Reduced Nonlinearity Effect on the Electronic Measurement of the Boltzmann Constant

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***Abstract*—The National Institute of Standards and Technology has developed a quantum-voltage-noise-source-calibrated Johnson noise thermometer (JNT) to provide a new electronic measurement technique for determining the Boltzmann constant. Improvements in electronics and synthesized noise waveforms have led to reduced uncertainty in the measurement. Recent investigations have shown that some of the distortion in the present electronics arises in the differential stage of both the preamplifier and the analog-to-digital converter (ADC). The distortion can be reduced by compensating the direct current offset of the signal at the inputs to the differential stage. A four-channel cross correlation JNT with optimized preamplifiers and new ADCs is being assembled. The improvements are on track to reach the goal of an electronic measurement of the Boltzmann constant at a relative uncertainty of 6×10^{-6}.**

***Index Terms*—Correlation, digital–analog conversion, Josephson arrays, noise, nonlinearities, quantization, signal synthesis, standards, superconductor–normal–superconductor devices, temperature.**

I. Introduction

JOHNSON noise thermometry (JNT) is one of the few thermometric techniques that can determine the absolute temperature of an object. In practice, one measures the thermal voltage noise of a resistor to reveal the thermodynamic temperature, which is based on the Johnson–Nyquist equation: $\langle V^2 \rangle = 4kTR\Delta f$, where the mean-squared voltage $\langle V^2 \rangle$ is proportional to the Boltzmann constant k, the temperature T, the resistance R, and the measurement bandwidth Δf [1], [2]. The main challenge is that the extremely small noise voltage ($\sim$1.2 nV/Hz$^{1/2}$ for a 100 Ω resistor at the triple point of water (TPW), i.e., 273.16 K) requires low-noise measurement techniques [3].

To improve this electronic-based temperature measurement technique, the National Institute of Standards and Technology (NIST) has developed a quantum voltage noise source (QVNS) with Josephson junction (JJ) arrays to calibrate the JNT cross correlation electronics [4]–[8]. The QVNS-JNT system uses quantum accurate pseudonoise as a reference source and thus links thermodynamic temperature to fundamental physical constants, providing an important independent method for determining thermodynamic temperature. To date, the system has been successfully used to understand the deviations of the International Temperature Scale of 1990 (ITS-90) from thermodynamic temperature. The measurements at the moderately high temperatures of the freezing points of zinc (692.677 K) and tin (505.078 K) [9] agreed well with those from archival gas thermometry and radiation thermometry [10].

The QVNS-JNT can be also used to determine the ratio between the Boltzmann and the Planck constants, i.e., k/h, by matching electrical power and thermal noise power at the TPW [11]. Because the relative standard uncertainty for the Planck constant is parts in 10^8, whereas it is parts in 10^6 for the Boltzmann constant (2006 Committee on Data for Science and Technology), the QVNS-JNT offers a unique electronic approach for redetermining the Boltzmann constant. The current Boltzmann constant is determined predominantly from a single measurement of the molar gas constant by another primary method, i.e., acoustic-gas thermometry [12]–[15]. NIST's goals are to reduce the relative uncertainty in the electronic temperature measurement to 6×10^{-6}, which is close to the lowest uncertainty of 1.7 μK/K achieved through acoustic-gas thermometry [12], and to contribute to the redetermination of the Boltzmann constant [11], [15].

In past years, NIST had made a number of improvements to the JNT system to pursue the aforementioned goals [16]–[20]. A specialized QVNS circuit was designed for lower voltage signals and longer integration period requirements for noise measurement. It consists of a symmetric pair of grounded lumped arrays that have a small number of junctions, typically only eight in total. New cross correlation electronics were developed, including a switchboard with symmetric connections, a lower noise preamplifier with higher common-mode rejection ratio (CMRR), and a lower noise broad-band buffer amplifier. Furthermore, the noise power and the impedance of the transmission line were matched to reduce the uncertainty of the temperature measurement, which will be described in detail in this paper. The improvements increase the measurement bandwidth, decrease the measurement period, and reduce the measurement uncertainty. However, there are still unwanted factors that limit the temperature measurement, i.e., the measured absolute temperature shows $\sim$50 μK/K disagreement with the International System of Units value, and the measured

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uncertainty in the ratio of the noise power is higher than the value expected from statistical analysis [18].

