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Computer methods of recognition and analysis of X-ray and gamma radiation parameters

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The rapid development of computer technologies makes it possible to use computer methods for spectral analysis of X-ray and gamma radiation, where analog electronics have been traditionally used. One of the difficulties in obtaining data from radiation detectors is the very high frequency of signal registration. However, the use of special devices called digitizers allows us to acquire, digitize and send data to a computer system at a sufficient speed. Large data arrays obtained during experiments reflect the characteristics of spectrometric signals. It is possible to recognize the registration of radiation quanta in the detector, as well as to draw conclusions about the quantitative characteristics of radiation with the help of computer methods, mathematical calculations and special algorithms.

The overview of the main methods of obtaining data in digital form for further computer analysis, namely by conducting real experiments on special equipment and by means of computer modeling (simulation) is presented in the article. Several existing methods for recognition and analysis of individual radiation particles based on the shape of the signal are described, also the methods and the software algorithms for analyzing the parameters of X-ray and gamma radiation are implemented. The computer program, that is capable of simulating data with given characteristics and can perform recognition and analysis of gamma quanta based on the loaded data, has been developed as a part of the research. The program also allows visualizing the results and checking the efficiency of the methods. The conclusions about potential directions for further research have been made.

Keywords: *computer methods, digitizer, pulse shape analysis, computer modeling, gamma radiation.*

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1. General formulation of research and its topicality

Spectral analysis of X-ray and gamma radiation is widely used in various fields of science, as well as in industry and everyday life. For many decades, the classic methods of spectral analysis were analog ones based on the use of expensive specialized electronic equipment for processing signals from detectors and spectrometric analog-to-digital converters (ADC) with high linear characteristics. Like any analog equipment, it requires ongoing debugging, adjustment and maintenance by highly qualified specialists.

In recent years computer methods of recording and measuring spectra have been intensively developed, which are primarily based on software processing of digitized signals coming directly from X-ray and gamma radiation detectors. There are tools available that allow registering and collecting data on the radiation spectrum of radioisotopes or secondary X-ray radiation of ordinary materials. Moreover, new specialized tools are being created. Such complexes usually include hardware and software components, use certain digital technologies and mathematical signal processing. The parameters of spectrometric signals obtained from hardware components, represent quite large arrays of data in digitized form that require recognition, detailed pulse shape analysis and processing. Currently some stages of analysis may be performed manually by specialists who can draw conclusions about the quality and qualitative characteristics of the objects of radiation thanks to their experience and necessary knowledge. Thus, it is important to explore computer methods for recognition and analysis of X-ray and gamma radiation parameters in digital form, which are received and digitized by using specialized hardware.

2. Setting of the problem and the aim of the article

The following tasks have been set in context of the research:

1. To review and describe the methods of obtaining digitized data that reflect the characteristics of X-ray or gamma radiation by conducting real experiments by using special electronic equipment or by means of computer modeling (simulation).
2. To analyze and describe existing approaches, methods for X-ray and gamma radiation parameters recognition and analysis, develop software algorithms capable of performing such analysis.
3. To develop a computer program capable of simulating signals and digital data arrays for computer analysis, that reflect radiation characteristics close to the data obtained from real experimental setups or alternatively allowing users to load digital data recorded during real experiments. Data being loaded, the computer program should perform recognition and analysis of radiation parameters, such as the number of recognized radiation quanta, its registration time, amplitude, shape, and perform visualization of the analysis results.

3. Methods of obtaining data for computer analysis

3.1. Data acquisition from real experimental setup

Special setups are usually used to acquire digital data that reflect the characteristics of gamma, X-ray or other types of radiation of various materials during real experiments. The following components are typically included in those setups:

- Source of X-ray or gamma radiation - radioactive isotope, X-ray tube, etc.
- Scintillation detector (CsI (Tl)).
- Photomultiplier tube (PMT)
- Analog-to-digital converter (ADC) or digitizer
- Computer or distributed computer system

Generic scheme of the setup is shown in Fig. 3.1 [1]. It is well known that photons of light are released when radiation particles hit the crystals of a scintillation detector, and scintillation pulse shape changes, depending on the type of radiation (gamma, neutron, X-ray, etc.) and its intensity [2-4]. Therefore, the general principle of setup work is that the particles from the radiation source falling into the scintillation detector generate photons of light. Subsequently, the signals from the scintillation detector are converted into electrical signals and amplified by using a photomultiplier tube (PMT). Electrical signals from the PMT are digitized and transferred to the computer system by a special device called digitizer. This device is capable of digitizing analog electrical signals with a high frequency and has an internal memory for storing and transmitting digitized data. Next, the data in digital form is transferred to a computer system that can process the data to recognize and analyze the radiation parameters, since the acquired digital arrays of data in a certain form reflect the characteristics of the radiation.

