NSDann2BS, a Neutron Spectrum Unfolding Code Based on Neural Networks Technology and Two Bonner Spheres

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Abstract. In this work a neutron spectrum unfolding code, based on artificial intelligence technology is presented. The code called "Neutron Spectrometry and Dosimetry with Artificial Neural Networks and two Bonner spheres", (NSDann2BS), was designed in a graphical user interface under the LabVIEW programming environment. The main features of this code are to use an embedded artificial neural network architecture optimized with the "Robust design of artificial neural networks methodology" and to use two Bonner spheres as the only piece of information. In order to build the code here presented, once the net topology was optimized and properly trained, knowledge stored at synaptic weights was extracted and using a graphical framework build on the LabVIEW programming environment, the NSDann2BS code was designed. This code is friendly, intuitive and easy to use for the end user. The code is freely available upon request to authors. To demonstrate the use of the neural net embedded in the NSDann2BS code, the rate counts of ^{252}Cf, ^{241}AmBe and ^{239}PuBe neutron sources measured with a Bonner spheres system.

Keywords: Artificial neural networks, optimization techniques, neutron spectrometry and dosimetry, unfolding codes, LabVIEW, programming, technological innovation.
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INTRODUCTION

The term radiation spectrometry can be used to describe measurement of the intensity of a radiation field with respect to energy, frequency or momentum. The distribution of the intensity with one of these parameters is commonly referred to as the "spectrum". A second quantity is the variation of the intensity of these radiations as a function of angle of incidence on a body situated in the radiation field referred as "dose". The neutron spectra and the dose are of great importance in radiation protection physics [1, 2]. This work is concerned primarily with measurements of the neutron spectrum with the Bonner sphere spectrometer (BSS) system and the simultaneous dose calculus for radiation protection porpoises [3, 4].

Determination of neutron dose received by those exposed to workplaces or accidents in nuclear facilities, generally requires knowledge of the neutron energy spectrum incident on the body. Spectral information must generally be obtained from passive detectors which respond to different ranges of neutron energies such as the multispheres Bonner system [3, 4]. BSS system has been used to unfold the neutron spectra mainly because it has an almost isotropic response, can cover the energy range from thermal to GeV neutrons, and is easy to operate. Drawbacks of the BSS system are the poor energy resolution, which does not allow appreciating fine structures as narrow peaks, the weight, the need to sequentially irradiate the spheres, requiring, in general, long exposure periods, the need to use an unfolding code and a very expert user.

The BSS consists of a thermal neutron sensor such as ^{6}LiI(Eu), which is placed at the center of a number of moderating spheres made of polyethylene of different diameter. In BSS, each detector is characterized by a response function. The combination of a thermal neutron detector plus moderating sphere has sensitivity to neutrons over a broad energy range. As the moderator size is increased, the maximum of the response function is shifted to larger energies. However, the sensitivity of each sphere peaks at a particular neutron energy is depending of the sphere diameter.

From the measured readings of a set of spheres, information can be derived about the spectrum of the neutron field in which measurements were made. The derivation of the spectral information is not simple; the unknown neutron spectrum is not given directly as a result of the measurements. The relationship among neutron spectrum, the count rates of BSS and the matrix response is described through the integral-differential equation of Fredholm of first type, showed in the discretized form in equation 1.

$$C_j = \sum_{i=1}^{N} R_{i,j} \Phi_j . \qquad (1)$$

Where C_j is the j^{th} detector's count rate, $R_{i,j}$ is the j^{th} detector response to neutrons at the i^{th} energy interval and N is the number of spheres used.

Once the neutron spectrum ($\Phi(E)$) has been obtained, the dose Δ can be calculated using the fluence-to-dose conversion coefficients ($\delta\Phi(E)$).

Because the number of detectors is smaller than the number of energy groups used to describe the spectrum, a unique solution does not exist and therefore unfolding procedures should be applied. At present, several unfolding methods are utilized by the researchers such as BUNKIUT [5], BUMS [6], FRUIT [7], UMG [8], etc., and most of them use iterative routines. However, the critical points of these codes are, in general, the complexity in its use, the need of a very expert user and the need of realistic a priori information, such as a "default spectrum" as close as possible to the spectrum to be obtained.

As mentioned, neutron spectrometry and dosimetry are not trivial problems; both are ill-conditioned systems with an infinite number of solutions and have difficulties that have motivated researches to propose new and complementary approaches. At present, researchers have been considering Artificial Neural networks (ANNs) technology as a promising alternative approach to solve these problems [9-14].

