

## PROGRESS OF THE JOHNSON NOISE THERMOMETRY PROJECT AT NMIJ/AIST

*K. Yamazawa/Presenter, J. Tamba, C. Urano, Y. Fukuyama, T. Oe,  
M. Maruyama, A. Domae and N. Kaneko*

National Metrology Institute of Japan, National Institute of Advanced Science and Technology (NMIJ, AIST),  
Tsukuba, Japan, [kazuaki-yamazawa@aist.go.jp](mailto:kazuaki-yamazawa@aist.go.jp)

**Abstract:** As a joint project of the Quantum Electrical Metrology Section and the Thermometry Section of the National Metrology Institute of Japan, AIST, we have initiated a project on developing a system for the Johnson Noise Thermometry (JNT). This paper describes the objective, how we combine the technologies, the various phases of the projected plan for the system development, as well as the results of the of the project up to the present.

**Keywords:** Johnson noise thermometry, Josephson junction, Quantum voltage noise source, AC resistance, Temperature standards

### 1. INTRODUCTION

The field of metrology is now entering a new era. The General Conference on Weights and Measures (CGPM) is making a decision towards adopting a dramatic revise of the International System of the Units (SI); now so called the “new SI” [1]. The unit of thermodynamic temperature, kelvin, is likely to be defined upon the fundamental constant  $k_B$ , the Boltzmann constant.

It is important that research activities for thermometry at national metrology institutes (NMIs) conduct research to make the transition through this drastic change as smooth as possible; to determine the value of  $k_B$  to be consistent to the present definition in the SI, and furthermore after the redefinition, to continuously ensure the link with the revised definition to the practical metrology standards and the temperature scale.

There exist various methods in thermometry that directly link the  $k_B$  to temperature [2]. Among, Johnson Noise Thermometry (JNT) is a method to measure the thermodynamic temperature through the measurement of the noise generated by thermal agitation of carriers within conductors. Discovered through the experiences from engineering the amplifiers in the telegram communication in the late 1920s, the well known approximation,

$$S_v = 4k_B TR \quad (1)$$

describes the relation, where spectral density  $S_v$  is Fourier transform of an autocorrelation function of a fluctuating potential difference across a resistor. Implementations of the

JNT have been published for various temperatures [3]. Most of them implement a cross-correlator, and compare the noise between that generated from a reference resistor placed at a known temperature and a sensing resistor placed at the unknown temperature. However, a strict constraint on the resistance value and the capacitance along the transmission lines does apply for the conventional implementation. This constraint makes the accurate measurement very difficult, due to the fact that the sensing resistance element generally has a temperature coefficient of  $10^{-4} - 10^{-2} \mu\Omega/\Omega$ , depending on the material used. Such temperature coefficient will surely make the adjustment of the analogue circuits when the JNT is applied at various temperatures, since precise matching would be needed at each temperature to accommodate the above mentioned constraints on the measurement circuit.

Equation (1) could also be linked to quantum standards as shown in figure 1. The noise voltage density could be linked to voltage standards, by employing Josephson Junction (JJ) arrays as the quantum realisation. NIST has been pioneering the method employing JJs as a quantum voltage noise source (called QVNS) [4-7]. Employing this QVNS can overcome some of the constraints for the adjustment of the circuit parameters and enables absolute measurement of the noise spectrum. Furthermore, the resistance measurement can be realised by Quantized Hall Resistance (QHR). The extension of the QHR to AC is the development needed for accurate evaluation of the resistance used in JNT, and determine the absolute noise power through calculations.

As a joint project of the Quantum Electrical Metrology Section and the Thermometry Section of the National Metrology Institute of Japan, AIST, we have initiated a project on developing a system for the JNT. The former section has actively developing JJs [8] and QHR for metrology standards. The latter has intensively worked on the temperature standards and development of comparison measurement techniques. The project aims to combine the potential of these two sections, and the ultimate goal of the collaboration is to measure the Boltzmann constant at the triple point of water temperature (0.01 °C) following the present plan aiming  $T-T_{90}$  measurements.

