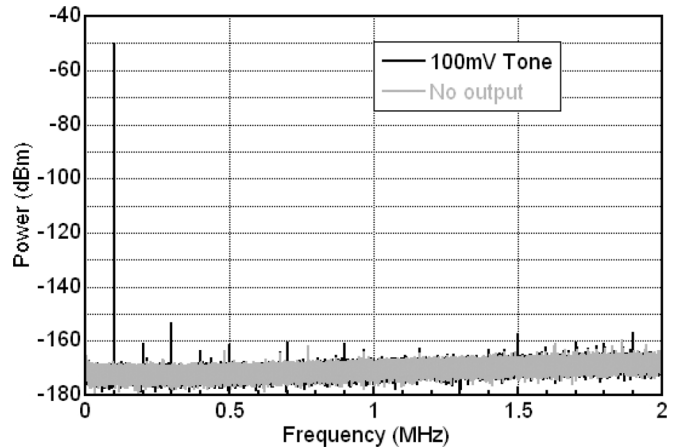


Fig. 3. Spectrum of a single tone 100 kHz sine wave (with one array operating) measured on the digitizer’s 10 V input range (10 averages, 50 Hz resolution bandwidth, and 5 MHz sampling rate). The measured noise floor is overlaid in grey (acJVS output off). Spur free dynamic range is  $-103 \text{ dBc}$ .

create a periodic waveform. This base frequency and harmonic spacing is determined by the ratio of the pattern generator clock speed and the number of bits in the pattern (10 GHz/4 Mbit). The pattern length is limited by the 8 Mbit memory of our commercial bitstream generator, which we typically divide into two equal 4 Mbit halves. By storing and subsequent switching between two different waveform patterns, we can quickly perform ac-dc and ac-ac comparisons by switching between the two memory blocks.

Different bit patterns are required for each waveform. However, to make measurements at one-half the voltage of a given waveform we routinely use only one of the two arrays, while turning off the biases to the other array. For example, the 100 mV, 100 kHz waveform shown in Fig. 3 is synthesized with only one array. We routinely operate the two arrays independently and compare their measured spectra because it is a useful tool for ensuring operating margins and measurement accuracy. For example, the arrays should produce the same measured spectra and output voltage when they are biased within the operating margins.

The primary challenge for practical applications of acJVS has been, and seems likely to continue to be, the ability to produce the largest possible voltage with as many junctions as possible generating pulses in unison. This implies that the junctions must operate coherently, such that each junction simultaneously generates precisely one quantized pulse (or higher integer multiples) for every input pulse. For this to occur, each junction must receive nearly the same microwave bias amplitude, typically within a  $\pm 15\%$  range [12]. Furthermore, the junctions must also have uniform electrical characteristics within a similar range. Operating margins degrade as a result of both non-uniform junctions and biases.

Much of the bias nonuniformity is caused by junction dissipation, which attenuates the pulse drive energy along the transmission line. Nonuniformity is also caused by low-speed bias and measurement leads that disrupt (by attenuating or causing reflections at specific frequencies) the inherently broadband (dc-to-microwave) digital bias signal, which is why

careful design of on-chip filters are very important. The junction, circuit, and bias techniques referenced in the introduction were all essential toward reducing these non-uniformities. In particular, the record 300 mV peak output presented in this paper was possible because we implemented tapered transmission lines to achieve operating margins on a record 5120 junctions per array [15].

In order to ensure accurate waveform synthesis and to optimize the operating margins, we independently tune all five bias parameters for each array: data, microwave, and compensation amplitudes, and the two relative phases between these three biases [11], [12]. Fig. 1 shows the double-array circuit schematic with the 10 total bias parameters. If any one of these parameters is incorrectly tuned, the synthesized waveform is “off margins” and will not produce an intrinsically accurate and calculable waveform. In order to quickly tune the bias parameters, we typically use a low-speed (less than 100 Hz) triangle-wave current bias to modulate the “dc” current supplied to the arrays; the arrays are considered “on-margins” when they can tolerate at least 1 mA peak-to-peak amplitude with no observed modulation of or increase in the measured distortion, that is, undesired harmonic tones at multiples of 2.5 kHz. Spectral measurements of such inaccurate waveforms have incorrect voltage magnitude and display distortion over the full measurement bandwidth (typically 500 kHz).

