# A NOVEL TECHNIQUE APPLYING SPECTRAL ESTIMATION TO JOHNSON NOISE THERMOMETRY

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## ABSTRACT

Johnson noise thermometry is one of many important measurement techniques used to monitor the safety levels and stability in a nuclear reactor. However, this measurement is very dependent on the minimal electromagnetic environment. Properly removing unwanted electromagnetic interference (EMI) is critical for accurate drift free temperature measurements. The two techniques developed by Oak Ridge National Laboratory to remove transient and periodic EMI are briefly discussed in this paper. Spectral estimation is a key component in the signal processing algorithm used for EMI removal and temperature calculation. The cross-power spectral density is a key component in the Johnson noise temperature computation. Applying either technique requires the simple addition of electronics and signal processing to existing resistive thermometers. With minimal installation changes, the system discussed here can be installed on existing nuclear power plants. The Johnson noise system developed is tested at three locations: Oak Ridge National Laboratory, SANDIA National Laboratory, and Tennessee Valley Authority (TVA) Kingston Steam Plant. Each of these locations enabled improvement on the EMI removal algorithm. The conclusions made from the results at each of these locations is discussed, as well as, possible future work.

*Key Words*: Electromagnetic interference, Johnson noise thermometry, signal processing, spectral estimation, cross-power spectral density

## 1 INTRODUCTION: JOHNSON NOISE THERMOMETRY RESEARCH AT OAK RIDGE NATIONAL LABORATORY

Johnson noise thermometry (JNT) is an important measurement technique for general stability and safety assessment of a nuclear reactor. This technique was initially applied to general temperature measurements more than 87 years ago and was demonstrated for in-core reactor temperature measurement more than 45 years ago [1]. The harsh environmental conditions associated with a nuclear

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reactor make stable sensor measurements over time extremely challenging. Johnson noise is a fundamental expression of temperature and is inherently immune to drift in the sensor's physical condition. In and near the core, only JNT and radiation pyrometry offer the possibility for long-term, high-accuracy temperature measurement. However, JNT has not been widely used to date for temperature monitoring in nuclear reactor cores due to electromagnetic interference (EMI) concerns. Removing unwanted EMI is critical for accurate, drift-free temperature measurements. Oak Ridge National Laboratory (ORNL) has recently developed a JNT-based system that removes EMI and reliably and repeatably reports the environmental temperature in reactor cores, enabling commercialization and broader application of this temperature measurement technique [2].

There are several sources of EMI in and around nuclear reactor facilities that may corrupt temperature measurements. Mechanical vibrations, pumps, and other equipment are EMI contributors [3]. For this reason, the front end electronics must be very low noise, and shielding is required. ORNL studied two types of EMI: transient and periodic. Spectral estimation is a key component in the signal processing algorithm used for EMI removal and temperature calculation. Applying spectral estimation requires the addition of specialized electronics and signal processing to existing resistive thermometers. The electronics are composed of a dual-mode resistance and Johnson noise thermometer in a rugged, integrated prototype form [3]. The resistance measurement serves the dual purpose of providing a real-time fast temperature measurement and providing an independent measurement for Nyquist equation computation. The Nyquist equation describes the voltage produced by the motion of electrons within a resistor at a given temperature. The most valuable contribution of the research is the addition of the signal processing using spectral estimation techniques. Because thermal noise in any conductive material is Brownian motion of electrons due to ambient temperature, the measurement is simply the observation of random motion [2]. Therefore, any nonrandom or periodic EMI can be detected in the frequency domain as a spike and removed leaving only the random transient EMI. Transient EMI is removed by detecting outliers in the time-domain signals.

Two EMI removal methods, for both transient and periodic EMI, were developed and demonstrated through experiments at ORNL and other facilities: the rejection method and the subtraction method. The results from these experiments are discussed in this paper. This research enables a cost decrease and a safety increase in nuclear reactor monitoring systems. Under normal operation the resistive thermometers degrade and are replaced every few years, sending technicians into unsafe zones to calibrate or replace the thermometers during a shutdown period. With the addition of this technology, the maintenance required by these thermometers would decrease which in turn would shorten shutdown time. A utility loses about $1M a day during a nuclear power plant shutdown. In this paper, the techniques developed for EMI removal are described, demonstrating a path forward for practical and reliable monitoring of nuclear reactor core temperatures.

