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Research Article

Neutron Flux Monitoring Based on Blind Source Separation Algorithms in Moroccan TRIGA MARK II Reactor

Hanane Arahmane,[1] El-Mehdi Hamzaoui,[2] and Rajaa Cherkaoui El Moursli[1]

[1]*LPNR, Department of Physics, Faculty of Sciences, Mohammed V University, 1014 RP, Rabat, Morocco*
[2]*National Centre for Nuclear Energy, Sciences and Techniques (CNESTEN), 1382 RP, 10001 Rabat, Morocco*

Correspondence should be addressed to Hanane Arahmane; hanane_ar1@hotmail.com
and El-Mehdi Hamzaoui; hamzaouielmehdi@gmail.com

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We present an overview of fission chamber's functioning modes, theoretical aspects of the nonnegative matrix factorization methods, and the opportunities that offer neutron data processing in order to achieve neutron flux monitoring tasks. Indeed, it is a part of research project that aimed at applying Blind Source Separation methods for in-core and ex-core neutron flux monitoring while analyzing the outputs of fission chamber. The latter could be used as a key issue for control, fuel management, safety concerns, and material irradiation experiments. The Blind Source Separation methods had been used in many scientific fields such as biomedical engineering and telecommunications. Recently, they were used for gamma spectrometry data processing. The originality of this research work is to apply these powerful methods to process the fission chamber output signals. We illustrated the effectiveness of this tool using simulated fission chamber signals.

1. Introduction

The major reason to control neutron flux inside any nuclear reactor is its proportionality to the power density. For this reason, we are concerned, in our research, with this variable which can be measured using one of the five following types of neutron detectors: Boron Trifluoride (BF3) proportional counters, Boron (^{10}B) lined detectors, fission chamber (FC), ^{3}He proportional counters, and self-powered neutron detectors (SPND) [1].

The TRIGA Mark II Reactor of the Nuclear Studies Centre of Maâmora (CNESTEN-Morocco) of the National Centre for Nuclear Energy, Sciences and Techniques (http://www.cnesten.org.ma/) is a standard design 2 MW power with graphite reflector, four beam tubes, and one thermal column. It is designed for use in several areas such as isotopes production for nuclear medicine, industry, and agriculture.

It is important to know neutron flux distribution inside such reactor as accurately as possible. This can be possible using fission chambers [2] that are commonly used to locally characterize the in-core and ex-core neutron fields. Several FC detectors geometries are available but the most widely used are the cylindrical chambers. They are composed of two concentric electrodes. A layer of fissile material is deposited on at least one of the electrodes. Actually, the FC output signal can be processed in three modes: pulse mode, current mode, and Campbelling mode. Each mode yields a signal proportional to the fission rate, which is in turn proportional to the neutron flux. Also, the selected mode depends on statistical order of the count rates. In addition, these three operating modes refer to the manner in which the charge is collected and processed. Several works have been done in this sense within large nuclear facilities by using pulse, Campbelling, and/or current counting techniques [3–5].

To improve the neutron flux monitoring, we seek to use new methods based on Blind Source Separation (BSS) algorithms. In fact, BSS methods require no hypothesis on the way that the signal and the noise are mixed inside a given system. That is why they have been used in several scientific fields to solve numerous problems (audio signal

