Simulation and Measurement of Gamma Ray and Annihilation Photon Imaging Detectors

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Abstract-- We have developed a simulation tool that model position sensitive gamma ray and annihilation photon detectors to realistically estimate the detector performance. The simulation is based on Monte-Carlo simulation code that calculates the probability of photoelectric or Compton interaction in a given detector geometry. The propagation of scintillation light of each interaction is simulated using DETECT2000. To approximate the actual signal response of a detector, the physical geometry of each position-sensitive photon detector is modeled. The simulation is tested using position sensitive PMTs with pixellated LSO and Na(Tl) crystals. Qualitatively, the simulated and measured flood images compared very well. Both show similar edge effects and resolved the same number of crystals (21x21 for LSO and 27x27 for NaI(Tl)) compared to the "ideal" position sensitive detector resolving 22x22 for LSO and 29x29 for NaI(Tl) crystals after energy gating is applied. An intrinsic spatial integral non-linearity (INL) of 1% (for simulation) and 1.4% (for measured data before gain correction) was calculated for NaI(Tl). For LSO less than 2.3% INL is obtained in both cases (??). The linearity match is expected to improve when more accurate detector model and gain correction are applied. A finite element method is used to model with good approximation a position sensitive avalanche photodiode (PSAPD) detector surface. A third or higher order polynomial fit is applied to to an electrical Finite Element Model of PSAPD detector and provided good match with measurement, including the generation of a similar pincushion distortion pattern.

I. Introduction

Monte Carlo simulation techniques have been powerful tools to study imaging detector performance [1,2,3]. In nuclear medicine Monte-Carlo simulation packages such as GATE [4] may be used to calculate the distribution of probability of photoelectric or Compton interactions in a tissue or scintillation crystal. In addition, GATE has a digitizer that simulates the detector behavior and signal processing chain of each gamma interaction. This is performed by following the history of interactions of a photon in elementary trajectory steps. It assumes an ideal detector surface. The actual physical geometry and sensitivity variation of each position sensitive detector behavior is generally not modeled to compare with measurements.

To realistically estimate the detector performance, it is important to simulate the propagation of light photons generated from each gamma ray or annihilation photon interactions [5]. This is typically performed using Detect2000 [6], a Monte Carlo simulation package that models the optics of scintillation detectors. Detect2000 also assumes an ideal position sensitive detector surface, but it models the crystal surfaces, the type of reflectors used between individual crystals and the number of pixellated crystals in a given detector geometry. To recover the actual signal response of a detector from simulation, the physical geometry and sensitivity variation of each position sensitive detector has to be modeled.

We are developing both gamma ray and positron emission tomography (PET) systems based on novel scintillation detector design concepts [7,8]. Our goals for these systems are high spatial resolution and high sensitivity. The systems will be optimized for specific applications in cancer imaging/staging and in pre-clinical imaging of small animals. In this work we modified and incorporated photodetector response to Detect2000 simulation package to include typical detector parameters such as anode plane dead area and spatial non-linearity. The simulation results then can be realistically compared to experimental data.

II. Material and Methods

A. Detector configuration and Measurement

Two detector systems have been considered based on PSPMT and PSAPD photodetectors. Both LSO and NaI(Tl) crystal arrays are used with 5x5 cm field of view (FOV) PSPMT detector (Fig. 1) with 8x8 anode channels. These detectors will be used in a single photon hand held gamma imaging system, which is being developed [9]. The LSO crystal array consists of 23x23 crystals each 2x2x3 mm with five GROUND surfaces and one POLISHED surface. Two layers of Teflon were wrapped over the ground side surfaces of each crystal. The array was optically coupled to PSPMT using silicon grease. The 5x5 cm^2 FOV NaI(Tl) crystal array (obtain from SAINT-GOBAIN) has 29x29 crystals each 1.5x1.5x6 mm^3 on a 1.7 mm pitch. A white reflector between crystals and surface treatment is applied to the crystal array. Flood irradiation was performed for both LSO and NaI(Tl) arrays using a Co-57 (122 keV) single photon source. The signals from each anode are readout in parallel using CAMAC readout system [10]. A centroid is calculated from list mode data of each event to form flood image.

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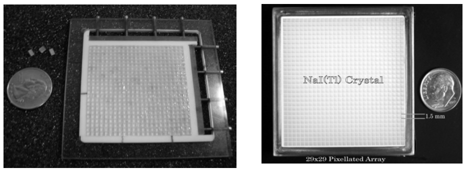

Fig. 1 Left, LSO crystal array (23x23) each of 2x2x3 mm3, Right, NaI(Tl) crystal array(29x29) each of 1.5x1.5x6mm on 1.7mm pitch.