## 2 ELECTROMAGNETIC INTERFERENCE AND SPECTRAL ESTIMATION

Various sources of EMI such as power lines, computer power supplies, cathode-ray tubes, cell phones, motors, pumps, and data lines are found in industrial environments such as nuclear reactors [4]. These sources can contribute different types of EMI; therefore, ORNL focused on transient and periodic EMI. Transient EMI is a signal that begins, persists for some time period, and then stops. This type of EMI is a substantially different signal from the expected noise voltage of the thermal noise (sensor noise). The sensor noise voltage has a Gaussian distribution within a known limit and a mean value of zero; any variation twice the standard deviation of the mean value is considered transient EMI [4]. Periodic EMI is a signal that is always present and repeats in a pattern indefinitely. Fourier transforming the signal to the frequency domain causes periodic EMI to become very evident as spikes in the spectrum. Because these two types of EMI have to be removed differently, a two-step process was developed where transient EMI is removed in the time domain and periodic EMI is removed in the frequency domain.

## 2.1 Electromagnetic Interference Removal Techniques: Rejection vs. Subtraction Method

In initial research, the Johnson noise thermometer electronics measured a ratio of two noise voltages to avoid the difficulties of measuring the resistance temperature detector (RTD) independently and accurately. Also the electronics measured the amplifier gain, passband, and filtering effects of the cable connections [5]. However, this measurement is still susceptible to EMI. ORNL started researching EMI removal techniques in 2013 to improve JNT as an option on advanced reactors [5]. The first technique developed "rejected" EMI using spectral estimation. The frequency band of the measurement is very important due to the parasitics of the system. An RTD is connected in parallel to the input of two high input-impedance amplifier electronics channels. The outputs of the amplifiers are partially correlated because each channel consists of the sum of a correlated noise voltage and the uncorrelated amplifier noise voltage. The two output signals from the amplifiers are combined and time averaged causing the uncorrelated noise to approach zero, leaving only the correlated noise. Figure 1 illustrates the concept of cross correlation: the measured voltage from each amplifier channel voltage is Fourier transformed and correlated to form a cross-power spectral density (CPSD) measurement, effectively eliminating the noise contribution from the amplifier electronics.

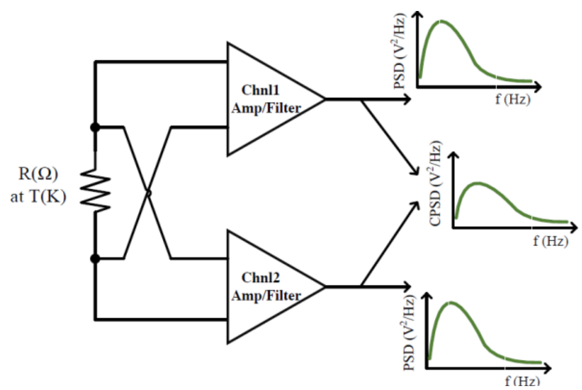


**Figure 1. Power spectral density function of each amplifier channel and cross-power spectral density function from both channels.**

The Johnson noise signal consists only of a flat white spectral energy distribution. The shape of the Johnson noise power-spectral density (PSD) is a result of the effects of filtering out low and high frequencies from the noise, as well as the frequency dependent gain of the amplifier channel. The high-band frequency filtering reduces the impact of sensor-to-amplifier cable capacitance. The low frequency filtering eliminates the nonthermal noise generated by mechanical vibrations. These low frequency microphonic signals are typically less than a few tens of a kilohertz. Then the CPSD is calculated and expressed in units of volts squared per hertz, ($V^2$/Hz). CPSD conveys the power content per unit frequency of the measured noise signal and is derived from the individual channel voltages. The channel voltages are sampled in time domain blocks composed of 16 subblocks, where each subblock is assessed for noise spikes. If a spike appears in a subblock that is twice the standard deviation of the baseline of the overall data block, the subblock containing the spike and the subblocks before and after are all rejected and replaced with the baseline value. Then the signal is windowed and Fourier transformed and runs through a "despiking"/rejection algorithm. Due to the averaging nature of this algorithm, the measurement takes a while to remove all periodic EMI. As the temperature computation is heavily dependent on a low-noise measurement of the RTD, a second EMI removal technique, the subtraction method, which is faster than the rejection method, was developed.

