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COMPARISON OF METHODS FOR NOISE REDUCTION OF GAMMA ENERGY SPECTRA

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Abstract – The article presents a comparison of three methods of noise reduction in the gamma spectrum evaluation. The distortions' elimination in this way can lead to increasing accuracy of elements content and identification of radionuclides. The proposed methods were applied for data obtained from the scintillation spectrometer for standards and samples of ash from coal power plants. For presented methods, the measurement system calibration and determination of the content of radioactive elements are described.

Keywords: gamma energy spectra, full spectrum analysis, super smoother, kernel estimator, Discrete Wavelet Transform.

1. INTRODUCTION

Spectrometric measurements of radioactive isotopes are the standard method used today, inter alia, in geophysics and environmental protection [1-3]. These are important studies in the search for hydrocarbons, as well as in radiation protection, due to the existing standards in individual countries, as well as the recommendations of the International Atomic Energy Agency, which precisely define the contents of radionuclides in food, building materials, etc.

For this type of measurement high-resolution detectors based on semiconductor and systems based on scintillation counters are used [4]. Especially common are scintillation probes, which in contrary to semiconductor detectors do not require refrigeration, and are cheaper, although have poorer energy resolution.

Additionally, due to the stochastic nature of radioactive decays and different sources of interference, the gamma-ray energy spectrum, have different signal to noise ratio (SNR) in the compared systems. In case of laboratory measurements, an unfavorable phenomenon can be eliminated by increasing the measurement time or the mass. This is not always possible, however, for example, rock samples from drill cores have often the weight of 100 g and well logging of spectrometric natural gamma radiation in 1 m thick layer lasts maximum 180 s. In that case, it is necessary to use advanced signal processing allowing improvement of the SNR. Currently, there are many different methods of filtering and deconvolution of those signals [5, 6].

In this work, we analyze the possibility of using algorithms based on following statistical methods:

- Friedman's super smoother [7, 8],
- Nadaraya – Watson kernel estimator [8],
- Dicrete Wavelet Transform [8-10].

To determine the content of potassium (K), uranium (U), thorium (Th), we used the method of full spectral analysis (FSA) [1, 2], which due to the use of the entire spectrum calculation, has higher accuracy than three- and multi-

window analysis. For the recognition of properties of the proposed methods of signal analysis, a laboratory spectrometric measurement of ash samples collected in coal power plants and radioactivity standards were applied.

2. METHODOLOGY OF MEASUREMENT

The gamma-spectrometric measurements were performed in the Laboratory of Radiometric Expertise, Institute of Nuclear Physics, Polish Academy of Sciences.

The measuring set was equipped with a scintillation probe with 76SF76 NaI(Tl) crystal 3" x 3" (CRISMATEC-SCINTIBLOC) of resolution (FWHM) for the line of cesium Cs-137 662 keV equal to 7%. The detector was shielded by cottage lead (Pb 200 mm side panels, top 250 mm + Pb X-ray filter: 10 mm Fe; 2 mm Cu, 2 mm Cd), in order to reduce the impact of radiation from the environment. The samples were measured in a Marinelli beaker geometry, which is an advantage in case of measuring low activity in order to increase the accuracy by maximising the efficiency of the gamma quanta registering the geometry for a given mass. Spectrometric track consists of a spectroscopy amplifier (Model 572a; ORTEC) and a multichannel analyzer (EG & G ORTEC Model 916A MCB), which measures the standard researches of 512 counts in channels with rise times of 1000 s. The samples were dried before measurement in a dryer at a temperature of at least 105 °C and kept several days in sealed test vessels, in order to obtain the radioactive equilibrium. In order to analyse the gamma spectra collected, the GammaVision®-32 software (ORTEC) was used. In addition, the laboratory was equipped with a certified calibration standard for potassium, uranium and thorium [11]. The concentrations of natural radionuclides Ra-226, Th-232 and K-40 were determined based on the ‘‘three-window’’ method [12-14]

Gamma-ray spectrum of ash sample (PO1459) from coal-fired power after subtracting the background is shown in Fig. 1.

