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Airborne gamma-ray spectra processing: Extracting photopeaks

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ABSTRACT

The acquisition of information from the airborne gamma-ray spectra is based on the ability to evaluate photopeak areas in regular spectra from natural and other sources. In airborne gamma-ray spectrometry, extraction of photopeaks of radionuclides from regular one-second spectra is a complex problem. In the region of higher energies, difficulties are associated with low signal level, i.e. low count rates, whereas at lower energies difficulties are associated with high noises due to a high signal level. In this article, a new procedure is proposed for processing the measured spectra up to and including the extraction of evident photopeaks. The procedure consists of reducing the noise in the energy channels along the flight lines, transforming the spectra into the spectra of equal resolution, removing the background from each spectrum, sharpening the details, and transforming the spectra back to the original energy scale. The resulting spectra are better suited for examining and using the photopeaks. No assumptions are required regarding the number, locations, and magnitudes of photopeaks. The procedure does not generate negative photopeaks. The resolution of the spectrometer is used for the purpose. The proposed methodology, apparently, will contribute also to study environmental problems, soil characterization, and other near-surface geophysical methods.

1. Introduction

In airborne gamma-ray spectrometry, AGRS, photopeaks of natural radioelements are the main and only information on geophysical and geological conditions of near-surface rocks. The presence of photopeaks and the ability to measure them allow to solve various geological, geophysical, and geochemical problems - from the general estimation of the content of radioelements over vast areas (IAEA, 1991; Killeen et al., 2015) to various detailed solutions of inverse problems (Druker, 2017). The regular AGR spectra are too complicated and noisy for simple and easy extraction of photopeaks from them. Therefore, various methods must be used to extract acceptable photopeaks from regular spectra. One of the most successful methodologies is the standard processing.

Standard processing (Grasty and Minty, 1995; IAEA, 1991; Killeen et al., 2015) necessarily uses three energy windows centered on three main photopeaks of potassium (K), uranium (U), and thorium (Th) energies. Each window is represented by the total number of counts in all its channels - this should improve the statistics of the window count rates. The width of the window is chosen to have more information about the main photopeak (Minty and Kennett, 1995). All photopeaks, except for uranium peak due to radon, have radiation sources on the ground, and all photopeaks in the windows have a background of the Compton continuum with sources in the entire space, aircraft, and detector (Schwarz et al., 1995). Here, the “Compton continuum” implies that part of the spectra that does not contain photopeaks. Such definition is not constructive and is useful only if there is a method that justifies it. In addition, the Compton continuum in ordinary spectra is in fact very noisy on energy axis, and can hardly be described by simple relations. Each standard energy window includes some sources from the decay series of uranium and thorium, which can be considered as noise in the calculation of the main photopeak of the window. The interdependence of the count rates in the windows (through Compton process and the decay chains) implies the necessity of simultaneous processing of values in all windows.

In standard processing, it is generally accepted that there are two basic types of gamma-field sources - natural in the ground and cosmic radiation. The important difference between them is in the energy ranges. Natural radioactive sources in the earth have energies less than 3.0 MeV, while cosmic gamma rays, as recorded in the cosmic channel, have energies of more than 3.0 MeV.

Consider in more detail the contents of energy windows (Schwarz et al., 1995). The summation (or averaging) of counts in the channels seems to be effective in reducing the influence of noise. However, this assumption is in some ways deceptive. For simplicity, suppose that in each channel (or in each window) there are only two independent summands - a photopeak and a Compton continuum. Each of the summands, like their sum, has a Poisson distribution that is approximated well enough by a normal distribution (see also Appendix). Consider a channel (or window) near the photopeak and the sum of counts from two summands in the channel.

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First a few reminders. If the random variable x has a normal distribution, it is written as $x \sim N(\mu, \sigma^2)$, where μ and σ^2 are the sample mean and variance of x. The sum and difference of two random variables $x_1 \sim N(\mu_1, \sigma_1^2)$ and $x_2 \sim N(\mu_2, \sigma_2^2)$ are described by distributions $x_1 \pm x_2 \sim N(\mu_1 \pm \mu_2, \sigma_1^2 + \sigma_2^2)$ if these random variables are independent, i.e. uncorrelated (Bonamente, 2013; Hayter, 2012), as suggested in the standard processing for the corrections. These formulas are true for normal, uniform and some other distributions, but may be incorrect for Poisson distributions, since the differences can lead to negative mean values.

Suppose that in a window (or channel) the number of photopeak counts is $C_p \sim N(\mu_p, \sigma_p^2)$, and the number of Compton continuum counts is $C_c \sim N(\mu_c, \sigma_c^2)$. Their sum, i.e. the measured number of counts in the window (channel), will be $C_s \sim N(\mu_p + \mu_c, \sigma_p^2 + \sigma_c^2)$. Suppose now that the correction for Compton continuum, which is also a random value, is approximately equal to the correct one, i.e. C_c. Applying the correction to the sum of two random variables C_s, the corrected value is $C_q \sim N(\mu_q, \sigma_q^2) = N(\mu_p, \sigma_p^2 + 2\sigma_c^2)$. In such situations, the Signal-to-Noise Ratio, SNR, is often used, which is defined as the ratio of the mean to the standard deviation: $SNR = \mu/\sigma$. With this notation, standard processing leads to ratios $SNR_p = \mu_p/\sigma_p$ and $SNR_q = \mu_q/\sigma_q$. Since $\mu_p = \mu_q$ and $\sigma_p^2 < \sigma_q^2$, standard processing leads to $SNR_q < SNR_p$, that degrades the SNR. It is obvious that in this argument it does not matter how many energy channels are summed up in the window, because for the average in the window the same relations are correct. It follows that making more corrections can further reduce the SNR.

