Implementation of the direct demodulation method for natural gamma ray spectral logging*

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Abstract: Spectrum analysis of natural gamma ray spectral logging (SGR) data is a critical part of surface information processing systems. Due to the low resolution, which is an inherent weakness of SGR, and the low signal-to-noise ratio problem of logging measurements, SGR is usually treated with a low confidence level. The Direct Demodulation (DD) method is an advanced technique to solve modulation equations interactively under physical constraints. It has higher sensitivity and spatial resolution than the traditional methods and can effectively suppress the logging noise. Based on standard count rate spectral data obtained from the China Offshore Oil Logging Company SGR Calibration Facility, this paper presents the application of the DD method to gamma-ray logging. The results are compared with four traditional algorithmic methods, showing that the DD method is a credible choice, with higher sensitivity and higher spatial resolution in gamma-ray log interpretation. The Point-Spread-Function of the Shengli Oil Logging Company's natural gamma ray spectroscopy instrument is obtained for the first time. The quantities of various radionuclides in their calibration pits are also obtained. The DD method was applied successfully to gamma-ray logging, offering a new option for SGR logging algorithm selection.

Key words: natural gamma ray spectral, well logging, spectral analysis, direct demodulation method, response function, physical constraints

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1 Introduction

Natural Gamma Ray spectral logging is an application of nuclear detection technology in geophysical exploration. The critical part of its surface information processing system is the spectral analysis method used to analyze the experimental data. The four spectral analysis methods that have been traditionally used are: the spectrum stripping method, the inverse matrix method, the least square inverse matrix method, and the weighted minimum squares inverse matrix method [1, 2]. Because of their inherent low resolution, there are usually very severe statistical fluctuations during the logging measurements[3]. In the early 1990s, the Direct Demodulation (DD) method [4–6] was proposed by Li Ti-Pei and Wu Mei to get high-resolution space images of complex celestial bodies from signal data with little statistical information and a low signal to noise ratio. The DD method has been used in high energy astrophysical observations and data analysis, and has made a number of important achievements [7–9]. It has also been used to obtain useful results in medical applications [10, 11]. Compared with traditional spectral analysis methods, this method uses more observational information and thus obtains higher accuracy and sensitivity. This paper, which is based on data from the China Offshore Oil Logging Company SGR Calibration Facility, presents preliminary research of the DD method applied to gamma ray logging, with high sensitivity and spatial resolution.

2 Calculation of standard spectral for natural gamma ray spectral logging

Natural gamma ray spectral logging can identify the formation properties of rock by directly measuring the relative content of elements like uranium, thorium, potassium, etc. Moreover, it can be used in qualitative analysis to get the clay content, high-permeability interval, the composition of clays and the division of fractured carbonate layers. It can also be used in quantitative

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calculations for the identification of argillaceous strata characteristics in source rocks and the study of depositional environments [12–16]. Natural γ-rays are mainly generated by the U, Th and K decay series in formation rock [17]. The original γ-ray spectrum always shows a discrete line spectrum shape, while a continuous spectrum is obtained using a Gamma Spectrometer Detector triggered by γ-rays. Usually this continuous spectrum is called the gamma found spectrum or instrument spectrum [18, 19]. In natural gamma ray spectral logging, the characterization of uranium is usually done using the 1.76 MeV γ-rays emitted by Bi in the U series, thorium characterization uses the 2.62 MeV γ-rays emitted by Tl in the Th series, and potassium characterization uses the 1.46 MeV γ-ray, which is the only γ-ray emitted by the K series[20].

2.1 The principles of natural gamma ray spectral logging

Natural gamma ray spectral logging can be used for both strength measurement and spectrum analysis. It identifies the nuclide emitting the ray by energy analysis, and the quantity of the nuclide and its corresponding elements by the intensity. The multi-functional compensating natural gamma ray spectral logging instrument can make full utilization of the natural gamma ray spectrum's information, the logging process is shown in Fig. 1.

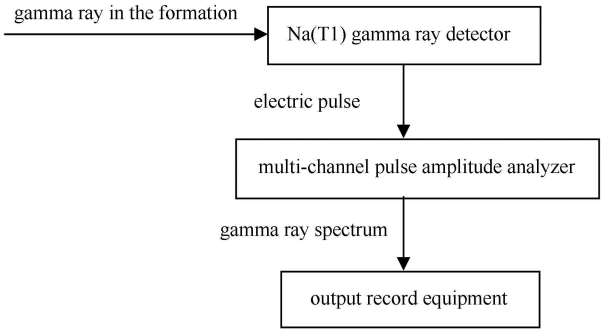

Fig. 1. Response of instrument #17 for elements K, U and Th.