These considerations, together with those suggested by the experience in radiation protection around neutron producing facilities, suggest that an unfolding code based on ANN technology devoted to the operational workplace neutron monitoring would be of great help to the radiation protection community. With this purpose, a new computer neutron spectrum unfolding code based on this technology was developed.

In this work is presented a customized software application designed under the LabVIEW programming environment called "Neutron Spectrometry and Dosimetry with Artificial Neural Networks and two Bonner spheres" (NSDann2BS), capable to unfold neutron spectra and to simultaneously calculate 15 dosimetric quantities, by using as input data only two count rates coming of a BBS system, in just fraction of seconds, not being needed to solve a mathematical equation or to proportionate a priori information about the spectra being calculated or fluence-to-dose conversion coefficients to calculate equivalent doses in contrast with classical approaches based on iterative procedures.

MATERIALS AND METHODS

For this work, an optimum ANN topology was designed employing the Robust Design of Artificial Neural Networks Methodology (RDANNM) [15], to obtain the neutron spectra and to simultaneously calculate 15 dosimetric quantities starting from two Bonner spheres spectrometer's count rates as the only piece of information. The neural network was trained using a large set of neutron spectra compiled by the International Atomic Energy Agency (IAEA) [16, 17]. These include spectra from isotopic neutron sources, reference and operational neutron spectra obtained from accelerators and nuclear reactors.

The group of spectra defined from thermal to 630 MeV in sixty energy groups, were converted from lethargy to energy distribution. These spectra were normalized to 1 neutron per second and the expected count rates produced in a Bonner sphere spectrometer with $^{6}LiI(Eu)$ were calculated using the IAEA´s PTB response matrix. The count rates were utilized as inputs in the neural network while the respective neutron spectrum and 15 dosimetric quantities were utilized as the network output during the training process.

The optimized neural network was designed with three layers; the first one (the entrance layer) has 2 neurons, corresponding to the input data of rate counts measured with the 5 and 8 inches from a BSS; The second layer (hidden) has 15 neurons and the last one layer has 75 outputs, first 60 values corresponds to the neutron spectrum and the last ones to 15 dosimetric quantities. The network was designed using a feedforward backpropagation neural net (FFBPNN). Training was carried using the whole spectra from IAEA compilation, 80% of the whole data were used to train the network and remaining one for testing purposes. To train the network, a training algorithm, mse, momentum and learning rate were selected as follows: trainscg, 1E-4, 0.001 and 0.1, respectively.

Because the novelty of ANN methodology applied in the neutron spectrometry and dosimetry research and the lack of technological tools for the analysis of the spectrometric and dosimetric results obtained with the optimized neural network in experimental and operational places, a customized computer unfolding code denominated “Neutron Spectrometry and Dosimetry with Artificial Neural Networks and two Bonner spheres”, (NSDann2BS), was designed in a graphical user interface under the LabVIEW programming environment. This unfolding code based on ANN technology is easy to use, intuitive, friendly and quick in the use for the end user.

One of the main features of NSDann2BS is that operate independently of the software used to design and to train the neural network which in this case was Matlab. This computer package was designed to be executed in a standard Window environment. Figure 1 shows that in order to install this code, a standard Windows executable program was designed. After the installation process is completed, the main window of the program can be initiated as a normal window application, through the start menu.

