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Energy calibration of individual crystals in a LYSO pixelated array for microPET detection modules using Voronoi diagrams

H. Alva-Sánchez *, A. Martínez-Dávalos, E. Moreno-Barbosa, B. Hernández-Reyes, T. Murrieta, C. Ruiz-Trejo, M.E. Brandan, M. Rodríguez-Villafuerte

Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, 01000 México D.F., Mexico

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Most small-animal positron emission tomography imaging systems nowadays use scintillator crystal arrays coupled to position-sensitive photomultiplier tubes (PS-PMT) as their detector modules. Individual crystal region identification to set tight energy thresholds has been introduced to reduce scatter and pileup events. In this work, we have used Voronoi diagrams to implement both tasks in a fast and efficient way for data analysis from a 20×20 LYSO crystal array coupled to Hamamatsu H8500 PS-PMT. This module forms part of a benchtop microPET system currently being developed at UNAM, Mexico. The results show that the use of individual crystal energy windows does not reduce image distortions, caused by pulse pileup, in 2-D data acquisition projections obtained with our system.

1. Introduction

Dedicated small animal positron emission tomography (microPET) systems have been developed by leading research groups since the early 1990s [1]. Most detector modules for microPET systems consist of pixelated scintillator crystals optically coupled to position-sensitive photomultiplier tubes (PS-PMT) and use Anger-type logic circuitry [2] to determine photon interaction position within the detector. New crystals such as LSO (cerium-doped lutetium orthosilicate) or LYSO ($Lu_{2(1-x)}Y_{2x}SiO_5$:Ce) are being used in modern animal PET systems obtaining spatial resolutions of 1 mm or better [3]. Its high effective atomic number ($Z_{eff} = 63$) and fast response time (~48 ns) make LYSO a suitable scintillation crystal for small animal PET systems which require superior spatial resolution characteristics than clinical scanners.

A benchtop prototype microPET system is being developed at Instituto de Física, UNAM, composed of two detection modules. Each module consists of one 64-channel Hamamatsu H8500 PS-PMT coupled to a 20×20 pixelated LYSO crystal array, provided by Proteus, Inc.[1] The dimensions of one crystal element are $2 \times 2 \times 10\,mm^3$ and each element is wrapped on five of its sides with a 75 μm thick reflective layer of VM2000. A position encoding circuit for this particular PS-PMT has been designed, built and tested together with a United Electronics[2] PD-MFS-2MS/s-8/14 acquisition board.

Typical PET acquisition data require energy windowing in the 350–650 keV interval [4]. The main reason for the use of energy discrimination is to reduce scattered photons, but it has been proposed that restrictive energy discrimination windows should be applied to individual crystals in 2-D array detectors to reduce unwanted pileup events [5]. These events not only carry incorrect energy values, but are also mispositioned by the Anger logic equations. The objective of this work is twofold: (a) to develop a method to obtain individual crystal energy spectra and (b) to correct for image distortions introduced by pulse pileup using the method proposed by Germano et al. [5]. For this purpose we have implemented Voronoi diagrams as a technique to divide the detector's area into regions around the crystal centroids. An energy calibration map for both detectors was produced, obtaining energy discrimination windows for individual crystal elements of the detector modules as a method to not only reject Compton scattered photons, but also to reduce unwanted pileup events. For each of the 400 individual crystals of each module, photopeak and energy resolution variations across the entire detector's area were investigated from flood source images using ^{22}Na. Individual crystal energy windowing was implemented in 2-D parallel beam geometry projections [6] of a microDerenzo

* Corresponding author.
E-mail address: halva@fisica.unam.mx (H. Alva-Sánchez).

[1] Proteus Inc., P.O. Box. 747, 120 Senlac Hills Drive, Chagrin Falls, OH 44022, USA.

[2] United Electronics Industries Inc., 27 Renmar Avenue, Walpole, MA 02081, USA.

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phantom with activities ranging from 51.4 MBq (1.39 mCi) to 543.9 kBq (14.7 μCi) of ^{18}F. Narrow energy discrimination was applied event by event in the projection data in order to investigate the effectiveness of the method to reduce unwanted pileup events, and thus, image distortion.

2. Materials and methods

2.1. Detector modules

One detection module consists of a 64-channel Hamamatsu H8500 PS-PMT coupled to a 20×20 pixelated LYSO crystal array. The dimensions of one crystal element are $2 \times 2 \times 10\,\mathrm{mm}^3$ (2.075 mm pitch, with a 75 μm thick reflective layer of VM2000). A 333 kBq (9.0 μCi) ^{22}Na source (3 mm diameter), placed 7.0 cm away along the central axis, was used. An image with 50 million events was acquired in singles mode for each detection module to obtain energy spectra with a sufficient number of counts for individual crystals. The event rate with this source was 6.8 kcps. Under these experimental conditions, in the absence of the ^{22}Na source, the registered background rate due to the natural radioactivity of the LYSO crystals was 4.2 kcps, taken with a lower energy threshold of 33 keV.

