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Nonnegative Tensor Factorization Approach Applied to Fission Chamber’s Output Signals Blind Source Separation

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Abstract. Inside nuclear reactors, gamma-rays emitted from nuclei together with the neutrons introduce unwanted backgrounds in neutron spectra. For this reason, powerful extraction methods are needed to extract useful neutron signal from recorded mixture and thus to obtain clearer neutron flux spectrum. Actually, several techniques have been developed to discriminate between neutrons and gamma-rays in a mixed radiation field. Most of these techniques, tackle using analogue discrimination methods. Others propose to use some organic scintillators to achieve the discrimination task. Recently, systems based on digital signal processors are commercially available to replace the analog systems. As alternative to these systems, we aim in this work to verify the feasibility of using a Nonnegative Tensor Factorization (NTF) to blind extract neutron component from mixture signals recorded at the output of fission chamber (WL-7657). This last have been simulated through the Geant4 linked to Garfield++ using a \(^{252}\)Cf neutron source. To achieve our objective of obtaining the best possible neutron-gamma discrimination, we have applied the two different NTF algorithms, which have been found to be the best methods that allow us to analyse this kind of nuclear data.

1. Introduction

Fission chambers (FC) are the most appropriate neutron detectors that are dedicated to deliver online neutron flux measurements for experimental fission reactors [1, 2, 3]. Those measurements have a wide range of applications, including characterization of experimental conditions, reactor monitoring and safety concerns [4, 5]. Depending on the application, such detector introduces a wide range of constraints, of several magnitudes with regard to neutron flux, gamma-ray flux and temperature. Hence, designing a specific fission chamber and measuring chain for a given application is a challenging task and can be achieved by a combination of experimental feedback and simulating tools. As thoroughly described in references [6, 7, 8], fission chambers can operate in three different modes: Pulse Mode, Campbelling Mode (also known as ”fluctuation mode” or ”mean square voltage mode”) or Current Mode. The Current mode does not allow for pulse height discrimination between neutron and gamma radiations as do pulse and Campbelling Modes.

In an earlier work based on Geant4 linked to Garfield++ simulations [9], discrimination of gamma-rays from neutrons in WL-7657 FC detector was investigated by using the Nonnegative Tensor Factorization (NTF) algorithms. The objective was to extract independent components
(IC) from signals recorded at the output of WL-7657 FC, and to characterize obtained ICs in order to reach the discrimination goal [9].

Recently the used code was updated to be capable of simulating the output signals with $^{252}$Cf neutron source [10]. The aim of the present work with a $^{252}$Cf source was to check these methods and at the same time to investigate the differences in pulse shapes of neutron and gamma-ray radiations. As a continuation of that work, the present paper investigates the application of two NTF algorithms to achieve the discrimination task. The figure 1 below summarize the steps which will be followed in this project.

![Block diagram of n-γ discrimination based on NTF approach.](image)

**Figure 1.** Block diagram of n-γ discrimination based on NTF approach.

2. **Mechanical and Physical features in WL-7657 Fission Chamber**

The WL-7657 fission chamber has been proposed for use as a neutron diagnostic system to measure the characteristics of neutrons from the TRIGA Mark II, research reactor of the Nuclear Studies Centre of Maâmora (CNESTEN-Morocco). The WL-7657 FC is a $\approx 1576.86 \text{ cm}^3$ volume and has two coaxial electrodes, the outer electrode (namely the cathode) have a diameter of about 76.2 mm, the inter-electrode space is filled with a 4% Nitrogen and 96% Argon at 1 atm pressure, with 90% enriched $^{235}$U in $\text{U}_3\text{O}_8$ (1.68 g) deposited on the inner electrode (namely the anode) [11]. The mass of the fissile deposit coating is a key parameter in this simulation, as it impacts directly the amounts of signal within a given neutron flux. When a neutron crosses the fissile deposit, it is likely to induce a fission reaction that generates two charged particles (Fission Fragment) emitted in two nearly opposite directions. The fission fragment emitted out of the deposit ionizes the filling gas on its trajectory and consequently generates a high number of electron-ion pairs ($\text{Ar}^+\text{e}^-$). Given that, a DC voltage of a few hundred volts is applied between the electrodes, the electrons and positive ions are separated and drift across the gas, generating current signal that can be amplified and processed. The figure 2 gives an outline of the neutron and gamma-ray interactions occurring in a fission chamber.
3. Nonnegative Tensor Factorization model

The basic 3D Nonnegative Tensor Factorization (NTF) model considered in this paper is illustrated in figure 3 [13]. The NTF is a generalization of Nonnegative Matrix Factorization (NMF) aimed at retrieving underlying components from high dimensional data. The basic formulation NTF is Parallel Factor Analysis Model (PARAFAC) with nonnegativity constraints and other possible natural constraints such as sparseness and/or smoothness on the basis of only the 3D tensor \( \mathbf{Y} \). This permits to extract two common factors: a basis mixing matrix \( \mathbf{A} \) and unknown components factors represented by a matrix \( \mathbf{X} \), which can be represented in slice factorization form:

\[
Y_k = AD_kX + E_k, \quad (k = 1,2, \ldots, K)
\]

