Development of a Four–channel System for Johnson Noise Thermometry*

A. Pollarolo[1], Jifeng Qu[2], H. Rogalla, P. D. Dresselhaus, and S. P. Benz

National Institute of Standards and Technology, Boulder, CO 80305 USA

Abstract

Long integration time is necessary to reach low uncertainty when measuring temperature through Johnson Noise Thermometry (JNT). The main goal of the NIST JNT experiment is to achieve a 6×10^{-6} relative uncertainty in the measurement of the water triple point, which could contribute to the re–determination of Boltzmann's constant. A four-channel JNT system, which will reduce the measurement time two–fold, is being developed with new components, including a switchboard, an analog to digital converter (ADC) and a programmable, recharging power supply system. While implementing the new ADC, a source of systematic error was revealed, as well as a means to increase the measurement bandwidth.

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 rms voltage) of a resistance, R, over a measurement bandwidth Δf. The relationship is defined by the Johnson-Nyquist equation, $\langle V^2\rangle = 4kTR\Delta f$, where k 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_{TPW} = 273.16 K [1].

The NIST JNT system uses a singular electronic technique that exploits the precision voltage synthesis capability of superconducting Josephson junctions, configured as a quantum-voltage noise source (QVNS). The QVNS produces accurate pseudo–noise voltage waveforms consisting of frequency combs of equal–amplitude harmonics with 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, thereby relating k to Planck's constant h via the Josephson constant [2–3]. The electrical voltage synthesized by the QVNS is matched to the thermal noise voltage of the resistor at the triple point of water, thereby enabling a measurement of the ratio k/h.

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 in 10^8, k would then be determined to order 10^{-6}. The present uncertainty in k is 2 μK/K as determined by acoustic gas thermometry alone. A QVNS-JNT determination of comparable uncertainty could uniquely contribute to the Boltzmann constant re–determination as the only electronically realized input [4].

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[1] Permanent address Politecnico di Torino, Corso Duca degli Abruzzi, 24 – 10129 Torino, Italy
[2] Current address National Institute of Metrology, Beijing 100013, P. R. China.

Four-channel System Design

The current NIST QVNS-JNT system operates with two channels and has been continuously improved [5–8]. The most important and unique feature is the QVNS chip is designed to generate a calculable, pseudo-random 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 CMRR and low noise, and optimizing the filtering for increased measurement bandwidth. These improvements allowed reproducible temperature measurements and have reduced the statistical uncertainty in the temperature measurement to nearly 11 μK/K [8].

Presently, the two–channel system alternately measures each noise source, switching between the resistor and the QVNS. One major limitation to the present approach is the long averaging time required to reduce the statistical uncertainty. A four-channel system, as shown in Fig. 1, would enable simultaneous measurement of both signals, which will reduce the measurement time two-fold.

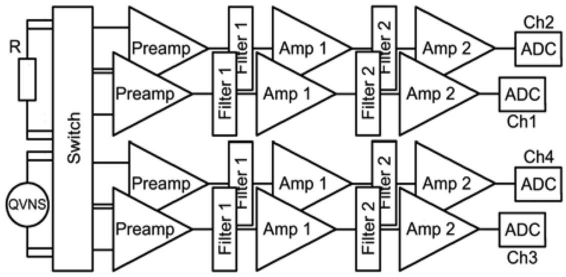

Fig. 1. Block schematic of the four-channel JNT system under development. R and QVNS sources are switched between different channel pairs. Details of each component were presented in [8].

In order to implement this four-channel system and to fully automate it for extended periods, some new components were required. First, a new switchboard was designed and assembled that is capable of four–channel operation and was improved by increasing the symmetry of the connections and shortening their lengths. These new features minimize the wiring capacitance and improve the transmission–line impedance matching. A new ADC was required because critical components were unavailable to make copies of the original ADC design, and it was desirable to have the capability of measurement bandwidths greater than the present 1 MHz Nyquist sampling frequency. The new ADC can be operated at a rate of 6 million samples per second with 16 bits of resolution and 106 dB of spurious–free dynamic range, which is significantly better than the old ADC. Finally, in order to prevent the integration time from being limited by battery capacity, a new system for distributing the power is being developed that permits automatic recharging of the batteries for all four channels without stopping the measurement.