In Fig. 3.2, the view of one gamma quantum pulse registered in the detector, digitized by a digitizer and saved as an array of data corresponding to the signal level in the detector at each discrete moment of time can be seen. These data were acquired from a real experimental setup by using a digitizer from the Spectrum Instrumentation company [5] and visualized by the developed computer program.

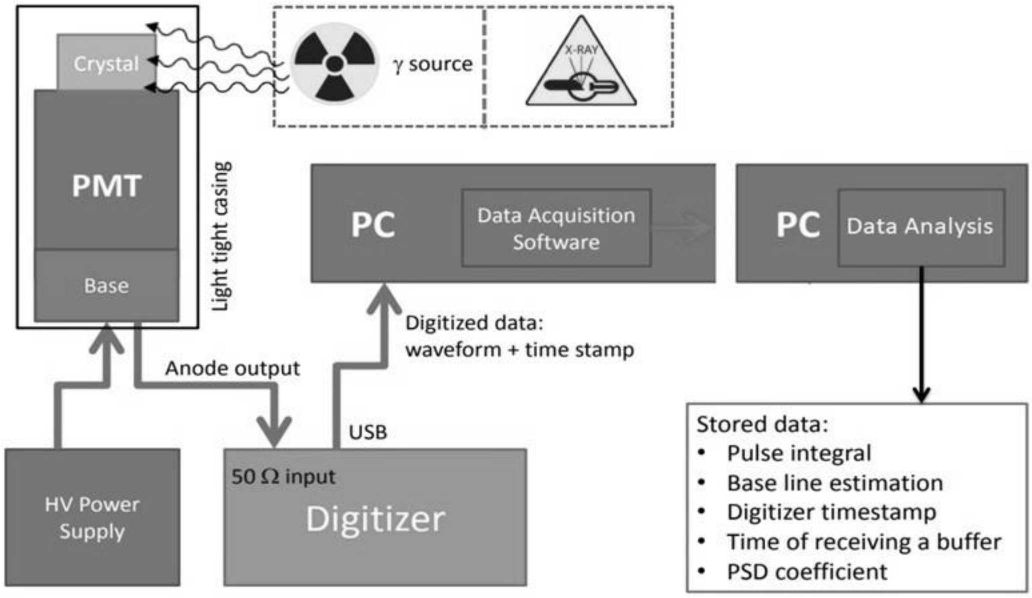

Fig. 3.1 Generic scheme of the setup for gamma source or pulsed X-ray tube excitation analysis