A detector system using LSO crystals and PSAPD detector is also being developed that will be used to image annihilation photons in a small animal PET system [11]. A prototype 4x3 LSO array of 2x2x3 mm^3 crystals was formed without reflector between crystals as shown in Fig. 2. The top and four sides of the crystal array are covered with Teflon and it is optically coupled covering the active 8x8mm^2 area of PSAPD. Flood measurement is then performed using Na22 (511keV) annihilation photon source irradiating from top. For each event, the signals from four corner anodes of the PSAPD are readout and digitized. The centroid of each event is calculated from the digitized anode signals.

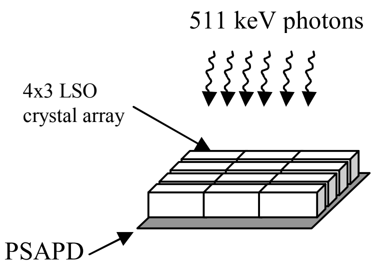

Fig. 2 LSO crystal array (4x3) coupled to PSAPD

B. Simulation

The simulation model combines two Monte-Carlo simulation codes to generate interaction gamma photons and ray tracing simulation of light transport generated and detected from each interaction in the defined crystal geometry (Fig. 3). In this work most of the simulated gamma interactions were generated using previously developed gamma interaction simulation code since it is relatively faster than GATE. We used GATE to verify the simulation output and indeed it produced the same result. A 3% blur in energy was applied in generating the gamma interactions. For each generated interaction from flood source, the interaction coordinate along with the corresponding calculated number of photons is recorded in the interaction list file, which was used as input to Detect2000.

DETECT2000 is used to simulate the light transport for a given crystal arrays and detector systems. The input and output parameters of DETECT2000 have been modified to include physical characteristics of a particular photodetector (PSPMT or PSAPD) and crystal array used. Detect2000 requires an input file that contains all materials, definition of surface finishes, component geometries, output options and program controls. Part of this file is generated using Builder, which is a utility program for managing model geometry definition for Detect2000. This file is updated for each event to include the interaction coordinates and the number of photons to be generated through the input program we developed for Detect2000. Once the input file is complete, Detect2000 runs to simulate the events and generate light photons. It then traces and follows each photon to its final fate. The coordinates of detected photons that reach the detect surface are recorded and sent to output program. Depending on the detector used, the final output is extracted through the output program, which is added in Detect2000. Currently, the program models the dead spaces for the PSPMT detector. If the photon falls in the dead space, it will be ignored. Otherwise it will be added as detected to the identified anode pixel for generating more realistic anode signals. The centroid is calculated from the total sum of photons over each anode. Through this program more physical properties of a detector such as sensitivity variation, non-linearity and detector noise were also modeled.

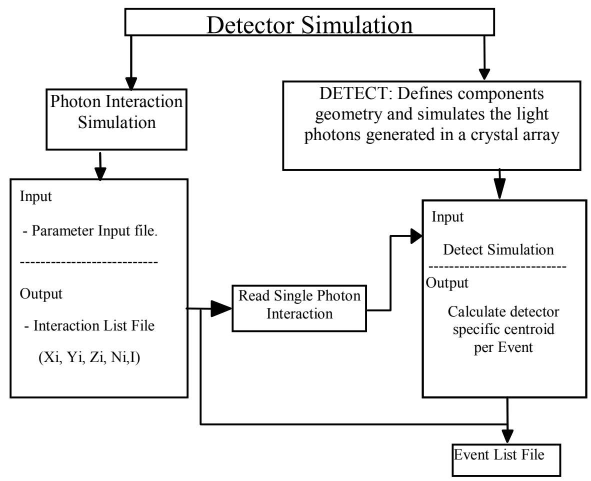

Fig. 3 Detector Simulation model that combines gamma photon interaction simulation code with DETECT2000 light propagation simulation software.

For simulation, to model the diffuse reflector surfaces between LSO and NaI(Tl) crystals, a UNIFIED surface model was used that treats the interaction of scintillation photons with dielectric surfaces. In UNIFIED surface model the refractive index of the reflector and the average roughness of a surface can be specified, while the angle between micro-facet normal and the average surface normal is assumed to follow a Gaussian distribution [12]. POLISHED surface model is assumed for the crystal surface connecting the PSPMT.

C. Finite Element method to model PSAPD response

The non-linear pincushion behavior of PSAPD was modeled using a finite element method. This assumed a uniform resistive mesh on the back surface of PSAPD coupled to the

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corner anode readout nodes. A polynomial function then relates the position of a current on the surface to the position that would be read out from detector. Since photons are converted into electron-hole pairs, the photons that strike the surface of the PSAPD can be mapped to distorted position based on the polynomial function.

