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Determination of correction factors for borehole natural gamma-ray measurements by Monte Carlo simulations

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ABSTRACT

The analysis of natural γ-ray spectra measured in boreholes has to take into account borehole parameters such as the presence of casings and borehole diameter. For large, high-efficiency γ-ray detectors, such as BGO-based systems, which employ full-spectrum data analysis, corresponding corrections were not previously determined. In a joint project of the Nuclear Geophysics Division of the Kernfysisch Versneller Instituut (NGD/KVI), Groningen, Medusa Explorations B.V. and the Dutch Institute for Applied Geosciences (TNO-NITG) a catalogue of corrections was constructed. Using the Monte Carlo code MCNP, the influence of steel casings, borehole diameter, central axis probe position and the diameter of the γ-ray detector on the γ-ray spectra has been investigated for nearly 20 geometries. The calculated γ-ray spectra are compared qualitatively and quantitatively. In a case study, γ-ray spectra from a borehole measured in a cased and uncased configuration are analyzed with simulated spectra. When no corrections are used, the activity concentrations deviated by as much as 50% between the two measurements. Taking into account the specific measurement geometry, the activity concentrations were found to be identical within the statistical and systematic uncertainties of the experiment for the same borehole, with and without casing. These results illustrate the need for borehole-specific corrections and this study demonstrates that Monte Carlo methods are a fast and reliable way to calibrate well-logging tools for a wide variety of configurations.

1. Introduction

Borehole measurements provide information on the subsurface geology. The oldest use of nuclear techniques was based on measurements of γ-radiation emitted by the natural radionuclides ^{40}K, ^{232}Th and ^{238}U. Transitions between two formation classes were located based on changes in count rates.

When the individual activity concentrations of the natural radionuclides are known, even the formation composition can be extracted from the spectra of natural γ-radiation since they are characteristic for geological classes (e.g., sand or clay). In other words, the particular set of activity concentrations of ^{40}K, ^{232}Th and ^{238}U can be considered as a "fingerprint" of the soil composition [1,2]. If the radiometric fingerprints of the components of a formation are sufficiently different, it is furthermore possible to make a distinction between two variations of the same class (i.e. clay members kaoline and illite [3]). In the second half of the 1990s, improvements in both γ-ray detector technology and computers made it possible to derive, *quantitatively*, the individual radionuclide concentrations in a geological matrix from *in situ* γ-ray measurements and thus classify a formation based on measurements of natural γ-radiation.

The measured γ-ray spectrum is considered to be a combination of a background spectrum (e.g. from a stabilization source within a detection system) and the contributions of the activity concentrations of the natural radionuclides. This technique, the "Full Spectrum Analysis" (FSA) [4], derives the activity concentrations for each of the natural radionuclides by unfolding the measured γ-ray spectrum. Using the (nearly) full measured γ-ray spectrum in the analysis, the statistical uncertainties are reduced.

In the Full Spectrum Analysis (FSA) method, the measured spectrum $S(i)$ (normalized for measuring time) is regarded for each channel i as the sum over all radionuclides of standard spectra ($X_j(i)$) multiplied by the activity concentration C_j plus a background ($Bg(i)$) component:

$$S(i) = \sum_{j=1}^{M} C_j X_j(i) + Bg(i) \quad (1)$$

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The index j runs from 1 to M, representing the number of radionuclides. A standard spectrum represents the response of the detector in a given geometry to activity concentration of 1 Bq/kg of a given radionuclide.

If for a certain geometry the standard spectra X_j and the background spectrum are known, a measured spectrum $S(i)$ can be analyzed with the standard spectra by the procedure that finds the best C_j values and minimizes χ^2, a measure of the discrepancy between the measured spectrum and the calculated spectrum. The standard spectra for the individual radionuclides, $X_j(i)$, are determined from measurements of samples with well-known activity concentrations. Because the samples will contain trace elements of more than one radionuclide, their concentrations combined give the activity concentration matrix, M. The calibration spectra, CS, are measured for each calibration sample. The standard spectra X then follow from the matrix equation $[CS] = [M] \times [X]$ and are calculated by inverting the concentration matrix M in $[X] = [M]^{-1} \times [CS]$.

Borehole characteristics such as the borehole diameter and the presence of casing material influence the shape and intensity of the measured γ-ray spectra. As a result *quantitative* data can be extracted only if calibrations are available for the particular field conditions.

