MEDUSA: a highly efficient detector system for in-situ gamma ray measurements

P.H.G.M. Hendriks, J. Limburg and R.J. de Meijer, Nuclear Geophysics Division, Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen, Zernikelaan 25, 9747AA Groningen, the Netherlands

1. INTRODUCTION

To measure natural γ-rays in the field, various methods have been used. At the beginning of the '90's, our group was confronted with the challenge to build a towable high-efficiency detector system to map underwater bottoms. The detector should be radionuclide sensitive and its efficiency should be high enough to obtain sufficient statistics in about 10 seconds. These boundary conditions led to a detector system that had to be an order of magnitude more sensitive than the available systems, which utilize NaI detectors and derive the activities from the ?-ray spectra using only the photopeak information.

To reach this goal, a detector system (MEDUSA) was designed, built and tested. The system consists of both an improved data acquisition and data analysis part. In the data acquisition part, a large (15cm long, 5cm diameter), high-efficiency $Bi_4Ge_3O_{12}$, (bismuth germanium or BGO) detector was used rather than NaI. The choice for BGO will be explained in the next chapter. In the data analysis part, the improvement in sensitivity was achieved by including the (near) full energy-spectrum in the analysis (FSA) instead of the standard method of using 'windows' for the individual radionuclides. In chapter 3, the two data analysis techniques will be elucidated and compared. The calibration of the system and geometry dependence of the calibrations will be discussed in chapter 4, which will be followed by concluding remarks and current lines of research.

2. DETECTOR CHOICE

To fully appreciate the choice for a specific detector, some of the basic properties of the interactions of ?-rays with matter need to be mentioned. Consider a piece of matter, either a detector or a geological matrix, in which γ-ray emitting radionuclides are incorporated. For natural γ-rays, with energies < 3MeV, two types of interaction are dominant:

- photoelectric effect: all the photon energy is transferred to an electron. The probability for this process depends on the (-ray energy as E_g^{-3}, and the atomic number as Z^n, with n − 4-5, and the material density r
- Compton effect: The photon is (in)elastically scattered by an electron. The electron and the scattered photon share the incoming momentum. The cross section depends on the electron density and hence on r.

The occurrence of these interactions in the matrix, means that the intensity of ?-ray photons emitted with energy E_g, will be reduced with distance and some of the photons will reach the detector with a lower energy. Additionally, these interactions will also take place in a detector, such that the spectrum of a mono-energetic γ-ray source will consist of a sharp peak (containing the ?-rays that have undergone the photoelectric-effect), and a continuum part at energies lower than the photo peak, the Compton continuum. The intensity ratio between the peak and the continuum of (-rays emitted by the matrix will depend, as outlined above, on the photo energy (E_g), the densities and Z-values of the matrix and the detector material, and also on the distance travelled by the γ-ray in the geological matrix. Based on the properties of these processes, for a given ?-ray spectrum the optimum photopeak efficiency will be obtained for a large detector volume with high density and high Z-values.

Bearing in mind that semi-conductors are generally not suited for in-situ measurements because of their need for Liquid Nitrogen cooling (LN_2), scintillation detectors are the best choice for field measurements. For a high-detection efficiency system, high-Z detector materials should be used. A simple calculation comparing the common scintillator material NaI (Z_I = 53) to the relatively new BGO (Z_{Bi} = 83), shows that the probability for photo-electric absorption is about six times higher for BGO. In other words, by using BGO for detector material, the acquisition time can be drastically reduced. The disadvantages of BGO, more expensive, larger temperature gain-drift and a reduced energy resolution than NaI, are outweighed by the higher density and higher Z value. This is also illustrated by figure 1 in which a comparison is given between the attenuation coefficients of BGO and the commonly used NaI crystals. This figure shows that the attenuation of ?-rays in BGO is about three times higher for BGO than for NaI. To operate the MEDUSA BGO-detector an on-line software gain-drift stabilisation was developed.

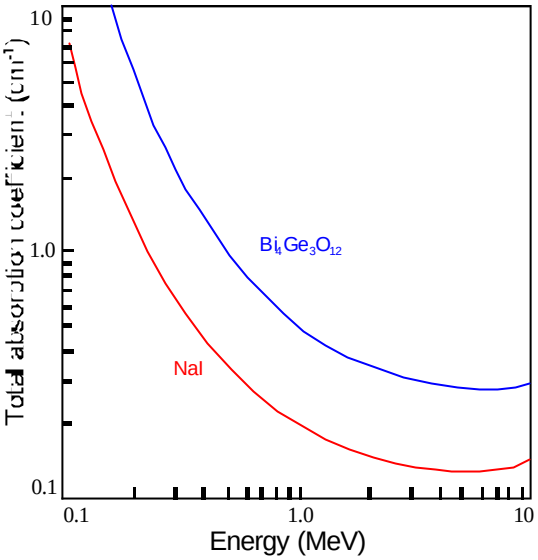

Figure 1: *The attenuation coefficients of NaI and BGO compared as a function of g-ray energy. Taken from "Harshaw Radiation Detectors".*