In this paper, as a progress report, we describe the above mentioned objective and how we combine the technologies, as well as the various phases of the projected plan for the

system development, and the results of the initial phases of the project.

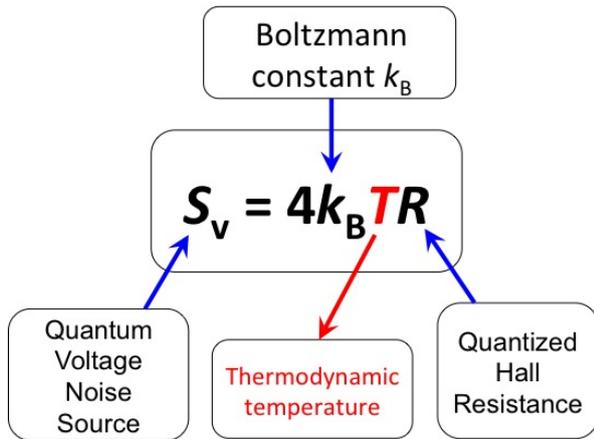


Fig. 1 The linking relation between JNT and the quantum standards realised by Josephson junctions (JJs) and the quantized Hall resistance standards (QHR). Either the Boltzmann constant or the thermodynamic temperature can be measured when the measurements are taken place at a stable realized temperature, such as in water triple point cells or even precisely temperature controlled comparison water baths. For the ultimate goal of our project, we aim to measure the Boltzmann constant at the triple point of water temperature (0.01 °C)

## 2. PHASES OF DEVELOPMENT

Our project is divided into the following phases.

**Phase 1:** Development of the basic structure of the JNT, such as the cross-correlator (including the amplification system), signal processing computation, resistance probes. Furthermore, thermal baths and the triple point of water cells for the temperature measurements are also prepared in this phase. Test measurements are undertaken with a configuration as like a conventional JNT system.

**Phase 2:** Development of the quantum standards (JJ array system and AC QHR) optimized for JNT measurements. In our development, a JJ array is especially designed for the generation of small voltage waveforms and fabricated in-house with the collaboration within the AIST. By driving this originally designed JJ array chip with a pulse pattern generator on an appropriate bit-stream pattern, the JJ array will produce the calculable pseudo-noise. This phase is projected to be undertaken during year 2012.

**Phase 3:** Measurement of the difference between the thermodynamic temperature and the current temperature scale ( $T-T_{90}$ ). Measurement of the AC resistance using the AC QHR system and the characterization of the frequency characteristics of the transmission lines will take place before the  $T-T_{90}$  measurements. This phase is projected to be undertaken in year 2013.

In this paper, we will first describe the structure of our system and then present the progresses in the phases 1 & 2.

## 3. THE BASIC STRUCTURE OF THE JNT SYSTEM

Figure 2 shows the block diagram of the JNT measurement system. Details of each component are described below.

**The resistance probe (DUT):** The resistance probe carries the resistor to be placed at the unknown temperature to measure by the JNT. For the conventional measurement method as in phase 1, another probe with the same design can be used as the noise reference when it is placed in a known temperature such as the triple point of water. Figure 3 shows the photograph of the resistance probe. A custom made metal foil resistor with an extremely low temperature coefficient and highly stable was developed for this work. The resistance is approximately 100 ohms, and wired with a four terminal connection. In addition to the ordinary four terminals, two terminals provide connection to the middle point of the resistor to be used as the reference grounding point for the differential amplifiers. The metal foil is mounted in a ceramic package of 5 mm x 5 mm x 1 mm with these 6 electrodes providing the connection points. The ceramic package was mounted on an oxygen free copper holder providing a sufficient thermal contact to the surroundings. Two twisted pairs of Teflon coated wiring are used for the connection within the probe structure. The resistor and the wiring are placed within a stainless steel protective sheath of 11 mm diameter, or 7 mm diameter, with a terminal connection box welded to the top. The protective sheath and the connection box are designed to be gas tight and could be purged with dry gas.