The remaining nonlinearity of the cross correlation electronics is the most important one of the problems that affects the temperature measurement. Distortion produced by nonlinearities adds to the noise spectra and thus produces systematic error and limits the measured uncertainty [19]. Figuring out the sources of the nonlinearities has been important but challenging because the distortion is extremely small and is usually buried below the noise floor of the amplifiers. The QVNS-synthesized waveforms are powerful tools to discover the small distortions of the JNT electronics because they can be synthesized with a wide range of amplitudes and harmonic content with quantum accuracy that produces pure undistorted waveforms [20], [21].

In this paper, which is an extended version of the digest summary in the 2010 Conference on Precision Electromagnetic Measurements [16], we describe how we detected the nonlinearities by auto- and cross correlation measurement with the QVNS-synthesized waveforms. We demonstrate that the quantized multitone comb waveforms with higher tone density are helpful for reducing the effect of the electronics nonlinearity. In addition, we present our recent measurement results, which reveal that some of the distortion in the present electronics arises in the differential stage of both the preamplifier and the analog-to-digital converter (ADC). Distortion from the preamplifier can be reduced by compensating the direct current (dc) offset of the signal at the inputs to the differential stage. Finally, we introduce the new four-channel JNT system that is under construction and is anticipated to further reduce the measuring uncertainty of k/h.

II. QVNS Synthesis and Cross Correlation Technique

The QVNS synthesizes intrinsically accurate precision waveforms with delta-sigma analog-to-digital conversion algorithms. The waveform accuracy is a result of the voltage pulses produced by the JJs that are always perfectly quantized and have a time-integrated area precisely equal to the inverse Josephson constant $K_J^{-1} \equiv h/2e$, i.e., the ratio of Planck's constant to twice the electron charge [22], [23]. The synthesis techniques were initially developed for building the ac Josephson voltage standard [22]. For noise thermometry, the lower voltages and longer integration periods require a specialized QVNS circuit design that consists of a symmetric pair of grounded lumped arrays, having only a small total number of junctions (typically $N_J = 8$ to 256). The chip used in the current JNT experiments contains two arrays, each having only four superconductor/normal-conductor/superconductor JJs. Each array is separately biased with a unipolar pulse drive that is clocked at the 10-GHz sampling frequency f_s. The synthesized waveform has a minimum frequency called the pattern-repetition frequency, i.e., $f_0 = f_s/M$, that is determined by the clock frequency and the bit length M of the digital code.

Pseudonoise waveforms, which are typically even-only or odd-only frequency combs, are constructed by summing equal-amplitude random-phase harmonics of f_0. The amplitudes of these tones are chosen so that the average power spectral density (PSD) $S_Q = \langle V^2\rangle/f_0 = D^2N_J^2f_sM/K_J^2$, where dimensionless factor D scales the voltage and closely matches the PSD of the sensing resistor $S_R = 4kRT$. Thus, the ratio k/h can be represented as

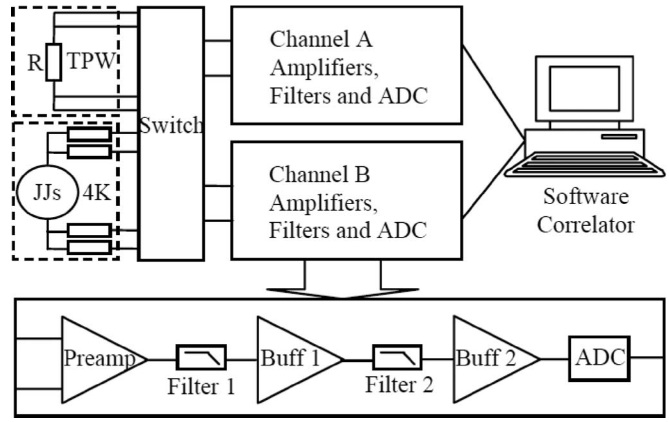

Fig. 1. Schematic of the two-channel QVNS-JNT cross correlation system. The sense resistor R is immersed in a TPW cell, and the JJ arrays are immersed in 4 K liquid helium.

$$\frac{k}{h} = \frac{\langle S_R\rangle}{\langle S_Q\rangle}\frac{D^2N_J^2f_sM}{16TX_R} \tag{1}$$

where X_R is the resistance expressed in units of the Von Klitzing resistance $R_K \equiv h/e^2$ [24]. Equation (1) is the basis for the QVNS-JNT system to determine the Boltzmann constant by measuring the ratio of the PSDs of the thermal noise and the voltage pseudonoise.