3. DATA ANALYSIS

For the analysis of the spectra, in practice two methods are used: peak (or window analysis) and full-spectrum analysis (FSA). In the first method, the activity concentration is determined from the net content of the window around individual peaks. In the second method the shape of the total spectrum is taken into account and is 'unfolded' into the spectra for the individual radionuclides (the so-called standard spectra) and a background spectrum. In the windows method an exactly determined set of equations is used for the calculation of the activity concentrations. Therefore, not enough parameters are available to monitor e.g., the quality of the gain-drift correction or the presence of additional radionuclides such as ^{137}Cs, whereas in the FSA a high c^2 is indicative of (amongst others) incomplete gain-drift correction or an improper set of fitting functions. Additionally, for nuclides emitting more than one ?-ray, the part of the ?-rays that are not included into the windows will contribute to the quality of the result in the FSA as well.

To compare both analysis methods, data that was acquired from measuring a monazite sample has been analysed using both techniques. For more than 20,000 one-second spectra, the activity concentrations of ^{40}K, ^{232}Th and ^{238}U were calculated and plotted in histograms. In the left panel of figure 2, an example of the distribution of calculated activities for ^{232}Th is given for an integration time of 4 seconds, using both the FSA as well as the windows method. This figure shows that, as expected, the mean values of both methods correspond well with the true concentration of the sample, however the distribution spread (or uncertainty) is larger using the windows analysis.

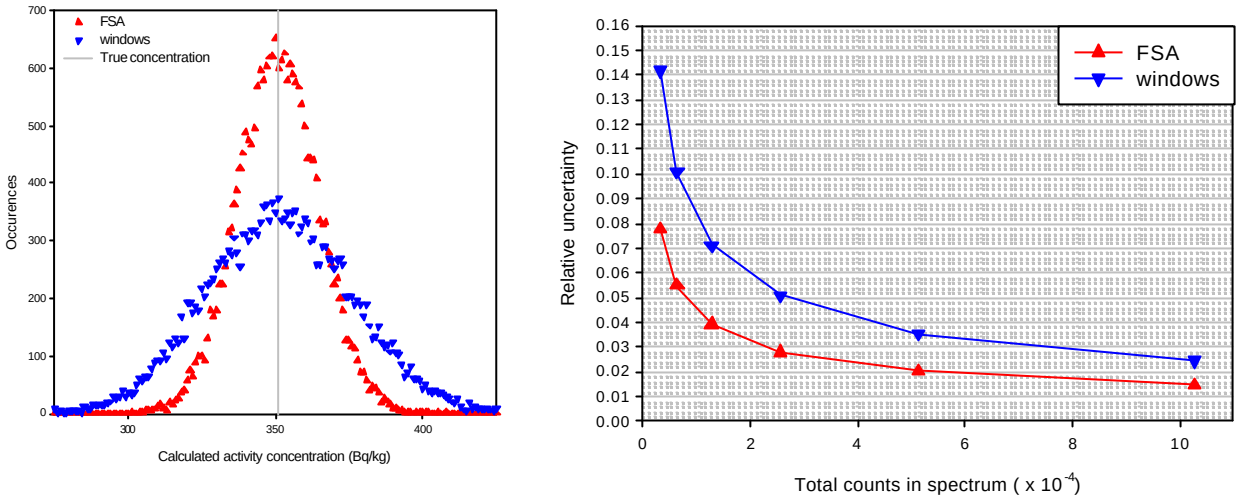

Figure 2: *Left panel: distribution of ^{232}Th activity concentrations extracted from repeated measurements on a test sample. Both the FSA-calculated (triangle up) and windows method results (triangle down) are shown. The right panel shows the variation of the relative uncertainty with counting statistics, taken from Hendriks, 2000.*

From these distribution plots, the mean values and widths were extracted from which the relative uncertainties were calculated, which are shown in the right panel of figure 2. Additionally, spectra have been summed to create spectra with varying integration times and the aforementioned procedure was repeated and relative uncertainties were calculated again. These results are also shown in the right panel of figure 2 giving the variation of the relative uncertainty with counting statistics. This figure shows that to obtain a similar accuracy as with the FSA, measuring times using the windows method need at least to be tripled.

