REDUCED NONLINEARITIES IN THE NIST JOHNSON NOISE THERMOMETRY SYSTEM

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Abstract

Improved electronics and synthesized noise waveforms for the NIST quantum-voltage-standard-calibrated Johnson noise thermometer (JNT) have lead to reduced uncertainty in the temperature measurement. Recent measurements show that some of the distortion in the present electronics arises in the differential stage of both the preamplifier and the analog-digital converter (ADC). Distortion from the preamplifier can be reduced by compensating the DC offset of the signal at the inputs to the differential stage. A four-channel system with a new ADC is under construction to achieve the goal of re-determining the Boltzmann constant at a relative uncertainty of 6×10^{-6}.

Introduction

Johnson noise thermometry (JNT) is one of the few thermometry 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. The main challenge is that the extremely small noise voltage (~1.2 nV/Hz$^{1/2}$ for a 100 Ω resistor at the triple point of water, 273.16 K) requires low-noise measurement techniques [1].

To improve this electronic-based temperature measurement technique, NIST has developed a quantum voltage noise source (QVNS) to calibrate the JNT cross-correlation electronics [2, 3]. The system links thermodynamic temperature to fundamental physical constants through quantum-based electrical measurements. In addition, the QVNS-JNT matches electrical power and thermal noise power at the triple point of water and thus can determine the ratio between the Boltzmann and the Planck constants, k/h. Because the relative standard uncertainty for the Planck constant is parts in 10^8, while it is parts in 10^6 for the Boltzmann constant (2006 CODATA), the QVNS-JNT offers a unique electronic approach for determining the Boltzmann constant. NIST's goals are to reduce the relative uncertainty in the ratio measurement to 6×10^{-6}, which is close to the lowest uncertainty of 2 μK/K achieved through acoustic gas thermometry, and to contribute to the re-determination of the Boltzmann constant [4].

Improved Electronics and Reduced Uncertainty

In past years, NIST had made a number of improvements to the JNT system [5-7]. A specialized QVNS circuit was designed for lower voltage signals and longer integration time 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, we matched the noise power and impedance of the transmission line to reduce the uncertainty of the temperature measurement [5, 6]. Most importantly, by characterizing the frequency responses of different configurations of the amplification chain, we optimized the electronics to eliminate the effect of the aliasing signal on the measurement [7].

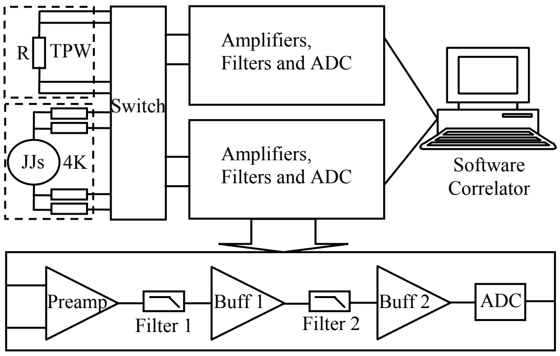

Figure 1. Schematic of the 2-channel JNT electronics.

Figure 1 shows the optimized amplifier chain. The preamplifier provides 70 dB ± 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, Filters 1 and 2, have respective cutoff frequencies of 650 kHz and 800 kHz that define the measurement bandwidth. The second filter reduces the finite stop band of the first filter and ensures that the aliased signal is 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× and 11×, respectively, to reach the full dynamic range of the ADC.

In addition to the above improvements to the electronics, the synthesized noise waveform was also improved to reduce the effect of nonlinearity in the electronics [7]. Although the distortion is very small and does not impact the measured temperature value, it does limit the measured uncertainty, making it difficult to ensure proper system operation. Cross-correlation measurements show that the second-order distortion, which is larger in magnitude than the others, dominates the measured uncertainty [7]. Measurements with different waveforms demonstrated that odd-only multi-tone comb waveforms are helpful for decreasing the effect of the second-order distortion. In addition, increasing the tone density of the synthesized waveform also reduces the measurement uncertainty.

With the electronics shown in Fig. 1 and improved synthesized noise waveforms, the JNT system has realized an absolute temperature measurement of the

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triple point of water in terms of h/e with ~11 μK/K statistical uncertainty in two days. Although there is still a ~50 μK/K offset from the CODATA value, the measured temperature was reproducible for the first time [7].

Another Source of Distortion

It's important and necessary to determine the exact sources of the distortion to further reduce the effect of the nonlinearity. 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 frequency 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 JFET preamplifier, where the second-order harmonics were 64 dB and 68 dB lower than the fundamental tone in the two channels, respectively. After the buffer amplifiers, the distortion amplitudes remained 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. 2. 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 (~ −78 dBc) than those of all the others. These results indicated that the distortion was not from the JFET stage.

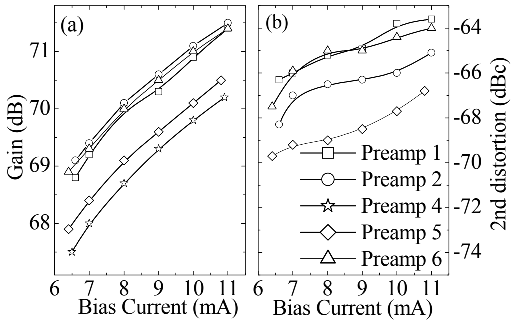

Figure 2. JFET bias current dependencies of (a) gain and (b) second-order harmonics of the preamplifiers.

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. Figure 3 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 mV to 40 mV. The second-order distortion was greatly reduced and could not be resolved from the noise floor. All the other preamplifiers behaved similarly.

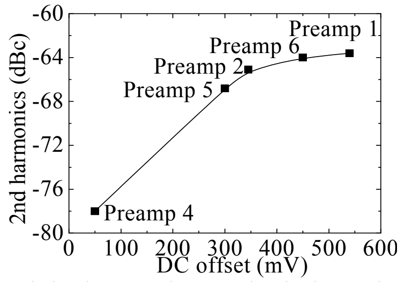

Figure 3. Relation between the second-order harmonics and the DC offset at input of the differential stage of the preamplifier.

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. While odd-only multi-tone comb waveforms were measured, increasing the DC offset of the signal at the input of the ADC from 85 mV to 125 mV increased the even-order distortion by about 10 dB.

Conclusion

Two sources of distortion in the JNT electronics were found to occur in the differential stages of the preamplifier and the ADC. 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. At the conference we will also report on a new JNT system that is under construction, which will have 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 achieving the goal of determining the Boltzmann constant at a relative uncertainty of 6×10^{-6}.

Acknowledgements

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