### III. PRECISION MEASUREMENTS

We routinely optimize the biases of our acJVS through precise measurements with either a Fluke 792A transfer standard or a National Instruments PXI-5922 digitizer [18]. In this paper, we focus on measurements with the digitizer, whose state-of-the-art low noise floor and accuracy allow us to quickly tune the acJVS bias parameters and ensure proper operation for different waveforms. Distortion harmonics are caused either by nonlinearities in the measurement instrument or by inaccurate acJVS synthesis when one of the biases is off margins. Once we have determined that the arrays are within operating margins, then the quantum-based waveforms will reveal the performance limitations of the digitizer (or any other instrument under test) that are caused by its internal nonlinearities.

This digitizer is based on a delta-sigma ADC and has two input voltage ranges (2 V and 10 V maximum) that access different amplifier configurations. The digitizer also has two input impedances, 50  $\Omega$  and 1 M $\Omega$ . For the measurements shown here we used the high impedance range. However, we also find identical measured spectra on the 50  $\Omega$  range after we increase the amplitude of the compensation biases to provide sufficient current to drive the lower impedance load.

The 50  $\Omega$  input range is also useful for determining whether distortion is produced by the acJVS or by the digitizer; inserting a 50  $\Omega$  attenuator (typically 10 dB) on the acJVS output decreases the supplied signal to the digitizer by a known amount: if the distortion decreases by the same amount as the synthesized tone, then it is likely produced by the acJVS system. If the distortion vanishes entirely or decreases more than the amount of attenuation, this suggests that the distortion is caused by nonlinearities of the digitizer. We have observed this effect particularly as we have increased our output voltage above 50 mV

rms, which is not surprising because distortion harmonics in nonlinear systems typically increase for larger amplitude signals. The distortion harmonics displayed in this paper appear to be produced by the digitizer nonlinearities, as we have presented only measurements of waveforms that are on operating margins.

For example, different distortion harmonics are observed for the two different input ranges of the digitizer, as shown in Fig. 2 for the 220 mV (−43.15 dBm), 10 kHz synthesized waveform. The distortion amplitudes at 30 kHz and higher frequencies are entirely different for the two input ranges. Amplitudes of the 20 kHz distortion tones are also different: 116 dB below the fundamental (−116 dBc) (2 V range) and −112 dBc (10 V range). These features have been observed for many different waveforms [4], [5]. Typically, the 2 V range has distortion with higher amplitude and at different harmonics than for those measured on the 10 V range, which is expected for higher gain. These observations (as well as additional measurements) suggest that the distortion harmonics in Fig. 2 are attributable to intrinsic digitizer nonlinearities, because each range has different amplifier stages that produce different harmonics. Another clue is that the frequency and amplitude of the harmonics change depending on the digitizer internal calibration (not shown). We note that for lower amplitude waveforms (below 50 mV), no distortion has been measured down to −124 dBc [4] on the 10 V range, which is the measurement noise floor. Even with the intrinsic nonlinearities, the digitizer is a powerful tool that allows a quick evaluation of the performance of the acJVS, since non-quantization related distortion over the full measurement bandwidth can be measured down to the digitizer’s very low −190 dBm (or lower for smaller resolution bandwidths) noise floor.

Measurements of synthesized tones at higher frequency, such as the 100 kHz, 100 mV sine wave shown in Fig. 3, can also be used to characterize the nonlinearities of a measurement instrument. The −103.6 dBc maximum amplitude for the harmonic distortion at 300 kHz was found to be the same, as expected, when synthesized with either array biased independently on this two-array chip. The amplitudes of distortion harmonics for this waveform as well as for other waveforms (with different frequencies and amplitudes) were also found to be identical for different arrays from different acJVS chips measured on different days. However, running the digitizer’s internal calibration routine will change its internal settings and yield different, although similarly stable, distortion patterns.

### IV. MULTIPLE-TONE ARBITRARY WAVEFORMS

It is straightforward to synthesize more complicated waveforms using the acJVS as a JAWS system by summing appropriate harmonics of the pattern repetition frequency. Arbitrary relative phases and amplitudes can be chosen for each harmonic, provided that the total amplitude  $V_t$  of the combined waveform remains less than about 98% of the maximum dc voltage. Appropriate waveforms can both simplify and improve measurements of the accuracy and performance of ADCs and other instruments. We will demonstrate three such interesting and useful waveforms for investigating intermodulation distortion, linearity over a wide dynamic range for different amplitudes, and linearity over a wide frequency range.