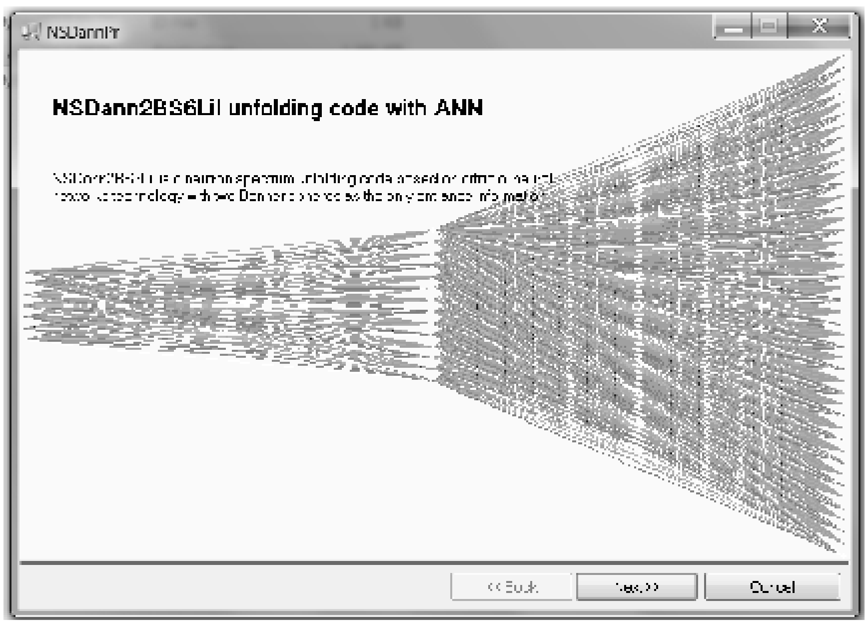


FIGURE 1. Windows executable program of NSDann2BS code to be executed in a standard Window environment

The principle of operation of NSDann2BS is the following: after executing the program, the main screen of the application will appear as showed in figure 2, where can be observed that the main screen of the code automatically register the actual time and date in the upper left side of the main screen. This code has the text boxes “User name” and “Notes and comments” where the user can add notes to record the unfolding in a full report with HTML format.

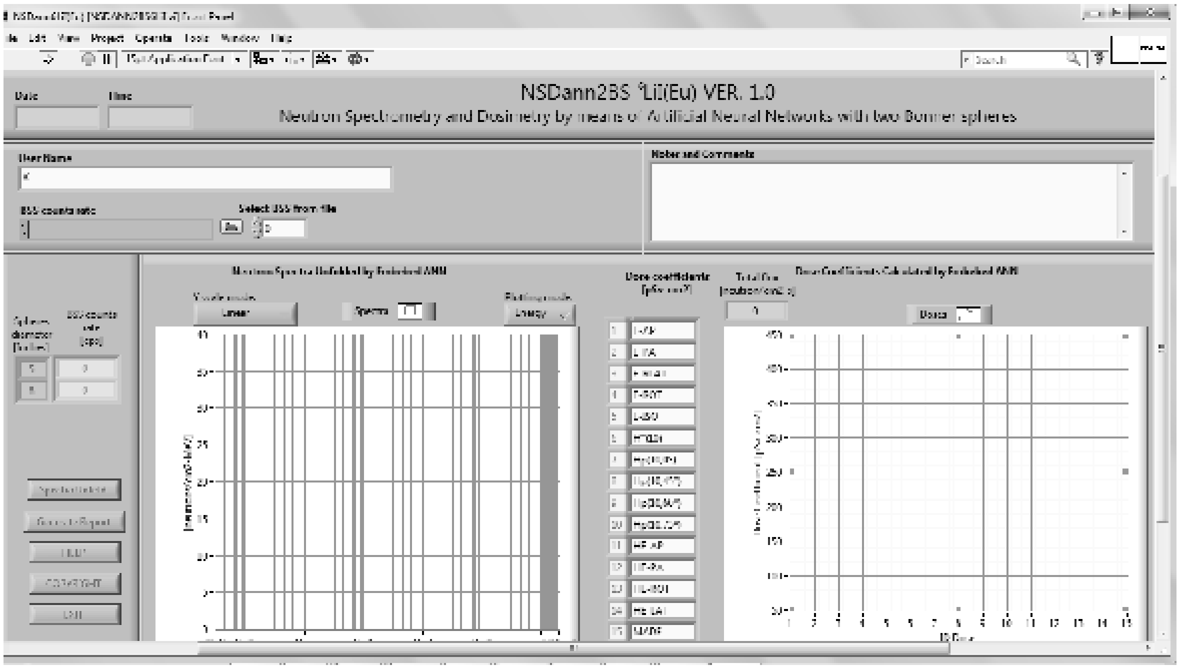


FIGURE 2. Main screen of NSDann2BS unfolding code

As can be seen from figure 2, the computer tool is divided in three main sections. The section of entrance data is located in the upper left side of the main screen. The command buttons are located at the bottom left side; these buttons are used to begin the unfolding process, to generate a full report in HTML format of the unfolding being realized and to terminate and leave of the program. In the half side of the screen is located the section of neutron spectrum unfolded by the embedded neural net. In a similar way, the right side of the screen show 15 dosimetric quantities calculated by this net.

To enter the rate counts measured with the BSS, end user should previously edit an entrance text file with extension *.txt. In this file, the rate counts measured with only two spheres of a BSS should be placed in form of column tabulated separated. The ordering of the data should be made in the following way: in the first line is placed the readings taken with the 5 inches sphere and in the second one the readings taken with the 8 inches sphere. The design of the code lets the end user to create a text file with more than one BSS reading. Each reading should be tabulated separated.