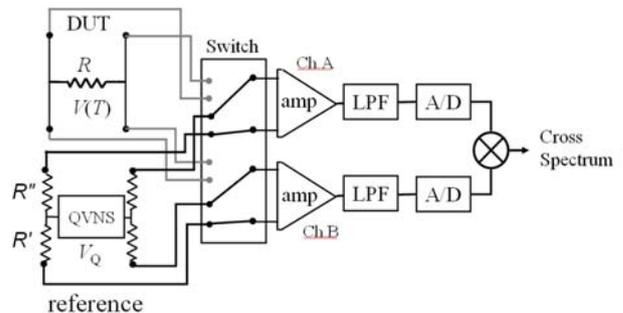


Fig. 2. A block diagram of the Johnson Noise Thermometry system. QVNS, amp, LPF, and A/D stand for quantum voltage noise source, pre-amplifier, low pass filter, and analog-to-digital converter. QVNS includes a bit code generator. Buffer amplifiers to match impedance are not shown for simplicity.



Fig. 3. Photograph of the resistance probe. A metal foil resistor with effectively zero temperature coefficient and highly stable is mounted within the protective sheath. Two versions of the protective sheath were fabricated for this work (11 mm and 7 mm diameter).

### The Josephson junction array probe and its driver:

The Josephson junction array probe and its driving system provide the pseudo-noise signal that is calculable and exact by quantum. The JJ array chips used in this work have 4 Josephson junctions with superconductor / normal metal / superconductor structure, where niobium and titanium nitride were used as superconductor and normal metal, respectively. A chip is mounted on a holder with a protective case with high magnetic permittivity to avoid magnetic flux captured by the superconductors on the JJ array. Two co-axial cables convey the microwave signal driving the JJs. These coaxial cables are connected to the pulse pattern generator via DC blocks. Two pairs of twisted Teflon coated wiring are used for the connection within the probe structure. Similar to the resistance probe, the middle point of the JJs are connected to the ground level to provide the reference for the differential amplifiers. For the cooling of the JJs, the probe is immersed into a liquid He dewar.

More details about the design of the JJ array chip and pulsed driving method could be found in the section “Developments in Phase 2”.

**Amplifiers, digitizers and the cross-correlator:** Since the noise spectral density is as small as  $1.12 \text{ nV Hz}^{-1/2}$  for a 100 Ohm resistor at 273 K, the noise signal is amplified with two identical amplification systems as shown in the block diagram, Fig. 2. The cross correlation is taken to measure the noise power at the sensing resistor or the JJ, to eliminate the uncorrelated noise signal generated or picked up elsewhere. The stability of the amplification is another engineering challenge requiring cancelation of any time dependent drift of the amplifiers through switching of the input in turn and observing the noise of a reference noise source with a known spectral density and determining the ratio of the unknown thermal source. In our system, we calculate the cross correlation in frequency domain by Fast Fourier Transformation (FFT).

There are various adjustments needed in the analogue circuits, especially to minimize the additional noise generated within the amplifiers, as well as improve the common mode noise rejection that the circuit is susceptible to. In this paper, we employed an amplification system which is very similar to that reported elsewhere [9]. The DC coupled JFET differential amplifier provides a CMRR as high as 120 dB [9]. The signal is amplified through a instrumental amplifier stage, and then filtered with a passive Butterworth low pass filter with a cut off frequency of 650 kHz to suppress the aliasing to below 1 ppm in the digital part. A commercial digitizer (National Instruments PXI-5922) is used to digitize the signal, and LabVIEW is used to perform the FFT calculations. With a state of art computer system, the software/hardware is capable to calculate the cross correlation and record the results real-time without interrupting the measurements. For the digitizing, we have tested two combinations; one that employs only one PXI-5922 card equipped with two channels, and the other employing two PXI-5922 cards using one channel each. For this paper, we report the results using only one PXI-5922.

**Baths and instrumentation for temperature measurements:** Two triple point of water cells and a Gallium melting point apparatus were prepared as temperature baths to insert the resistance probes at reference temperatures. All of these were calibrated to the national standards owned by the thermometry section at NMIJ and their equivalence being confirmed through international key comparisons [10, 11] and internal evaluation [12-14].