III. RESULTS

A. Flood Image of LSO coupled to PSPMT

Fig. 4 shows the comparison of flood images from simulation and measurement using LSO crystal array and PSPMT. The simulated "ideal" position sensitive PMT (left) can continuously detect all scintillation photons impinging upon its active photocathode. After the size and dead spaces between each anode of the 8x8 anode PSPMT has been modeled, the simulation result (middle) matched better to experimental measurements (right) with a Co-57 flood source. In both cases, 21 x 21 crystal array could be resolved when energy gating is applied, while the "ideal" detector resolved 22x22 crystals that cover the sensitive area of the PSPMT.

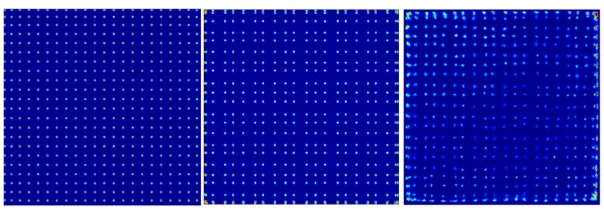

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Fig. 4 Flood Images of LSO crystal array (23x23) coupled to 5x5cm2 FOV PSPMT, from a) Simulation assuming an "ideal" detector, b) Simulation after the size and dead area has been modeled and c) Measurement using Co-57 single photon source.

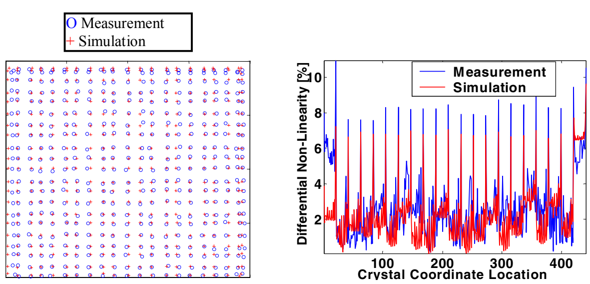

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Fig. 5 a) Peak coordinates of flood images of LSO crystal array coupled to PSPMT from corrected simulation (red) and measurement (blue o), b) Differential non-linearity of simulation and measurement with respect uniform grid.

The coordinates of peak location of each crystal calculated from the simulation and measurements are plotted together to illustrate the match as shown in Fig. 5a. The peak location of flood images from simulation and measurement matched very well. The differential non-linearity with respect to a uniform grid is very similar for both simulation and measurement (Figure 5b). Less than 2.3% integral non-linearity (INL) is obtained in both simulation and measurement with respect to a uniform grid. Note that the noise from PSPMT and electronics are ignored in the simulation. The result is expected to improve when gain and sensitivity variation of the PSPMT detector is also modeled in the simulation, which is not considered for this report.

B. Flood Image of NaI(Tl) coupled to PSPMT

Similar flood simulation and measurement with the NaI(Tl) crystal array resolved 27x27 crystals after energy gating is applied. Both simulated and measured data showed near perfect match with similar edge effect (Fig. 6). The "ideal" detector model resolved all 29x29 crystals.

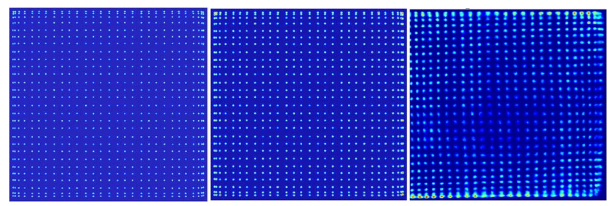

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Fig. 6 Flood Image using NaI(Tl) crystal array (29x29) coupled to 5x5cm2 FOV PSPMT, a)Simulation data assuming "ideal" detector, b) Simulation after anode size and dead area has been modeled and c) Measurement data using Co-57 single photon source.

The superimposed peak coordinates of both simulated and measured data (Fig., 7a) show a very good match. Excluding the edge crystals, a 1% and 1.4% intrinsic spatial INL was obtained respectively both for simulation and measurement (Fig. 7b). The linearity match is expected to improve when more accurate detector model is derived and gain correction to each anode is applied.

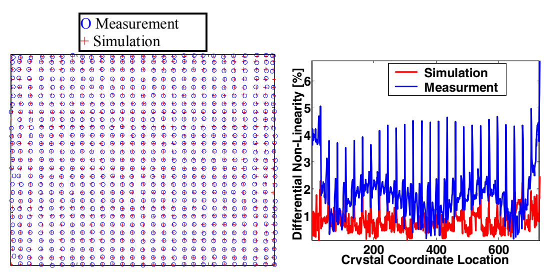

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Fig. 7 a) Peak coordinates of flood images of NaI(Tl) crystal array coupled to PSPMT for corrected simulation (Red +) and measurement (Blue o), b) Differential non-linearity of corrected simulation and measurement with respect uniform grid.