The subtraction method also depends on PSD of the two channels and CPSD between them. However, the subtraction method does not solely rely on cross-correlation and averaging over time to remove the EMI noise. An antenna voltage is measured alongside the JNT channel voltages. The antenna signal is sampled at a high speed and is used to model the EMI environment surrounding the system. The EMI is then subtracted from each of the two JNT channels before the CPSD is calculated. This ensures the CPSD between channel 1 and channel 2 of the JNT system is not biased by the EMI environment, resulting in a more accurate and reliable temperature computation.

## 2.2 Applying Electromagnetic Interference Removal Methods to Existing Resistive Thermometers

The front-end electronics are composed of two channels with a low noise amplifier and bandpass filtering. A noise model of the simplified electronics is displayed in Fig. 2, where $R_S$ is the resistance of the RTD sensor, $V_{Rs}$ is the noise voltage due to the sensor, $V_E$ is the noise voltage of the EMI, $R_c$ is the cable resistance, and $V_{Rc}$ is the cable noise voltage. $V_1$ and $V_2$ are the output voltages from channel 1 and channel 2.

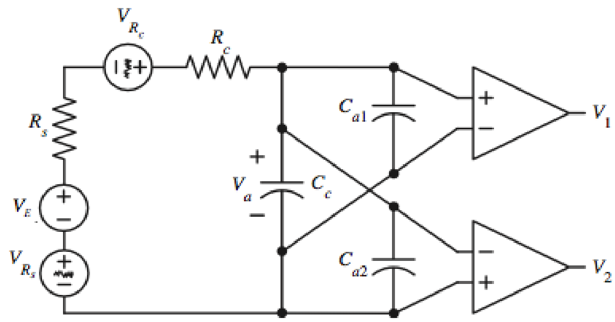

**Figure 2. Simple electrical representation of JNT amplifier/filter channels, resistance temperature detectors, and associated noise sources.**

The subtraction method requires only that an antenna and associated electronics be added to the Johnson noise front-end electronics system. To keep the noise channels as similar as physically possible, an identical front-end amplifier board is used for the antenna electronics. The EMI noise voltage ($V_E$) is subtracted from $V_1$ and $V_2$ before the CPSD between channel 1 and channel 2 is computed.

The JNT system is installed with existing RTDs (see Fig. 3). The system is portable and can drive very long RTD cables; therefore, it can be installed in an existing nuclear power plant without much reconfiguration.

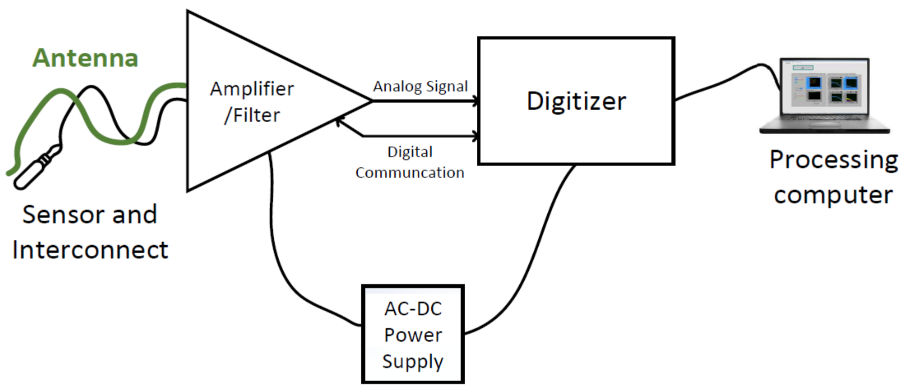


**Figure 3. JNT system illustration.**

## 3 VALIDATION THROUGH TESTING

To validate the theory that the hardware using the algorithm can survive in industrial EMI environments, ORNL tested the system at several locations with the goal of measuring temperature to within 1%. Initial testing was conducted in a very clean lab environment at ORNL. This environment exposed the system to little external EMI and allowed for a baseline measurement of the internal EMI due to the physical electronics. Next, the system was installed on a Brayton loop at Sandia National Laboratories (Sandia). Based on the testing at Sandia, the subtraction method is superior to the rejection method. Testing at ORNL continued with generated EMI added to the clean lab environment. Finally, the improved system was installed at a Tennessee Valley Authority (TVA) facility, the Kingston Fossil Plant (KFP), for final experimentation. The experimental results from all these sites are discussed in this section.