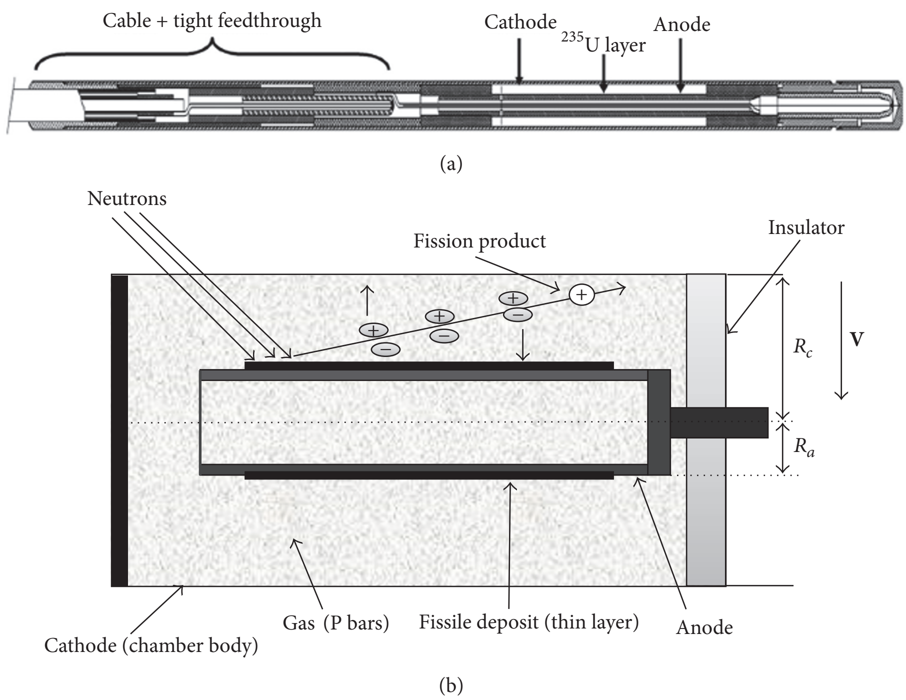

Figure 1: (a) Overall plan of FC with fissile element ^{235}U [12] and (b) simplified schema of cylindrical FC [13].

processing, astronomy, biomedical engineering, telecommunications, and geophysics) [6]. Recently, Mekaoui et al. have used these methods for gamma spectrometry data processing [7]. Thus, their work aims at detecting and identifying gamma-emitters using only the signals recorded at the HPGe preamplifier's output signals [7, 8]. Also, they tried to solve the pileup problem at the HPGe output [7, 9]. This encouraged us to apply these powerful signal processing algorithms to control the neutron flux in Moroccan TRIGA MARK II Reactor. In addition, there is no published work dealing with the application of these new tools to analyze fission chamber's signals.

This paper is organized as follows: first, we briefly discuss the FC's principle and their different operating modes (Section 2). Second, we present, in Section 3, the Blind Sources Separation algorithms used for the on-line neutron flux monitoring.

2. Fission Chambers (FC)

2.1. Detector Principle. The FCs are simple generic ionization chambers with fissile deposit on at least one of the electrodes (Figure 1). Cylindrical FCs are made of two electrodes: The internal electrode which is always anode, whereas the external one is the cathode. The filling gas, usually Argon, separates them. The anode is coated with a fissile element layer from few micrograms to few grams. In the case of TRIGA MARK II Reactor, the fissile coating is U-235 (90%). Under irradiation, neutrons induce several kinds of reaction (1), but the main reaction is the fission one (U-235 is mainly sensitive to thermal neutron). This reaction results in two high energy fission fragments (FF), around 166 MeV in total [10], which subsequently are emitted in opposite directions. One FF passes through the gas, whereas the other one is absorbed by the anode [11].

$$\begin{aligned} {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow \left({}^{236}_{92}\mathrm{U}\right)^{*} &\longrightarrow \mathrm{FF}_1 + \mathrm{FF}_2 \\ &+ 2 \text{ to } 3 \text{ neutons} \end{aligned} \tag{1}$$

The fission product emitted to the gas creates about $1E^5$ to $1E^6$ electron-ion pairs along its path [10]. There is a probability that the two FF remain trapped in the fissile layer. This phenomenon is named self-protection. Another phenomenon, called autoabsorption, which consists of making the inner layers of the element fissile submitted to a different neutron flux of the outer layers, is then appropriate to minimize the thickness of the deposit to make both phenomena negligible.

The electric field that is applied to the electrodes separates electrons and ions. The anode collects the negative charges, while the cathode collects the positive ones. This causes an observable pulse of current. The resulting signal reflects the interaction of the neutron flux with the fissile deposit. It can also be gamma ray (γ-ray) from gamma flux or from the (γ, n) reaction in the materials [3, 15]. The measured signal is strongly related to the chamber characteristics such as gas pressure and pulses' charge which varies according to the creation charge induced by fission product. The pulse charge's spectrum characteristics inform us about the FC specifications and their evolution over time.

2.2. Fission Chamber (FC) Operating Modes. As mentioned above, there are three operating modes of an FC according to its design and external coupled electronic devices. Indeed, they are commonly used to process the FC output signal that corresponds to the induced current.