D. Flood Image of LSO coupled to PSAPD

To understand and also correct the non-linear pincushion behavior of PSAPD, simulation is performed that applied the new PSAPD model developed using finite element method. Fig.8 compares the flood images obtained from simulation and measurement using 4x3 LSO crystal array coupled to PSAPD. Results from a third order polynomial fit to ??? is shown in the flood image of 4x3 LSO crystal array (Fig. 8b) that matches better to measured data (Fig. 8c) compared to “ideal” detector model (Fig. 8a).

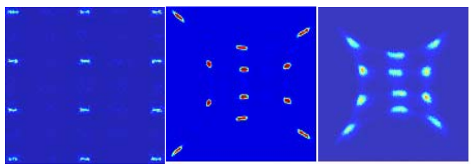

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Figure 8, Flood image using LSO coupled to PSPAD of a) “Ideal” detector simulation, b) Corrected simulation, and c) measurement

Peak coordinate location are plotted (Fig. 9) to show the match between the simulation and measurement. The measured data was scaled to facilitate comparison. The simulation provided good approximation following similar pincushion pattern. Further refinements of the detector sensitivity and gain non-uniformity will provide better approximation.

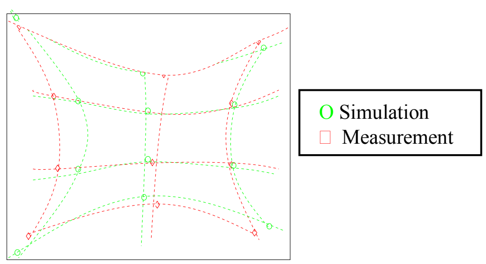

Fig. 9 Peak coordinates of simulation (Green) and measurement (Red) of PSAPD detector.

IV. Discussion and Conclusion

In this paper we presented a simulation model that includes the physical parameters of photodetectors to realistically compare with measurements. More accurate simulation data generally help to more accurate design of single photon or annihilation photo imaging systems, which are being developed. Accurate modeling of crystal identification and edge effects of each detector in simulation allows one to easily study the detector performance when. We have developed relatively accurate model of a scintillation detector array that compares very well to measured flood data. Further refinements incorporating specific parameters of the detector will provide a more accurate match with measurement depending on the accuracy required for the system design.

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V. Acknowledgment

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VI. References

[1] G.Tsang, C. Moisan, and J.C. Rogers, “A simulation to Model Position Encoding Multicrystal PET Detectors”, IEEE Trans. Nucl. Sci, Vol. 42, No 6, December 1995.

[2] I.Buvat and I. Castiglioni, “Monte Carlo simulation in SPET and PET”, Q J Nucl Med, 46:48-61, March 2002.

[3] L. M. N. Tavora and W. B. Gilboy, “Study of compoton scattering signals in single-sided imaging application using Monte Carlo methods”, Nucl. Instr. And Meth. In phys. Res. B 213, 155-161 (2004).

[4] Luc Simon, et al., “Simulation of time curves in small animal PET using GATE”, Nucl. Instr. and Meth. A 527 (2004) 190-194.

[5] H. Rothfuss, et al, “Monte Carlo Simulation Study of LSO Crystals”, IEEE Trans. Nucl. Sci, Vol. 51, No 3, June 2004.

[6] F. Cayouette, et al., “Monte Carlo Modeling of Scintillator Crystal Performance for Stratified PET Detectors with DETECT2000”, IEEE Trans. Nucl. Sci, Vol. 49, No 3, June 2003.

[7] Levin CS. “Design of a High Resolution and High Sensitivity Scintillation Crystal Array for PET with Nearly Complete Light Collection”. *IEEE Trans Nucl Sci.*2002; 49(5): 2236-43.

[8] A. P. Dhanasopon, C.S. Levin, A.M. Foudray, P.D. Olcott, and F. Habte “Scintillation Crystal Design Features for a Miniature Gamma Ray Camera”. *IEEE Trans Nucl Sci.*2004 (in pres).

[9] P.D, Olcott, J. A. Talcott, C.S. Levin, F. Habte, A, M. Foudra, Compact Readout Electronics for Position Sensitive Photomultiplier Tubes. *IEEE Trans Nucl Sci.*2004 (in press).

[10] F. Habte, P.D. Olcott, C.S. Levin, and A.M. Foudray, “Prototype Parallel Readout System for Position Sensitive PMT based Gamma Ray Imaging Systems”, *IEEE Trans Nucl Sci.*2004(in press).

[11] C. S. Levin, F. Habte. “Initial Studies of a New Detector Design for Ultra-High Resolution Positron Emission Tomography”, *IEEE Trans Nucl Sci.*2004 (in press).

[12] A. Levin and C. Moisan, “A More Physical Approach to Model the Surface Treatment of Scintillation Counters and its Implementation into DETECT”, Conference Record of IEEE Nuclear Science Symposium 1996.