Development of a Four-Channel Johnson Noise Thermometry System

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***Abstract*—Long integration periods are necessary to reach low uncertainty when measuring temperature through Johnson noise thermometry (JNT). The main goal of the National Institute of Standards and Technology JNT program is to achieve a combined relative uncertainty of 6×10^{-6} in the measurement of the water triple point temperature, which, in turn, allows determination of Boltzmann's constant at the same uncertainty. To this end, a four-channel JNT system, which will reduce the measurement period twofold, is being developed with new components, including a switchboard, analog-to-digital converters (ADCs), and a programmable recharging power supply system. A significant source of systematic error that was discovered while implementing the new ADCs is described. New measurements are presented using a doubled ADC sampling rate, which show the potential for higher measurement bandwidth.**

***Index Terms*—Boltzmann's equation, correlation, digital–analog conversion, Josephson arrays, measurement units, noise measurement, quantization, signal synthesis, standards, temperature.**

I. INTRODUCTION

JOHNSON noise thermometry (JNT) is an electronic approach for determining thermodynamic temperature. The temperature T is determined by measuring the Johnson noise $\langle V^2 \rangle$ (mean-squared voltage) of a resistance R over a measurement bandwidth Δf. The relationship is defined by the Johnson–Nyquist equation $\langle V^2 \rangle = 4k_{\mathrm{B}}TR\Delta f$, where k_{B} is Boltzmann's constant. Low-noise measurement techniques must be used for measuring the very small noise ~ 1.2 nV/Hz$^{1/2}$ generated by a 100 Ω resistor at the triple point of water (TPW) $T_{\mathrm{TPW}} = 273.16$ K [1].

The National Institute of Standards and Technology (NIST) JNT system uses a purely electronic technique that exploits the precision voltage synthesis capability of superconducting Josephson junctions, which are configured as a quantum-voltage noise source (QVNS). The QVNS produces accurate pseudonoise voltage waveforms whose Fourier transforms are "frequency combs" of multiple harmonic tones. The tones are defined such that they have equal amplitude and are equally spaced in frequency but have random relative phases. The QVNS, which is used to calibrate the electronics, allows the JNT system to link thermodynamic temperature to quantum-based electrical measurements. The electrical voltage synthesized by the QVNS is matched to the thermal noise voltage of the resistor at the TPW. This results in a direct determination of k_{B}/h, where h is Planck's constant [2], [3].

The QVNS-JNT measurement has the potential to achieve a relative uncertainty of order 10^{-6}. Since h is already known to a relative uncertainty of order 10^{-8}, k_{B} could then be determined to order 10^{-6} with this electronic measurement. The present uncertainty in k_{B} is 2 μK/K, as determined by acoustic gas thermometry alone [3]. A QVNS-JNT determination of comparable uncertainty could uniquely contribute to the redetermination of Boltzmann's constant as the only electronically realized input [4].

The dominant source of uncertainty in the JNT measurement is the statistical uncertainty of the voltage noise measurements of the resistor and the QVNS. Their 1.2 nV $\cdot$ Hz$^{-1/2}$ noise voltages are small and comparable in value to the 0.9 nV $\cdot$ Hz$^{-1/2}$ noise of the amplifiers. Thus, cross correlation is required to measure the voltage noise of the two sources, and the measured statistical uncertainty depends on the integration period and bandwidth. Previously [5], [6], the lowest measurement uncertainty obtained for the TPW that was obtained with our two-channel cross-correlation JNT system was 13 μK/K with a 36 h measurement period and 600 kHz bandwidth. (The originally reported value, i.e., 19 μK/K, was 50% high due to a calculation error.)