### 3.1 Oak Ridge National Laboratory Experiment

The initial testing at ORNL allowed for a baseline measurement and model of the physical system noise. Overall, the system is fairly clean with consistent noise sources at 42 kHz due to an internal signal generator and 64 kHz due to the power supply of the system. Also, even though the environment is a fairly low EMI lab environment, the light ballast generates EMI at 27 kHz (see Fig. 4) [6]. The CPSD has a large impact on the temperature calculation [equation (1)], and therefore, removing this EMI ensures an accurate computation of JNT temperature ($T_s$), where $G_{12}(f)$ is the CPSD between channel 1 and channel 2, $H_{12}(f)$ is the cross frequency response between channel 1 and channel 2, $G_{RC}(f)$ is the PSD of the cable resistance, $k$ is Boltzmann's constant, and $Rs$ is the sensor resistance.

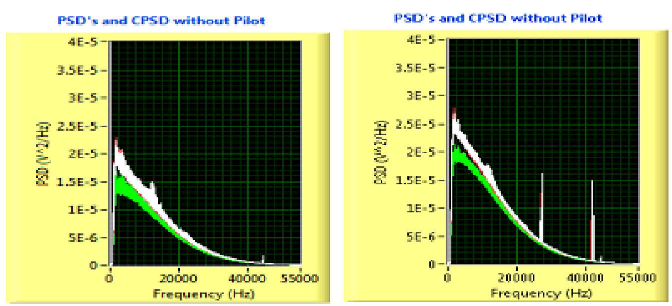


**Figure 4. Spectral data from channel 1 (green) and channel 2 (red). The white is the cross-power spectral density between channel 1 and channel 2.**

$$T_s = \left[\frac{G_{12}(f)}{H_{12}(f)} - G_{RC}(f)\right] \times \left[\frac{1}{2kRs}\right]. \quad (1)$$

The sensor resistance is measured in real-time and not frequency dependent. It is inversely proportional to temperature and monitored for fast temperature changes. The system is able to achieve less than 1% error in temperature computation

### 3.2 Sandia National Laboratories Brayton Loop Experiment

The testing at Sandia provided a lot of information about the limitations of the hardware and software algorithm. The hardware can become saturated with EMI due to the limitations of the amplifiers in the front-end electronics. If the EMI magnitude is greater than the peak-to-peak range of the amplifiers, the system becomes saturated and is unable to provide any reasonable data. The software algorithm can recover from this state but only after the EMI is no longer present. While this measurement proved to be difficult, the system was able to measure temperature within a few percent of accuracy.

This was discovered as the Brayton loop generated progressively more EMI as it went through a start-up process. However, before the electronics were saturated, several measurements were obtained (see Fig. 5) [7]. From these measurements, it was concluded that while the system could obtain temperatures accurately even under a large amount of EMI, it still had its limitations. Having a good model of the EMI environment proved to be very useful as it motivated further development of the subtraction method.

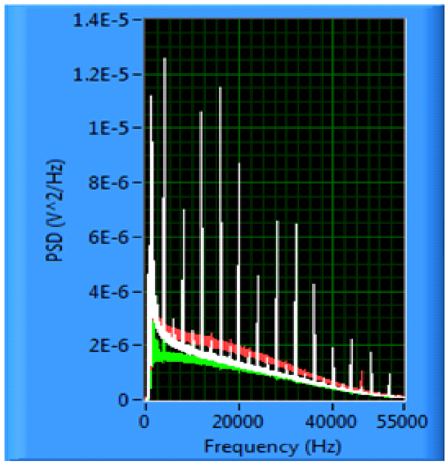


**Figure 5. Sandia spectral data from channel 1 (green) and channel 2 (red). The white is the cross-power spectral density between channel 1 and channel 2.**

## 3.3 Oak Ridge National Laboratory–Generated EMI Experiment

Because the subtraction method proved to be superior to the rejection method at Sandia, more development was put into the subtraction method algorithm. Multiple experiments continued at ORNL in the same clean lab environment, with added EMI generated using a signal generator and antenna (see Fig. 6) [2]. Controlling the additional EMI simplifies the validation of the operation of the EMI removal algorithm. The results from this experiment are displayed in Fig. 7 [7].