Cross correlation electronics are used to measure the noise power. Fig. 1 shows the schematic of the present QVNS-JNT system, which consists of the thermal noise sense resistor R, the QVNS, a switching network, two nominally identical amplifier chain channels, and a software correlator. The resistors of similar resistance R are inserted in the QVNS transmission lines to match the impedance. Depending on the position of the switching network, the resistor and the QVNS-synthesized voltage signals are alternately amplified and filtered in both amplifier chain channels. The preamplifier provides 70 dB $\pm$ 0.5 dB gain over a bandwidth of 1 MHz and up to 100 dB CMRR at 100 kHz. The 11-pole low-pass filters, i.e., Filters 1 and 2, have the respective cutoff frequencies of 650 and 800 kHz that define the measurement bandwidth. The second filter reduces the finite distortion of the electronics in the stop band of the first filter and ensures that signals aliased below 650 kHz are more than 120 dB lower than the synthesized fundamental tones. Buffer amplifiers Buff 1 and Buff 2 are used to drive Filter 2 and the ADC. The gains are chosen to be $1\times$ and $11\times$, respectively, to reach the full dynamic range of the ADC. The ADC electronics samples these signals for 1 s with a 2.08 MHz sampling frequency. This produces the frequency resolution bins of 1 Hz and a 1.04 MHz Nyquist frequency f_N, above which the sampled frequencies are aliased back into this measurement bandwidth. The autocorrelation signals of each channel are averaged over 100 (1 s) intervals, and their complex frequency domain signals are separately stored. The measured signals from both channels are then cross correlated in software to remove the uncorrelated noise from each channel.

The cross-correlated electrical and thermal noise powers, i.e., $\langle V_R \rangle^2$ and $\langle V_Q \rangle^2$, are compared over discrete bandwidths centered at each harmonic tone, such that the bandwidth corresponds to the tone spacing of the synthesized waveform, typically f_0 for all harmonic tones and $2f_0$ for odd or even tones. The ratio of the noise power $\langle V_R \rangle^2 / \langle V_Q \rangle^2$ is of order unity. The frequency-dependent noise-power ratio is fitted with a two-parameter model $(a_0 + a_2 f^2)$ to remove the remaining differences in the frequency responses due to the mismatch between transmission lines connecting the resistor and the QVNS to the preamplifiers. The parameter a_0 is then used to calculate the temperature. The uncertainty of a_0 presents the statistical contribution to the uncertainty in the temperature measurement. With increasing integration period, the statistical uncertainty is expected to fall as the inverse of the square root of the period.

III. Reduced Nonlinearities

The nonlinearity affects both the spectral density of the noise power and their variance and thus introduces systematic errors and contributes uncertainty to the temperature measurement. In our earliest measurements, the most significant source of systematic errors arose from distortion generated by various poor wiring connections, such as oxidized solder and kinked wires, throughout the measurement circuit and electronics. The specific sources were found through careful auto- and cross correlation measurements of the QVNS-synthesized multitone waveforms. Typically, odd-tone waveforms are measured so that large even distortion can be detected, which would occur in 1-Hz bins that are centered precisely between the synthesized tones. Large even distortion was also detected in an active antialias filter used in previous circuits, which was probably due to a damaged component. Removing these features greatly reduced the scatter in the noise power ratio [19].

Mismatch between the thermal noise sense resistor and QVNS was another origin of the nonlinearity [17]. Although the amplitude of the QVNS-synthesized waveform was chosen by the factor D in (1) to closely match the thermal noise power of the sense resistor to within 0.05%, our autocorrelation measurements showed that the total noise powers input to each channel were still different for the two sources, which contributed to the measurement uncertainty according to numerical analysis [17]. The total noise power of the QVNS circuit was matched (in each channel) to that of the resistor circuit by inserting short $\sim 0.5\ \Omega$ nichrome wires in the leads of the QVNS circuit. Their resistance values, which can be calculated from the difference between the measured autocorrelation noise powers, were carefully trimmed in order to match the autocorrelated noise power in each channel.