In this paper, which is an expanded version of the extended abstract in the 2010 CPEM conference [7], we describe our efforts to realize a fourfold reduction in measurement uncertainty by constructing a four-channel system, implementing longer measurement periods (through continuous operation with a battery recharging system), and increasing the measurement bandwidth (with faster analog-to-digital converters (ADCs) and higher cutoff frequency filters). We also describe a significant source of error caused by spurious signals that we uncovered while implementing these improvements. When the four-channel system is in operation, we expect to realize our goal of 5 μK/K statistical measurement

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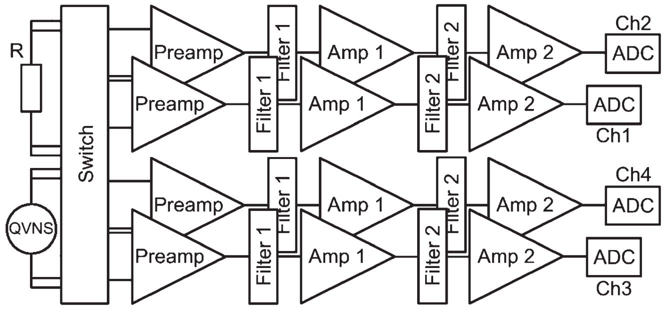

Fig. 1. Block schematic of the four-channel JNT system under development. R and QVNS sources are switched between different channel pairs. Details of each component were presented in [7]–[11].

uncertainty with a measurement period of less than ten days.

II. Four-Channel System Design

The current NIST QVNS-JNT system operates with two channels and has been continuously improved [4]–[11]. The most important and unique feature is the QVNS chip, which is designed to generate a calculable pseudorandom voltage signal whose power spectral density (PSD) is closely matched to that of the temperature-sensing resistor. Other improvements include matching the transmission–line impedances, implementing an amplifier with high common-mode rejection ratio and low noise, and optimizing the filtering for increased measurement bandwidth. These improvements allowed reproducible noise temperature measurements and have reduced the statistical uncertainty in the temperature measurement to nearly 13 μK/K [5], [6].

Currently, the two-channel system consecutively measures or "chops" between the resistor and the QVNS noise sources; the switch board alternately connects each noise source to the two measurement channels for 100 s. One major limitation to the present approach is the dead time associated with switching out one of the two sources. A four-channel system, as shown in Fig. 1, would enable simultaneous measurement of both noise sources, which will reduce the measurement period twofold. New components were required in order to implement this four-channel system and to fully automate it for extended measurement periods.

A. Switchboard

A new switchboard that is capable of four-channel operation and was improved by increasing the symmetry of the connections and shortening their lengths was designed and assembled. These new features minimize the wiring capacitance to around 7 pf for each connection and improve the transmission-line impedance matching. Moreover, the symmetric design allows for a number of possible permutations of the connections between the noise sources and the preamplifiers, which will allow us to investigate and reduce potential systematic errors related to the input circuits. The relays are controlled by a field-programmable gate array (FPGA), which is placed in low-power low-noise standby mode during the measurement period between the switching sequences.

B. ADC

New ADCs were required, because critical components were unavailable to make copies of the original ADC design and also because it was desirable to measure bandwidths greater than the present 1 MHz Nyquist frequency. The new ADCs, which are based on the AD7626 chip,[1] can be operated at sampling rates up to 10 MS/s, which corresponds to a 5 MHz maximum Nyquist frequency, with 16 bits of resolution and 106 dB of spurious-free dynamic range.[1] Each new ADC has a separate power supply connection for the digital and analog stages. The analog input amplifier can be operated with either a single voltage supply or dual ±6 V supplies, which provide double the output dynamic range. Currently, we are operating the ADCs with only the positive analog voltage, which has a dynamic range similar to that of the original converter. We are also currently using a common power supply for the digital and analog stages of the ADC, because initial ADC tests showed that the ADC output noise was below that of the amplifier stages.

C. Automatic Power Supply Distribution

To prevent the integration period from being limited by battery capacity, combined with the double power requirements of the four-channel system, a new system for distributing the power that permits automatic recharging of the batteries for all four channels without pausing the measurement for repeated battery recharging is being implemented. The new power supply system uses lithium-ion batteries, instead of lead-acid batteries. Eight separate supplies are used for the different components, depending on their power requirements and isolation importance: one each for the four preamplifiers, two for the buffer amplifiers, and two for the four ADCs. Each charger has two sets of batteries, which are alternately switched between their electronics loads or the 10 V dc linear power supplies that are connected to ac wall power.