The tool was designed in such a way that the end user can select the column of data to enter to the program, simply writing the column number that is wanted to read from the entrance file, starting from the value 0, that it would correspond to the first group of rate counts located to the left side of the entrance. To select the column of rate counts, the end user should clicking in the tool “Select BSS from file” showed in the top left corner of the figure 2.

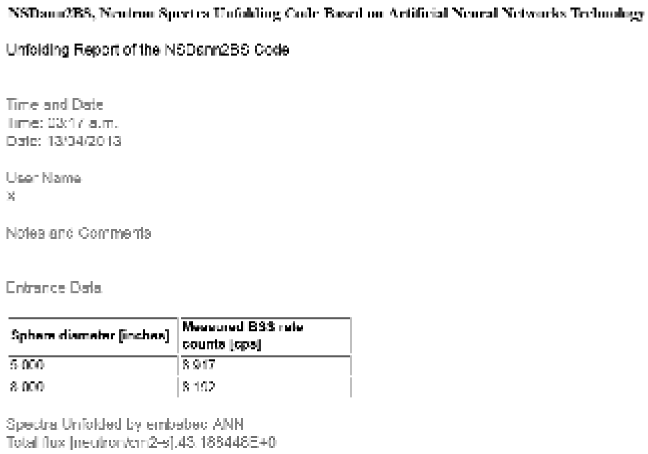
In order to enter the entrance file with the two rate counts measured with the BSS system, the user should clicking on the folder icon of the tool “ BSS counts rate “ showed in figure 2. Made the above-mentioned, a selection window will open up allowing selecting the path where the text file is located. Once the BSS rate counts are entered, the numerical values will be shown in the entrance data section of the main screen.

Having entered the rate counts, in order to begin the neutron spectra unfolding and doses calculation processes, the end user should click on the button “Spectra Unfold” of the main screen application. After carrying out this action, the selected count rates enter to the entrance layer of the embedded ANN and propagate through the hidden and output layers until obtaining, in fraction of seconds, the corresponding results. The spectrometric and dosimetric information is showed in figures 4 through 6. With his information and pressing the button “Generate report”, the computer package is capable to generate a full report in HTML format, showed in figure 3, with the most important information of the unfolding being done, for a later analysis and treatment.

For demonstrating the performance and generalization capability of the trained neural network, the rate counts measured with the Bonner spheres count rates produced by ^{252}Cf, ^{241}AmBe and ^{239}PuBe neutron sources were used.

RESULTS

Figure 3 shows a sample of the report generated by this code after the unfolding was done. This report, in HTML format, stores the most important information about the neutron spectrum unfolding being realized.



NSDann2BS, Neutron Spectra Unfolding Code Based on Artificial Neural Networks Technology

Unfolding Report of the NSDann2BS Code

Time and Date
Time: 03:17 a.m.
Date: 13/04/2013

User Name
x

Notes and Comments

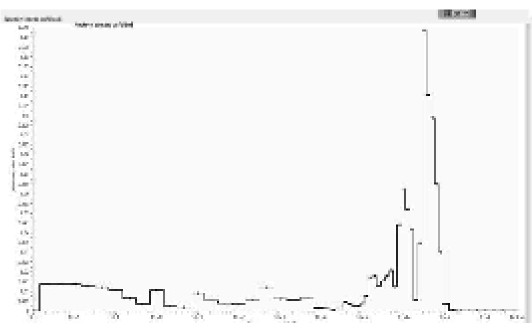
Entrance Data

Sphere diameter [inches]	Measured BSS rate counts [cps]
5.000	8.917
8.000	8.102

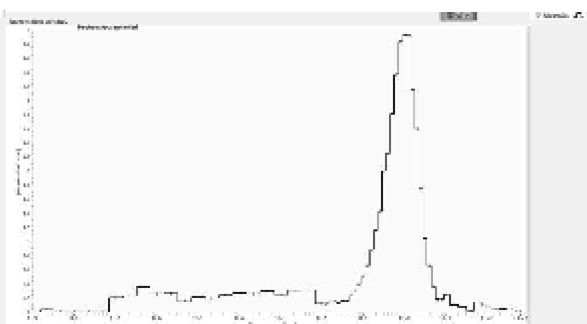
Spectra Unfolded by embebed ANN
Total flux [neutron/cm2-s].43.185446E+0