In addition to matching the noise power, the transmission line impedance mismatch between the resistor and the QVNS circuits leads to significant frequency dependence of the noise power ratio, and thus limits the measurement bandwidth and introduces higher uncertainty [19]. Rewiring the QVNS input cable with Teflon wire instead of magnet wire reduced the

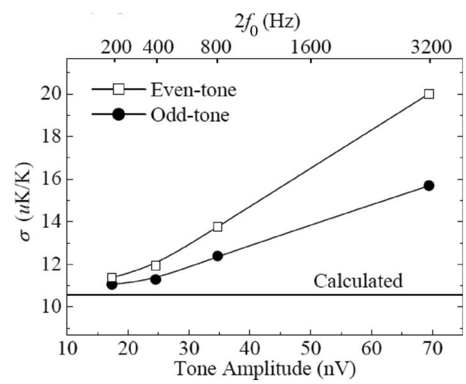

Fig. 2. Dependence of the fitted uncertainty (after integrating for a period of 80 000 s) on the tone amplitude and $2f_0$ for both odd- and even-tone waveforms. (Straight line) The statistical uncertainty calculated with [18, eq. (38)].

capacitance of the transmission line and improved impedance matching. These improvements resulted in flatter noise power frequency response (the parameter a_2 from the two-parameter fit for a 600 kHz bandwidth decreased to $\sim 10^{-9}$) [19], [20].

For the present electronics, the remaining intrinsic nonlinearities are so small that the even harmonic distortion for odd-tone combs is buried deeply below the noise floor. Measurements with the QVNS-synthesized waveforms consisting of only odd harmonics of $f_0 = 400$ kHz nearly resemble the statistical uncertainty, as expected for white noise. However, in the measurements that use the even-tone pseudonoise waveforms, the fitted uncertainty of the noise power ratio is saturated quickly and did not significantly decrease with further integration of the data, indicating that the nonlinearities of the electronics produce larger even-order than odd-order distortion, which still dominated the measurement variance for comb waveforms. In order to measure the remaining distortion, larger amplitude two-tone waveforms were used so that the amplitudes of some distortion harmonics were greater than the amplifier noise floor for autocorrelation measurements of each channel. Careful cross correlation measurements demonstrated that the even-order distortion is much higher than the odd-order one and is always present at some significant level [19].

In order to reduce further the effects of nonlinearities, another means is required other than replacing components and circuits with those having better linearity. One approach is to use synthesized pseudonoise waveforms with higher density of tones that have closer tone spacing (smaller f_0). As the number of tones in a given bandwidth increases, their amplitudes proportionally decrease in order to keep the PSD constant. The resulting lower amplitude tones will produce considerably smaller distortion from the same nonlinearity. The effect of the distortion on the variance will fall as the density of the QVNS-synthesized tones increases because of the following reasons: 1) the amplitudes of the distortion products decrease (and more quickly for those of higher order) as the tone amplitudes decrease, and 2) the variance simply decreases for a larger number of tones.

The resistor-QVNS noise power ratio was measured for both odd- and even-tone waveforms with different tone spacing $2f_0 = 3200$, 800, 400, and 200 Hz. Fig. 2 shows that after an

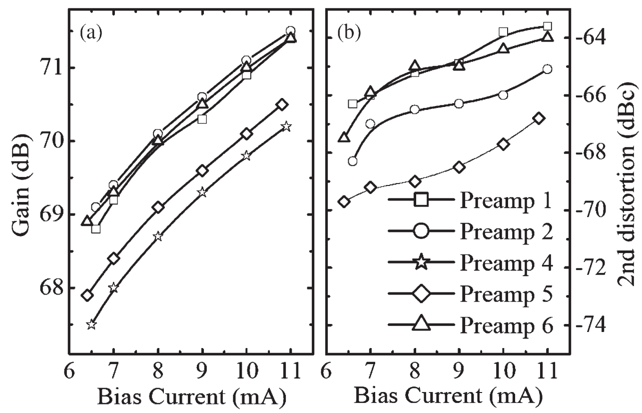

Fig. 3. JFET bias current dependences of (a) the gain and (b) the second-order harmonics of the preamplifiers.

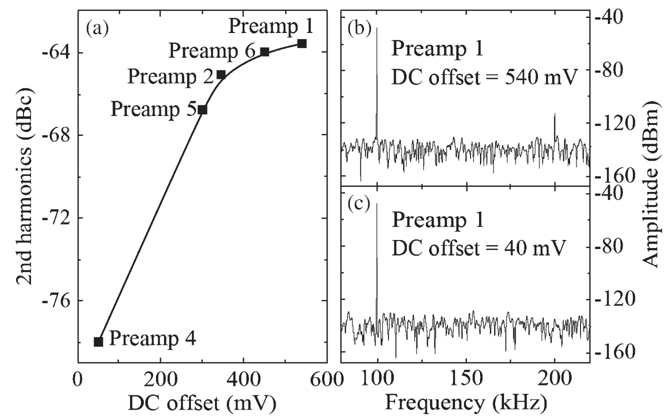

Fig. 4. Relation between the second-order harmonics and the dc offset at the input of the differential stage of the preamplifier.