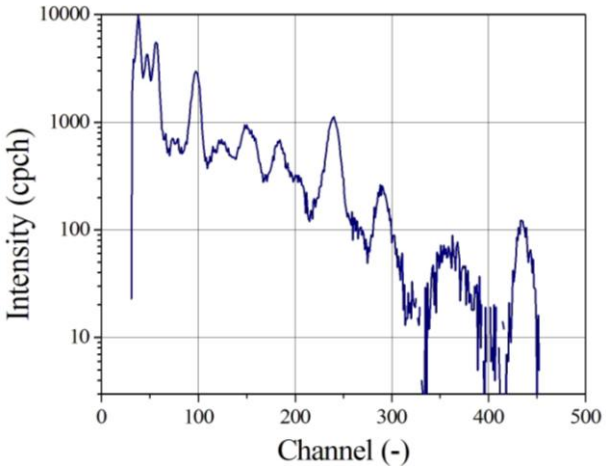

Fig. 1. Gamma-ray energy spectrum of ash sample (PO1459) from coal power plants.

3. NOISE REDUCTION METHODS

In case of a large number of counts, the impact of the noise is minimal, as it can be seen in channels 1-150 (Fig. 1) where the efficiency of the spectrometric track with NaI(Tl) crystal was the largest. With the increase of the registered energy radiation efficiency decreases and the number of counts falls (channels 150 - 512), the impact of noise becomes visible. The consequence of this phenomenon is an ambiguous definition of a full absorption maxima peaks, and the increasing uncertainty of the K, U, Th determination.

Fig. 2 shows the gamma ray energy spectrum of the Th standard. Frame indicates fragment selected to illustrate the application of noise reduction method.

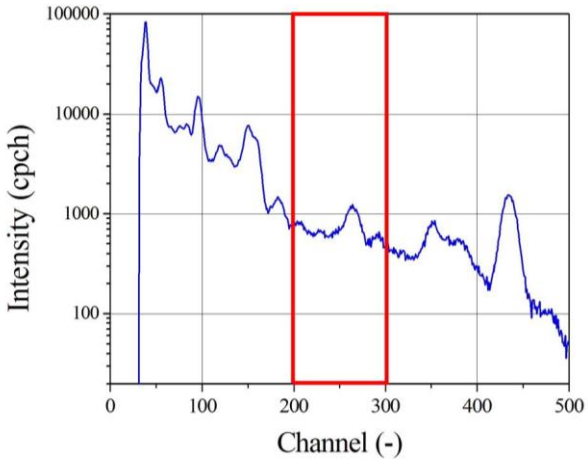

Fig. 2. Gamma-ray spectrum of the Th standard. Frame indicates a fragment selected for analysis.

3.1. Friedman's super smoother

The method by J. Friedman super smoother (SS), is an example of a locally linear estimator, obtained by averaging a certain neighborhood [7, 8]:

$$f(x) = E[y \mid x], \tag{1}$$

where: x, y – quantity observed, in this case: y – intensity of radiation, x – number of channels.

For the presented algorithm an important parameter is span (J), determining the size of the neighborhood, to which the averaging was applied. This parameter has the following value: $0 < J < 1$ [7]. The cross-validation method was proposed, due to the significance of the slightest error or adjustment imposed by the user. The use of the SS algorithm for a fragment of spectrum of the Th standard is shown in Fig. 3.

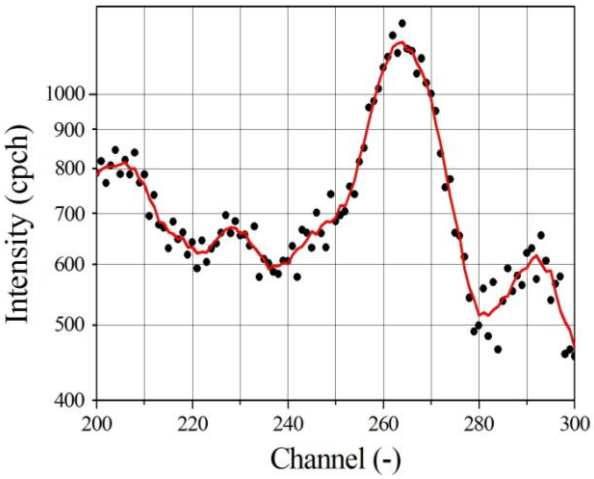

Fig. 3. The use of the SS method for a fragment of the Th standard spectrum (span: $J = 0.005$). The solid line represents the fitted function, points illustrate the observed values.