To circumvent these issues, mineral (uranium) and petroleum exploration/exploitation industries have pioneered development of techniques for borehole and casing corrections of spectral γ-ray logs since the early 1980s. Evans and Wilson [5], for example, produced simulated correction curves for centered and side-walled KUT tools, using the Department of Energy (DOE) energy windows. Furthermore, Koizumi et al. [6] have derived corrections for a steel borehole casing and a diameter of a water-filled borehole from contaminant-assessment measurements with calibration standards for an HPGe detector system, while Stromswold and Wilson [7] have generated similar correction factors to assay for uranium ore with KUT probes. In [8], Koizumi introduces the derivation of environmental corrections for a natural spectral γ-ray logging system through computer modeling calculations using analog Monte Carlo code GAMRES [9], originally developed by Evans, to calculate scintillation detector response functions. However, the efforts to assess the borehole logging tool correction factors are not limited only to natural γ-ray (KUT) spectrometry. Koizumi [10] utilizes DOE passive γ-ray calibration standards to calculate correction factors for shallow subsurface Pulsed Neutron Capture (PNC) logging tool equipped with HPGe detector, while Mickael et al. [11] account for variations in completion geometry, borehole diameter and formation porosity and mineralogy in dual-detector carbon/oxygen (C/O) logging. In the late 1990s Monte Carlo (MC) simulations of radiation transport became increasingly popular as a benchmark and calibration tool for nuclear logging sondes. Odom et al. deployed MCNP [12] and GAMRES [9] to model detector response functions to γ-rays, induced by thermal neutron capture and inelastic scattering of fast neutrons [13] and to model the depth of investigation and cased-hole well-bore uncertainties [14], while Michael developed MC-based algorithm to correct PNC decay logs for borehole and diffusion effects [15].

Typically, the response of well-logging equipment is calibrated in test pits in which the elemental composition, activity concentrations and lithology are known [16]. These test facilities consist of pits with several diameters and contain cased and uncased intervals. An overview of available test facilities is given by Arnold and Butler [17]. The results of the pit-calibrations are extrapolated to field conditions using departure curves to correct for factors such as tool eccentricity, borehole diameter and mud-cake thickness. The compiled data are published by manufacturing and vendor companies for the use in data analysis (e.g. *"Log Interpretation Charts"* by Schlumberger [18]). This approach, however, has several disadvantages. Firstly, all major test pits (such as those approved by the American Petroleum Institute, API) are in the USA. This makes calibration of new detector systems expensive and impractical. Secondly, even after extrapolation, the test facilities only cover a limited number of combinations of drill systems and lithology.

Although most correction functions available in the open literature are energy and nuclide independent and thus do not take into account changes in spectral shape, Koizumi et al. [6] derived source- and energy-dependent environmental corrections and calibration factors for the three-window KUT analysis of spectral γ-ray logging data. Unfortunately, for novel spectrometry tools, which employ large, high-efficiency BGO detectors and FSA, the available correction factors are too limited, thus imposing the need for the study outlined in this paper.

In a joint project of the Nuclear Geophysics Division of the Kernfysisch Versneller Instituut (NGD/KVI), Groningen, Medusa Explorations B.V. and the Dutch Institute for Applied Geosciences (TNO-NITG), a catalogue of corrections for natural γ-ray measurements in boreholes is constructed. This correction catalogue accounts for the effect of the following parameters on measured γ-ray spectra:

1. presence of steel borehole casings;
2. borehole diameter;
3. probe central axis position;
4. dimension of the γ-ray detector.

In practice, a vast number of combinations of these parameters occur, too large to be covered by experimental set-ups. In this work, the detector calibration is done by means of Monte Carlo (MC) simulations. Furthermore, the inclusion of environmental corrections is tested in a case study in which experimental γ-ray spectra are analyzed from a borehole that has been measured with and without the presence of casings.

2. Modeling aspects

2.1. Borehole configurations

For boreholes up to 100 m deep, the most commonly used drilling technique for unconsolidated sediments is the so-called *pulse-drilling* technique, where a stainless-steel casing is pushed into the ground by applying a pulsating pressure on the casing. For a given casing diameter, the maximum depth is approximately 30–35 m. For deeper holes, additional casings with a smaller diameter are inserted to pulse the next 30 m. Therefore, for boreholes deeper than 30–35 m, each stage of the borehole differs in diameter and the number of casings. As a consequence, the absorption of radiation by the borehole constituents (fluid, clays and casings) differs for the stages. The simulated configurations are listed in Table 1 and schematically depicted in Fig. 1: open-central, open, one-, two- and three-casings and side-walled (note: "two-casings" and "side-walled" geometries are the same, except for the detector/housing diameters). A listing of the material properties is given in Table 2. It is established from auxiliary simulations that a formation of 50 cm thickness reproduces the total intensity of an infinite bed within 98.6% [19]. This is in agreement with experiments where an equivalent infinite thickness of 50 cm was found for a density of 2.25 g cm^{-3} [20]. In this work and throughout this document, it is assumed that the borehole is filled with fresh water.

The energy-resolution for the BGO detector with a crystal diameter of $\varnothing$5.0 cm was extracted from measurements and