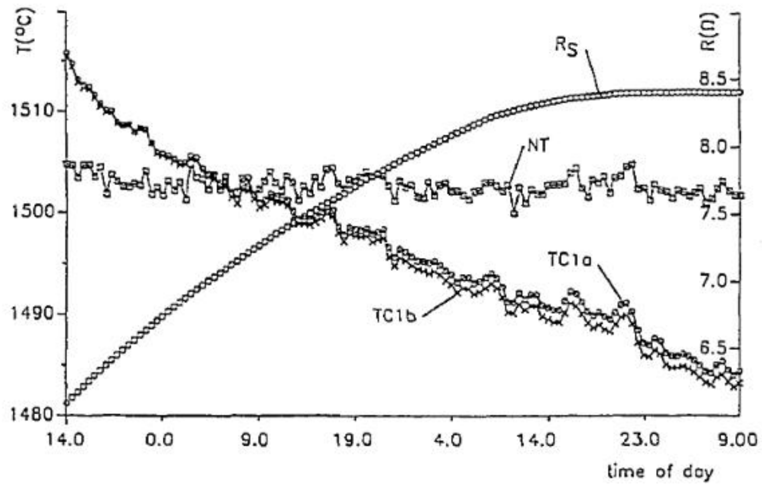
A Practical Approach to Johnson Noise Thermometry

We will give a brief overview of the history of Johnson noise thermometry. Starting with the discovery by John Johnson in 1926 and subsequent explanation by Harry Nyquist in 1927, in which Johnson noise was defined as the random fluctuation in voltage due to the movement of electrons through a material. This voltage is completely temperature dependant and present in all electrical conductors – it is just very small. We will describe the benefits of Johnson noise thermometry and how that can relate to primary thermometry: that the Johnson noise present remains consistent regardless of the resistive material of the probe, making it ideal for harsh environments. Johnson noise can be associated to absolute temperature using the Johnson-Nyquist equation below:

$$V_n = \sqrt{4kTR\Delta f}$$

$$\Rightarrow T = \frac{1}{4k} \left\{ \frac{V_n^2}{R} / \Delta f \right\}$$

We will describe the required elements to be able to calculate Johnson noise: the resistance of the probe, the measurement bandwidth, and our Johnson noise density. We will show that, as this is a primary measure, it is absolute, which means it is completely drift free. We will discuss an experiment conducted by Brixy in 1996, which demonstrated the comparison of temperature drift between a thermocouple and a Johnson noise thermometer, the results of which showed that, at high temperatures, there was a temperature drift in thermocouples of around 20°C over the course of 24 hours and no drift from the noise thermometer despite a change in resistance of the sensor.

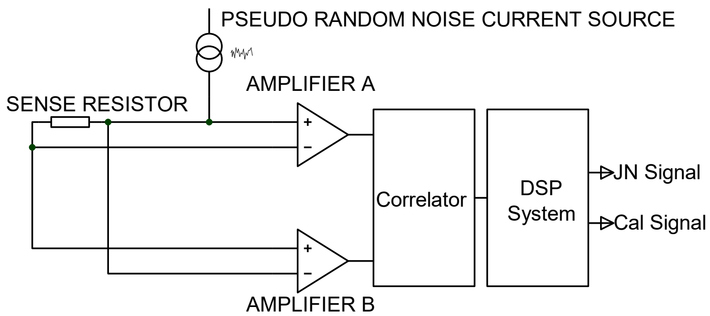


We will discuss the limitations of practical Johnson noise thermometry: Rice's Equation, which represents the ultimate uncertainty limit relative to sample time, bandwidth, and Johnson noise itself. This equation highlights that, for high temperatures, the sample time required to achieve low uncertainties is particularly large due the inverse square root relationship.

$$\frac{\sigma_V}{V} = \sqrt{\frac{1}{\Delta t \Delta f}}$$

We will talk about two existing Johnson noise thermometers, developed by NIST & NIM to contribute to the research of the redefinition of the Kelvin in 2019, and the limitations which made them unsuitable as practical Johnson noise thermometers in industry. These thermometers are physically large and required screened rooms to operate because they are so susceptible to external interference. Another problem was that the measurement time could take weeks to get an accurate reading, which is not particularly quick and therefore not suitable in industry. This long measurement time is due to the long correlator computation times that are needed to remove the uncorrelated noise of the system from the correlated Johnson noise we wish to measure, once again due to the limitation of Rice's equation. Another factor of the prolonged measurement periods is due to the method of comparing the measured signal to an isolated reference which needs to be switched to periodically through the measurement sample for calibration.

We will discuss internationally patented technology developed by Metrosol that helps combat the long correlation issue: the use of a current source located close to the first amplification stage allows the calibration signal to be generated within the sense resistor, so no switching is required between the reference signal and the sensor signal which most Johnson noise thermometers use.



Moreover, any frequency response applied to the sensor reading is now also applied to the calibration signal so we can computationally compensate for these characteristics to improve our measurements. One of the benefits of this technique compared to the typical voltage reference switching setup, is that we can increase the resistance value of the sense resistor which provides us more Johnson noise signal within our bandwidth. We are then able to separate the Johnson noise from the calibration signal in the frequency domain to be able to calculate the Johnson noise density.

We will conclude by describing the various applications for a practical Johnson noise primary thermometer, including applications that were previously hazardous or costly to maintain accurate temperature measurement and calibration. Some such industries include nuclear power, waste storage, aerospace, manufacturing, and, of course, metrology.