Where \( Y_k = Y_{:, :, k} \in \mathbb{R}^{I \times T} \), are frontal slices of a 3D tensor \( \mathbf{Y} \in \mathbb{R}^{I \times T \times K} \), \( K \) is a number of frontal slices, in our application, \( \mathbf{Y} \) is formed by recorded FC preamplifier's output signals, also referred to as "observations" or "data", \( A = [a_{ir}] \in \mathbb{R}^{I \times R} \) is the basis (mixing matrix) representing common factors, \( D_k \in \mathbb{R}^{R \times R} \) is a diagonal matrix that holds the \( k \)-th row of the matrix \( D \in \mathbb{R}_{+}^{K \times R} \), in its main diagonal, \( X \in \mathbb{R}_{+}^{R \times T} \) is an unknown matrix of independent components to be estimated, and \( E_k = E_{:, :, k} \in \mathbb{R}^{I \times T} \) is an additive noise for a \( k \)-th frontal slice of the tensor \( E \in \mathbb{R}^{I \times T \times K} \) [13].

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**Figure 2.** Outline of the neutron, gamma-ray interactions occurring in a fission chamber [12].

**Figure 3.** Decomposition of 3D tensor into three nonnegative matrices using the standard NTF model [14].
3.1. NTF1 model

In 3D NTF1 model, which is an extension of the NTF model (figure 4), a given data tensor \( Y \in \mathbb{R}^{I \times T \times K} \) (Observed data) is decomposed to a set of matrices \( A, D \) and \( \{X_1, X_2, ..., X_K\} \) with nonnegative entries.

\[
Y_k = AD_kX_k + E_k, \quad (k = 1,2, ..., K)
\] (2)

Figure 4. Illustration of NTF1 model.

Since the nonnegative diagonal matrices \( D_k \in \mathbb{R}^{R \times R}_+ \) are scaling matrices, they can usually be absorbed by the matrices \( X_k \in \mathbb{R}^{R \times T}_+ \) by introducing row-normalized matrices \( X_k := D_kX_k \in \mathbb{R}^{R \times T}_+ \), hence \( Y_k = AX_k + E_k \) [13].

3.2. NTF2 model

In 3D NTF2 model, which can be illustrated as in figure 5, the observed data \( Y \in \mathbb{R}^{I \times T \times K} \) is decomposed to a set of matrices \( \{A_1, A_2, ..., A_K\}, D \) and \( X \) with nonnegative entries.

\[
Y_k = A_kD_kX + E_k, \quad (k = 1,2, ..., K)
\] (3)

Figure 5. Illustration of NTF2 model.

The NTF2 model is similar to the NTF1 but in this case the nonnegative diagonal matrices \( D_k \in \mathbb{R}^{R \times R}_+ \), they can usually be absorbed by the matrices \( A_k \in \mathbb{R}^{I \times R}_+ \) by introducing column-normalized matrices \( A_k := A_kD_k \in \mathbb{R}^{I \times R}_+ \), hence \( Y_k = A_kX + E_k \) [13].

4. Simulation results

In this paper the WL-7657 FC was simulated using Geant4 toolkit (version 4.10.02.p02) and Garfield++ (version 2015.1). A \(^{252}\text{Cf}\) neutron source having an intensity of \( 2 \times 10^3 \) n/s, was used to test the new neutron-gamma discrimination approach. In the first stage, Geant4 is used to simulate the FC geometry and the reaction models. We have included all necessary libraries in order to take all physical aspects of FC into account. In the second stage, we calculated via the Garfield++ software, the current signal generated by the drifting electrons and ions.

To test both NTF1 and NTF2 algorithms, we used the NTFLAB toolbox developed by Cichocki A. et al., which is implemented under MATLAB® environment [15]. To demonstrate
the effectiveness of NTF algorithms, tensors of size $5 \times 600 \times 5$ were created from the simulated FC preamplifier’s output signals (Observations), as shown in the figure 6. The algorithms were evaluated according to the values of their performance index of separability (PI) [16, 17]. Figure 6 shows the selected slices of mixed signals.

Figure 6. Selected slices of mixed signals.

The figure 7 and 8 show the sources recovered by the application of NTF1 and NTF2 algorithms respectively. The simulations results have been performed for neutron and gamma signals in which the nonnegative depend 10 hidden components or sources are collected in 5 slices $X_k \in \mathbb{R}_+^{2 \times 600}$ in case of NTF1 application and 2 hidden components or sources are collected in 1 slice $X \in \mathbb{R}_+^{2 \times 600}$ in case of NTF2 application, each representing 2 different kind of signals.

Figure 7. Spectra signals estimated with the NTF1.

Figure 8. Spectra signals estimated with the NTF2.

It can be seen that the sources have been reasonably well separated. The computation of the Signal-to-interference ratio (SIR) of individual columns of the mixing matrix $A$, permits us to confirm that the WL-7657 FC output mixture signals are formed by two main independent components which may be corrupted by noise (figure 9). This leads to say that the neutron-gamma discrimination task has been well achieved.
5. Conclusion

The main objective and motivations of this study were to apply the Nonnegative Tensor Factorization algorithms to extract independent components that from the preamplifier’s outputs of a simulated fission chamber. This last have been simulated through the Geant4 linked to Garfield++ using a $^{252}\text{Cf}$ source, which emits both neutrons and gamma-rays. The performance index values permit us to conclude that the NTF1 and NTF2 algorithms are the best blind source separation methods which can be applied to analyse such nuclear data. The plots of obtained independent components permit to define a qualitative criterion for the discrimination between neutron and gamma signals.

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