2.2 Calculation of the natural gamma ray standard spectrum

In our field logging, the wellhead size in the China Offshore Oil Logging Company wells at their Yanjiao base is very close to 8.5 inches, so the programming data used in this paper to describe the standard natural gamma ray spectrum is the data for 8.5-inch wells. The data is used to calculate the resolution in spectral analysis of natural gamma ray spectral [21]. Table 1 shows the quantity of the radioactive elements U, Ra, Th and K in each layer at these wells. In the site measurement, if not specially declared, the K measurements use % as the unit, and the U and Th measurements use g/t (ppm).

The standard instrument spectrum of each radioactive element can be obtained in the calibration well by making measurements in the simulated formation while considering only one of the radioactive elements U, Th or K at a time. The standard spectrum can determine the count rate of U, Th and K in each channel, which is used as the basis for the spectral solution of the unit quantity under standard conditions. Fig. 2 shows the standard spectrum diagram for the five modules, including the three nuclides of U, Th, K, the high mixed layer and the low mixed layer. The count rate is obtained by taking a fixed point measurement of 600 s at each depth point. Due to the count rate being very low after Channel 80, Fig. 2 shows the data from Channel 80 onwards multiplied by a factor of 30.

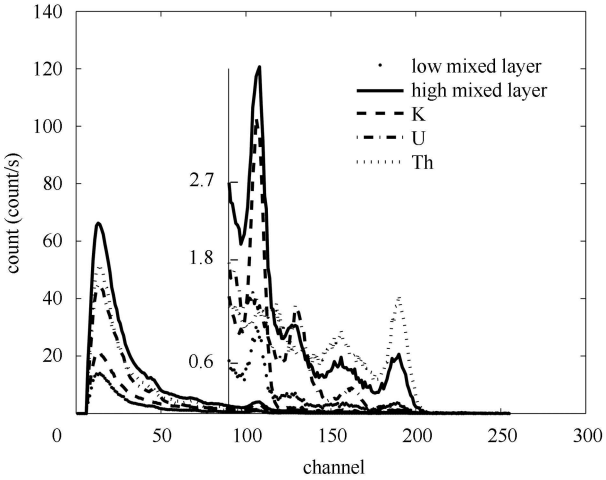

Fig. 2. Standard spectral for the five modules.

Below, four traditional data processing methods and the DD method are used to process data from the Yanjiao wells and obtain the quantities of U, Th and K. These values are then compared with the standard values given in Table 1; the closer the value is to the standard measurement, the better the method is. Data for the two analog modules, the high mixed layer and the low mixed layer, were used in this paper to verify the four traditional spectral analysis methods.

3 Implementation of the DD method in natural gamma ray spectral logging

The DD method is mathematically similar to spectral analysis for natural gamma ray spectral logging because both solve ill-conditioned equations. The two methods also have the same physical basis, spectroscopy. The implementation of the DD method for natural gamma ray spectral logging is as follows.

Table 1. Quantities of U, Ra, Th and K from China Offshore Oil Logging wells at Yanjiao.

layer	U/10^{-6}	Ra/10^{-12}	(Ra/U)×100%	Th/10^{-6}	K/10^{-2}
wall rock	0.40	1.7	—	1.12	0.23
Th layer	0.79	2.3	—	63.5	0.22
K layer	0.97	2.6	—	1.45	5.60
U layer	22.1	75.1	101.4	1.21	0.25
low mixed layer	2.4	8.3	103.2	5.41	1.05
high mixed layer	12.3	39.4	95.6	34.8	5.17
high mixed thin layer	12.2	40.9	100.1	36.0	5.11

Note: Ra/U is uranium-radium equilibrium coefficient,used to calculate accurate uranium content.

3.1 Principles of the DD method

The essence of the DD method is to introduce reasonable nonlinear constraints into the process of solving an ill-conditioned observation equation. The core issue is firstly to create the observation equation, and then to select appropriate upper and lower limits for the physical constraints to use an iterative method for solving this observation equation. The observation process is a radiation detection process, and can be described by the following equation:

$$\sum_{i=1}^{N} P(k,i)f(i)=d(k), \quad (k=1,2,\cdots,M), \tag{1}$$

where $d(k)$ is the observation data, $P(k,i)$ is the instrument response function (modulation function), and $f(i)$ is the radiation intensity of the observation space zone.