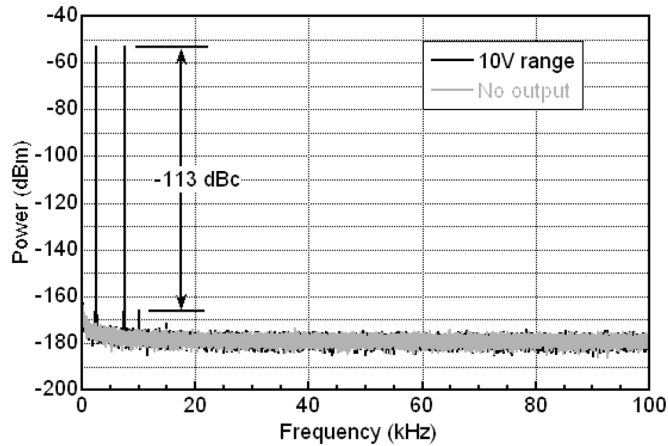


Fig. 4. Spectrum of a two-tone waveform whose first and third harmonic tones have 70 mVrms amplitude (with one array operating) and were measured on the digitizer’s 10 V input range (10 averages, 10 Hz resolution bandwidth, and 500 kHz sampling rate). The measured noise floor is overlaid in grey (no acJVS output).

One electrical performance characteristic that is important for many instruments (including amplifiers, mixers and ADCs) is intermodulation distortion, which is the distortion that occurs at linear combinations of the applied frequencies, namely the sum and difference frequencies of the maximum amplitude signals or fundamentals. One possible synthesized waveform that is useful for characterizing such distortion is one with two tones of identical amplitude. We have synthesized such a waveform with tones at 2.5 kHz and 7.5 kHz, each having 70 mV rms amplitude. These two tones were chosen to have zero relative phases so that the amplitude of the combined waveform is 96% of the peak voltage.

Only one array was used to generate this waveform because both AWGs were needed to produce the appropriate dual tone compensation signal. When this waveform was measured with the digitizer we found that it has very low intermodulation distortion, as seen in the spectrum shown in Fig. 4. The largest distortion harmonic at 10 kHz is 113 dB below the amplitude of the fundamentals ( $-113$  dBc). The JAWS system can be used to characterize intermodulation distortion over a wide range of frequencies by synthesizing any pair of tones with arbitrary amplitudes and phases [19]. It can perform this task better than any other analog or digitally synthesized source because the waveform accuracy is produced by the quantum-based properties of the Josephson junctions. JAWS waveforms of larger amplitude will be even more useful in the future.

Measured spectra of two waveforms with more than two harmonics are shown in Figs. 5 and 6. Both waveforms were constructed with multiple odd harmonics having random phases. In both cases, only a single array was used, either for simplicity or because the second AWG was needed for compensation. We commonly use unipolar versions of such waveforms in the NIST Johnson noise thermometry application [20]. We developed this “no-compensation bias” technique for this application because it was ideal for synthesizing the low-voltage quantum-accurate waveforms that are used to calibrate the frequency-dependent gain of low-noise cross-correlation electronics [20].