2.2.1. Pulse Mode. At a low fission rate, the sensitivity range of FCs in pulse mode is between 0.01 cps/nv and 4 cps/nv. Here, the pulses are separated from each other. The probability spectrum of the pulses charge is estimated to extract the signal from background noise. The monitoring of the pulse counting rate allows measuring a quantity that is proportional to the flux and the fission rate. The maximum count rate depends on various chamber parameters such as size, filling gas pressure and composition, and interelectrode distance. According to Böck and Villa [1], for a negligible dead-time correction, the max count rate is of the order of $1E^{6}$ cps (for pulse widths of the order of 80 ns); so a high sensitive chamber (1 cps/nv) can be operated in pulse mode up to $1E^{6}$ nv and a low sensitivity chamber (0.01 cps/nv) up to $1E^{8}$ nv. The chamber can withstand gamma radiation up to $1E^{4}$ Gy/h [1].

2.2.2. Current Mode. At a higher fission rate, individual pulses cannot be separated. The mean value of the current, generated by the pileup pulses is measured according to the Campbell theorem which states that the first two statistical moments of current average and variance are proportional to fission rate [16]. The usual maximum current produced by a FC is of order of 1 mA. In current mode the saturation characteristics of FC are quite similar to those of Uncompensated Boron-Coated Ionization Chamber (UIC). Then, the sensitivity to neutrons depends on the quantity of element fissile (U-235) at the electrode. Typical values are between $1E^{-14}$ A/nv and $1E^{-12}$ A/nv. A very sensitive FC with $6E^{-13}$ A/nv can measure maximum fluence of about $2E^{9}$ nv. The gamma sensitivity in this mode is around $1E^{-9}$ A/Gy/h [1]. It is noticed that gamma contribution may be important and varies typically between 1% and 10% of the global signal [5]. This contribution is, in general, about 0.1% of the global signal's amplitude.

2.2.3. Campbelling Mode. For high neutron fluence rate, the generation of the pulses is limited by the pulse pileup phenomenon. The signal fluctuation is a measurement of the neutron fluence rate. The greater the energy deposit caused by a neutron event, the more accurate the measurement [1]. Due to high energy deposited by neutron compared to a gamma interaction in the filling gas, the FC is the only detector able to create neutron proportional signal using fluctuations. In Campbelling mode, the neutron signal is proportional to the square of the charge deposited in the gas. Consequently, this mode permits dramatically reducing gamma ray contribution [4, 5].

In general, Campbell's theorem gives the relationship between the intensity of a shot noise process and cumulates. The Campbelling mode [17, 18] is based on the second part of Campbell's theorem which states (1) the average value of the current from a source of random current pulses is proportional to the average pulse rate and the charge produced per event which is itself related to the pulse height; (2) the variance of this current is proportional to the average pulse rate and to the square of the charge produced per event which is turn related to the square pulse height. The detector's sensitivity depends directly on the mean charge deposited by fission products in the gas [5]. Figure 2 illustrates the electronic system used for the IRINA project [19, 20] to analyze the output signal of the FC according to the three possible modes (pulse, Campbelling, and current).

3. Application of the Blind Sources Separation Algorithms to Neutron Flux Monitoring

In this section, we present a general view on the actual methods used in the control of the neutron flux. It consists of using the FC in pulse, Campbelling, and current modes. We also present the state of the art about Blind Sources Separation algorithms as alternative techniques which may improve the use of FC's output signal in neutron flux control.

3.1. Pulse, Campbelling, and Current Methods. In TRIGA MARK II Reactor, the FC is a key to monitor and measures the on-line neutron flux. From processing the FC's signals, we estimate the fission rate related directly to the neutron flux. Different methods are used for this processing with different electronics according to the statistic order of the count rates and depending on low, medium, and high detection rate, respectively. At a low count, the signal has the shape of individual pulses. For this reason, pulse counting technique, which is based on level crossing, is applied. At medium and higher count rate, the pulses are overlapped. Therefore, the counting becomes impossible and the detection rate is estimated with both Campbelling and current techniques. To solve this problem, several investigations have been carried in this sense. Among these scientific works is Elter et al. survey which suggests applying Higher Order Campbelling methods (HOC) in neutron flux monitoring with FCs to suppress the impact of gamma ray contribution [5, 21]. Filliatre et al. used simulations to evaluate the FC signal in current and Campbelling modes in order to derive mean current and variance [10], whereas Geslot et al. works tackled the FC measurement and calibration in pulse mode for a given discrimination threshold applied on pulse height spectrum [22].