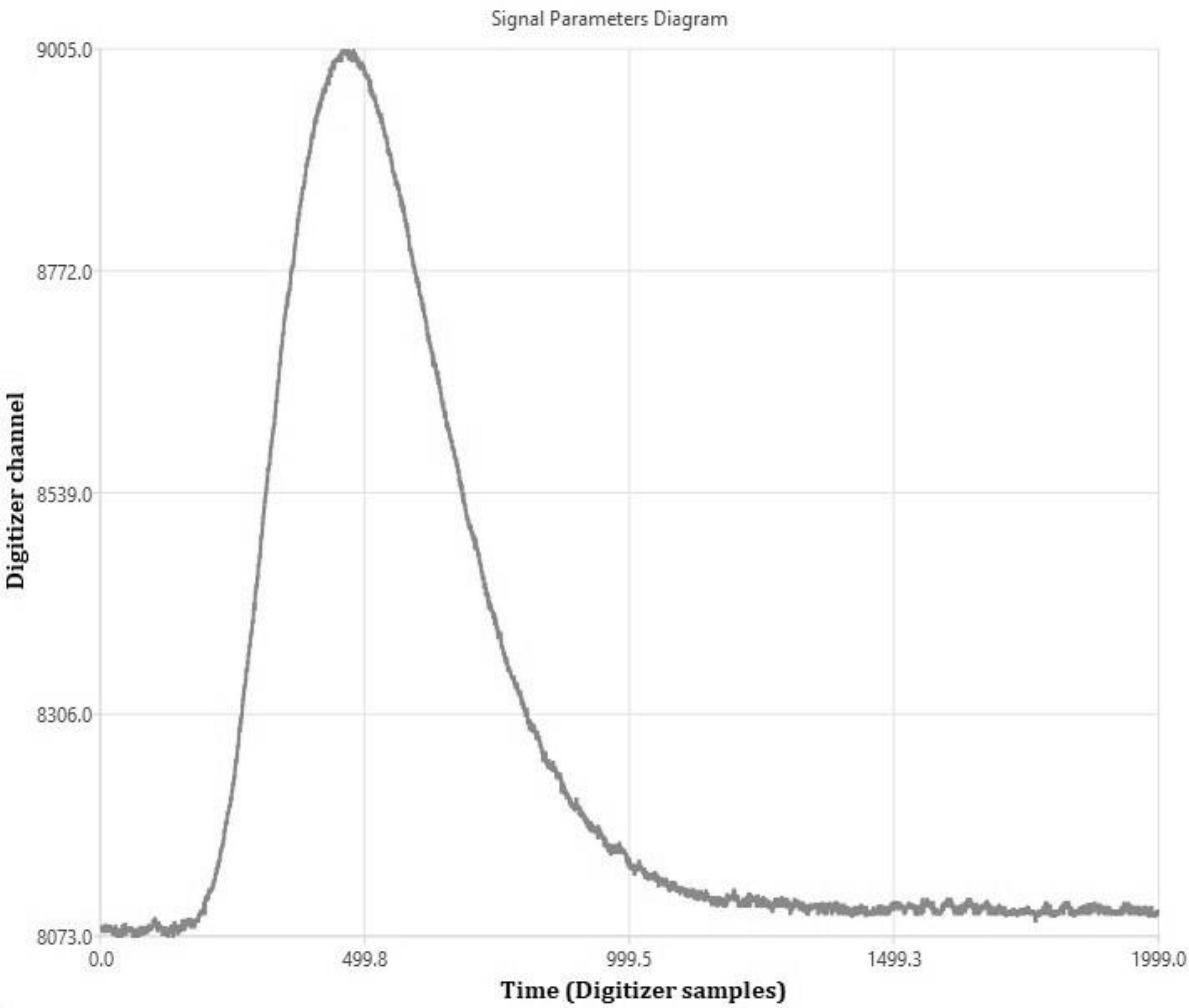

Fig. 3.2 Visualization of one gamma quantum pulse shape acquired from real experimental setup

3.2 Computer modeling (simulation)

Since it is not always possible to conduct real experiments to register and record various types of radiation parameters, another way to obtain data for computer analysis is to simulate the waveform of pulses of gamma radiation or other types of radiation. The fully simulated waveform of gamma radiation particles registration in detector can be represented by formula 3.1 [6]:

$$s(t) = z(t) + n(t) + \sum_{j=0}^{L} A_j p\left(t - t_j\right) \quad (3.1)$$

where t – the time, s(t) – the signal value at time t, z – the constant or very slow changes in time compared to the signal pulse width component, n(t) – the signal noise component, L – the number of registered gamma quanta, A_j and t_j are the amplitudes and registration times of event j, p(t) – the waveform generated by registered gamma quanta.

Since the digitizer or analog-to-digital converter (ADC) digitizes the analog signal from the detector at a certain frequency, generating a discrete set of signal level values, in this case the above formula can be represented in discrete form as 3.2 [6]:

$$s_i = z_i + n_i + \sum_{j=0}^{L} A_j p\left(i - t_j\right) \quad (3.2)$$

where i – the sequence number of ADC or digitizer sample.

In order to model the noise level component caused by various random factors, we can use the formula $n(t) = R_g(\sigma_n)$, where $R_g(\sigma_n)$ is the random number for each moment t, with the Gaussian distribution, that has an average value of 0 and a standard deviation of σ_n.

