VALIDATION OF THE NEUTRON AND GAMMA FIELDS IN THE MOROCCAN TRIGA MARK II REACTOR USING NONNEGATIVE TENSOR FACTORIZATION APPROACH: COMPARISON OF PERFORMANCES OF THE Geant4/Garfield++ AND pyFC INTERFACES*

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Possibilities of discriminating neutrons and gamma rays in the Moroccan TRIGA Mark II reactor have been investigated with the aim of reducing intensity causes pile-ups of the pulses in the fission chamber preamplifier's output signals, the effect of the electronic noise and the unwanted background of the gamma radiation. This background may become a significant problem especially in neutron detection. To remedy this problem, we applied NTF2 model as Nonnegative Tensor Factorization (NTF) method to extract useful neutron signal from recorded mixture and thus to obtain clearer neutron flux spectrum. In this study, a full simulation of a WL-7657 fission chamber detector based on the Geant4/Garfield++ interface has been developed and the verification of the code through comparison with the results of pyFC (python-based simulation of Fission Chambers). Since we have achieved the separation task, the power spectral densities and the normalized cross-correlation of each extracted independent components computed by NTF2 algorithm from Geant4/Garfield++ interface output was compared to those computed from pyFC suite output. The results show that the computed Geant4/Garfield++ interface results are in a good agreement with the pyFC results.

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1. Introduction

The WL-7657 Fission Chambers (FCs) are routinely used for the on-line monitoring of thermal neutron fluxes in Moroccan TRIGA Mark II reactor. To make a WL-7657 FC sensitive to thermal neutrons, a coating with the enriched ^{235}U is added in the chamber [1]. They can be used in pulse mode, Campbell mode, or current mode regarding the encountered neutron flux level and the associated signal acquisition system [2–5].

The WL-7657 FC is essentially an ionisation chamber in which the electron–ion pairs are generated by fission fragments (FF) in the gaseous volume of the detector. When a voltage of a few hundred volts is applied, an electric field is generated between the two electrodes, involving a migration of charges. The collected charges are responsible for the creation of an electric current which consists of a random sum of such pulse shapes that can be amplified and processed. The WL-7657 FC's signal contributions from neutrons and from gamma rays will be separated by using NTF2 algorithm [6, 7]. In this way, a pure neutron flux measurement should be possible.

The paper is organized as follows: Geant4/Garfield++ interface *vs.* pyFC suite (Section 2); Nonnegative Tensor Factorization: NTF2 algorithm (Section 3); Simulation Results (Section 4); then we conclude (Section 5).

2. Geant4/Garfield++ interface vs. pyFC suite

The earlier work based on Geant4/Garfield++ interface simulation [8] presents the code which simulated the pulse creation in WL-7657 FC. The characteristics of the investigated WL-7657 FC is summarized in [1]. The current signals are generated due to the charge created from the ionization of the filling gas by the fission fragments. This work describes the performance of the application of the NTF2 algorithm to extract independent components from the Geant4/Garfield++ interface and from the pyFC [9] simulations outputs respectively, and the verification of the results through comparison of the power spectral densities and normalized cross-correlation of these extracted independent components.

3. Nonnegative tensor factorization: NTF2 algorithm

Nonnegative tensor factorization (NTF) methods, such as NTF1 and NTF2, aim at retrieving underlying components from high dimentional data [6, 7]. NTF is much more attractive because it takes into account spacial and temporal correlations between variables more precisely than NMF, and provides usually sparse common factors or hidden (latent) components with physical or physiological meaning and interpretation [10].

One of our motivations is to apply the NTF algorithms, implemented into the NTFLAB toolbox [11], to achieve Blind Source Separation (BSS) task of WL-7657 FC's output signals. In this paper, we consider an example of 3D NTF model (referred here to as the NTF2 model) that is described as follows:

$$Y_k = A_k D_k X + E_k\,, \qquad (k = 1, 2, ..., K)\,, \tag{1}$$

where $Y_k = \underline{Y}_{:,:,k} \in \boldsymbol{R}^{I\times T}$ are frontal slices of the observed data (signals) tensor $\underline{Y} \in \boldsymbol{R}^{I\times T\times K}$, K is a number of frontal slices in our application, Y is formed by recorded WL-7657 FC's output signals. The component matrices $A_k = [a_{\mathrm{irk}}] \in \boldsymbol{R}_+^{I\times R}$ is a mixing or basis matrices, $D_k \in \boldsymbol{R}_+^{R\times R}$ is a diagonal matrix that holds the k^{th} row of the matrix $D \in \boldsymbol{R}_+^{K\times R}$ in its main diagonal, $X \in \boldsymbol{R}_+^{R\times T}$ is an unknown matrix of independent components to be estimated, and $E_k = \underline{E}_{:,:,k} \in \boldsymbol{R}^{I\times T}$ represents the k^{th} frontal slice of the tensor $\underline{E} \in \boldsymbol{R}^{I\times T\times K}$ representing noise in the input matrix Y. Since the nonnegative diagonal matrices D_k are scaling matrices, they can usually be absorbed by the matrices A_k by introducing column-normalized matrices $A_k := A_k D_k \in \boldsymbol{R}_+^{I\times R}$, hence $Y_k = A_k X + E_k$.

4. Simulation results

4.1. Simulation data

In this section, we aim at applying NTF2 algorithm to analyze the WL-7657 FC's output signals simulated using Geant4/Garfield++ interface and pyFC suite. Indeed, the recorded signals are considered as time-series mixtures of several components (sources) which we try to extract using blind sources separation methods in order to reach the discrimination goal.

Current pulses spectra from Geant4/Garfield++ interface simulation of detector response to WL-7657 FC are shown in Fig. 1. Figure 2 shows the sources recovered by the application of NTF2 algorithm, the simulation results have been performed for neutron and gamma-ray mixed radiation field in which the nonnegative dependent 5 hidden components or sources are collected in 1 slice $X \in \boldsymbol{R}_+^{5\times 600}$.

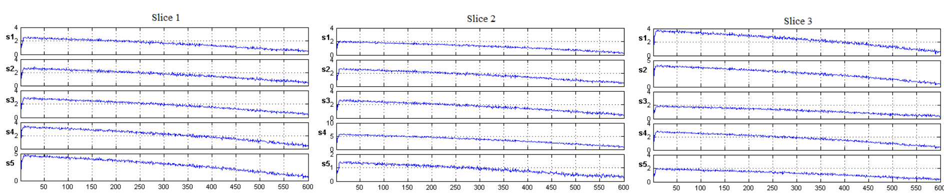

Fig. 1. Selected slices of the mixed signals from Geant4/Garfield++ interface.

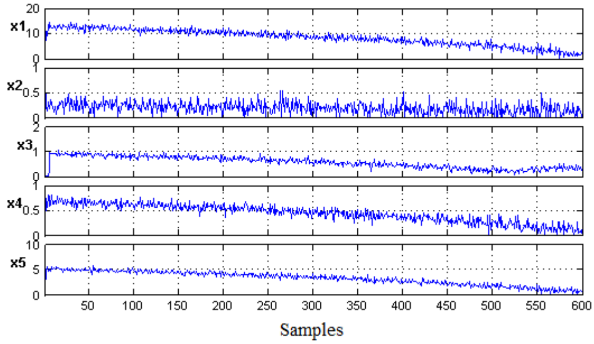

Fig. 2. Spectra signals estimated with the NTF2 from Geant4/Garfield++ interface output.

The current pulses obtained from pyFC suite was loaded with additional Gaussian white noise at various slices (Fig. 3). Figure 4 shows the sources recovered by the application of NTF2 algorithm, the simulation results have been performed for neutron and gamma-ray mixed radiation field in which the nonnegative dependent 5 hidden components or sources are collected in 1 slice $X \in \boldsymbol{R}_{+}^{5\times 600}$.

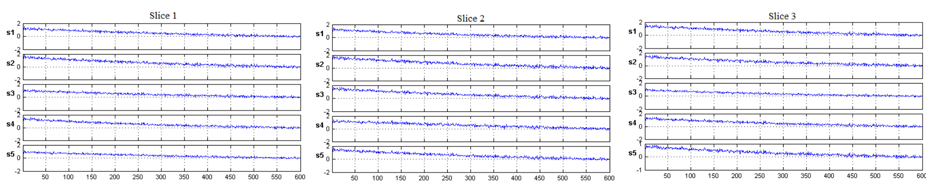

Fig. 3. Selected slices of the mixed signals from pyFC suite.