4. CALIBRATIONS

Although the MEDUSA system was originally intended for mapping the natural radioactivity levels on the underwater bottom, lately it also has been successfully applied in airborne, borehole and even car-borne measurements. One of the key features of the system is that it can measure nuclide specific, i.e., the spectral contributions of the constituents ^{40}K, ^{232}Th and ^{238}U can be resolved. Furthermore, MEDUSA is able to measure absolute radiation levels and not just changes in abundances. This enables the additional step of "radiometric fingerprinting", in which the concentration levels are translated to sediment types. Applying the system in different geometries requires a calibration of the system in each of the geometries, under conditions that mimic the experimental conditions as closely as possible. The calibration procedure is the same for both the windows analysis as the FSA and uses separate set-ups for the radionuclides of interest plus an additional set-up to assess the background radiation. The sediment composition of the set-ups was chosen such that the "orthogonality" of set-ups was optimized; thus each contains a high concentration of one natural radionuclide, and low concentrations of the other nuclides. The activities were determined (in Bq/kg) by measuring representative samples on a HPGe detector. This way, for each set-up a concentration matrix is constructed, containing the ^{40}K, ^{232}Th and ^{238}U concentrations and the background term that is subtracted from each measured spectrum. Combined, this gives the total activity-concentration matrix $\boldsymbol{A}$. Of course this procedure can be extended to include any nuclide of interest (such as ^{137}Cs). For calibration, the detector system is placed in each of the set-ups to measure the so-called *calibration* spectra $\boldsymbol{CS}$. These calibration spectra are the response of the detector to the known activity concentrations. Once the response of the detector to a known activity concentration is measured, the response to 1 Bq/kg of a radionuclide, the *standard* spectra $\boldsymbol{X}$, can be calculated from $\boldsymbol{X = CS \cdot A^{-1}}$.

Comparing the results of calibrations carried out using the NGD borehole facility and seabed/airborne facility of the British Geological Survey in Keyworth, United Kingdom, the geometry dependent

component has been investigated. As an example, in figure 3 the total counts in the standard spectra for ^{40}K is compared for airborne and towed seabed geometries. The contents of the spectra are shown as a function of γ-ray energy, and are scaled with the contents of the borehole standard spectra.

This figure shows that the maximum spread around the average is about 10%. As a result of this, only one calibration geometry is needed and via factors that account for the differences between geometries, an absolute calibration in one geometry can be scaled to another geometry. If the required accuracy is not better than 10%, the scaling can be carried out independent of energy. If a better accuracy is needed, the scaling of the standard spectra must be done, using a scaling factor that depends on the γ-ray energy. The great benefit of geometry-scalable calibrations is that the need for time consuming and expensive calibrations is removed, and only one calibration facility is needed.

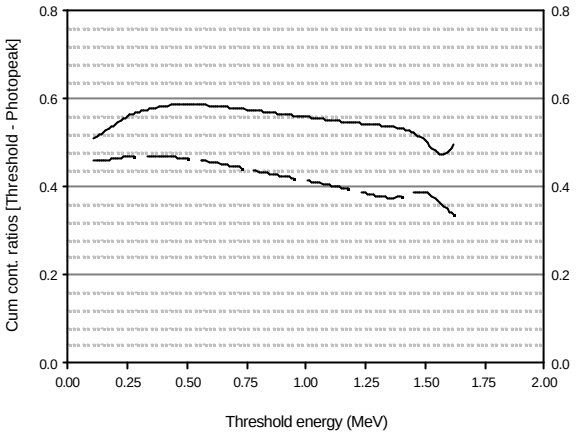

***Figure 3**: Cumulative contents (counts) of the standard spectra for airborne (solid line) and towed seabed (dashed) geometry, as function of g-ray energy for ^{40}K. The contents have been scaled with respect to the standard spectrum for borehole geometry, from Hendriks (2000).*

5. CONCLUSIONS AND OUTLOOK

The high detection-efficiency of a BGO detector, together with a Full-Spectrum Analysis of the (-ray spectra makes the MEDUSA system at least one order of magnitude more sensitive than traditional systems based on NaI detectors and 'windows' analysis. This is due to a combination of the four to five times higher efficiency of BGO compared to NaI and an extra factor of at least three due the advanced data analysis. When count rates become smaller, the difference in sensitivity between the new system and traditional systems grows progressively, due to the propagation of errors via the stripping factor in the windows method, notably so for the higher energies (uranium and thorium). The improved sensitivity allows for smaller integration times, hence shorter measurements or a higher spatial-resolution. This makes MEDUSA very suited to measure the generally low activity concentrations of naturally occurring radionuclides *in-situ*, such as towed seabed, borehole logging or airborne surveys. If the desired accuracy is in the range of 10%, the standard spectra determined for one geometry can be adjusted to the appropriate geometry, independent of ?-ray energy. If a better accuracy is needed, a scale factor that varies with energy should be used for conversion of standard spectra. This is important because only *one* calibration environment is now necessary, and a scaling factor encompassing the geometry effects can be used to construct to convert the standard spectra for the other geometries. Recently, Monte Carlo simulations of ?-ray transport have been started. The goal of the new investigation is to better understand the shape of the ?-ray spectra as recorded by the detector. We anticipate to extract from the measured spectra information on density variations and/or layer structures in the geological matrix. At a longer term we intend to check these achievements by ground thruthing. Eventually we aim at combining the γ-ray information with other physical parameters to improve the geological information.

6. REFERENCES

Hendriks P., Limburg J. and De Meijer R.J. "Full Spectrum Analysis of Natural Gamma Ray Spectra", submitted for publication, Journal of Environmental Radioactivity