3.2 Establishing use of the DD method for natural gamma ray spectral logging

The radiation detection process can be seen as the convolution of the source and detection system for a function like:

$$Pf=d. \tag{2}$$

Usually, this equation is ill-conditioned and its solution is often a negative source, which is physically meaningless. The response of the instrument can be regarded as the same under the same instrumental parameters and environments. In the Yanjiao experiment, due to the consistent measurement environment, the response function of the Shengli Oilfield logging spectroscopy instrument #17 SL6329 can be regarded as a constant value. The instrument response function can, therefore, be calculated based on the standard counting rate spectrum. Using the successive iteration method to solve the spectrum directly with the introduction of certain constraints can not only inhibit the oscillation of the solution, but it can also greatly improve the resolution of the system. Thus, it can be concluded that the DD method for spectral analysis of natural gamma ray spectral logs is feasible.

For natural gamma ray spectral logging, once the count rate from the detector output spectrum is known, working out the content of K, U and Th in the measured layer then becomes a problem of solving an ill-conditioned matrix. With Yanjiao experiment data, the DD method can be used to solve this problem. The steps are as follows.

(1) Calculation of the response function of the Shengli Oilfield natural gamma ray spectral logging tool according to the data from the China Offshore Oil Logging experiment. The quantities of the three standard modules K, U, Th are shown in Table 1. and can be represented by a 3×3 column matrix X. C their standard counting rate spectral data, uses 256 channel addresses, so C is then a measurement column matrix of dimension 256×3. According to the formula $A=X^{-1}C$, it can be found that the response matrix of instrument #17 is a 256×3 column matrix. Fig. 3 shows the response of instrument #17 for elements K, U and Th.

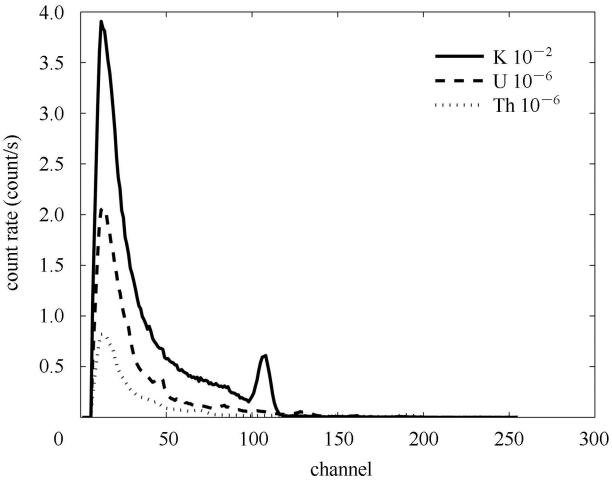

Fig. 3. Response of instrument #17 for elements K, U and Th.

(2) Solving the background constraints. Solving out the background constraints $x_{\mathrm{R}}(i)$ is based on the preceding analysis, which introduces non-negative constraints. A three-point filter was adopted when computing the physical constraints because this gave optimal results when compared with the fit. At any point on the original signal spectrum, the a_i is be replaced by b_i if a_i is bigger than b_i, and the calculation process is iterated until the

count rate fitting curve no longer changes. The minimum value point is then selected. Fig. 4 shows the signal spectrum fitting curve for the b8h signal spectrum from instrument #17, where b represents instrument #17, 8 indicates the 8.5-inch wells, and h indicates the high mixed layer.

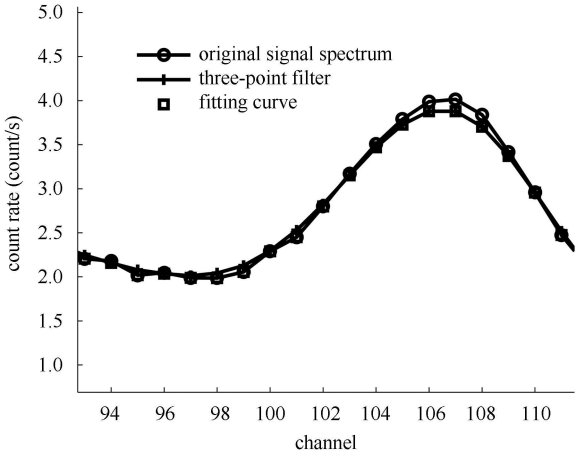

Fig. 4. The signal spectrum fitting curve for instrument #17 sample b8h.

Calculation of the "lower" constraint of the background radiation count rate d_{R} is done by interpolating the fitting curve. Fig. 5 shows the background radiation count rate spectrum for instrument #17 sample b8h.

(3) Solving the measurement equation with the DD method. With the non-negative constraints, the Gauss-Seidel iterative method can be used to iteratively solve the detecting equation, giving the results shown in Table 2 and Table 3. Table 2 gives a comparison between the four traditional methods and the DD method for the high mixed layer, while Table 3 does the same for the low mixed layer.