Similar to switchboard operation, the battery controllers are placed in quiet mode during the measurement, such that the microcontroller's digital components produce no spurious signals that might couple into the measurement. Unfortunately, during implementation, a number of spurious signals were found in the charger circuits, even in quiet mode. These signals were related to oscillations in the charger controller circuit and could be eliminated by changing the time constants and explicitly disabling the controller during relay switching.

Currently, our best temperature measurements are still obtained when the charger circuits are disconnected from ground. When the chargers are connected, the frequency response (and apparent temperature) shifts, and occasional spurious signals appear that cause the amplifiers to saturate and produce distortion. These effects were significantly reduced through the use of extensive ac power isolation and filtering. However, we are still determining how to eliminate this ground-loop effect.

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[1] This commercial chip 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.

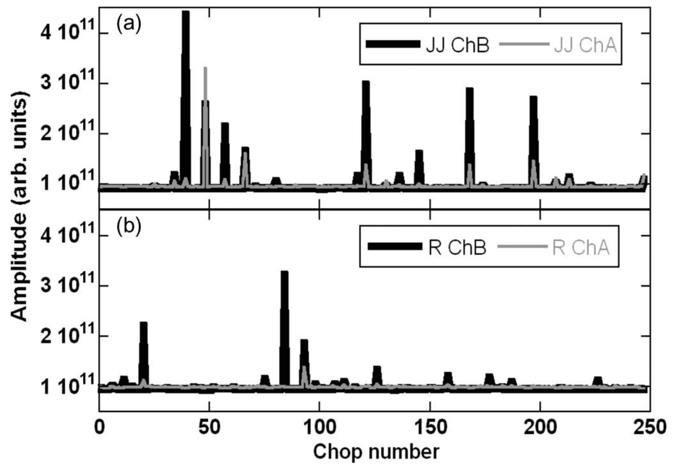

Fig. 2. Autocorrelation measurements for QVNS and resistor signals from both channels for a single-frequency bin at 1 MHz as a function of the chop interval number (with 100 s/chop).

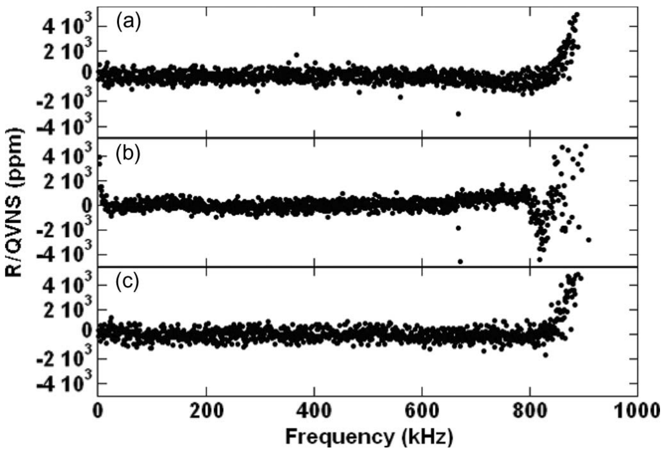

Fig. 3. Residuals of PSD ratio fits (ppm = parts in 10^6) of the QVNS and resistor signals versus frequency after averaging ≈250 chop for (a) a standard 60× gain in Amp 2 and 650 kHz bandwidth, (b) EMI saturation of Amp 2, and (c) the same 11× gain in Amps 1 and 2 and 800 kHz bandwidth.

III. ADC CHARACTERIZATION AND NOISE MEASUREMENTS

Single tone and multiple tones from both the QVNS and the ac Josephson voltage standard (ACJVS) system were used to characterize the distortion of the new ADC. With the present two-channel system, the QVNS was used in combination with the full amplification chain of each channel. The ACJVS was independently used to provide signals of larger amplitude to various stages in each chain. The second-harmonic amplitude was extracted from the reconstructed output signal of the ADC. The distortion of the amplifiers in each channel was already reduced as a result of previous optimization [5], [6] and was largely indistinguishable from the correlated noise floor. For a synthesized 100 kHz sine wave with 100 mV amplitude, which accesses the ADC's full dynamic range after amplification, the ADC distortion was still buried below the -80 dBc noise floor and was not measurable.