The works have been carried out with these methods for monitoring and controlling power in nuclear reactors ensure their reliability to better reactor's control and increase the reactor's safety parameters during operation. However, they are implemented electronically in analog data acquisition chains. For this reason, we encourage applying other techniques to digitally process the FC's output signal by using new signal processing methods.

3.2. Blind Source Separation Methods. Many recent publications have dealt with digital processing of nuclear signals in general. We cite here as an example Elbadri et al. works in which they have applied linear and nonlinear adaptive filters to improve the quality of HPGe preamplifier's output signals which are used in environment monitoring gamma ray spectrometry [23]. Trigano et al. used statistical methods

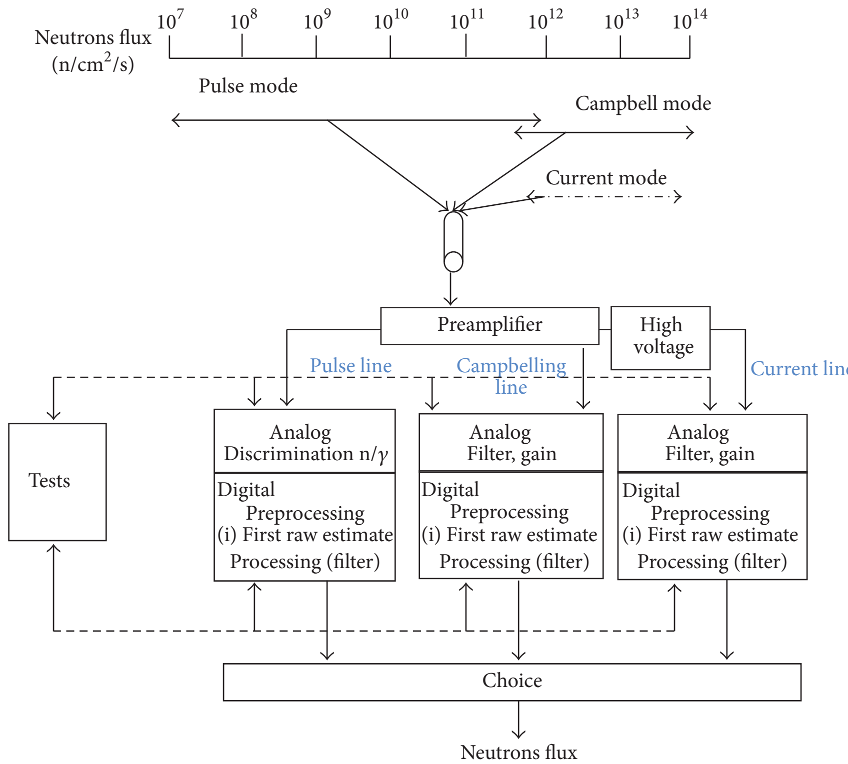

Figure 2: Schematic of the electronic system used in the IRINA project [5].

to solve the problem of pulse pileup [24]. In addition, Amiri et al. used Fourier transform to analyze organic scintillators' signals in order to achieve neutron gamma discrimination task [25].

The application of new digital signal processing methods, the so-called Blind Source Separation (BSS), on nuclear data was introduced by Mekaoui et al. [7–9]. It was used, as mentioned above, for the detection and identification of gamma radiation emitters and for solving the pileup problem at the output of HPGe preamplifier used in gamma spectrometry chains. This has encouraged us to apply these methods for neutron flux monitoring and neutron gamma discrimination inside TRIGA MARK II Reactor.

Moreover, BSS tools now raise great interest and play an important role in many application areas. Their first application solved the "cocktail party" problem [14, 26]. More than that, no bibliographic reference has been found regarding the application of BSS methods or other digital signal processing techniques to process and analyze the output signals of FC. Hence, the originality of our research works. We are especially interested in the application of Nonnegative Matrix and Tensor Factorizations to analyze the signals recorded at the output of the FC detectors.

The BSS principle can be schematized as shown in Figure 3. Thus, BSS methods are used to estimate the original sources from the measured observations so as to solve the problem of recovering mutually independent components.