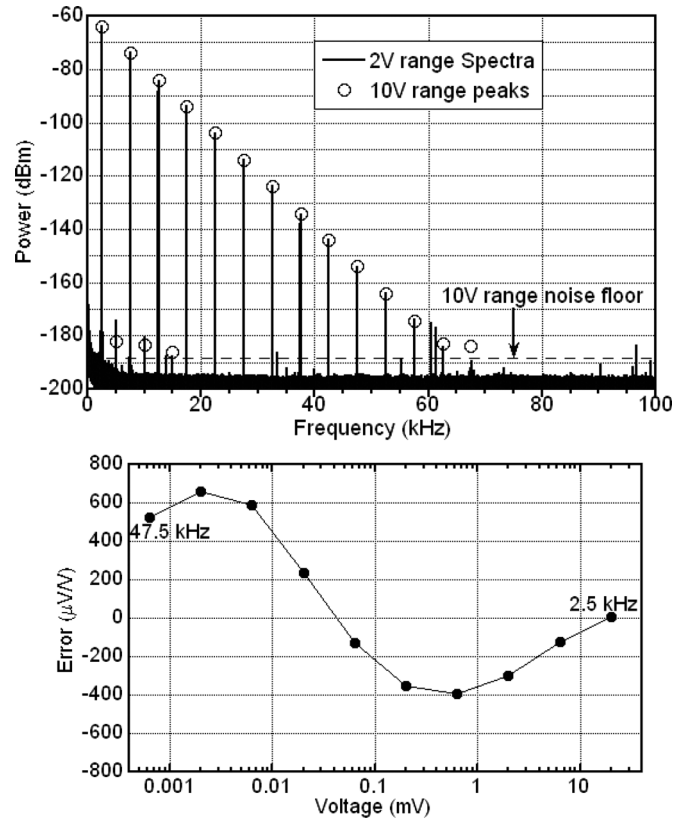


Fig. 5. (a) Spectrum of a waveform with only odd harmonic tones and random relative phases. The amplitude of each higher frequency tone is 10 dB lower than the previous tone, beginning with the 2.5 kHz fundamental at 20 mV rms ( $-63.979$  dBm). (50 averages, 1 Hz resolution bandwidth, 500 kHz sampling rate, 2 V range) Open circles show the amplitudes of both the desired and distortion tones that were measured on the 10 V range. Dashed line shows the nominal noise floor on the 10 V range using the same number of averages and resolution bandwidth. (b) Deviation of the measured voltage from expected synthesized value for 2 V range from 632 nV to 20 mV for the odd harmonic tones from 2.5 kHz to 47.5 kHz.

In the waveform whose spectrum is shown in Fig. 5, the amplitudes of consecutive harmonics were intentionally decreased by precisely 10 dB starting at 20 mV rms for the fundamental tone at 2.5 kHz. The peak amplitude of this “10 dB-stepped” waveform is 98% of the maximum dc voltage. Compensation bias was therefore applied to the first two tones to achieve adequate (1 mA dc range) operating margins.

In Fig. 5 we also show the peak amplitudes and the noise floor as measured on the 10 V range of the digitizer. Notice that the digitizer nonlinearities appear at even harmonics (5, 10, and 15 kHz) and that they are different for the two different input ranges. The intentional use of odd harmonics allows the even harmonics to be directly observed so that the largest intermodulation harmonics are apparent within the dynamic range of the digitizer. Note also that the measured distortion harmonics for this waveform are 6 dB larger for the 2 V range compared to the 10 V range, where the even tone at 5 kHz was measured at nearly  $-120$  dBc.

In Fig. 5(b) we display the normalized error representing the deviation in the measured amplitude from the expected, synthesized voltage for each tone ( $V_{meas} - V_{expect}$ ). (We don’t show the error for lower voltages at frequencies  $>50$  kHz