3.2. Nadaraya-Watson kernel estimator

Similarly to a super smoother, Nadaraya-Watson kernel estimator (NW) is a non-parametric regression method. The algorithm allows to introduce the weights $w_{n,i}$ for registered values x_i depending on the distance of the point x which is in the center of the neighborhood. The NW kernel estimator is determined as follows [8]:

$$\hat{g}_{NW}(x) = \sum_{i=1}^{n} w_{n,i} y_i \ , \tag{2}$$

and $w_{n,i}$ is expressed as:

$$w_{n,i}(x) = \frac{K\left((x - x_i)/h_n\right)}{\sum_{j=1}^{n} K\left((x - x_i)/h_n\right)}, \tag{3}$$

where: $K((x - x_i)/h_n)$ is a kernel function, e.g. the Epanechnikov function, normal or triangular distribution; h_n is a smoothing bandwidth. In the presented calculations the normal distribution was used.

Parameter h_n can be selected by the user, through the optimization, e.g. based on cross-validation method. Application of the NW kernel estimator for a fragment spectrum of the Th standard is shown in Fig. 4.

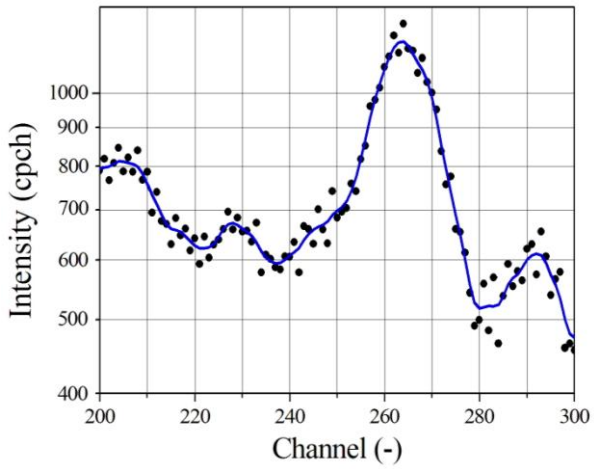

Fig. 4. Application of the NW kernel estimator to smooth of the Th standard spectrum (smoothing bandwidth: h = 1.3). The solid line represents the fitted function, points represent the recorded values.

3.3. Discrete Wavelet Transform

Another estimation method is the Discrete Wavelet Transform (DWT). By means of the DWT, the $y(x)$ signal can be represented as [9-10]:

$$y(x) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} d_{m,n} \cdot g_{m,n}(x), \tag{4}$$

where $d_{m,n}$ is the coefficient calculated from the equation:

$$d_{m,n} = \int y(x) \cdot \gamma^*_{m,n}(x) dx \ . \tag{5}$$

The $g_{m,n}(x)$ is base function arising from scaling and translation of the mother wavelet $\gamma(x)$:

$$g_{m,n}(x) = 2^{-m/2} \cdot \gamma\left(2^{-m} x - n\right). \tag{6}$$

where $\gamma_{m,n}(x)$ function is a dual to the $g_{m,n}(x)$ one.

Most of the currently used wavelets are orthogonal functions. However, there is a family of wavelets, which are not orthogonal, but biorthogonal ones. Such functions are only orthogonal to each other in pairs, and in many cases they significantly better bulge the characteristics of the signal. An important issue in application of the DWT is selecting the level of rejection of details for the analyzed information. In this case, the biorthogonal 3.1 wavelet was applied, where details were rejected at the level of 2. The effect of processing of the Th standard gamma spectrum using DWT is shown in Fig. 5.

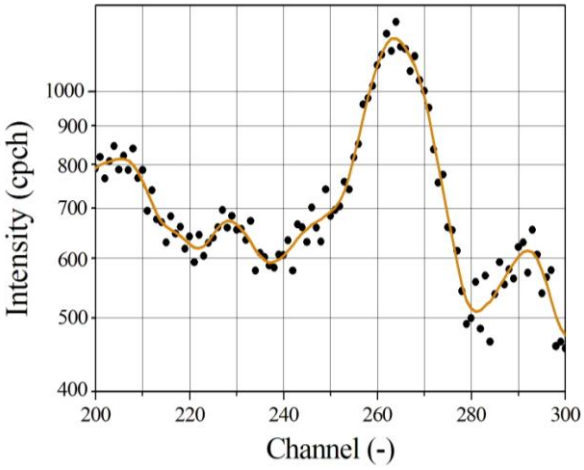

Fig. 5. Application of DWT to smooth the spectrum of the Th standard. The solid line represents the fitted function, points represent the recorded values.

