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Processing of Airborne Gamma-Ray Spectra: Extracting Photopeaks

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Summary

Receiving information from airborne gamma-ray spectra is based on the ability to estimate the photopeak areas in the regular spectra of natural and other sources. In the airborne gamma-ray spectrometry, extracting the photopeaks of radionuclides from regular one-second spectra is a complicated problem. In the region of higher energies, the difficulties are associated with low count rates, while in the region of lower energies, difficulties are due to a significant background level and its statistical noise. In this article a new procedure is proposed to process the measured spectra up to extracting evident photopeaks. The procedure consists of decreasing noises in energy channels along the flight lines, transforming spectra to equal resolution, removing baselines from each spectrum, and sharpening details. The resulting spectra are better suited for examining and using the photopeaks. No assumptions regarding the number, positions and amplitudes of photopeaks are needed. Non-negativity of photopeak areas is ensured by the procedure. The proposed technique is likely to contribute to studies of environmental issues, soil characterization and other near surface geophysical methods.

Introduction

In Airborne Gamma-Ray (AGR) spectra, the photopeaks are the primary information about the geological and geophysical state of soil and subsurface rocks. The availability of photopeaks and possibility to measure them allow for solving a number of geological, geophysical and geochemical problems, from estimating the concentrations of radioactive elements on vast areas (Grasty and Minty, 1995) to achieving detailed polytypic solutions of inverse problems (Druker, 2012). As for extracting photopeaks, standard processing solves two main problems: removal the Compton background and taking into account the mutual influence of radionuclides. This requires careful calibrations and strong averaging, but still can lead to unreliable results - a loss of spatial resolution and negative values. In addition, it is difficult to include in this processing man-made radionuclides. The proposed procedure mitigates these drawbacks (mutual influence to be considered after all, if it really is necessary) and enables to acquire more reliable and accurate photopeaks. General elements of the technique are smoothing the spectra along lines and along the energy axis, building the (Compton) baseline to obtain spectra of photopeaks only.

Note that all the numbers, values, examples and figures below are related to input airborne spectra with 512 channels of a 6.0 keV width each, with the usable measured data being between approximately 0.3 MeV and 3.0 MeV, i.e., in channels from approximately 46 to 510.

Processing the spectra

P.1. Smoothing along the lines

The count rate in the spectrometer channels agrees with Poisson distribution (Billings et al., 2003; Minty, 2003; Tsoulfanidis, 1995). Poisson distribution variables have equal mean M and variance V: M = V. The number of pulses in energy channels along the flight lines is a Poisson process, at least on short distances

comparable to a footprint size where M is almost constant. Competent smoothing of Poisson data is a separate problem because of the strong relation between «signal» M and «noise» V. For AGR spectra one more difficulty is that at higher energies, the M values are often quite small, M < 4. One way to properly smooth AGR spectra with various values of M in channels is to transform a Poisson signal into a Gaussian signal, then apply a well-known filter for additive Gaussian noise. Therefore, the first step is to replace a Poisson process by usual Gaussian process:

Poisson (M) $\rightarrow$ Signal (M) + Noise (0), (2)

where Noise (0) is close to the standard Gaussian noise from distribution N(0,1). The importance of the transformation is in the variance stabilization. For AGR spectra, a suitable transformation is

$$y = \sqrt{x} + \sqrt{x+1}, \quad (3)$$

which is better suited for small values of x (Freeman and Tukey, 1950). Any well-known bell-shaped filter might be used for smoothing, but preferrable are Savitzky-Golay filters (Press et al., 2007), which keep several first moments of the process; the filters are local, and produce negative values very rare. Good filter lengths are 5 to 9 points, which are comparable with a footprint sizes. Smoothed channel data are to be transformed to the original data scale according to inversion of formula (3) - just because a better back transform is not known. Note that using local filters avoids redundant (global) smoothing.

P.2. Estimation of spectra baselines

The next step is to build the baselines of spectra, which are essentially approximations of the Compton continuum. Generally, this problem is notably complicated, even for spectra with large Signal-to-Noise-Ratio that looks like cumulative AGR spectra. Usually, it is explicitly or implicitly adopted that baseline is very smooth compared to the original spectrum or their difference. A promising approach seems to be using the formulations that are similar to those in solution of ill-posed problems (Eilers, 2003):

$$\Sigma w_i (b_i - s_i)^2 \rightarrow \min, \quad (4)$$

where $\mathbf{B}$ is vector of baseline values; $\mathbf{S}$ is vector of spectrum; $\mathbf{W}$ is vector of weight, with some obvious limitations. In this formulation the problem seems to be more complicated than the original one: in addition to the baseline vector $\mathbf{B}$, which has the length of the spectrum $\mathbf{S}$, one also has to find $\mathbf{W}$, a vector of weights. Therefore, the iterative weighting approach is applied. The smoothness of a solution should be provided by the algorithm. To make a smooth baseline, an effective width of a smoothing linear filter F should be several times (2-5) more than FWHM (Full Width at Half Magnitude) of expected photopeaks.