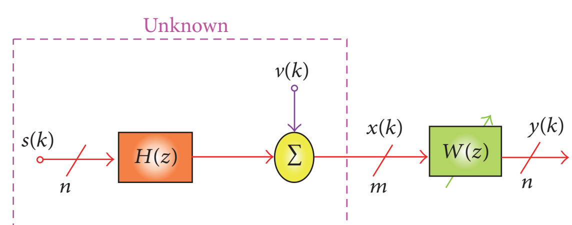

Figure 3: Block diagram of the basic BSS problem [14].

3.2.1. Mathematical Formalism of BSS. In theory, the measured observations $x(k)$ are recorded from the sensors such as microphones, cameras, and detectors, while coming from the mixture of the sources $s(k)$ through unknown propagation channels $H(z)$.

Mathematically speaking, according to Cichocki et al. (2) expresses the matrix form of BSS system [14, 26]:

$$x\left(k\right) = Hs\left(k\right) + v\left(k\right) \tag{2}$$

where

(i) $x(k) = [x_1(k), x_2(k), \ldots, x_m(k)]^T$ and $s(k) = [s_1(k), s_2(k), \ldots, s_n(k)]^T$ represent the m observations and the n sources to be estimated respectively;

(ii) H is the mixing matrix $(n \times m)$;

(iii) $v(k)$ is an additive noise.

The power of BSS techniques resides in their ability to determine the matrix W, called "demixing matrix," which

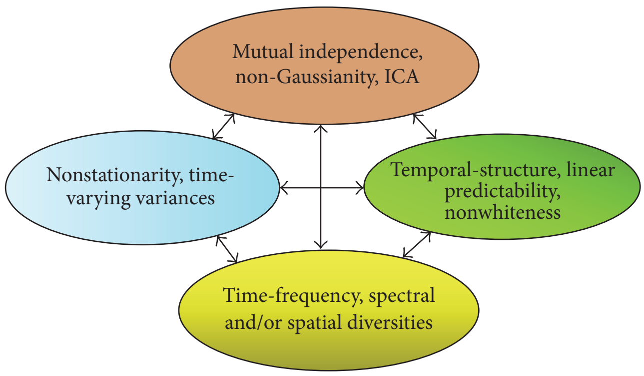

FIGURE 4: Basic approaches for Blind Sources Separation [14].

approach better H^{-1} matrix and the components of the vector $\hat{s}(k)$ based only on the observation vector $x(k)$:

$$\hat{s}(k) = Wx(k). \tag{3}$$

The estimated sources are given by the vector $s(k)$ and their corresponding projections to the different sensors are given by the estimated matrix of the mixture:

$$\widehat{H} = W^{-1}. \tag{4}$$

There are several BSS algorithms which are grouped into four approaches as shown in Figure 4 [14].

In addition to these classical methods, the linear instantaneous mixtures can be processed using Nonnegative Matrix and Tensor Factorizations (NMF and NTF), Sparse Component Analysis (SCA), and Morphological Component Analysis (MCA). In our research, we are interested in the use of NMF and NTF approaches to analyze FC's output signals.

3.2.2. Nonnegative Matrix and Tensor Factorizations Algorithms. The NMF is a technique of the dimension reduction adapted to sparse matrix containing positive data. It was introduced by Lee and Seung [27] to decompose nonnegative two-dimensional data into a linear combination of elements in a dictionary.

The NMF of a matrix E of dimensions $F \times N$ aim is to estimate two nonnegative matrices W and H of dimensions $F \times K$ and $K \times N$, respectively.

$$E \approx WH = \widehat{E}. \tag{5}$$

The factorization is solved by finding a local optimum of the optimization problem:

$$\min_{W,H>0} \left[L(E, WH) + P(W, H)\right], \tag{6}$$

where

(i) L is the loss function measuring the quality of approximation. It is a criterion of the Least Square (LS) or Kullback-Leibler Divergence (KL);

(ii) P is optional penalty function.

Several algorithms and implementations are used to compute the NMF [26, 27]. The most used are the standard NMF algorithm with multiplicative update, the Alternate Least Square (ALS) Algorithm, and the Gradient Descent Algorithm [26].

