IMPROVEMENTS IN THE NIST JOHNSON NOISE THERMOMETRY SYSTEM*

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Abstract

We have developed a Johnson noise thermometry system that is calibrated by precision waveforms synthesized with a quantized voltage noise source (QVNS). Significant improvements to the QVNS and the cross-correlation measurement electronics have dramatically reduced systematic errors and measurement uncertainty. We describe some of these improvements and discuss the potential for this system to contribute to the redefinition of the Boltzmann constant.

Introduction

Johnson noise thermometry (JNT) is a primary technique based on the Johnson-Nyquist noise of a resistor, for which the mean-square voltage is proportional to Boltzmann's constant *k*, the temperature *T*, the resistance *R*, and the measurement bandwidth Δf: $\langle V^2 \rangle = 4kTR\Delta f$. Because the relation is fundamental, JNT is one of the few techniques that can determine absolute (thermodynamic) temperatures. Accurate, low-noise, correlation techniques are required to measure the extremely small ~1.2 nV/Hz$^{1/2}$ noise voltage of 100 Ω resistors at the triple point of water (273.16 K). The system performance is dramatically improved by using quantum-accurate voltage waveform synthesis techniques to calibrate the electronics [1-4].

NIST's main goals for the JNT program are to improve thermodynamic temperature measurements and to link thermodynamic temperature to fundamental physical constants through quantum-based electrical measurements. In particular, JNT offers an electronic approach, distinctly different from the various gas-thermometry approaches, for contributing to a determination of Boltzmann's constant (current relative standard uncertainty 1.7×10^{-6}), provided that the total measurement uncertainty can be reduced to about 5×10^{-6}. The primary method that has demonstrated the lowest uncertainty to date, 2 μK/K, is acoustic gas thermometry. The next lowest uncertainty, 15 μK/K, was achieved with dielectric-constant gas thermometry. Because we match electrical power and thermal noise power at the triple point of water, our QVNS-JNT measurements determine the ratio of the Boltzmann and Josephson constants, k/K_J. Since the relative standard uncertainty in the Josephson constant $K_J = 2e/h$ is 2.5×10^{-8} (2006 CODATA), the ratio measurement is not limited by the uncertainty in the Josephson constant.

To date, the most important contribution produced by the QVNS-JNT system has been a better understanding of deviations of the International Temperature Scale of 1990 (ITS-90) from thermodynamic temperature. Measurements were performed at the moderately high temperatures of the zinc (692.677 K) and tin (505.078 K) freezing points [5]. The JNT results agreed with those from acoustic gas thermometry and provided an important independent method for determining thermodynamic temperature.

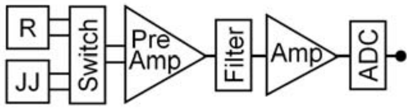

Figure 1. Component schematic for a single channel of the JNT electronics. All components from the Josephson (JJ) QVNS circuit up to the second amplifier have been improved, including the differential transmission lines to the preamplifier (shown as paired wires).

The QVNS-JNT system has also been used to measure lower temperatures, such as the water and gallium (302.9146 K) triple points. However, our previous best measurement at the water triple point was limited by systematic errors, which resulted in a 165 μK/K disagreement with the SI value [4]. Similarly, the Ga triple point temperature disagreed by 150 μK/K from the ITS-90 value. Fortunately, the temperatures disagreed similarly, so that good agreement occurred for the ratio of the two temperatures.

Improvements

Extensive research and development have reduced these systematic errors by further improving both the measurement electronics and the QVNS [5-7]. With these improvements, some of which will be mentioned below, we have increased the measurement bandwidth six-fold from 100 kHz to 600 kHz and reduced the Type A, 1-σ uncertainty of the absolute measurement of the water triple point temperature to 19 μK/K (with only 36 h of integration). Most importantly with respect to the uncertainty, we now have good agreement, 20 μK/K, between the JNT-determined thermodynamic temperature and the ITS-90 temperature.

The most important source of systematic error was distortion from various wires and wiring connections throughout the measurement circuit and electronics. Weak or oxidized solder connections, dirty gold-gold connections, kinked wires, and some multifilament wires were all found to behave nonlinearly and produce distortion. They were identified and removed only through careful measurements of QVNS-synthesized tones. Directly soldering the superconducting circuits to microwave packaging (instead of wire-bonded or gold spring finger connections) also reduced distortion.

The second major improvement resulted from matching the frequency response of the resistor in the thermal probe and QVNS sources by adding lumped resistive, inductive or capacitive components to appropriate transmission lines [5].

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This has allowed us to characterize and improve other frequency-dependent effects caused by aliasing, filters, and numerical integration of the measured spectra [6-7].

The QVNS waveforms also have been improved in a number of ways. The waveforms now have four-times finer tone spacing by the use of a bitstream generator with larger memory. The QVNS circuits use grounded, lumped, symmetric arrays to remove common-mode signals. All of the above improvements contributed to lower uncertainty and better agreement for measurements of both the "2006" and "2007" circuits (below) and for the previous high-temperature comparisons [5].