FIGURE 3. Report sample of the NSDann2BS unfolding code

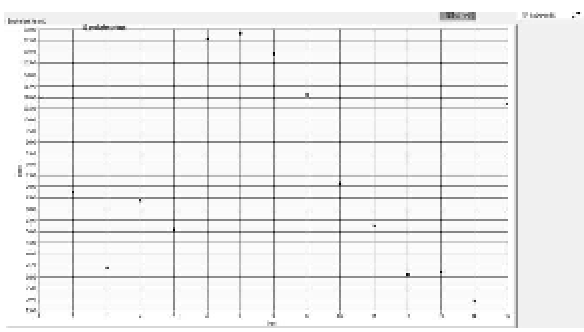
Figures 4 to 6 show the unfolded spectrum and 15 dosimetric quantities of ^{252}Cf, ^{241}AmBe and ^{239}PuBe neutron sources obtained with the NSDann2BS unfolding code compared with the IAEA´s reference spectrum.



(a) IAEA reference neutron spectrum



(b) Neutron spectrum unfolded with NSDann2BS

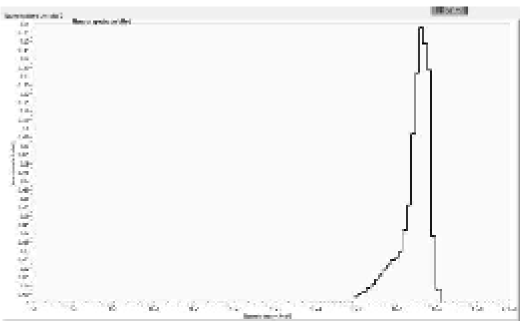


(c) Dosimetric quantities calculated by NSDann2BS code

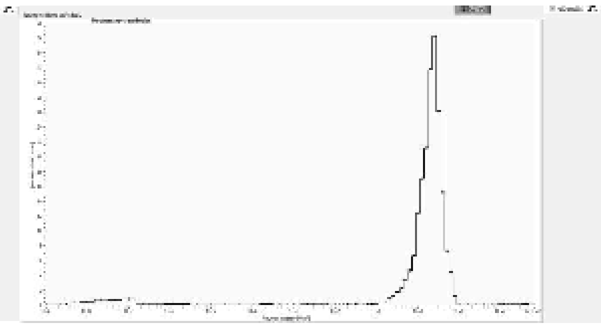
FIGURE 4. Neutron spectrum and equivalent doses of a PuBe neutron source

Figure 4-6 (a) show the reference spectrums of a PuBe, AmBe and Cf neutron source taken from IAEA compilation respectivelly. IAEA reference spectrums are normalized to 1 neutron per second and in order to calculate the dosimetric quantities, fluence-to-dose conversion factor should be used. Figure 4-6 (b) show the neutron spectrum unfolded using the NSDann2BS code as well as 15 dosimetric quantities calculated by the embedded ANN. Because the training process of the neural net, the spectrum and equivalent doses are calculated in parallel at one time, not being needed to solve the fredholm equation at first using an “initial guess” spectrum and then to use the fluence-to-dose conversion factors as in classical approaches.

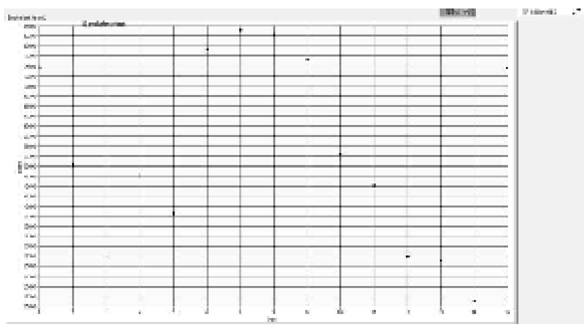
As can be seen from these figures, neutron spectrum shapes are alike which demonstrate the powerful of neural nets technology in this research area. The results obtained make evident the high performance and generalization capacity of the optimized neural network designed with a robust design methdodology.