For some problems, the matrices can be seen as second-order tensors. In some cases, they can go up to the third or higher order. For this reason, the NMF can be generalized to Nonnegative Tensor Factorization (NTF).

The NTF problem can be expressed as nonnegative canonical decomposition/parallel factor decomposition denoted by CANDECOMP and PARAFAC, respectively [26]. According to Flatz [28], the mathematical formalism of NTF is as follows:

Given an Nth order data tensor $\underline{Y} \in \mathscr{R}^{I_1\times I_2\times\cdots\times I_N}$ and a positive integer J, we factorize $\underline{Y}$ into a set of N nonnegative component matrices $A_j^{(n)} = [a_1^{(1)}, a_2^{(2)}, \ldots, a_J^{(n)}] \in \mathscr{R}^{I_n\times J}$, $n = 1, 2, \ldots, N$, called loading matrices or factors, which perform the approximation representing the common (loading) factors. That can be expressed as

$$\begin{aligned}
\underline{Y} &= \underline{\hat{Y}} + \underline{E}, \\
\underline{Y} &= \sum_{j=1}^{J} a_j^{(1)} \circ a_j^{(2)} \circ \cdots \circ a_j^{(N)} + \underline{E}, \\
\underline{Y} &= \left[A^{(1)} \times A^{(2)} \times \cdots \times A^{(N)}\right] + \underline{E},
\end{aligned} \tag{7}$$

where $\|a_j^{(n)}\|_2 = 1$ for $n = 1, 2, \ldots, N-1$ and $j = 1, 2, \ldots, J$ and $\circ$ is the outer product of tensors.

The tensor $\underline{E}$ is an approximation error.

In order to compute the nonnegative component matrices $A_j^{(n)}$, we usually apply constrained optimization approach by minimizing a suitable design cost function. Typically, the NTF optimization problem is formulated as [26]

$$\min_{a_i^{(n)}\in\mathscr{R}^{I_i}} = \left\| \underline{Y} - \sum_{j=1}^{J} \bigotimes_{i=1}^{N} a_j^{(i)} \right\|_F^2 ; \quad 0 \le a_j^{(i)}, \tag{8}$$

where $\bigotimes$ is the Kronecker product.

NTF is a technique for computing and decomposing a nonnegative value tensor into sparse and reasonably interpretable components. Four algorithms are implemented in NTF [26, 28]:

(i) Simple and Fast Hierarchical Alternating Least Squares (Simple/Fast HALS).

(ii) Multiplicative alpha divergence algorithms.

(iii) Multiplicative beta-divergence algorithms.

(iv) Block principal pivoting.

In our project, we aim at applying NMF and NTF algorithms to analyze the FC's output signals. Indeed, the recorded signals are considered as time-series mixtures of several components (sources) which we try to extract using

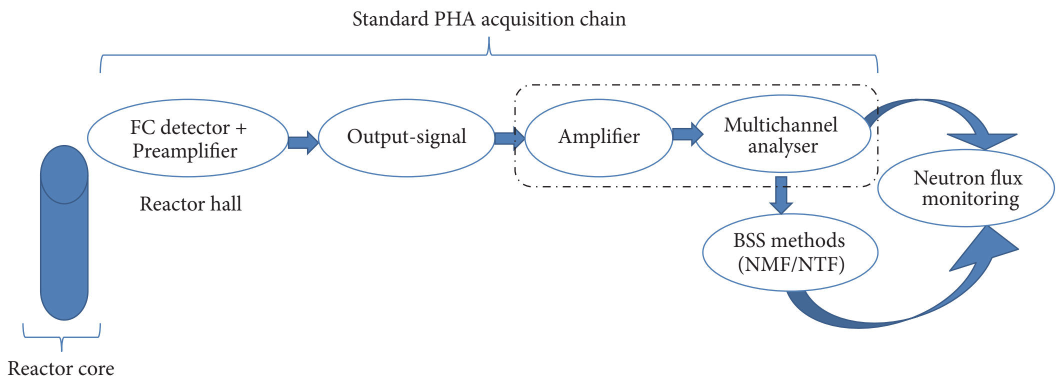

FIGURE 5: Project steps for the neutron flux monitoring using BSS methods.