For the tests in phase 1, the reference noise source is a resistance probe inserted into a triple point of water cell, and the other resistance probe (DUT) is inserted into the center of a stirred water bath. The water bath currently used has a stability of  $\pm 20 \text{ mK}$  at temperatures 280 K – 300 K. To monitor the temperature fluctuation within the water bath during the JNT measurements, a temperature indicator with a thermistor probe was used. At this point, the coefficients setting of the temperature indicator are set to the values calibrated by the manufacturer and traceable to NIST. However, at the Gallium melting point temperature, the indication of this temperature indicator with thermistor is confirmed to be coincident to the national standards at NMIJ within measurement uncertainties.

## 4. DEVELOPMENTS IN PHASE 1: MEASUREMENTS WITH A COVENTIONAL JNT SYSTEM

As described above, in Phase 1, we built the basic structure of our JNT system and performed measurements with two resistance probes as a conventional JNT system.

Figure 4 shows an example of cross-correlation spectrum when one PXI-5922 card is used. The in-band spectrum up to 650 kHz where the 11pole Butterworth filter cuts the signal is rather flat and free of EMI.

Figure 5 shows an example of the ratio spectrum yielded by dividing two spectrums such yielded as in Fig. 4 but measuring at different temperatures. The reference probe is placed at the triple point of water (273 K) and the other at 280 K. The measurements at both temperatures were undertaken simultaneously by switching every 105 seconds. The resistance element was stable and did not fluctuate among different temperatures by the extremely low temperature coefficient of the element.

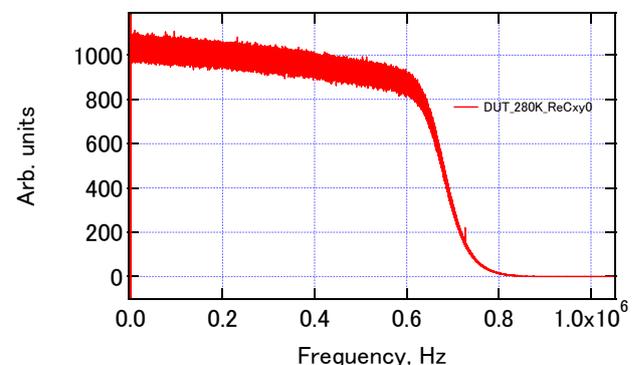


Fig. 4. An example of the cross-correlation spectrum yielded with the amplification system and digitized with only one digitizer card with two channels. Average of approximately 6.5 hours is calculated at each frequency individually.

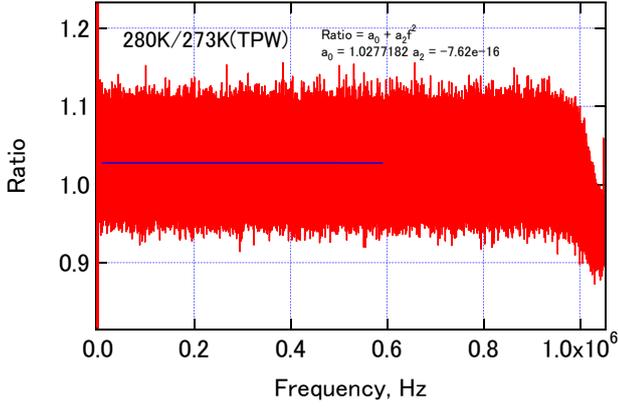


Fig. 5. An example of the ratio spectrum with the reference probe at the triple point of water (273 K) and the other at 280 K. Average of approximately 8.5 hours is calculated at each frequency individually.

## 5. DEVELOPMENTS IN PHASE 2: CIRCUIT DESIGN AND OPERATION OF A JOSEPHSON JUNCTION DEVICE

The Josephson junction device for our JNT experiment consists of two identical Josephson junction arrays, which share same ground. Each array has 4 Nb/TiN/Nb-based over-damped Josephson junctions. These Josephson junctions are arranged in the centerline of a 50 -Ohm coplanar waveguide within 200 um. Termination resistor for impedance matching was omitted, because the arrays are lumped, i.e., Josephson junctions are confined in a smaller length scale than the wavelength of pulse of 5 GHz.