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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 used independently 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 from previous optimization [8], and was mostly buried in the noise floor. For a synthesized sine wave with 100 kHz frequency and 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.

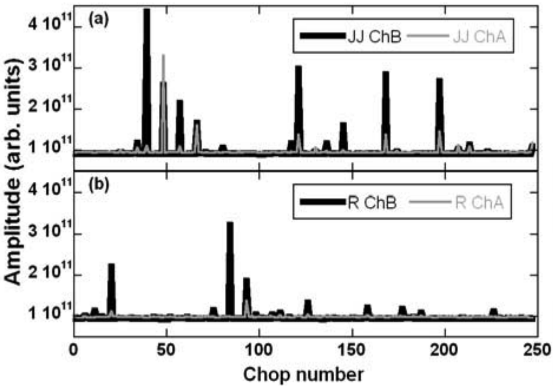

Fig. 2. Autocorrelation measurements for QVNS and resistor signals from both channels for a single frequency bin at 1 MHz as a function of the chop interval number (with 100 s/chop).

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. Figure 2 shows the intermittently larger voltage signals that appear to be caused by spurious electromagnetic interference (EMI). These disturbances appear to saturate various amplifier stages. When the amplifiers saturate, even briefly, they produce distorted signals with undesirable frequency response, as shown in Fig. 3b. The intermittent amplifier saturation was also observed with an external FFT digitizer, which confirmed that they were not produced by the ADC. It appears that these transient signals, which had previously remained unnoticed within the large amount of time–integrated data, may have been an important systematic source of error in previous measurements [7-8].

To prevent the saturation, the gain of the second amplifier was reduced from 60 to 11 and that of the preceding amplifier was increased from 2 to 11. Two interesting features were observed for this new gain configuration. First, the noise above 900 kHz was reduced, which allows better observation of high–frequency distortion. Second, the QVNS/resistor "offset" ratio remained flat to ≈ 800 kHz (Fig. 3c), much higher than the typical 600 kHz flat response of the other gain configuration (Fig. 3a). This positive effect of wider measurement bandwidth is caused by faster roll-off from filter 2 (reduced aliasing) of the signals provided to Amp 2. Figure 3 compares the fit residuals of JJ and resistance PSD ratios for these different measurements.

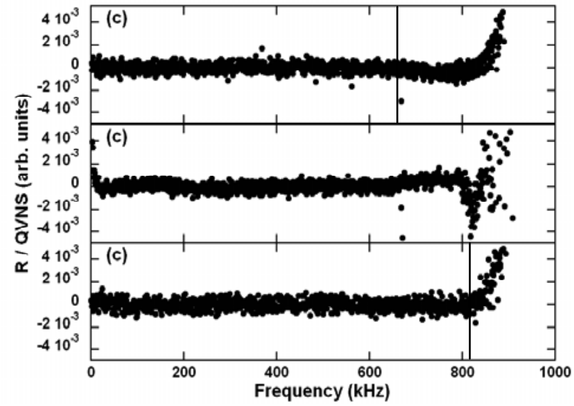

Fig. 3. Residuals of PSD ratio fits of the QVNS and resistor signals vs. frequency after averaging ≈ 250 chop for: (a) standard 60x gain in Amp 2 and 600 kHz bandwidth; (b) EMI saturation of Amp 2; and (c) same 11x gain in Amps 1 and 2 and 800 kHz bandwidth.

Conclusion

We are developing a four–channel JNT system. Extremely low distortion, better than -80 dBc, was measured for the new ADC. A large and intermittent EMI signal, which appears to be correlated to spurious signals from adjacent laboratories, was shown to compromise the linearity of the system and affect the temperature measurement.

Acknowledgements

We thank C.J. Burroughs for chip packaging, A. Koss for developing the new ADC, and D.R. White and W. Tew for fruitful discussions.

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