The pulse shape p(t) of one gamma quantum depends on the characteristics of the detector, but for a scintillation detector the shape of the signal of one quantum can be approximately represented by the following analytical formula 3.3 [7,8]:

$$p(t) = \begin{cases} t > 0 & P_n(1 - e^{-\frac{t}{t1}})^k (e^{-\frac{t}{t2}} + Be^{-\frac{t}{t3}}) \\ t \le 0 & 0 \end{cases} \quad (3.3)$$

where P_n – the normalization factor, $t1$, $t2$, $t3$, B and k are numerical parameters of the pulse, that depend on crystal and light characteristics of the detector. The values of these parameters given in Table 3.1 were used for the simulation [6]:

Table 3.1 *Parameters of the pulse shape of the registered radiation particle, which were used to generate the signal model.*

Parameter	Value
K	4
t1	2.64893
t2	2.90428
t3	7.79602
B	0.323497

During the simulation, the time of each gamma quantum registration in the detector is randomly generated: $t_i = t_{max} \cdot R_u$, where t_{max} is the total duration of the signal simulation from the detector and R_u is a random number in the range from 0 to 1. In a simpler version, the gamma quanta pulse amplitude A_j can be set by a random number in a certain range $[A_{max}/2, A_{max}]$, where A_{max} is the chosen maximum pulse amplitude.

The following parameters are also important for generating and displaying simulated data: the frequency of digitization and transmission of the digitizer frames F_d, the total time of data recording during the simulation and the total count of the discrete digitizer samples N, and the average number of gamma quanta F_g, that are registered in the detector per one second. These parameters can be modified by users through the graphical user interface of the program in order to receive various data sets for analysis, as well as to see how the general shape of the signal changes with an increase or decrease in the number of radiation particles appearing in the detector per second.

Fig. 3.3 demonstrates the signal shape generated by simulation with the following parameters:

- digitizer frequency F_d = 250 MHz
- total count of discrete samples N = 1000
- signal noise standard deviation σ_n = 25
- constant baseline (lower bound) of the signal z = 5000
- normalization factor P_n = 5.5
- the maximum amplitude of gamma quanta pulses A_{max} = 10000
- the average number of registered gamma quanta in the detector per one second $F_g = 10^6$

Fig. 3.4 shows the simulated signal shape with the average number of gamma quanta registered in the detector per second $F_g = 10^7$. As we can see, when the number of particles registered in the detector per second increases, the so-called pile-up effect appears. It happens when the pulses are superimposed on each other, because during the registration of one pulse, another pulse appears and is superimposed on the previous one.

