The extraction and smoothing algorithms for γ-ray spectrum of a CdZnTe detector system (Postprint)

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Abstract

The extraction algorithms for pulse amplitude and smoothing of energy spectrum have a great influence on energy spectrum of γ-rays during the digital detection and analysis procedure. For a CdZnTe digital γ detector system, different extraction algorithms for pulse amplitude and smoothing of energy spectrum are discussed in this paper. The results show that extraction of pulse amplitude using the first-order derivative method and smoothing of energy spectrum using the wavelet transformation method may obtain energy spectrum with good performance.

Full Text

Preamble

The Extraction and Smoothing Algorithms for γ-Ray Spectra from a CdZnTe Detector System

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Abstract: The algorithms used for pulse amplitude extraction and energy spectrum smoothing significantly influence the quality of γ-ray spectra in digital detection and analysis systems. For a CdZnTe digital γ detector system, this paper investigates different algorithms for pulse amplitude extraction and energy spectrum smoothing. The results demonstrate that extracting pulse amplitude using the first-order derivative method combined with wavelet transformation for spectrum smoothing yields optimal performance.

Keywords: Pulse amplitude extraction, Energy spectrum smoothing, Optimization algorithm
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Introduction

Cadmium zinc telluride (CdZnTe) digital γ detector systems consist of a CdZnTe detector, a high-speed data acquisition card, and associated software. The data acquisition card receives analog signals from the detector and converts them into digital signals, which the software processes to extract signal amplitudes, perform statistical analysis, and generate the energy spectrum. The quality of the resulting energy spectrum depends on both the extraction algorithm employed and the statistical characteristics of the physical processes involved. To obtain high-quality CdZnTe γ-ray spectra, this paper investigates various algorithms for pulse amplitude extraction and energy spectrum smoothing, along with their optimization.

Methodology

The method used to determine pulse amplitude directly affects the peak position and energy resolution of the resulting spectrum. We evaluated three amplitude extraction algorithms to identify the most suitable approach.

Amplitude Extraction Algorithms

1. Extremum Method [FIGURE:1(a)] In this method, the maximum (y_{max}) and minimum (y_{min}) values of each pulse are extracted, and the pulse amplitude is calculated as $A = 0.9(y_{max} - y_{min})$, accounting for noise effects and signal backflushing. The energy spectrum is then generated through statistical analysis of all pulse amplitudes.

2. First Derivative Method [FIGURE:1(b)] The channel addresses corresponding to zero-crossings of the first derivative (t_{1s} and t_{1b} in [Figure 1: see original paper]) represent the initial and final channels of the pulse. The amplitude A is extracted from the original pulse coordinates (t_{1s}, y_{1s}) and (t_{1b}, y_{1b}) using the formula $A = y_{1s} - y_{1b}$.

3. Second Derivative Method [FIGURE:1(c)] The channel addresses of the maximum and minimum values of the second derivative are obtained to determine the initial and final channel addresses (t_{2s} and t_{2b} in [FIGURE:1(a)]). The amplitude A is then extracted from the original pulse coordinates (t_{2s}, y_{2s}) and (t_{2b}, y_{2b}) as $A = y_{2s} - y_{2b}$.

[Figure 1: see original paper] illustrates these three methods, showing (a) the original pulse, (b) the first derivative pulse, and (c) the second derivative pulse. Using the first derivative of pulse amplitudes enables accurate identification of the channel addresses corresponding to maximum values.

Filtering Algorithms for Energy Spectrum Smoothing

1. Wavelet Transformation Wavelet transformation is employed to decompose and reconstruct pulse signals. To suppress noise during reconstruction, coefficients from branches with higher noise content are attenuated while those with stronger signal features are preserved. The denoising procedure proceeds as follows:

1. The sym4 wavelet basis function decomposes the original signals into three components. The decomposition formulas are:

   $$h_0(n-2k)x_{j+1} = \sum h_1(n-2k)x_{j+1}$$

   $$h_1(n) = (-1)^n h_0(N-n) \quad (j \geq 0, j \in \mathbb{Z})$$

   where $x(j)$ and $d(j)$ represent the low-frequency and high-frequency coefficients at decomposition scale j, respectively, and $h_0(n)$ and $h_1(n)$ are the low-pass and high-pass filter coefficients.

2. The soft threshold method contracts the high-frequency coefficients of all three components.

3. Wavelet reconstruction restores the original signal using the low-frequency coefficients from the third component and the threshold-processed high-frequency coefficients from all three components. The reconstruction formula is given by:

   [Reconstruction equation]

2. Finite Impulse Response (FIR) Filter The fundamental concept of FIR filtering involves separating low-frequency signals from high-frequency noise using an appropriate window function and cutoff frequency. Given an ideal filter frequency response $H_d(e^{j\omega})$, an FIR filter frequency response $H_d(e^{j\omega}) = h(n)e^{-j\omega}$ ($n = 0$ to $N-1$) approximates the ideal response. A finite window function $\omega(n)$ truncates $h_d(n)$: $h(n) = \omega(n)h_d(n)$.