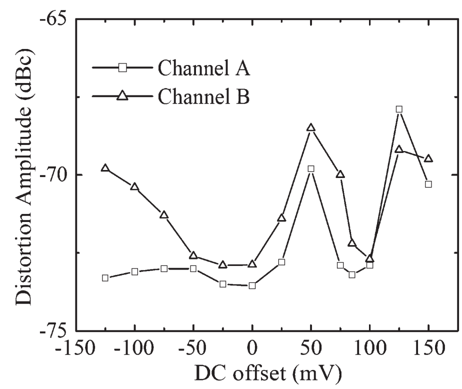

Fig. 5. Dependence of the distortion from ADC on the dc offset of the input signal.

integration period of 80 000 s, the fitted uncertainty σ of the noise power ratio decreases and more closely approaches the expected statistical uncertainty for white noise with decreasing tone spacing for both odd- and even-tone waveforms, indicating that the QVNS-synthesized waveforms with higher tone density more closely reproduce the same nonlinearities that are produced by the thermal noise. In fact, the fitted uncertainties of the noise power ratio are nearly identical, i.e., $\sim 11\ \mu$K/K, for odd- and even-tone waveforms with the closest tone spacing ($2f_0 = 200$ Hz), indicating that the even-order distortion has been significantly reduced, and the fitted uncertainty almost follows the desired and expected behavior of white noise.

IV. Distortion From Preamplifier and ADC

Figuring out the exact sources of the distortion is necessary to further improve the JNT electronics. To illuminate this, we measured the amplitude of the second-order distortion after every stage of the amplifier chain in order to locate the main source of the distortion. The input signal was a single sine wave of amplitude 41 μV and a frequency of 100 kHz synthesized by the ac Josephson voltage standard system. Amplitudes greater than 41 μV saturate the buffer amplifier.

First, the distortion was measured after the differential stage of the junction field-effect transistor (JFET) preamplifier, where the second-order harmonics were 64 and 68 dB lower than the fundamental tone in the two channels, respectively. After the buffer amplifiers, the distortion amplitudes remained at the same value, indicating that the dominant nonlinearity was in the JFET and/or differential stage of the preamplifier for both channels.

To characterize the distortion coming mainly from the JFET stage, the second-order harmonics were measured for different JFET bias currents and, therefore, different preamplifier gain. The variation in second-order harmonics for different JFET bias currents and gain for five different preamplifiers are shown in Fig. 3. One can see that the amplitude of the distortion is not necessarily related to the gain. For example, although the gain of Preamp 2 is highest among all the five preamplifiers, the second-order harmonics are lower than those for Preamp 1 and Preamp 6. Another interesting result is that for Preamp 4, even for the highest bias current and gain, the distortion is much lower ($\sim$78 dBc) than those of all the others. These results indicated that the distortion was not from the JFET stage.

The amplitudes of the second-order harmonics for all five preamplifiers were found to depend on the dc offset at the input of the differential stage, which follows the JFET stage. Fig. 4(a) shows the monotonic relationship between the second-order distortion and the dc offset. To verify this result, we nulled the dc offset by connecting the input of the differential stage to the power supply via a resistor with a properly chosen value. For Preamp 1, a 34 MΩ resistor reduced the dc offset from 540 to 40 mV. As shown in Fig. 4(b) and (c), the second-order distortion was greatly reduced and could not be resolved from the noise floor. All the other preamplifiers similarly behaved.

Similar to the differential stage of the preamplifier, we found that the dc offset of the signal at the input to the ADC also introduced distortion. For a multitone waveform, Fig. 5 presents the variation of the highest distortion tone that can be observed in the autocorrelation spectra for both channels with different dc offset of the signal at the input to the ADC. One can see that the amplitudes of the distortion for both channels are dependent on the dc offset. Although the distortion does not monotonically increase with the increasing dc offset of the signal as for the amplifiers, Fig. 5 shows that the ADCs have the smallest nonlinearity with a null input dc offset. While

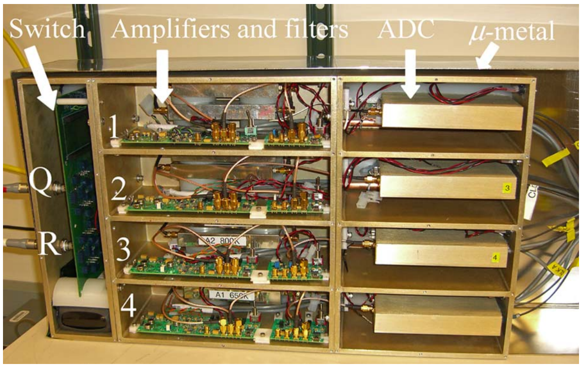

Fig. 6. Photo of the four-channel JNT electronics under development. Q and R represent the QVNS and resistor noise inputs, respectively. The two noise sources are alternately measured by the two pairs (1, 3 and 2, 4) of channels.

increasing the dc offset of the signal at the input of the ADC from 0 to 125 mV, the distortion increased by about 5 dB for both channels, and the cross-correlated distortion increased more than 10 dB.