In standard AGRS processing for the three energy windows, there are six coefficients for describing the interaction of the decay chains and Compton process. The three main coefficients for estimating the effects of higher energies on lower ones are rather large and cannot be neglected. Of the three other coefficients estimating the effect of lower energies on higher ones, usually only one differs from zero. This one estimates the fraction of the uranium decay series in the thorium window and is often ignored in processing (Minty et al., 1997). However, even the significant coefficients describe rather Compton scattering (from higher energies to lower ones) than the interaction of the primary radiation sources. This can be demonstrated on models that have only natural gamma-field sources on the Earth, without any other field sources, such as cosmic rays or the Compton effect in the detector and associated processes. For this example, the complete decay series of K, U, and Th are taken as sources (Grasty, 1979; IAEA, 2003; Peterson, 1996). The potassium decay series consists of potassium itself. The Earth model is a homogeneous (for each radioelement) half-space, whose field depends on the height of the detector and energy of the gamma rays. This dependence is described by an exponential integral of the second kind $E_2(\mu h)$ (Grasty, 1979; IAEA, 2003; Kogan et al., 1969). The model is described in the IAEA (2003, Table 5.2), with the parameters: a 33L detector at a height of 100 m and a typical crustal material. To complete the model, it remains to select the sensitivity to obtain the numbers in the table. It turned out that these sensitivities are in good agreement with the previously known ones (Grasty et al., 1992; IAEA, 1991). The main result is presented in Table 1, where the rows show the percentage of the gamma counts from different decay chains, and in the columns – the decay series. For example, the contribution of the uranium decay series in the thorium window is 2%, and the contribution of the thorium decay series in the uranium window is 6%.

Table 1
The contributions, in percent, of the decay chains to standard energy windows. The model includes only primary gamma rays and typical energy resolution, but not Compton scattering or other effects.

Decay series:	Potassium, K	Uranium, U	Thorium, Th
Windows (MeV) (Left Center Right)			
K (1.36 1.46 1.56)	95	3	2
U (1.66 1.76 1.86)	0	94	6
Th (2.41 2.61 2.81)	0	2	98

The main conclusion from this table is that the neglecting mutual effects of the natural decay chains leads to relatively small errors of a few percent, which if necessary can be further reduced by subsequent corrections. It can be noted that in the uranium window, from its decay series there are several primary energies, and therefore the share of the major uranium at 1.76 MeV in the uranium window is about 2/3.

Thus, the standard processing includes sort of "paradoxical" procedure. At first, energy windows are formed, which include all the counts, both photopeaks, and the Compton continuum. Then much of the processing is devoted to eliminating this complicated and noisy background. For the success of such improvement, rather cumbersome and expensive calibration flights and operations are needed. The result of these calibrations are the statistically valid coefficients in the processing formulae, which are thus designed for data with little noise. Such low-noise measured data are usually not available, and simple noise reduction entails the need for serious averaging to obtain data more suitable for accurate correction formulae. In many cases, the averaging parameters are quite arbitrary, and such averaging may not even be local - it may cover several or many footprint sizes. Sometimes averaging is performed by rectangular filters that can distort the signal to the wrong one (Killeen et al., 2015). And yet, even with such simplifications, the results may not be so good, generating, for example, vast areas of negative values, and not just over the water. Strong averaging can even lead to a significant loss of spatial resolution and to poor-quality output data. On the other hand, such averaging leads to more reliable (and sparse) data, which are closer (believable) to the nominal situations of standard survey conditions: approximately constant height of measurements over a homogeneous half-space.

An example of such "paradoxical" mixing in standard AGRS processing is the correction for the aircraft and cosmic background. Both these field sources are combined into a single hybrid correction (Grasty and Minty, 1995; IAEA, 1991; IAEA, 2003) as the linear combination. The cosmic part of the correction requires high altitude flights for calibration. However, from the point of view of the splitting the spectra into photopeaks and Compton continuum, the differences between these fields are so important that they cannot be added. Cosmic gamma rays, both measured at energies above 3.0 MeV, and at lower energies, do not contribute to photopeaks, but only to Compton continuum. The aircraft contamination is believed to be created by the natural decay series, possibly with cesium, in a certain for the aircraft proportion, and therefore creates the spectrum similar to the natural, including the photopeaks. In the proposed approach, such a hybrid correction is meaningless. Still, the correction for aircraft field is necessary and can be estimated from the data of simple not-so-high-altitude flights, where there are no gamma field sources in the AGRS natural energy range, except for aircraft ones.

In standard processing it is difficult to use more than three energy windows, especially in the energy region of less than 1 MeV, and therefore some photopeaks of radioelements, such as artificial ones or used for radon correction (Jurza et al., 2005; Minty et al., 1997), cannot be detected by three-window processing. Of course, one can use simple-minded calculated areas of photopeaks, although this approach should have a correct idea of the background of photopeaks. Usually, near the peak, the background is represented by a segment between the end values in the energy window. However, the end values themselves are random values and have quite a wide range of changes depending on the window edges and on the method of their calculation. Such random values can vary abruptly from spectrum to spectrum or from channel to channel (with a small displacement of the energy windows). Therefore, simple-minded calculated areas of photopeaks should be (well) averaged, again with the loss of spatial resolution and perhaps other local information.

This study proposes a procedure for obtaining more reliable and