While investigating the ADC linearity, we noticed intermittently higher signals disturbing the frequency response of the two channels at both high ($>$ 900 kHz) and low ($<$ 2 kHz) frequencies. Fig. 2 shows the intermittently larger voltages, which appear to be caused by transient electromagnetic interference (EMI). These disturbances were observed to saturate various amplifier stages and, in particular, the preamplifiers. This intermittent amplifier saturation was also observed with an external fast Fourier transform (FFT) digitizer, which confirmed that they were not produced by the ADC. When the amplifiers saturate, even partially, they produce distorted signals with correspondingly distorted spectral response. The widely varying spectral response of these "transient overload" chops can be large enough to modify the measured residual fits of the PSD ratios, as shown in Fig. 3(b).

The varied frequency response in the spectral measurements that are caused by amplifier saturation affect the quadratic fit that is used to extract the measured temperature and the statistical uncertainty. This "overloaded amplifier" behavior is quite different from the typical distortion due to "well-behaved" nonlinearities of the electronics, which have previously been shown [10] not to affect the measured temperature but only limit the measurement uncertainty. These transient interferences, which had remained undetected in previous experiments because they were buried within the large amount of time-integrated data, may have been an important systematic error in those measurements [4], [5], [8], [9], [12]. In fact, they may have been the primary cause of shifts in the apparent temperature offset.

We spent many weeks discovering methods to reduce these transient overloads and found many complementary factors. For example, the amplifier overloads increased when the new charger circuits were connected and even when the chargers were simply grounded. Magnetic shielding was implemented around the measurement electronics and, additionally, around the preamplifiers. The preamplifiers were found to be very sensitive to both acoustic and mechanical vibration, both of which were addressed by mechanically isolating the preamplifiers.

Another contributing factor was the presence of large undesirable 10 MHz signals at the amplifiers' broadband outputs. A 10 MHz reference signal is used to frequency lock the QVNS code generator and the sampling clock of the cross-correlation electronics, which is used to generate and distribute the clock and frame signals to the ADCs and the data collection card. This 10 MHz signal source provides the SI frequency reference, because it is synchronized to the NIST atomic clock. The undesirable 10 MHz signal in the amplifiers was reduced by implementing optical isolation between the 10 MHz source and the clock board, presumably reducing radiated signals in the room by replacing the 15 m of coax with optical fiber.

In order to fully utilize the ADC dynamic range, we increased the gain of Amp 2 by a factor of five. This inadvertently increased the distortion with a less stable gain and higher susceptibility to saturation in the presence of spurious signals. We fixed this problem by reducing the gain of Amp 2 from 60 to 11 and increasing that of Amp 1 from 2 to 11, such that the total gain of the full amplifier chain was nearly unchanged.

Two interesting features were observed for this new gain configuration. First, the noise above 900 kHz was reduced, which allowed better observation of high-frequency distortion. Second, the QVNS/resistor PSD ratio remained flat to