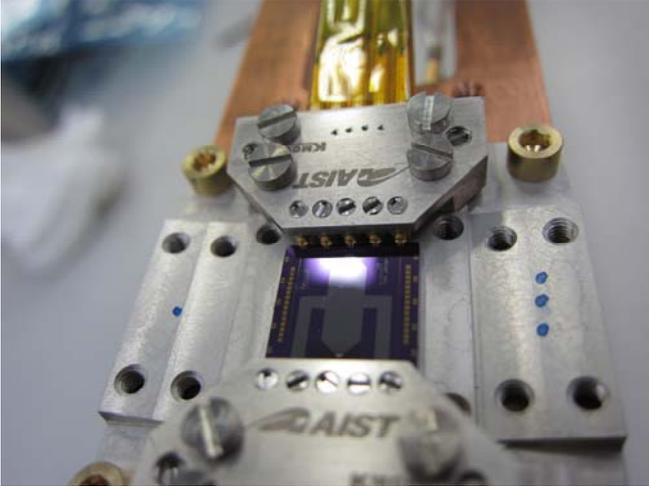


Fig. 6. The JJ chip and its mounting holder.

Pseudo random waveform is encoded in a  $2^{22} \times 5^2$  (=104857600) bit-long binary pulse pattern using 3<sup>rd</sup>-order Delta-Sigma modulation technique. The original waveform is made up of summation of odd harmonics with same amplitude and with random phase. First tone appears at 95.367 Hz and harmonics appears at every 190.734 Hz when pulse pattern generator is clocked at 10 GHz. Negative dc-offset corresponding to 3/8 of maximum output voltage is

added in order to decrease pulse density and increase operating margin for experiments with dc-block. As a result, averaged dc-voltage of a Josephson junction array become 1/8 of maximum output voltage.

Current-Voltage characteristics of a Josephson junction array with and without pulse are shown in Fig.7. Critical currents of Josephson junctions are  $I_c \sim 6.0$  mA, and normal resistance is  $R_n \sim 2.3$  Ohm per junction. Characteristic frequency  $f_c$  of an over-damped Josephson junction defined by  $f_c = K_{J-90} I_c R_n$  become 6.8 GHz, which is of the same order of the pulse frequency of 5 GHz. Therefore, the Josephson junctions in the array can respond to Return-to-Zero bit codes clocked at 10 GHz. Quantized voltage steps are actually observed with bit codes for pseudo random signal applied. Voltage difference between quantum voltage step  $n=1$  and  $n=2$  is 5.2 uV. This value corresponds to  $f_{clk}/K_{J-90} \times N_{jj} \times M_p$ , where  $f_{clk}=5$  GHz,  $K_{J-90}=483597.9$  GHz/V,  $N_{jj}=4$  and mark ratio  $M_p=1/8$ .

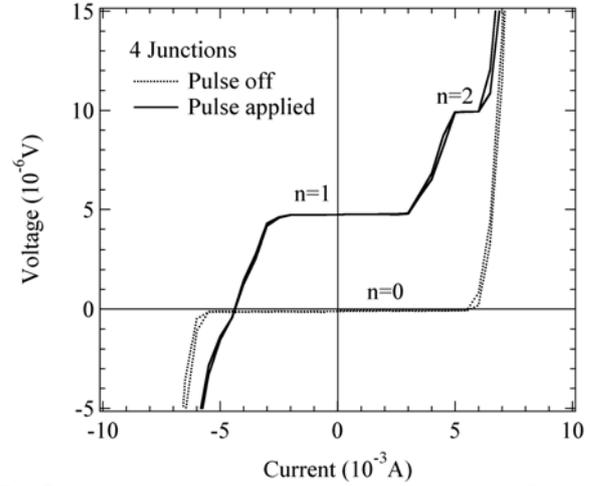


Fig. 7. Current-voltage characteristics of a 4 Josephson junction array with and without pulse applied.