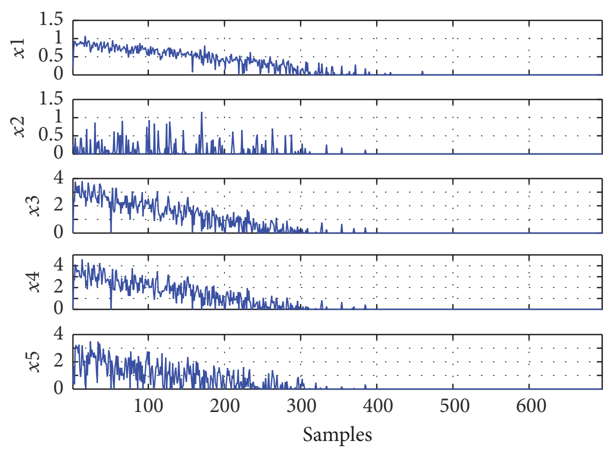

FIGURE 6: The observations used as input of the NMF algorithm.

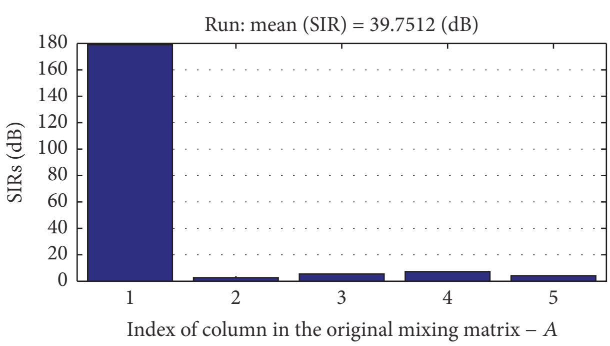

FIGURE 7: Signal to interference ratio for the mixing matrix.

these new signal processing methods. Figure 5 shows the steps which will be followed in this project.

As an example, we are going to represent in Figures 6, 7, and 8 the results of the application of the Lee-Seung NMF algorithm [26], to a data set formed by fission chamber output signals, simulated through the Python-based simulation of fission chamber (pyFC) [29]. Indeed, five recorded signals (observations) are used as input of the algorithm (Figure 6). The plot of the Signal to Noise Ratio

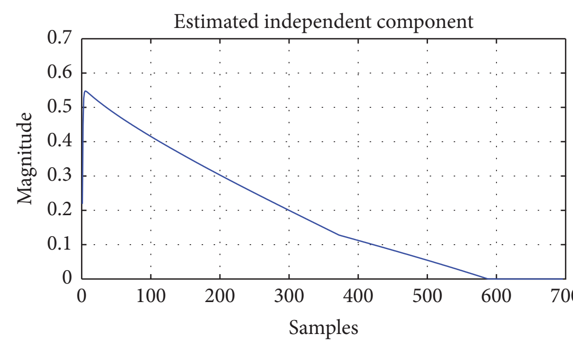

FIGURE 8: The estimated source.

(SIR) calculated according to the computed mixing matrix A shows only one important SIR value (Figure 7). This means that our mixture is composed of one main source which may be corrupted by noise. Figure 8 shows the estimated source.

Since we achieve the separation task, we can then characterize each isolated component through the computation of the auto- and cross-correlation functions and the power spectral densities and/or according to time-frequency analysis in order to extract meaningful features permitting achieving the neutron flux monitoring task.

4. Conclusion

The state of the art concerning classical and new methods used to control the neutron flux within the experimental and research nuclear reactors has been summarized. Indeed, the on-line flux neutron monitoring is most important task for control, fuel management and safety concerns, and material irradiation experiments. Consequently, it is a challenge shared by wide range of scientific areas, from the fundamental physics to the control reactors. The fission chamber is privileged instrument for recording directly the fast fluctuations of neutron flux. Therefore, it is the most appropriate neutron detector that fulfills that need.

The output signal of the fission chamber can be processed through pulse mode, Campbelling mode, and current mode. Each of these modes operates within a specific range of the neutron flux. The originality of our research work is to apply the nonnegative matrix factorization algorithms to achieve Blind Sources Separation task of fission chamber output signals operating at any neutron flux range. Indeed, we seek better characterization of neutron signals with very high precision through the analysis of extracted independent components. Forthcoming works are going to deal with the implementation of the Blind Sources Separation Algorithms and their application in neutron flux monitoring area.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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