IAEA reference neutron spectrum

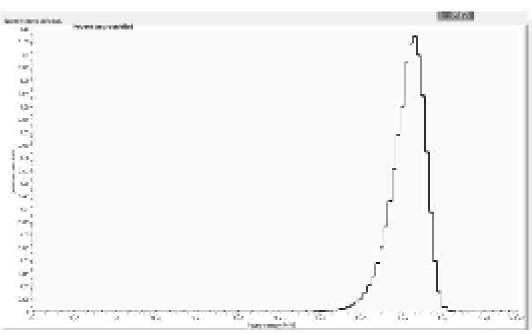


(b) Neutron spectrum unfolded with NSDann2BS

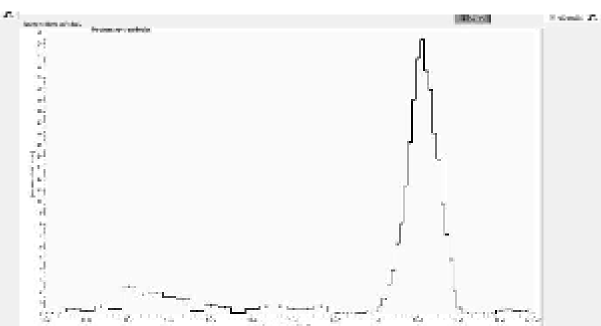


(c) Dosimetric quantities calculated by NSDann2BS code

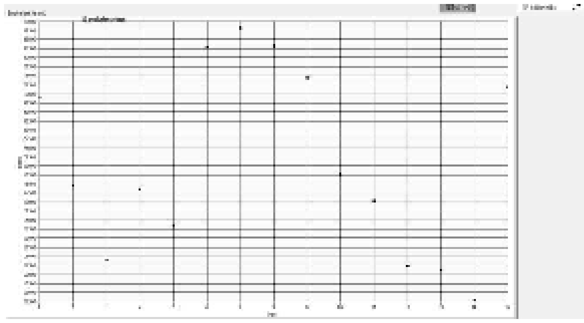
FIGURE 5. Neutron spectrum and equivalent doses of a neutron source of ^{241}AmBe at 50cm on air



(a) IAEA reference neutron spectrum



(b) Neutron spectrum unfolded with NSDann2BS



(d) Dosimetric quantities calculated by NSDann2BS code

FIGURE 8. Neutron spectrum and equivalent doses of a neutron source of 252Cf at 100 cm in water

It is important to mention that in contrast with classical approaches based on iterative procedures which require a very expert user, an initial guess spectrum and the dose-to fluence conversion factors to calculate the equivalent doses after neutron fluence was unfolded, the code here presented based on artificial neural networks uses as the only entrance data the rate counts measured with the 5 and 8 inches Bonner spheres. In this case, the optimized neural network unfolds the neutron spectrum based on a process known as “training”. After training the neural net knowledge is stored in synaptic weights which in the present case were extracted and with them, the NSDann2BS unfolding code was designed.

CONCLUSIONS

The use of ANN to unfold neutron spectra from the count rates measured with the Bonner sphere spectrometer is a promising alternative procedure in neutron spectrometry. In contrast with classical approaches based on iterative methods which require a very expert user, an initial guess spectrum and the dose-to fluence conversion factors to calculate the equivalent doses after neutron fluence was unfolded, the code here presented based on artificial neural networks technology uses as the only entrance data the rate counts measured with the 5 and 8 inches Bonner spheres. This is an effort to overcome the problems associated with such ill-conditioned problem.

The NSDann2BS neutron spectra unfolding code based on ANN technology was designed to have an efficient form of entrance and exit of data; is easy to use; the program is executed in a quick way, obtaining the results in fraction of seconds, requiring only as entrance data the rate counts measured with two Bonner spheres of a BSS system (5 and 8 inches), was designed for a ^{6}LiI(Eu) thermal neutrons detector and is expressed in 60 energy bins, contrary to the codes used at the present time, based on iterative or parametric unfolding algorithms, which require very experts users, many configuration parameters and an initial guess spectrum.

This code was designed in such a way that the end user find it easy to use, without caring about the complexity of the programming routines in which is based. Results obtained demonstrate that the unfolding code based on ANN technology has high performance and generalization capability.

The code here presented is oriented to be used in laboratory, experimental and/or research environments, and its aim is to overcome the drawbacks associated with the classical approaches currently used, when applied to solve the neutron spectra unfolding problem.

For demonstrating the performance and generalization capability of the trained neural network, the rate counts measured with the Bonner spheres count rates produced by ^{252}Cf, ^{241}AmBe and ^{239}PuBe neutron sources were used and compared with IAEA compilation.

For validation purposes of the software designed, a comparison with other unfolding procedures should be necessary in order to validate the performance and generalization capability of the neural network embedded in this computer package. At present, work is being done in this sense.

This unfolding code is freely available upon request to authors.

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