In this study, the sampling frequency is $f = 10^8$ Hz (angular frequency $\Omega_s = 2\pi \times 10^8$ rad/sec). The passband cutoff frequency is $f = 10^3$ Hz ($\Omega_p = 2\pi \times 10^3$ rad/sec), while the stopband begins at $f = 2 \times 10^3$ Hz ($\Omega_{st} = 2\pi \times 10^3$ rad/sec) with a stopband attenuation of at least -50 dB. The Hamming window provides a minimum decay constant of -53 dB, satisfying the stopband requirement. The Hamming window function is:

$$\omega(n) = \left[0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right)\right] R_N(n)$$

The amplitude frequency response function is:

$$W(n) = 0.54W_R(\omega) + 0.23\left[\frac{N-1}{2}\right] \approx 0.54W_R(\omega) + 0.23\left[\frac{N-1}{2}\right]$$

This method concentrates 99.6% of the energy in the main lobe of the window spectrum, with a main lobe width of $2\pi/N$ and side lobe peaks less than 1% of the main lobe peak.

3. Least Squares Smoothing The least squares smoothing method operates as follows: to obtain the m-th point in the smoothed spectrum, $k+1$ points on each side of the m-th point are selected to form a window containing $2k+1$ data points. Within this window, polynomial fitting is applied to the original data, and the value of the m-th point on the fitted polynomial becomes the smoothed spectrum value at that point. As the m-th point moves across the spectrum, the entire smoothed spectrum is generated.

Let y_m be the original data and $\bar{y}_m$ be the smoothed data. The smoothed value at the m-th point is $\bar{y}_m = S(x)|_{x=m} = a_0$, where a q-order polynomial approximates y_m:

$$S(x) = a_0 + a_1(x-m) + a_2(x-m)^2 + \cdots + a_q(x-m)^q$$

We employ 11-point smoothing ($k = 5$, forming an 11-point window). A quadratic polynomial fits the data, and least squares methods determine the polynomial coefficients. The 11-point smoothing formula is:

$$\bar{y}_m = \frac{-36y_{m-5} + 9y_{m-4} + 44y_{m-3} + 69y_{m-2} + 84y_{m-1} + 89y_m + 84y_{m+1} + 69y_{m+2} + 44y_{m+3} + 9y_{m+4} - 36y_{m}}{429}$$

Comparison of Algorithms

A CdZnTe digital γ detector system measured ^{60}Co γ-rays to compare and evaluate the performance of different algorithms in obtaining energy spectra of varying amplitudes and smoothing results. The algorithms described above were applied to process the acquired γ-ray pulse data. Evaluation metrics included energy resolution, integral nonlinearity, peak-to-Compton ratio, peak area, and other relevant parameters.

Amplitude Extraction Performance

The initially obtained energy spectrum exhibits significant roughness. To extract characteristic parameters and minimize statistical error effects, wavelet smoothing was applied to the spectrum [14, 15]. [Figure 2: see original paper] shows the spectra obtained using the first derivative, second derivative, and extremum methods.

The spectrum from the first derivative method [FIGURE:2(a)] is both smooth and features prominent, well-defined peaks. The second derivative method [FIGURE:2(b)] produces distortion in both the Compton plateau region and peak positions. The extremum method [FIGURE:2(c)] yields results similar to the first derivative method but with reduced peak amplitudes. summarizes the parameters calculated for all three methods.

Analysis of reveals that the first derivative method produces the best overall results, achieving the highest energy resolution, peak height, peak-to-Compton ratio, and peak area among all evaluated methods.

Energy Spectrum Smoothing Performance

[Figure 3: see original paper] displays the original energy spectrum alongside spectra smoothed using the three different methods.

The wavelet method [FIGURE:3(b)] produces a smooth spectrum while preserving the original spectral features without shifting peak positions. The FIR filter method [FIGURE:3(c)] generates a smooth spectrum but introduces noticeable peak position shifts. The least squares method [FIGURE:3(d)] performs inadequately, exhibiting glitch-like artifacts. presents the parameters of the smoothed spectra.

According to , the least squares method fails to effectively remove statistical fluctuations or maintain the original spectral shape due to limitations in the discrete Fourier transform basis vectors. The FIR filter cannot adequately suppress integral nonlinearity, resulting in significant peak position deviations from the original. In contrast, the wavelet transform method' s multi-resolution basis vectors enable high resolution in both channel and frequency domains, allowing effective extraction of both slow and rapid variation features, making it a superior approach for γ-ray spectrum smoothing.

Conclusion

This paper establishes integral nonlinearity, peak area, and peak-to-Compton ratio as evaluation criteria for assessing extraction algorithms for pulse amplitude and smoothing algorithms for energy spectra obtained from CdZnTe digital γ-ray detector systems. The results demonstrate that combining the first derivative method for pulse amplitude extraction with wavelet transform for energy spectrum smoothing yields superior results, disregarding computational time considerations.

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Note: Figure translations are in progress. See original paper for figures.

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