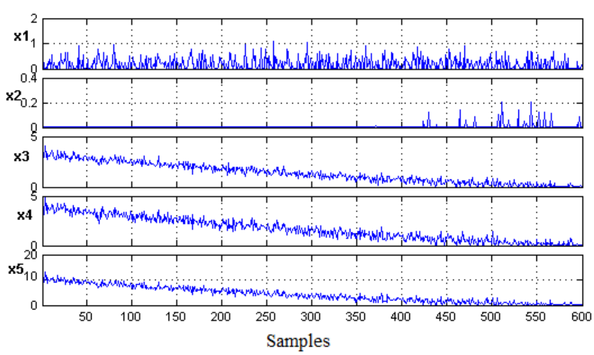

Fig. 4. Spectra signals estimated with the NTF2 from pyFC suite output.

The plot of the Signal-to-Interference Ratio (SIR) of individual columns of the mixing matrix A from both Geant4/Garfield++ interface and pyFC suite outputs cases (Fig. 5) shows that two independent components sources are dominating in both simulations cases since their SIR values are very high. These two sources may correspond to neutron and gamma-ray radiations which are completely buried in a background noise.

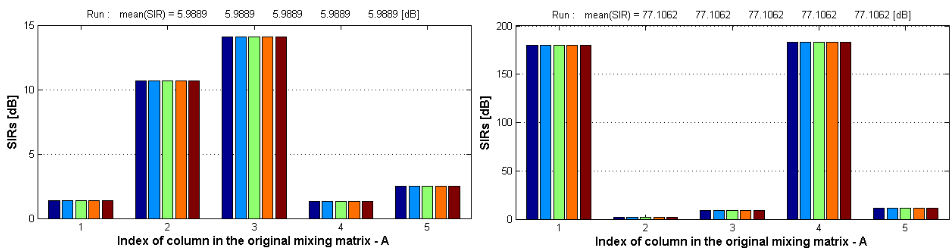

Fig. 5. SIR evaluation according to the mixing matrix A from: (left) Geant4/Garfield++ interface (right) pyFC suite.

4.2. Verification and comparison

The sources being extracted by using NTF2 algorithm, in both Geant4/Garfield++ interface and pyFC suite simulations cases, were analyzed through the computation of their PSD and normalized cross-correlation functions which we compared in order to achieve neutron gamma-ray discrimination task. Indeed, the average of five of these extracted sources results from Geant4/Garfield++ interface strongly fit to the ones extracted from the pyFC suite output, as shown in Fig. 6.

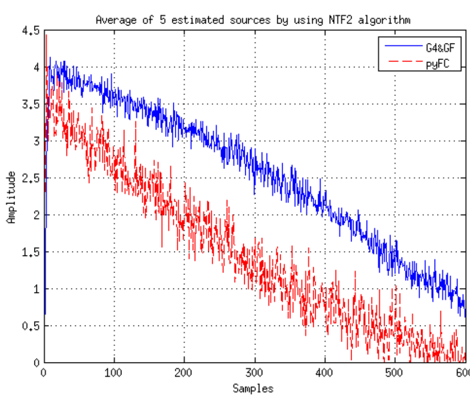

Fig. 6. (Color online) Average of 5 estimated sources from: Geant4/Garfield++ interface (higher graph/blue) and pyFC suite (lower graph/red).

We compared the computed PSD functions of the extracted independent components calculated by using NTF2 algorithm from Geant4/Garfield++ interface to those computed from the pyFC suite. Figure 7 illustrates the results found in this study. Indeed, by comparing the PSD shape of plots, we notice that in the Geant4/Garfield++ interface case, the 2$^{\text{nd}}$ estimated independent component is very close to the 1$^{\text{st}}$ estimated independent component in the pyFC suite case. Furthermore, the spectrum of the 3$^{\text{rd}}$ estimated independent component in the Geant4/Garfield++ interface case is very close to the 4$^{\text{th}}$ estimated independent component.

