Development of methods to use CdTe detectors in field measurements

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Abstract. We are currently investigating the possibility to use CdTe detectors for in situ determinations of radionuclide concentration in soil. Buried activity can be reliably determined by a comparison of the count rate in the photo peak and the region between the photo peak and Compton edge. However, the pulse-height spectrum from CdTe detectors is severely deteriorated, due to poor charge collection, in particular for high gamma-ray energies. Our efforts have, therefore, been concentrated on improving the peak to valley ratio for such detectors. A simple, non-discriminating, algorithm for the analysis of output from two amplifiers with different shaping times is described. By means of this algorithm the peak-to-valley ratio for a small planar CdTe detector is improved by more than a factor of six compared to the uncorrected ratio without loss of efficiency.

1. Introduction
We are currently investigating the possibility to use CdTe detectors for in situ determinations of radionuclide concentration in soil. As a detector for gamma radiation CdTe is rugged and requires no cooling. In addition, due to high atomic numbers, the detectors can be made small. However, their application is hampered by poor charge collection in particular due to trapping of holes (figure 1).

In a previous study [1] with HPGe detectors it has been shown that buried activity can be reliably determined by a comparison of the count rate in the photo peak and the region between the photo peak and Compton edge (the valley region). We therefore concentrate our efforts on improving peak to valley ratios for CdTe detectors (figure 2).

Figure 1. Pulse shapes at the preamplifier output from a small planar CdTe detector. All pulses correspond to the same deposited energy. The pulses are the sum of two contributions; one fast component due to electrons and one slow due to holes. The variations in pulse height are (mainly) due to trapping of holes (c.f. text).
The pulse from a CdTe detector is the sum of two components, originating from the drift of electrons and holes respectively. The proportion of the pulse generated from each one of these components depends on the relative distance from the point of interaction in the detector to the anode and cathode respectively. Following an interaction close to the cathode (anode) the pulse shape is dominated by the contribution from electrons (holes). In the following the point of interaction is characterized by the interaction depth, $x$, increasing from $x = 0$ at the cathode to $x = 1$ at the anode.

The major contribution to the dependence of the pulse height on the interaction depth is due to trapping of charge carriers (c.f. figure 1). The mobility of the electrons is approximately ten times greater than that of holes, whereas the trapping time is of the same magnitude for both [2]. Hence the contribution of holes to the pulse height is more severely affected by trapping. This results in a distorted pulse height spectrum characterized by large tails to the full-energy peak for higher gamma-ray energies. Other, minor, contributions are due to the escape of x-rays and electrons.

There are several methods to diminish the problems caused by the variations in pulse shape and thereby to improve the spectrum. One such method is to use rise time discrimination [3], i.e. to reject pulses with a significant contribution due to holes (i.e. slow rise time). This, however, may lead to a severe loss of efficiency. Another possibility is to fit an analytical expression to the sampled shape of individual pulses in order to determine the energy deposited [4-6]. The drawback being that large amounts of data have to be stored and analysed.

We have chosen to develop further a method using multiple amplifiers [6]. We have implemented a simple algorithm using two standard spectroscopy amplifiers with different shaping times resulting in what is effectively a determination of the interaction depth of individual events which is then used to correct the pulse height.

2. Algorithm
The pulses from the preamplifier of the CdTe detector are fed to two spectroscopy amplifiers with different shaping times. In a scatter plot of the events built from the pulse heights from the two amplifiers a region corresponding to the full energy events can be distinguished from the Compton continuum (c.f. figure 3). In the scatter plot events corresponding to an interaction depth $x = 0$ fall along the diagonal. For larger interaction depth the events fall increasingly below the diagonal. The resolution in this representation is much better than in the one-dimensional case. The pulse-height distribution displayed in figure 2 is obtained by projection onto the y-axis of all data in the scatter plot.