V. New Four-Channel System

Currently, the uncertainty budget for the Boltzmann constant is still dominated by the statistical uncertainty in the noise power ratio. To reach the goal of electronically measuring the Boltzmann constant at a relative uncertainty of 6×10^{-6}, the statistical uncertainty in the noise power ratio has to be reduced to around 5×10^{-6}, which means about ten days of measurement with the present two-channel cross correlation electronics. However, both the lead-acid battery power supply and the stability of the environment may limit such a long measurement. One possible method to reduce the measurement period is to increase the signal-to-noise ratio. We are planning to increase the resistance of the sense resistor from 100 to 200 Ω. Correspondingly, the resistor on the JJ chip will also be increased to keep the impedance matching.

Another straightforward way to reduce the measurement uncertainty is to construct a four-channel cross correlation system that enables simultaneous measurement of both the signals from the resistor and the QVNS, which will reduce the measurement period twofold. Fig. 6 shows a photo of the four-channel JNT electronics that are currently being assembled. Q and R represent the QVNS and resistor noise inputs, respectively. All of the electronics are shielded in a μ-metal box (the cover of the box is not shown in the photo) to reduce the electromagnetic interference. The switchboard, four channels of amplifier chain, and ADC are electrostatically shielded, respectively, in separate metal boxes to minimize electrical interactions with each other.

A four-channel switchboard was designed to enable the simultaneous cross correlation measurement of the two noise sources. The two noise sources Q and R are alternately connected to the two pairs (1, 3 and 2, 4) of the amplifier chain channels, depending upon the state of the relays. The nearly perfect symmetry is achieved for every wiring connection pair between the input and output leads, which will further improve the transmission line impedance matching. Commutation of the input leads can also be realized with this switchboard design, which will be useful in further canceling the effects of the even-order distortion [17]. This feature was not available in previous switchboards.

The amplifier chain for every channel is similar to the two-channel system, except that the filters have been replaced with higher cutoff frequency ones in order to increase the measurement bandwidth. The goal is to increase the bandwidth to at least 1 MHz, which also requires increasing the ADC sampling frequency. A new 16-bit ADC that supports sampling at up to 10 MHz was designed and characterized, which will be reported in detail in another paper [25]. The gains of the two buffer amplifiers will be adjusted to reach the full dynamic range of the new ADC.

Finally, in order to prevent the integration time from being limited by the power supply batteries, a new Li-ion battery power supply system is developed. For every channel, two sets of Li-ion batteries are switched between the cross correlation electronics and the linear dc power charger, which enable automatic recharging of the batteries without interrupting the measurement.

VI. Conclusion

Precision waveform synthesis with the QVNS has provided an accurate quantum-based electronic reference and allowed us to characterize electronic nonlinearity. By careful auto- and cross correlation measurements with different synthesized waveforms, we have detected and reduced some of the nonlinearities of the measurement electronics. QVNS-synthesized waveforms with higher tone density decrease the effect of nonlinearity and thus improve the measurement uncertainty. Two sources of distortion in the present JNT electronics were found to occur in the differential stages of the preamplifier and the ADC. The signal symmetry at the differential circuits appears to be very important because the distortion was proportional to the dc offset of the input signal to the differential amplifiers. Reducing this distortion will further decrease the measurement uncertainty.

We are constructing a new JNT system that has four amplification channels and can simultaneously measure the noise power from the QVNS and sense resistor. Characterized and optimized amplifiers will be used in every channel. A new ADC with higher symmetry, higher resolution, and higher dynamic range was also designed. With the new system, we anticipate reaching our goal of determining the Boltzmann constant at a relative uncertainty of 6×10^{-6}.

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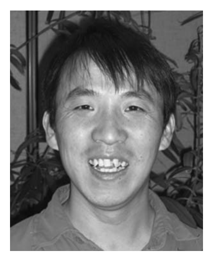

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