4. DETERMINATION OF RADIOACTIVE ELEMENTS

The full spectral analysis is based on a mathematical combination of the method of least squares fit to the sample spectrum, the spectra derived from the earlier practices and background subtraction. Due to the complex shape of the spectrum and adjusting the elemental spectra, which are also complicated, fitting coefficients are obtained by solving a matrix equation, according to [1]:

$$[CS] = [A] \cdot [Y]. \tag{7}$$

where: [*CS*] - matrix with counts of calibration spectra, [*A*] - concentration coefficient matrix K, U, Th, [*Y*] - array of counts of the test sample spectra.

Table 1 summarizes the values of the K, U, Th content in the ash sample (PO1459) obtained for presented methods of noise reduction and without denoising data.

Table 1. Summary of the contents of the K, U, Th set by the FSA for smoothed spectrum algorithms: SS, NW and DWT.

Noise Reduction Method	Q_K (%)	Q_U (ppm)	Q_{Th} (ppm)
Without denoising	1.2	10.7	49.9
SS	1.3	11.0	47.6
NW	1.3	11.0	48.0
DWT	1.2	10.7	50.0

5. THE ACCURACY ASSESSMENT OF SMOOTHING METHODS

Smoothing methods to evaluate the gamma energy spectra can be seen in many aspects relating to the interpretation of the results. Table 1 shows that the differences between the designated contents of natural radioactive elements K, U and Th do not exceed 10 % of the data in comparison to the results without denoising. It should be noted that the analyzed data demonstrate a good signal to noise ratio due to the high content of radioactive elements and laboratory measurement conditions. In case of weak signals, you can expect major discrepancies.

The second way to evaluate the suitability of the presented methods is based on the energy calibration of the spectrometric track. In this case, the capabilities of detection system are limited, which has a certain energy resolution (FWHM) [4]. The methods of smoothing (filtering) are generally not able to improve the FWHM, but they should not cause its deterioration. Presented methods improve the calibration process, giving unique values, and even in case of DWT, it is possible to find significant absorption peaks, which previously were not detected. Table 2 presents the estimated gamma radiation energy E of the channel number x according to the method of least squares. The calibration relationship was determined from the equation:

$$E = a \cdot x + b\,, \tag{8}$$

where: a, b – fitting coefficients.

Table 2. Summary of value fitting coefficients for scintillation spectrometer resulting in the use of: SS, NW and DWT smoothing methods. (R^2 - coefficient of determination).

Noise Reduction Method	a (MeV/ch)	b (MeV)	R^2
Without denoising	0.00602	0.0141	0.99996
SS	0.00603	0.0127	0.99996
NW	0.00603	0.0122	0.99998
DWT	0.00603	0.0126	0.99998

Table 2 shows that all presented methods yield similar values, and the variables (channel number and energy) are correlated very well. In order to assess if smoothing methods make improvements, the attention should be paid to the value of free expression, which should be as close to 0 as possible. In all three cases, for which filtering algorithms were applied, intercept has a lower value than for no smoothing spectra.

In Table 3 the values of standard uncertainties for fitting coefficients $u(a)$ and $u(b)$ are presented. Using the proposed method of noise reduction, we have not only better approximation of calibration function (value of R^2), but also smaller values of standard uncertainties for fitting coefficients. Authors think that increase in the accuracy of the calibration of measurement track, should lead to increased accuracy in the K, U, Th determining in the tested samples.

Table 3. Standard uncertainties of the fitting coefficients for calibration line, resulting from the use of: SS, NW and DWT.

Noise Reduction Method	$u(a)$ (MeV/ch)	$u(b)$ (MeV)
Without denoising	$1.1 \cdot 10^{-5}$	0.0023
SS	$1.0 \cdot 10^{-5}$	0.0022
NW	$9.0 \cdot 10^{-6}$	0.0019
DWT	$7.4 \cdot 10^{-6}$	0.0015

6. CONCLUSIONS

The proposed method of gamma-ray spectra smoothing has the following advantages:

- the benefits include noise reduction and random counts, so that energy lines can be more accurately analyzed from radioactive elements occurring in the test samples and a more accurate calibration of the measurement system can be carried out (Table 2);
- does not distort the information on the content of radionuclides, as shown in Table 1. In addition, it does not reduce the FWHM of the spectrometer;
- increased accuracy in the calibration of the spectrometric track should increase the accuracy of the K, U, Th determination.

The disadvantage of this method is the necessity to perform additional calculations. Therefore, it is important to select the filtration parameters properly. Unfortunately, in the part of parameters, as for example, level of the details rejection for DWT might be selected on the basis of experience.

In consequence, the work should be continued, as the statistical method of analysis of signals can significantly improve the methodology for the measurement of natural gamma radiation.

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