We may now proceed along two different paths, either continue working in the 2-dimensional representation, this is currently being investigated, or use the 2-dimensional representation to establish an improved 1-dimensional energy distribution for which the conventional peak-to-valley method [1]
can then be applied directly. In this communication the latter approach is presented in some more
detail. We assume that the pulse height from one of the amplifiers, $p_i$, is given by

$$p_i = E \cdot f(x, \tau_i) + p_i^0$$

(1)

where $E$ is the deposited energy, $f(x, \tau)$ is a function of the interaction depth, $x$, and the shaping time of
the amplifier, $\tau$. We assume $f(x, \tau)$ to be a monotone function of $x$. This is not strictly the case for
interactions in a region close to the cathode. The maximum pulse height corresponds to events with a
finite (but small) contribution due to holes. This effect, however, is small compared to the noise of the
system and can safely be neglected. The pulse height, $p_i^0$, corresponding to zero energy deposition we
assume to be zero for reasons of pedagogic simplicity.

The ratio of the pulse heights from the two amplifiers is then given by

$$\frac{p_1}{p_2} = \frac{E \cdot f(x, \tau_1)}{E \cdot f(x, \tau_2)} = F(x, \tau_1, \tau_2)$$

(2)

where the function $F$ is again a monotone function of the interaction depth, $x$, disregarding the small
region close to the cathode. The interaction depth is then given by

$$x = F^{-1}\left(\frac{p_1}{p_2}, \tau_1, \tau_2\right)$$

(3)

and inserting this in (1) we obtain

$$p_i = E \cdot f\left(F^{-1}\left(\frac{p_1}{p_2}, \tau_1, \tau_2\right), \tau_i\right) = E \cdot G_{\tau_i} \left(\frac{p_1}{p_2}\right)$$

(4)

Fitting (4) to the (2-dimensional) pulse-height distribution pertaining to a known gamma-ray
energy allows us to determine the pulse height correction factor $G_{\tau_i}(p_1/p_2)$. An arbitrary pulse height
distribution (measured with the same system) can then be transformed event by event according to

$$E = p_i \left[G_{\tau_i} \left(\frac{p_1}{p_2}\right)\right]^{-1}$$

(5)

3. Results
The method has been applied to a 5×5×2 mm$^3$ CdTe detector. A pulse height distribution was recorded
using a $^{137}$Cs source and shaping times of 0.5 µs and 3.0 µs respectively (c.f. figure 3). In order to
determine the correction factor $G_{\tau_i}$ we made the approximation

$$G_{\tau_i} \left(\frac{p_1}{p_2}\right) = a_0 + a_1 \left(\frac{p_1}{p_2}\right) + a_2 \left(\frac{p_1}{p_2}\right)^2$$

(6)

and fitted the polynomial to the data points belonging to the full energy events (assuming the noise for
all events to be equal). The result of applying the correction to the pulse height distribution in the
faster amplifier is presented in figure 4 and table 1.
Table 1. Comparison of the characteristics of the energy distributions before and after correction for a $^{137}$Cs source. The peak to valley ratio is taken between the maximum of the full energy peak (662 keV) and the average height in the valley region (550-570 keV). The peak to Compton ratio is taken between the maximum of the full energy peak and the average of the Compton distribution (340-370 keV). The full energy to Compton ratio is taken between the integrated peak (647-677 keV) and the integrated Compton distribution (340-370 keV).

|                  | CdTe Corrected | CdTe Uncorrected |
|------------------|----------------|------------------|
| FWHM at 662 keV  | 2.0 %          | 2.0 %            |
| Peak / valley    | 30             | 4.6              |
| Peak / Compton   | 1.6            | 0.8              |
| Full energy / Compton | 3.2          | 1.0              |

4. Discussion and conclusion
Applying the described algorithm improves the peak-to-valley ratio by more than a factor of six. However, we notice a broadening of the photo peak at the base compared to the uncorrected spectrum. In the uncorrected spectrum there is a negligible number of counts above 680 keV. In the corrected spectrum there is a non-negligible number of counts even above 700 keV. However the resolution measured at half maximum of the full energy peak is essentially unchanged. The broadening can be reduced by leaving out events corresponding to smaller values of $p_1/p_2$, i.e. larger interaction depth. The peak to valley ratio is then increased further and the energy resolution is improved, although at the loss of efficiency.

In conclusion we have described an algorithm that is simple to implement and that is shown to substantially improve the peak-to-valley ratio in case of a small planar CdTe detector without loss of efficiency. The rate of improvement depends strongly on the ratio of trapping and drift times of the charge carriers, in particular that of holes.

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