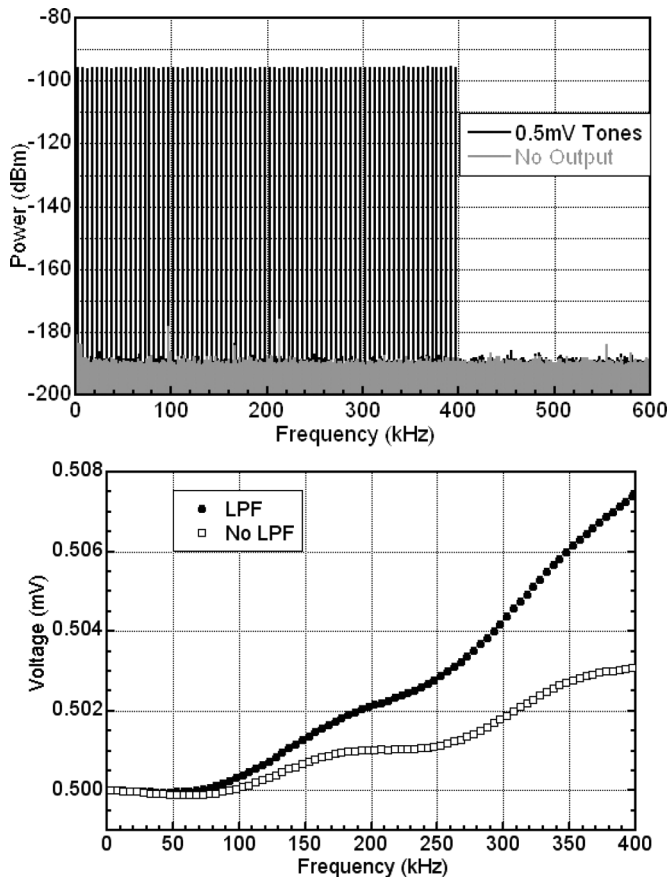


Fig. 6. (a) Single array spectrum of a synthesized waveform with 159 consecutive odd harmonic tones from 2.5 kHz to 397.5 kHz with random relative phase and identical 0.5 mV rms amplitude, measured on the digitizer's 2 V input range (no averages, 1 Hz resolution bandwidth, and 2 MHz sampling rate). The measured noise floor is overlaid in grey (no acJVS output). (b) Measured voltage linearity vs. frequency for peak amplitudes of the odd harmonic tones with (solid circles) and without (open squares) a 10 MHz low pass filter between the acJVS output and the digitizer input.

because the data don't fit on the plot and there is a lot of scatter, indicating that longer integration time is required to yield useful information.) This is not a true voltage-linearity measurement because the different voltages appear at different frequencies. Nevertheless, one could use such a single waveform to quickly evaluate an instrument's amplitude linearity over a narrow bandwidth by choosing an appropriate starting frequency and spacing the tones at the 2.5 kHz pattern repetition frequency. Although it is not surprising that the "error" increases for smaller voltages, other waveforms and measurements are necessary to separate the frequency- and amplitude-dependent nonlinearity. Nevertheless, the digitizer displays impressive absolute error and voltage linearity over nearly five orders of magnitude in amplitude.

A waveform with constant amplitude tones is much more useful for revealing frequency-dependent linearity. In Fig. 6 we show the spectrum of such a waveform with identical 0.5 mV rms amplitude odd harmonic tones up to the 159th harmonic at 397.5 kHz. Since compensation was impractical (requiring more than two tones) for this complex waveform, we constructed a waveform whose peak amplitude is only 8% of the maximum dc voltage so that compensation wouldn't be

necessary. This was accomplished through appropriate choice of the amplitude, the number of harmonics, and their relative phases. Random relative phases are particularly useful for minimizing the peak voltage of such waveforms. With a small (1 Hz) resolution bandwidth the noise floor was reduced to nearly  $-95$  dBc. No distortion harmonics were observed above the noise floor over the full measurement bandwidth and the available dynamic range.

In order to evaluate the voltage linearity of this measurement, in Fig. 6(b) we show the tone amplitudes when measured both with and without a 10 MHz low-pass filter inserted between the JAWS output and the digitizer input. The linearity is nearly constant up to 100 kHz. Above 100 kHz the voltage modulates and dramatically increases for higher frequencies. Furthermore, the voltage differences from the expected 0.5 mV are nearly 2.5 times larger when measured with the filter (e.g., 7.5  $\mu$ V at 400 kHz) compared to the error from the unfiltered measurement (3  $\mu$ V at 400 kHz).

These measurements demonstrate the challenge in interpreting broadband precision measurements because the observed frequency-dependent behavior is produced not only by intrinsic nonlinearities, such as those from the digitizer's input amplifiers, but also from frequency-dependent input impedance and capacitive loading effects from the measurement transmission line and the low-pass filter [5]. The input impedance of the digitizer was 1 M $\Omega$  for these measurements. However, the effective input impedance is likely much lower at higher frequencies because of input capacitance. Likewise, the capacitance of the low-pass filter loads the JAWS voltage source at higher frequencies, giving an apparent increase in measured voltage. Additional measurements are needed, especially using the 50  $\Omega$  input range, to determine the true frequency-dependent voltage linearity of the digitizer. Fortunately, because the JAWS circuit behaves as an ideal voltage source, such measurements are straightforward.

## V. CONCLUSION

We have more than doubled the output voltage to 220 mV rms of our JAWS quantum-based voltage standards. Using this new system, we have explored and demonstrated the practical application of this quantum-based source through precision measurements of a commercial ADC. The accurately synthesized sine waves and arbitrary waveforms successfully illuminated important and interesting performance characteristics of this instrument. Without such an accurate waveform synthesizer, many of these characteristics would be difficult or impossible to measure. Once we have demonstrated the accuracy of the 220 mV superconducting integrated-circuit chip with precision ac-dc transfer standard measurements, this new chip will replace the 100 mV chip in the acJVS system that is now installed in the NIST AC-DC Difference Calibration Service. Further research and development of junctions, circuits, and instrumentation will be required to achieve our goal of a JAWS with 1 V rms output voltage.

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