**Figure 6. EMI generation system.**

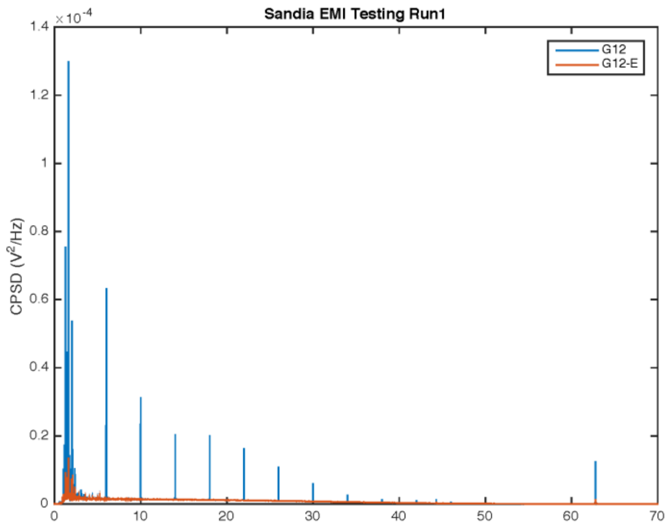


**Figure 7. ORNL-generated Sandia EMI spectral data with EMI (blue) and with EMI removed (red)**

Several other EMI conditions were tested, including broadband EMI, which is known to be difficult for the rejection method to properly remove. The antenna with the subtraction method in addition to the spectral estimation used by the rejection method increased the robustness of the JNT system and software. The subtraction method improved the temperature computation error rate, and the system was again able to measure temperature with less than 1% error.

## 3.4 TVA KFP Experiment

The last measurement location was an actual industrial environment. The JNT system was installed on the discharge and suction of a boiler feed pump at the TVA KFP. The EMI in this environment consists of broadband EMI, transient EMI, and periodic EMI (see Fig. 8) [8]. Because KFP was operational during these experiments, the temperature varied somewhat over time. The boiler feed pump under test was turned on and off several times during the experiment. At first, it was unclear whether the JNT system would survive quick temperature changes because it is designed to operate in nuclear power plants where temperatures change at slow rates. However, the system proved capable of keeping up with the temperature changes and tracked the real-time temperature (see Fig. 9) [8].

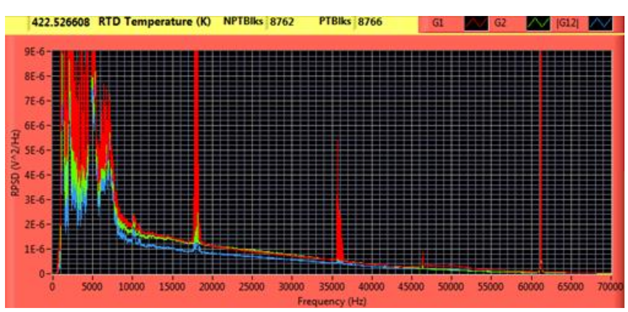


**Figure 8. Kingston Fossil Plant spectral data from channel 1 (green) and channel 2 (red). The blue is the cross-power spectral density between channel 1 and channel 2.**

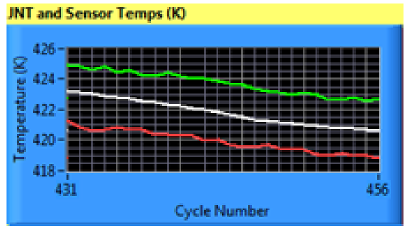


**Figure 9. Kingston Fossil Plant temperature measurement: real-time temperature of sensor (white), JNT temperature (green),**

The JNT temperature consistently stayed within a few percent of the real-time temperature measurement. These measurements were made over a very short period of time, so the results could have converged if the measurements continued for a longer period of time. However, the goal of the experiment was just to determine whether the system would survive such a harsh EMI environment, and it did.

## 4 CONCLUSIONS

JNT is an important measurement tool for monitoring safety levels and stability in a nuclear reactor. Guaranteeing a reliable and accurate temperature measurement previously depended heavily on a low EMI noise environment. However, ORNL has proven that properly removing unwanted EMI is possible and delivers drift-free temperature measurement. The two techniques developed, rejection and subtraction algorithms, and the required additional electronics were discussed in this paper. Installation of this JNT system at an existing nuclear power plant requires only minimal reconfiguration but provides a more robust measurement than current systems. This research is a platform that can be used for self-calibrating RTD systems. Integrating a self-calibrating system would reduce maintenance and costs in nuclear power plants in the future.

## 5 ACKNOWLEDGMENTS

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