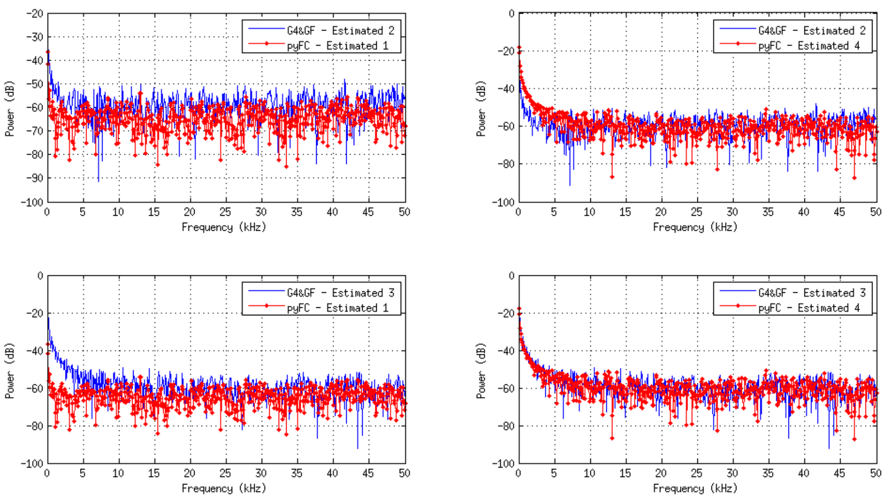

Fig. 7. PSD of estimated source from Geant4/Garfield++ interface simulation *vs.* PSD of estimated source from the pyFC simulation.

Our investigation aimed also to find if there is any relationship between the identified sources in both Geant4/Garfield++ interface and pyFC suite simulations. For this reason, we have calculated the normalized cross-correlation between 2$^{\text{nd}}$ and 3$^{\text{rd}}$ extracted independent components in the case of Geant4/Garfield++ interface and 1$^{\text{st}}$ and 4$^{\text{th}}$ extracted independent components in the case of pyFC suite. Figure 8 shows that a strong correlation exists between both the 2$^{\text{nd}}$ Geant4/Garfield++ interface and 1$^{\text{st}}$ pyFC suite estimated independent components sources and between the 3$^{\text{rd}}$ Geant4/ Garfield++ interface and 4$^{\text{th}}$ pyFC suite estimated independent components sources. Consequently, we can deduce that the first correlation may correspond to gamma source and the second one to the neutron source.

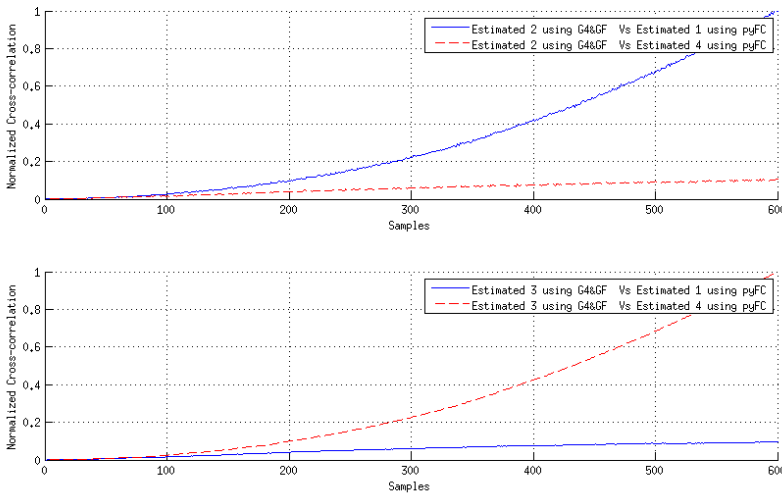

Fig. 8. Normalized cross-correlation function between estimated sources in both the Geant4/Garfield++ interface and pyFC simulations.

5. Conclusion

In this study, we have presented the results of the blind source separation of the nuclear sources which may compose the recorded WL-7657 FC's output signals. We applied the NTF2 model as nonnegative tensor factorization algorithm to simulated WL-7657 FC's output which correspond to both the Geant4/Garfield++ interface and the pyFC suite. The NTF2 algorithm was then incorporated into a nuclear signals separation algorithm which was shown to be capable of separation mixtures of neutron and gamma-ray radiations recorded at the output of the FC detectors. It is intended to improve the performance of the NTF2 algorithm to the Geant4/Garfield++ interface and to the pyFC suite outputs through the computation of PSD and normalized cross-correlation functions of each extracted independent components sources.

Blind source separation showed that the computation of the Signal-to-Interference Ratio (SIR) of individual columns of the mixing matrix A in both Geant4/Garfield++ interface and pyFC suite cases permits us to confirm that the WL-7657 FC's output mixture signals are formed by two main independent components which may be corrupted by noise. Comparing the PSD functions to estimated independent component sources and calculated the normalized cross-correlation allows us to confirm that these two dominant sources correspond to neutron and gamma-ray radiations.

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