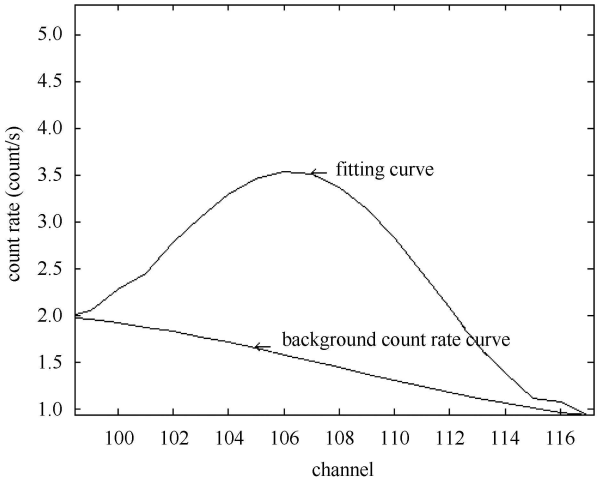

Fig. 5. The background count rate spectrum for instrument #17 sample b8h.

The results show that the DD method can be applied to the spectral analysis of natural gamma ray spectral logging because the radionuclide content obtained by the DD method is close to the standard values. The accuracy of the radionuclide quantity results obtained by the DD method is better than that of the four traditional data processing methods.

Table 2. Comparison of the four traditional algorithmic methods and the DD method for the high mixed layer.

method	K_1	K_2	K_3	U_1	U_2	U_3	Th_1	Th_2	Th_3
spectrum stripping method	5.17	4.6257	10.53	12.3	11.1050	9.72	34.8	34.2108	1.69
inverse matrix method	5.17	5.0546	2.23	12.3	11.9729	2.66	34.8	33.2381	4.49
least square inverse matrix method	5.17	4.9516	4.22	12.3	12.9838	5.56	34.8	32.1849	7.51
weighted minimum squares inverse matrix method	5.17	5.0463	2.39	12.3	12.5666	2.17	34.8	32.7411	5.92
direct Demodulation method	5.17	5.1057	1.24	12.3	12.3288	0.23	34.8	33.5966	3.46

Note: (1) K_1, U_1, Th_1 are the real values; (2) K_2, U_2, Th_2 are the observed values; (3) K_3, U_3, Th_3 are the relative errors (the unit is %); (4) the magnitude for K_1, K_2 is 10^{-2}, the magnitude for the others is 10^{-6}.

Table 3. Comparison of the four traditional algorithmic methods and the DD method for the low mixed layer.

method	K_1	K_2	K_3	U_1	U_2	U_3	Th_1	Th_2	Th_3
spectrum stripping method	1.05	1.0795	2.81	2.4	2.5873	7.8	5.41	5.9133	9.3
inverse matrix method	1.05	1.1802	12.4	2.4	2.8607	19.2	5.41	5.4717	1.14
least square inverse matrix method	1.05	1.0996	4.72	2.4	3.2256	34.4	5.41	4.9706	8.12
weighted minimum squares inverse matrix method	1.05	1.1416	8.72	2.4	2.9841	24.34	5.41	5.3735	0.67
direct Demodulation method	1.05	1.0699	1.9	2.4	2.5853	7.72	5.41	5.3622	0.88

Note: (1) K_1, U_1, Th_1 are the real values; (2) K_2, U_2, Th_2 are the observed values; (3) K_3, U_3, Th_3 are the relative errors (the unit is %); (4) the magnitude for K_1, K_2 is 10^{-2}, the magnitude for the others is 10^{-6}.

4 Conclusions

This paper has presented a method to obtain the standard counting rate of radionuclide spectral. Experimental data from the China Offshore Oil Logging Company were analyzed and tested with the DD method, and high sensitivity and spatial resolution were achieved. The main features of the DD method were discussed. The detection equation for natural gamma ray spectral logging was established, and the contents of various radionuclides in the China Offshore Oil Logging calibration pits were obtained, confirming the feasibility of the DD method for gamma-ray logging. The paper also compared the DD method and four traditional data processing methods, finding that the use of the DD method gave a much higher accuracy than the four traditional methods. Due to the lack of a deep understanding of the actual measurement environment of high-energy astrophysics and logging, this paper has only presented preliminary theoretical research for the DD method. Also, for the establishment of the DD method in natural gamma ray spectral logging, we simply obtained physical constraints for the standard count rate spectrum in this paper. Further work should include investigation of the variation of K, U and Th quantity with depth, whether or not to fit background radiation to the filter, and how to make use of the cross-correlation method to solve the background constraints.

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