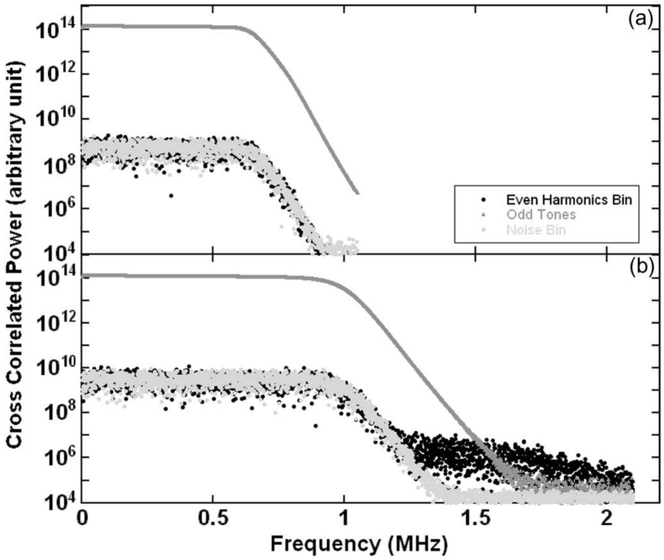

Fig. 4. Measured FFT cross-correlation power spectra obtained with different sample frequencies and low-pass filters. (a) 2 MS/s and combined 650 and 800 kHz filters, with 1 Hz bin width. (b) 4 MS/s and dual 1 MHz cutoff filters, with 2 Hz bin width. Legend indicates the synthesized odd tones, bins at the even harmonic frequencies, and an arbitrary sequence of bins that represent the noise floor. (b) ADC generated distortion and expected 6 dB-higher noise amplitude due to the 2× wider 2 Hz bins.

≈800 kHz [Fig. 3(c)], which is much higher than the typical 600 kHz flat response of the other gain configuration [Fig. 3(a)]. This positive effect of wider measurement bandwidth is created by the faster rolloff from filter 2 (reduced aliasing) of the signals provided to Amp 2. Fig. 3 compares the fit residuals of the QVNS and resistor PSD ratios for measurements with these different gain configurations and amplifier overload effects.

IV. INCREASED MEASUREMENT BANDWIDTH

In previously presented results, the original ADC operated with a 50 MHz clock frequency and a 2.08 MHz sample frequency. The measurement bandwidth was determined by the 650 kHz cutoff frequency of the low-pass passive filters, whose combined 22 poles were chosen to minimize aliasing effects. Having successfully implemented the new ADC at the sample frequency of the original ADC, we attempted to operate the new ADC at twice the sampling frequency 4.16 MS/s, which required doubling the clock frequency to 100 MHz. This required extensive modification to the FPGA program for the clock board and required nanosecond tuning of the delays between the various signals. The resulting 2.08 MHz Nyquist frequency will allow us to implement new low-pass filters. Filters with cutoff frequencies of 1.4 MHz and 22 poles (combined Filters 1 and 2) will be implemented in the future, which would more than double our measurement bandwidth and still ensure that it remains unaffected by aliasing effects.

Fig. 4 compares measurements with the new ADCs operating at the two different sampling rates. Fig. 4(a) shows the original sampling frequency, and Fig. 4(b) is one of our first measurements of the new ADCs operating at the higher 4.16 MS/s rate. In the latter measurement, the two filters in each channel (Filter 1 and Filter 2 [6]–[11]) were replaced with 1 MHz cutoff frequency filters. This first measurement at higher sampling frequency of our typical QVNS comb of odd harmonic tones shows even harmonic distortion at frequencies above 1.25 MHz. This nonlinearity was also present with the original filters and when separate power supplies were used for the analog and digital sections of the ADC. The cause of this nonlinearity is still under investigation but may be due to either clock jitter or power supply fluctuations due to the high ADC current requirement for higher operating speeds. Since the ADC is specified to operate at even higher sampling rates, we are optimistic that we can eliminate this nonlinearity, so that we can eventually double our measurement bandwidth.

V. CONCLUSION

We are developing a four-channel JNT system. Extremely low distortion of less than −80 dBc was measured for the new ADC. Intermittent EMI signals have been found to compromise the linearity of the system and affect the temperature measurement, in terms of both the measured temperature and the measurement uncertainty. Various sources of these intermittent overloads have been reduced by improved filtering, shielding, and implementation of optically coupled frequency references. Initial measurements of the ADC operating at twice the previous sampling rate have revealed an unexpected nonlinearity that requires further investigation. We are optimistic that the four-channel system with new ADCs, power supplies, and switchboard will soon be implemented and provide a dramatic reduction in measurement uncertainty.