The algorithm for building a baseline of spectrum is as follows. Let $\mathbf{S}_m$ be measured or smoothed (as in P.1) spectrum. Initially, set all the weights of vector $\mathbf{W}$ to be equal $w_k = 1$; set weight modifier u = 0.9. Then make the iterations: smooth the spectrum $\mathbf{S}_m$ with weights $\mathbf{W}$ by filter F to obtain the spectrum $\mathbf{S}_c$; increase weights ($w_k / = u$) if $\mathbf{S}_c[k] < \mathbf{S}_m[k]$, decrease ($w_k * = u$)otherwise. Repeat the iterations until: (a) functional (4) decreases slowly and/or (b) weights $\mathbf{W}$ become stable within some tolerance and/or (c) the numbers of iterations run up to maximum, etc. Now $\mathbf{S}_c$ is baseline spectrum (as approximation of Compton continuum) and the difference $\mathbf{S}_p = \mathbf{S}_m - \mathbf{S}_c$ is the sought photopeaks spectrum.

A drawback of the algorithm is that FWHM noticeably depends on the energy (on channel number), which means that at least the filter F should be changed according to energy. To avoid this drawback we transform a spectrum to a constant value of FWHM, that is, to the spectrum in which the resolution (in the number of channels) is independent of the channel number.

P.3. Reducing the spectrum to constant resolution

The resolution of NaI(Tl) spectrometers is strongly related to the energy of gamma rays. It depends mostly on the sensor size and energy range. For large (airborne) gamma spectrometers, both theoretically and by

experiments (Gilmore, 2008; Knoll, 2000; Kogan et al., 1969; Tsoulfanidis,1995) good approximation in the airborne energy range is

$$E\,R^2(E)=const, \quad (6)$$

where $R(E)$ is the resolution for energy E. Hence, the transform of the spectra channels is:

$$k=cn^2, \quad (7)$$

where k - channel number of input (measured) spectrum; n - channel number of output (transformed) spectrum; c - a coefficient. The inverse transform is:

$$n=\sqrt{k/c}, \quad (8)$$

Let m be the channel of the input spectrum with the same width before and after transformation, then,

$$c=1/4m. \quad (10)$$

It is convenient to take the m value somewhere in the middle of the spectra, for example, $m=243$, which corresponds to the Potassium photopeak at 1.46 MeV. After the transformation, effective values of FWHM are almost the same. The transformation (8) of spectra channels improves the statistics of low counts at high energies and decreases the dynamic range of the spectra at low energies. The full length of spectra is about the same: channels [40, 512] are transformed to channels [197, 705]. Due to large noise in the measured spectra, sophisticated interpolations have no sense. Linear interpolation is sufficient, and level of the differences between input spectrum and its "there and back" spectrum is about few counts for all the energy range, and even less in the channels.

P.4. Sharpening the photopeaks

The transformed photopeak spectra are suitable for sharpening. To keep the solutions positive, the multiplicative methods are better suited. There are many such methods and their modifications (Meng and Ramsden, 2000). One of the well-studied, Gold's ratio method (Jansson, 1984), will be considered below. The method is designed to solve the convolution equation

$$\mathbf{f}=\mathbf{A}*\mathbf{u}, \quad (11)$$

where $\mathbf{f}$ – measured data; here the vector of (non-negative) photopeak areas, $\mathbf{u}$ – primary data to find; here the vector of primary photopeaks, $\mathbf{A}$ – matrix of transformation, and symbol $*$ means convolution. Gold's ratio method consists of the iterations:

$$\mathbf{u}^{i+1}=\mathbf{u}^i\frac{\mathbf{Bf}}{\mathbf{BA}*\mathbf{u}^i},\ where\ \mathbf{B}=\mathbf{I}\ or\ \mathbf{B}=\mathbf{A}^{\mathrm{T}};\ \ \mathbf{u}^0=\mathbf{f};\ \ i=0,1,2,\ldots, \quad (14)$$

If $\mathbf{B}=\mathbf{I}$, the solution after several iterations takes a delta-like form; this solution is better for special problems like looking for man-made radionuclides. If $\mathbf{B}=\mathbf{A}^{\mathrm{T}}$, the solution after several iterations becomes more distinct; for typical AGR spectrometry problems this solution is better.