## 6. FUTURE PLAN

A quantum voltage noise source based on Josephson junction arrays with a mechanical cryo-cooler is under construction. One of the merits of implementing a Josephson junction arrays in a mechanical cryo-cooler is reduction of frequency dependent decay of output voltage by reducing length of readout cables. The other merit is that frequency response of the readout cables is time-independent, unlike systems with liquid helium, where frequency responses of the readout cables vary with helium level. In addition to building a quantum voltage noise source with a mechanical cryo-cooler, we plan to replace the dc-blocks with a bipolar optical interface. Without dc-blocks bit codes with any pulse density are available. Furthermore, dc-component in the output voltage is expected to be zero by using bipolar pulses.

## ACKNOWLEDGEMENT

This project is funded by Grant-in-Aid for Scientific Research (KAKENHI) project (A) 22246013.

## REFERENCES

- [1] [http://www.bipm.org/en/si/new\\_si/](http://www.bipm.org/en/si/new_si/)
- [2] J. Fischer et al., "Preparative Steps Towards the New Definition of the Kelvin in Terms of the Boltzmann Constant", *International Journal of Thermophysics*, vol. 28, pp. 1753-1765, DOI: 10.1007/s10765-007-0253-4.
- [3] D R White et al, "The status of Johnson noise thermometry", *Metrologia*, 33, 325 (1996).
- [4] 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 Proceedings of TEMPMEKO 2001*, B. Fellmuth, J. Seidel, and G. Scholz, Eds., Berlin Apr. 2002, pp. 37-44, VDE Verlag.
- [5] S. Nam, S. Benz, P. D. Dresselhaus, W. L. Tew, D. R. White, and J. Martinis, "Johnson noise thermometry measurements using a quantized voltage noise source for calibration," *IEEE Trans. Inst. Meas.*, vol.52, pp. 550-554, Apr. 2003.
- [6] S. P. Benz, P. D. Dresselhaus, and J. Martinis, "An ac Josephson source for Johnson noise thermometry," *IEEE Trans. Inst. Meas.*, vol.52, pp. 545-549 (2003).
- [7] S. P. Benz, A. Pollarolo, J. Qu, H. Rogalla, C. Urano, W. L. Tew, P. D. Dresselhaus and R. White, "An Electronic Measurement of the Boltzmann Constant," *Metrologia*, 48, No.3, pp.142-153 (2011).
- [8] C. Urano, M. Maruyama, N. Kaneko, H. Yamamori, A. Shoji, M. Maezawa, Y. Hashimoto, H. Suzuki, S. Nagasawa, T. Satoh, M. Hidaka, and S. Kiryu, "Operation of Josephson Arbitrary Waveform Synthesizer with Optical Data Input", *Supercond. Sci. Technol.*, 22, 114012 (2009).
- [9] Qu et al., *Metrologia*, 46, pp.521-524 (2009).
- [10] M. Stock, et al "Final report on CCT-K7: key comparison of water triple point cells", *Metrologia*, 43 (Tech. Suppl.) 03001 (2006).
- [11] B W Mangum et al., "Summary of comparison of realizations of the ITS-90 over the range 83.8058 K to 933.473 K: CCT key comparison CCT-K3", *Metrologia*, 39, 179- (2002).
- [12] J. Tamba, M. Sakai, I. Kishimoto and M. Arai, "Isotopic Correction of Water-Triple-Point Cells at NMIJ", *International Journal of Thermophysics*, 29, pp.1749-1760 (2008).
- [13] M. Arai and H. Sakurai, "Stability study on the gallium triple point using sealed glass cells", *Temp.: Meas. Control Sci. Indust.* 6 315-8 (1993).
- [14] N Kuramoto et al., "Volume measurements of  $^{28}\text{Si}$  spheres using an interferometer with a flat etalon to determine the Avogadro constant", *Metrologia*, 48, pp. S83-95 (2011).
- [15] S. P. Benz, P. D. Dresselhaus, C. J. Burroughs, "Multitone Waveform Synthesis with a Quantum Voltage Noise Source," *IEEE Trans. Applied. Supercond.*, vol.21, pp. 681-686 (2011).