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REFERENCES

[1] D. R. White, R. Galleano, A. Actis, H. Brixy, M. De Groot, J. Dubbeldam, A. L. Reesink, F. Edler, H. Sakurai, R. L. Shepard, and J. C. Gallop, “The status of Johnson noise thermometry,” *Metrologia*, vol. 33, no. 4, 325–335, 1996.

[2] S. P. Benz, J. M. Martinis, S. W. Nam, W. L. Tew, and D. R. White, “A new approach to Johnson noise thermometry using a Josephson quantized voltage source for calibration,” in *Proc. TEMPMEKO*, 2001, pp. 37–44.

[3] P. J. Mohr, B. N. Taylor, and D. B. Newell, “CODATA recommended values of the fundamental physical constants: 2006,” *Rev. Mod. Phys.*, vol. 80, no. 2, pp. 633–730, 2008.

[4] S. P. Benz, D. Rod White, J. Qu, H. Rogalla, and W. Tew, “Electronic measurement of the Boltzmann constant with a quantum-voltage-calibrated Johnson noise thermometer,” *C. R. Physique*, vol. 10, no. 9, pp. 849–858, Nov. 2009.

[5] S. P. Benz, J. Qu, H. Rogalla, D. R. White, P. D. Dresselhaus, W. L. Tew, and S. W. Nam, “Improvements in the NIST Johnson noise thermometry system,” *IEEE Trans. Instrum. Meas.*, vol. 58, no. 4, pp. 884–890, Apr. 2009.

[6] J. F. Qu, S. P. Benz, H. Rogalla, and D. R. White, “Reduced nonlinearities and improved temperature measurements for the NIST Johnson noise thermometer,” *Metrologia*, vol. 46, no. 5, pp. 512–524, Oct. 2009.

[7] A. Pollarolo, J. Qu, H. Rogalla, P. D. Dresselhaus, and S. P. Benz, "Development of a four-channel system for Johnson noise thermometry," in *Proc. 27th CPEM Dig.*, Daejeon, Korea, Jun. 13–18, 2010, pp. 490–491.

[8] S. W. Nam, S. P. Benz, P. D. Dresselhaus, W. L. Tew, D. R. White, and J. M. Martinis, "Johnson noise thermometry using a quantum voltage noise source for calibration," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 2, pp. 550–554, Apr. 2003.

[9] S. W. Nam, S. P. Benz, P. D. Dresselhaus, C. J. Burroughs, Jr., W. L. Tew, D. R. White, and J. M. Martinis, "Progress on Johnson noise thermometry using a quantum voltage noise source for calibration," *IEEE Trans. Instrum. Meas.*, vol. 54, no. 2, pp. 653–657, Apr. 2005.

[10] D. R. White, S. P. Benz, J. R. Labenski, S. W. Nam, J. F. Qu, H. Rogalla, and W. L. Tew, "Measurement time and statistics for a noise thermometer with a synthetic-noise reference," *Metrologia*, vol. 45, no. 4, pp. 395–405, Aug. 2008.

[11] J. F. Qu, S. P. Benz, A. Pollarolo, and H. Rogalla, "Reduced nonlinearity effect on the electronic measurement of the Boltzmann constant," *IEEE Trans. Instrum. Meas.*, vol. 60, no. 7, pp. 2427–2433, Jul. 2011.

[12] W. L. Tew, S. P. Benz, P. D. Dresselhaus, H. Rogalla, D. R. White, and J. R. Labenski, "Recent progress in noise thermometry at 505 K and 693 K using quantized voltage noise ratio spectra," in *Proc. TEMPMEKO ISHM. Joint Int. Symp. Temp., Humidity, Moisture Therm. Meas. Ind. Sci.*, Portoro, Slovenia, May 31–Jun., 4, 2010.

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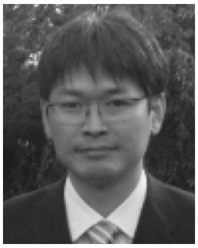

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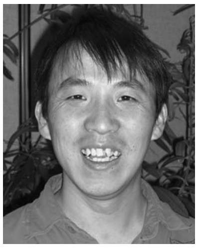

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