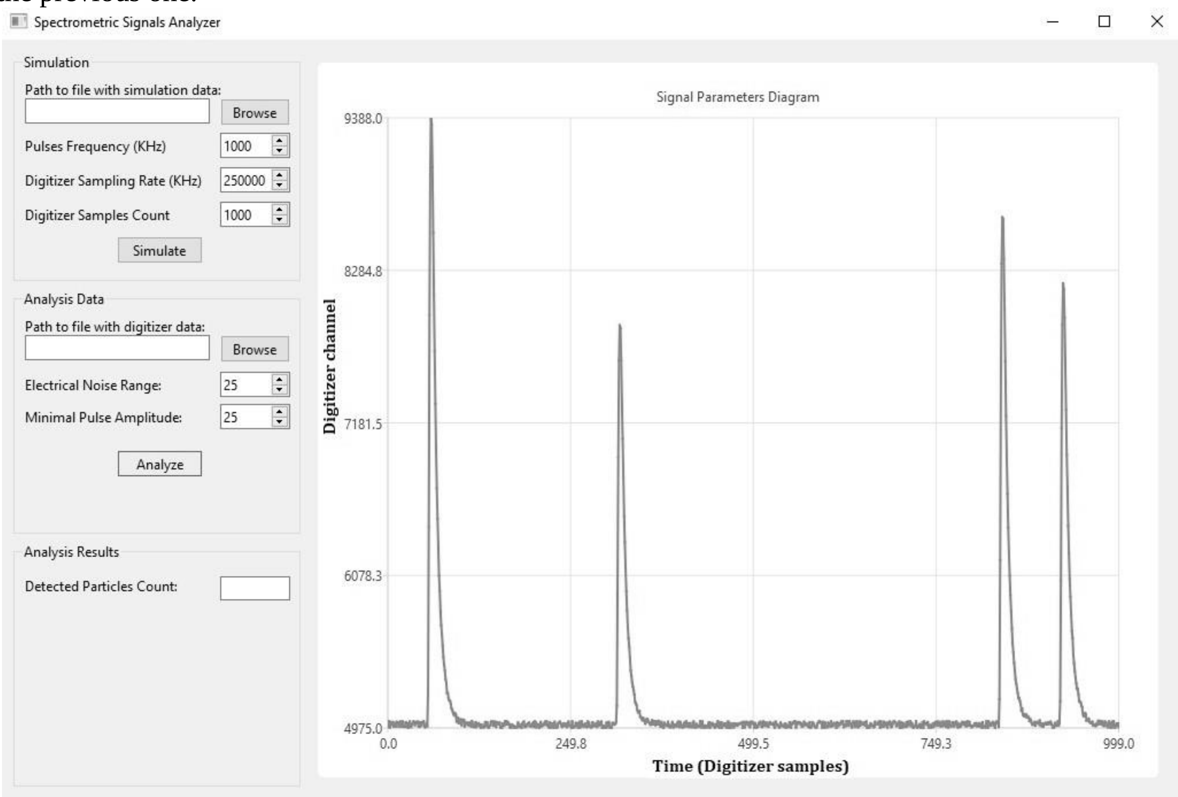

Fig. 3.3 Signal shape generated by simulation with the average number of gamma quanta registered in the detector 10^6 per second.

Recognizing and analyzing the shape of individual pulses at high counting rates with the appearance of the pile-up effect is a more difficult task than recognizing the shapes of pulses which do not overlap each other. Therefore, the methods and algorithms performing analysis for such cases should be developed considering the possibility of the pile-up effect. At the current moment, there are the published articles [6, 9], the authors of which conduct the research of methods for effective analysis of the signals shape with the pile-up effect.

4. Computer methods of signal shape recognition and analysis

As part of the research, a computer program that provides the possibility of computer modeling (simulation) [10] of data that reflect the characteristics of gamma radiation with various parameters or provides the possibility of loading data recorded with a digitizer during real experiments has been developed. The program also performs recognition and analysis of loaded data based on the signal shape, outputs the results of analysis (the number of registered radiation quanta, its registration time, amplitudes) and visualizes the results of work on a diagram. The program has been developed in C++ programming language by using the QT library [11]. Usage of this library allows developing cross-platform software, so the program can be compiled and run under Windows or Unix-like operating systems. Besides that, the QT framework provides useful UI controls to render the diagrams.

Let us review the methods of recognition, analysis and calculation of individual gamma quanta for the signal shape obtained by simulation shown above in Fig. 3.3. The first step is to determine the baseline of the signal, which is essentially the lower bound of the signal with the presence of an electrical noise component. Baseline determination is necessary in order to continue further recognition of individual gamma quanta pulses starting from the baseline of the signal. The authors [6] describe in detail several methods that allow determining the baseline of the signal, in particular "Average and Median", "Averaging over the selection set", "Averaging over the flat chunk selection set" and analyze their effectiveness. Since the "Averaging over the flat chunk selection set" method has demonstrated better efficiency compared to others, this method has been implemented in the program algorithm to determine the baseline of the signal z.