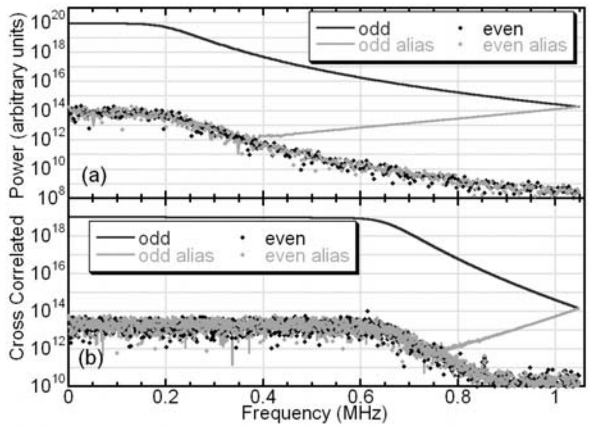

Figure 2. Measured FFT cross-correlation spectra of Josephson synthesized pseudo-noise waveforms with only odd harmonic tones using the (a) "2006" (digitally filtered, 1.6 kHz spaced 1 Hz bins, 128 junctions) and (b) "2007" (passively filtered, 400 Hz spaced bins, 8 junctions) circuits.

The most significant improvement in the 2007 circuit is a new preamplifier design that has excellent common mode rejection and (0.72-times) lower noise compared to the previous preamplifier's 1.9 nV/Hz$^{1/2}$ noise floor. Another recent improvement has been the replacement of the 150 kHz, 4-pole digital filter (that followed the ADC in Fig. 1) with a 650 kHz, 11-pole passive filter (shown between the amplifier stages).

Results

Figures 2 and 3 compare our best measurements of the 2006 and 2007 circuits. The 2007 circuit uses the improved amplifier, the passive filter, and closer QVNS tone spacing. The different frequency response for these two circuits, due to the different filtering, can be seen in Fig. 2. We plot only the odd and even bins of the measured FFT spectra, which have a 1 Hz resolution. Bins that contain aliased signals, that are due to tones above 1.04 MHz, are shown in grey. The odd tones map the transfer function of the respective circuits, while the even tones show the noise floor and undesirable intermodulation or distortion signals.

Fig. 2a shows no even distortion harmonics above the noise floor, while the 2007 circuit measurement in Fig. 2b shows a large even tone near 630 kHz, and others above 900 kHz. These "distortion" tones indicate the presence of unwanted nonlinearities or other waveform errors, which are respectively caused by a bitstream code error and nonlinearity caused by the passive filter. Since we use only the data below 600 kHz, these errors don't affect the temperature measurement.

Fig. 3 shows the ratio of cross-correlated power spectra for the resistor and QVNS as measured by the two different circuits. The frequency dependence is quite small for both ratios, as a result of the matched transmission lines. Both circuits produce reasonably linear frequency response up to the cut-off frequency of their filters. The remaining frequency dependence results from small differences between the QVNS and resistor transmission lines, which are accounted for with a quadratic fit to determine the temperature.

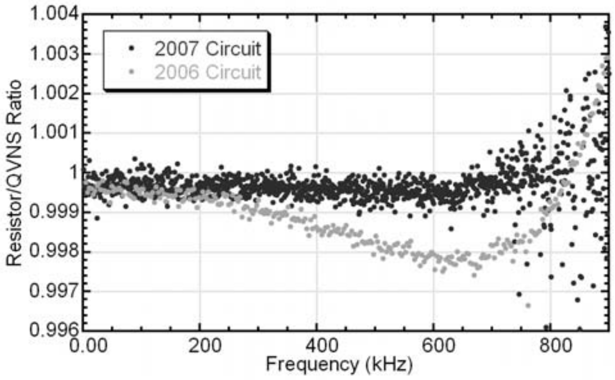

Figure 3. Ratios of the measured cross-correlated power of the resistor Johnson noise and the QVNS pseudo-noise waveform, comparing the frequency response of the 2006 and 2007 circuits.

Signals from the 2006 circuit were integrated over 36 h to achieve a Type A, 1-σ uncertainty of 42 μK/K over a 150 kHz bandwidth. The indicated temperature is consistent with the SI-assigned temperature for the water triple point, yielding a relative temperature difference of –28 μK/K. The 2007 circuit achieved 19 μK/K uncertainty in the same 36 h over a 600 kHz bandwidth and yielded a relative temperature difference of 3 μK/K at 273.16 K. The lower-noise amplifier and higher cut-off frequency filters of the 2007 circuit allow faster integration time for a given uncertainty. By increasing the integration time to 20 days, which is short compared to other noise thermometers, this 2007 circuit configuration could achieve a 5 μK/K uncertainty.

Acknowledgements

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