Both solutions do depend on the system matrix $\mathbf{A}$ in (11) that is essentially on a given resolution. In the sharpening process it is not necessary to use the accurate value of the resolution. On the contrary, in many cases using the worse resolution is preferable.

After the sharpening, the spectrum should be scaled back to a regular energy scale to find the photopeaks and compute their areas.

Discussion

A full procedure to extract photopeaks from AGR spectra for a flight line is as follows:

A. Smooth spectra channel-by-channel along the line (P.1).

B. For each spectrum:

B.1. Transform it to equal resolution scale (P.3).

B.2. Remove Compton background (P.2).

B.3. Sharpen the photopeak spectrum (P.4).

B.4. Transform it to input channels scale (P.3).

B.5. Create list of photopeaks, calculate areas of photopeaks.

Depending on such factors as the spectra quality and geophysical problem to solve, certain position might be skipped, e.g., for good low-noisy spectra, step A might be redundant. Additionally, to estimate the detector resolution, step B.3 for sharpening must be omitted.

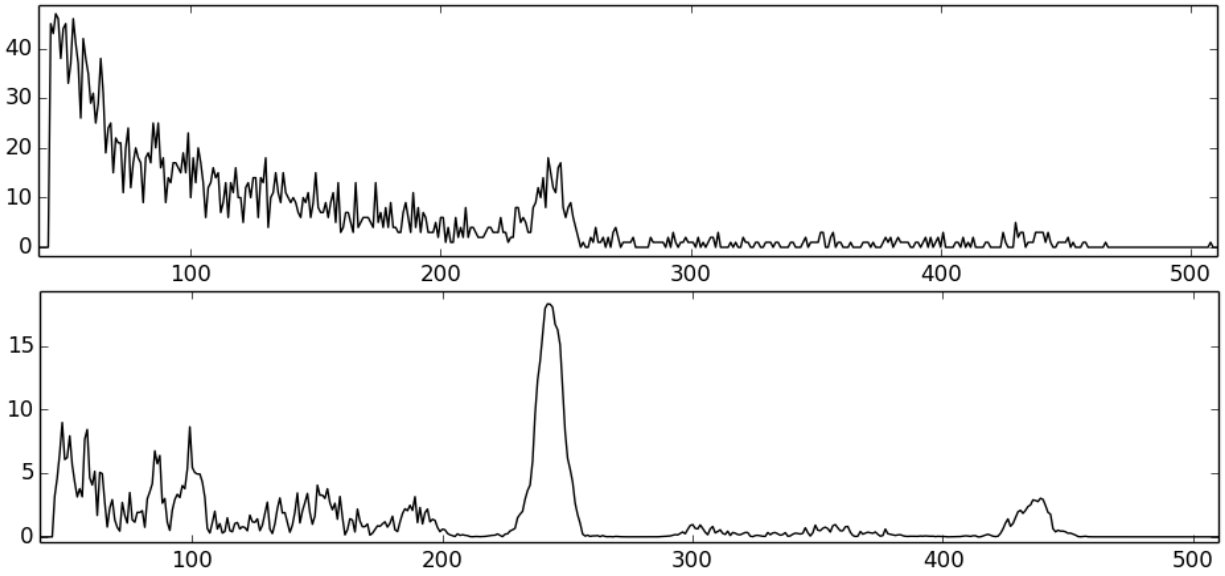

Fig. 1. Example of spectra processing: typical input AGR spectrum (top), its photopeak spectrum (bottom).

Conclusions

A new approach is proposed for transforming the input regular one-second AGR spectra to the photopeak spectra with essentially removed baselines. The primary stages of the procedure are the following: (a) suppressing the noise in the input spectra; (b) conversion of the spectra to equal resolution spectra; (c) building baselines to approximate Compton continuum; (d) sharpening the photopeaks; (e) returning to the input energy scale to find photopeaks and their areas. An important advantage of the approach is that there are no assumptions regarding the number, positions and amplitudes of photopeaks. Mutual influences of radionuclides on each other in photopeaks can be accounted for afterwards. Cumulative photopeaks spectra are suitable (without sharpening) for estimations of resolutions at various energies throughout the spectra.

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