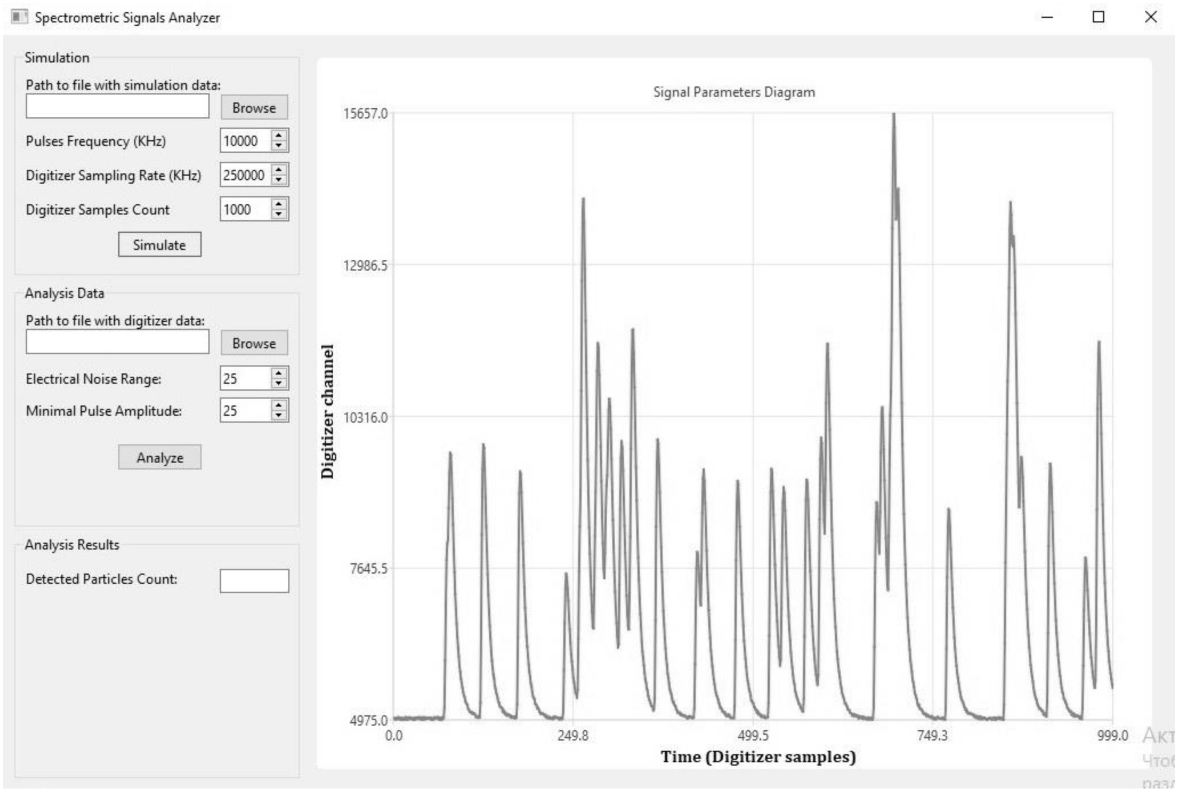

Fig. 3.4 Signal shape generated by simulation with the average number of gamma quanta registered in the detector 10^7 per second.

It should be noted that signal shape obtained during real experiments, as well as simulated signal, contains a component of electrical noise. This noise introduces continuous small pulse shape changes (signal level increase and decrease), which is shown in detail in Fig. 4.1.

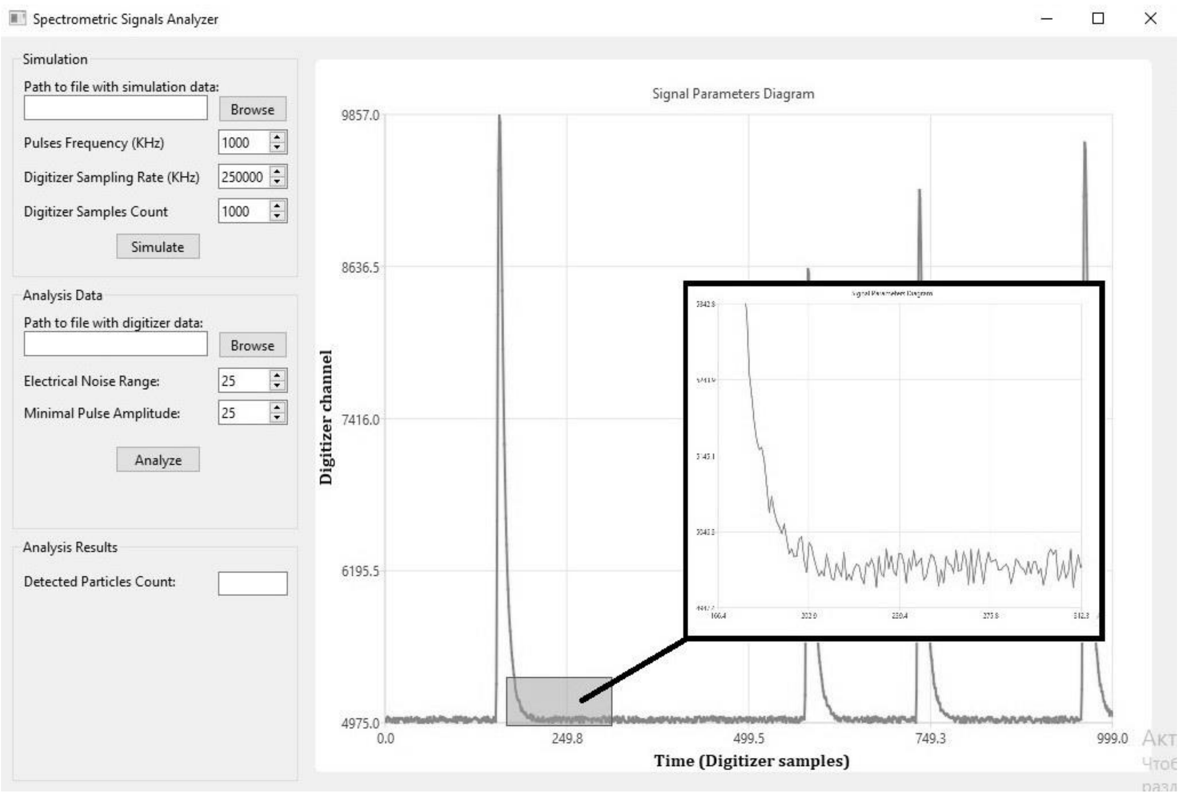

Fig. 4.1 The impact of electrical noise on signal shape

In order to reduce the impact of electrical noise we apply a filter that can smooth the shape of the signal to a certain extent. As described in detail in the article [1], the following filters can be used for this purpose: moving average or Bessel filter. In our case, moving average filter is used, which calculates the filtered value of the signal d[i] according to formula 4.1:

$$d[i] = \frac{1}{M}\sum_{k=M*i}^{M*(i+1)} f[i] \qquad (4.1)$$

where f[i] – signal value for sample i, M – the averaging coefficient (the number of samples for which the average value is calculated). For this coefficient value 16 has been chosen. After applying the filter, the waveform is smoother, without continuous small changes (as can be seen in Fig. 4.2), which makes the further analysis in order to determine the beginning and end of each pulse possible.

After that, the algorithm, created and implemented in the program, starts the analysis of the array of average signal values d[i] from the first sample (the beginning of the signal) to the last sample and analyzes the signal level. When the value of the signal level exceeds a certain threshold from the baseline $d[i] > z + 3\sigma_n$ (i.e., signal value is greater than the baseline level plus electrical noise), then the beginning of the gamma quantum pulse is registered. Next, the algorithm monitors the growth of the signal level, its peak and decrease till the baseline threshold $d[i] \leq z + 3\sigma_n$, thus one pulse from the gamma quantum is recognized and its characteristics are stored (namely the start-end interval of one pulse, the peak value and the amplitude A_i). When the beginning of one gamma quantum is recognized, and later the signal level decreases but does not reach the lower threshold (baseline + noise), and starts to grow again, that is the evidence of the pile-up effect, when the next gamma quantum pulse is superimposed on the previous one. In this case, the algorithm from this moment assumes that the next pulse from another gamma quantum has already arrived and begins to monitor its growth, peak value and decrease anew. Program also has a UI setting to specify minimum pulse amplitude, in order to filter out small pulses caused by random factors. The results of the program analysis and recognition of the number of registered gamma-quantum pulses and a visual indication of recognized particles are shown in Fig. 4.2.