2.2. Data acquisition board and electronics

A fast acquisition board is required for high counting rates, in particular for coincidence detection in PET. The data acquisition system of our benchtop system is based on a United Electronics PD-MFS-2MS/s-8/14 board, which has eight analogue channels with 14 bits resolution, a sampling frequency of 2.2 M samples per second, using a sample and hold technique. The acquisition board is computer controlled by software written in LabVIEW 7.1, and used to simultaneously collect large amounts of data. The 64 output signals from the crystal-PS-PMT modules are reduced to 4 by using an Anger-type logic DPC resistive chain [2]. Fig. 1 shows schematically the electronic modules used for the acquisition system.

Only the pulse height at peak maximum is sampled by triggering the DAQ board using a Gate & Delay module, in a similar way as reported by Judenhofer et al. [7]. A 3.0 μs integration time at the CAEN N568 shaping amplifier was used. This relatively long integration time is a requirement for the board to correctly digitize the signal. For shorter integration times the amplitude of pulses is incorrectly sampled. This limitation introduces a pileup problem at high counting rates.

2.3. Dead time and pileup measurements

The system dead time, working in coincidence mode between both detection modules, was measured using the decaying source method [8] with a vial (1.0 ml volume) containing an activity of 91.39 MBq (2.47 mCi) of ^{18}F, placed 10 cm away from the detectors. A CAEN N455 coincidence unit was used with a 40 ns coincidence window (20 ns width of the NIM pulses from a CAEN N452 constant fraction discriminator). Data were stored in list mode.

Pileup was measured in singles mode for one detector by mixing pulses from a pulse generator with pulses from the detector with a 370 kBq (10 μCi) ^{137}Cs source at the preamplification stage creating an artificial peak in the energy spectrum. Since the number of pulses injected by the generator is known, a comparison of the area under the artificial peak with and without detector pulses yields the fraction of pileup events. Then, the assumption is made that the observed pileup in the artificial peak is the same for all pulse amplitudes [8].

2.4. Voronoi diagrams

In a 2-D array detector, each registered event has to be energy discriminated according to the energy response of the detecting crystal element. However, the non-uniformities of the detection modules (crystals, PS-PMTs, resistive chains, electronics, etc.), produce distorted images that prevent the use of regular grids for crystal identification. It is in this analysis where the Voronoi diagrams can be useful. Given a set of fixed points or sites, Voronoi diagrams divide the plane according to a nearest-neighbour rule: each point is associated with the region of the plane closest to it. The Voronoi diagram consists of regions divided by boundaries whose edges and vertices are the loci of points equidistant to exactly two sites and at least three sites, respectively. The work by Aurenhammer [9] provides an excellent reference to Voronoi diagrams and their use in many applications.

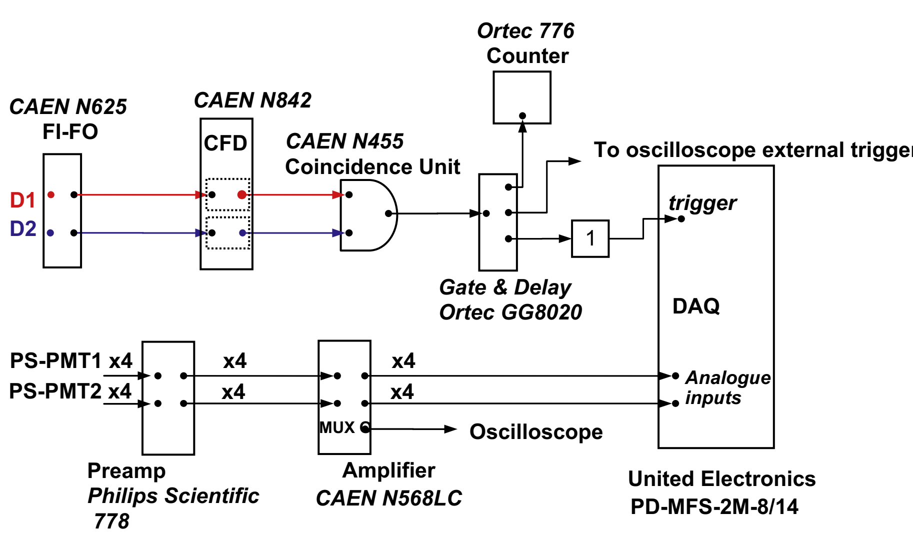

Fig. 1. Schematic of the electronics showing the DAQ UE PD-MFS-2M-8/14 being triggered with the dynode 12 from the PS-PMT only when an event is detected in coincidence in both detectors. Only the peak maximum of pulses is digitized.