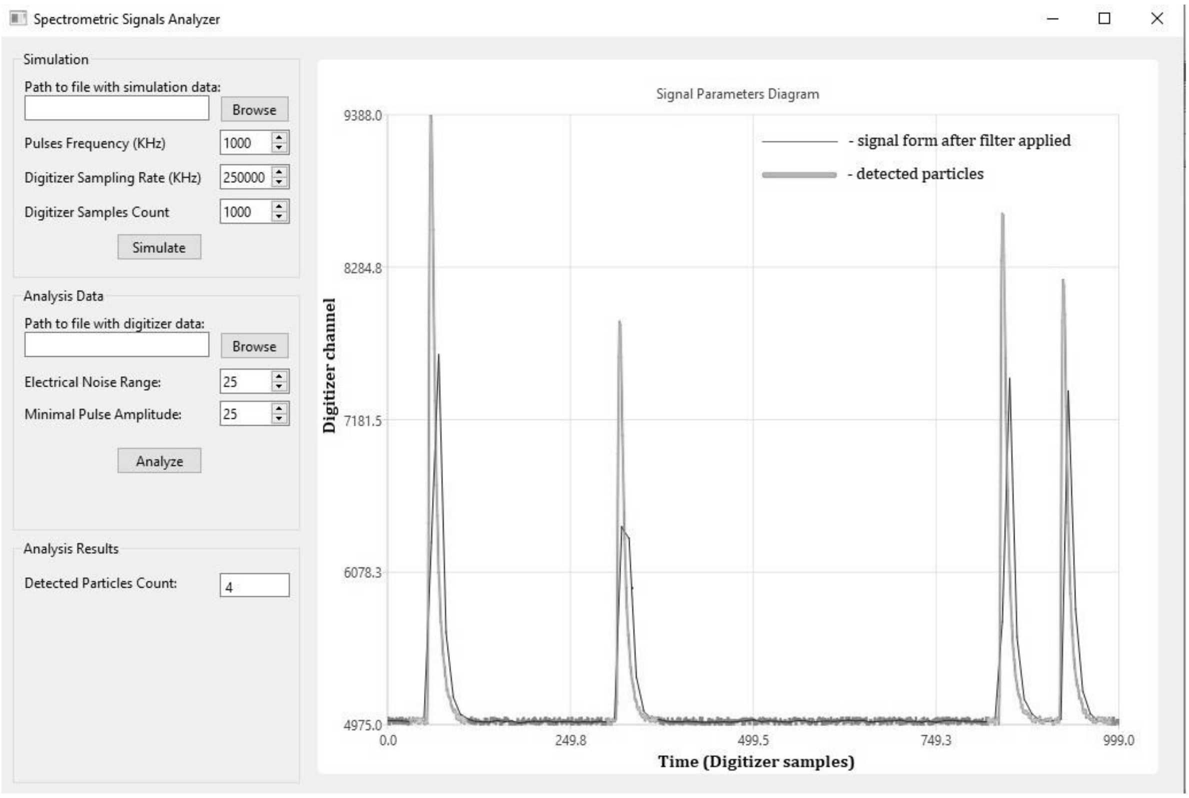

Fig. 4.2 The results of the program analysis and recognition of the number of registered gamma-quantum pulses.

5. Results and Conclusions

The research reviews and describes the mechanisms and methods of obtaining data on radiation parameters in digital form for computer analysis using special electronic equipment, as well as using computer modeling (simulation). The existing methods for recognizing and analyzing radiation parameters (the number of registered quanta, its amplitudes) by signal shape have been also analyzed. The work on improving existing methods or creating new, more effective methods and software algorithms will be continued. In the context of the research, a computer program has been developed that implements the possibility of simulating the necessary data arrays for analysis and allows adjusting the key characteristics of generated signals. It is important to notice that the program provides a way to check the effectiveness of computer methods and algorithms, as well as visualizes the results of recognition and analysis of radiation parameters.

One of the directions for further research is the expansion of the list of radiation parameters that can be analyzed. In addition to recognizing the number of registered radiation quanta and their amplitudes, it is also essential to calculate the energy of radiation quanta and build the energy spectrum diagram. Another promising direction of research is improving existing methods of parameters recognition and creating new, more effective methods. It is especially relevant for the analysis of X-ray and gamma radiation at high counting rates, when the pile-up effect is clearly visible. Further research and development of the software algorithms can be expanded in the direction of recognizing and distinguishing the pulse shapes from different types of particles in the analyzed radiation, for example, distinguishing neutrons from gamma quanta [12,13,14], with the calculation of the quantitative composition of different types of particles and their energy.

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Комп'ютерні методи розпізнавання та аналізу параметрів рентгенівського і гамма-випромінювання

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Стрімкий розвиток комп'ютерних технологій зробив можливим використання комп'ютерних методів для спектрального аналізу рентгенівського та гамма-випромінювання, який традиційно в основному базувався на використанні аналогової електроніки. Однією з основних складнощів в отриманні даних з детекторів випромінювання є дуже велика частота реєстрації сигналів. Тим не менше, використання спеціальних пристроїв, які називаються діджітайзери, робить можливим отримання, оцифрування та передачу даних до комп'ютеризованої системи з достатньою швидкістю. Великі масиви даних отриманих від діджітайзера під час експериментів відображають характеристики спектрометричних сигналів. За допомогою комп'ютерних методів, математичних обчислень та спеціальних алгоритмів можна розпізнати реєстрацію квантів випромінювання в детекторі, а також зробити висновки про кількісні характеристики випромінювання.

В ході виконання роботи було зроблено огляд основних способів отримання даних в цифровому вигляді для подальшого комп'ютерного аналізу, а саме за допомогою проведення реальних експериментів на спеціальному обладнанні та за допомогою комп'ютерного моделювання (симуляції). Було розглянуто деякі існуючі методи для розпізнавання та аналізу окремих квантів випромінювання за формою сигналу і реалізовано методи та програмні алгоритми для проведення аналізу параметрів рентгенівського та гамма-випромінювання. В ході дослідження було розроблено комп'ютерну програму, яка здатна виконати симуляцію даних з заданими характеристиками, провести розпізнавання і аналіз квантів випромінювання на основі завантажених даних. Також програма дозволяє візуалізувати результати та перевірити ефективність роботи методів. Наприкінці статті робляться висновки про потенційні напрямки для подальшого дослідження.

Ключові слова: *комп'ютерні методи, діджітайзер, аналіз форми сигналів, комп'ютерне моделювання, гамма-випромінювання.*

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