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SCOUT: A Fast Monte-Carlo Modeling Tool of Scintillation Camera Output

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Abstract

We have developed a Monte-Carlo photon-tracking and readout simulator called SCOUT to study the stochastic behavior of signals output from a simplified rectangular scintillation-camera design. SCOUT models the salient processes affecting signal generation, transport, and readout. Presently, we compare output signal statistics from SCOUT to experimental results for both a discrete and a monolithic camera. We also benchmark the speed of this simulation tool and compare it to existing simulation tools. We find this modeling tool to be relatively fast and predictive of experimental results. Depending on the modeled camera geometry, we found SCOUT to be 4 to 140 times faster than other modeling tools.

Keywords

Monte Carlo; simulation; photon tracking; scintillation camera; signal generation; random processes

I. Introduction

SCOUT is a Monte-Carlo photon-tracking and readout simulator. It originated at the University of Arizona [1] as a fast and simple tool for studying statistics of Scintillation Camera OUTput. This modeling tool is now supported at the University of Washington.

SCOUT currently considers only simple rectangular camera geometries (Fig. 1). However, it accurately models the salient processes affecting signal generation, transport, and readout. SCOUT has proven useful in studying how basic camera design affects the joint distribution of multiple output signals [1, 2].

In our ongoing effort to use this tool for surface-treatment optimization of dMiCE crystal-pair interfaces [3–5], we have recently extended optical-surface modeling to include several more surface treatments, mixtures of surface treatments, tabulation of bidirectional scatter distribution, and depth-dependent patterning and mixtures. We have also revised this tool to accurately model arrayed-scintillator cameras, dual-ended optical readout, and noise processes for Geiger-Müller avalanche photodiodes.

For this purpose and in preparation to make this tool publicly available, we conducted several validation and benchmark tests, comparing with experimental results [3–8] and other simulation tools (Geant4 [9] and Detect2000 [10, 11]). We find this modeling tool to be relatively fast and predictive of experimental results.

II. Camera Model

A. Detector geometry

SCOUT presently assumes the modeled camera is a rectangular array (one or more) of scintillation crystals with optional photodetectors (PD) and optical spacer (LG) on either or both the front and back faces (Fig. 1). The photodetectors are also presently assumed to be a rectangular array.

B. Stochastic processes

SCOUT generates signals as a series of random processes (Fig. 2). High-energy photons up to 1.022MeV (pair-production is not modeled) are input at a specified position/direction and subsequently interact and/or scatter in a fixed or stochastic manner within the detector volume. A number of scintillation photons are randomly generated from an energy-dependent normal distribution at each interaction point. Optical photons are tracked through the bulk and surfaces until the photons are absorbed or detected. Inputs of the photodetectors are then conditioned (accounting for random amplification, saturation, crosstalk, and after-pulsing) and then are electronically read out (accounting for conversion gain and added noise). Parameters that configure these processes include:

γ —ray transport (photoelectric, Compton, Rayleigh):

- Incident energy, position, and direction
- Fixed or stochastic first interaction type
- Linear attenuation coefficients vs. energy

Scintillation:

- Energy-dependent light yield (mean & variance)
- Characteristic rise and decay times

Optical transport:

- Linear probability densities of scatter and attenuation
- Optical-model selection for each surface
- Model-specific parameters

Photodetection:

- Number PD front and/or back
- Quantum efficiency (spectral average)
- Complex refractive index (spectral average)
- Active-area (support) shape & size
- Gain and gain noise
- Saturation, crosstalk, after-pulsing

Acquisition:

- Conversion gain
- Integration time
- Additive noise

C. Optical-surface models

The boundaries and interfaces of the scintillators, optical spacers, and photodetectors can either absorb or redirect incident light. Current models for reflectors and interfaces supported by SCOUT are illustrated in Fig. 3.

The specular reflector and interface models are described as usual by Snell's Law and the Law of Reflection. The Lambertian reflector yields a radiant intensity that obeys Lambert's Cosine Law. The Multifaceted (MF) diffuse model consists of locally specular surfaces whose slopes are sampled randomly from a parameterized normal distribution; self-shadowing is also considered by this model. The Diffuse-Cone model yields a uniform radiant intensity within an opening angle about the specular directions (both reflected and refracted); this opening angle is a parametric linear function of the incident angle [12]. The specular-coupling and MF-coupling models are similar to their standard counterparts except that a third optical material (of negligible thickness) is included at the interface. The Ideal Retroreflector simply reverses the incident direction. However, the Cube-corner Retroreflector is an accurate geometric model of a cube-corner array; cube size and orientation are parameterized. The isotropic reflector and interface model isotropically randomize the photon direction in the appropriate hemisphere. The bidirectional lookup is for use with experimentally calibrated scatter distribution data (e.g. [13–15]). For all interface models, reflectivity is governed by the Fresnel equations; we assume unpolarized light for this purpose, and average over both polarizations.

To allow more flexibility, a mixture of models can also be specified for each surface; for vertical surfaces, this mixture can be depth-dependent. Furthermore, vertical surfaces of the scintillator (the sides of each crystal element) can be subdivided into two regions that are symmetric about a vertical midline; a different depth-dependent mixture model can be specified for each region of each side of each crystal element.

For each surface we also model a probability for absorption and a probability of an air gap; randomly trapped air bubbles are a real issue that can affect the refractive properties of an interface or the effective coupling of a reflective or absorptive treatment.

D. Simulation record

The user specifies what results are to be saved by SCOUT. These may include: gamma-ray track history, optical photon track histories, track statistics, list-mode data of photodetector-input & amplifier-output signals, and signal statistics.

III. Experimental Comparison

We examine the fidelity of SCOUT simulated signals as compared with measurements made for both, discrete and monolithic detector geometries.

A. Discrete detector model

We consider a dMiCE crystal pair [3–5], which is optically isolated from other crystal pairs by 3 layers of Teflon tape. The interface of this pair consists of a shaped mirror film, which changes the amount of light shared by the photodetectors of these two crystals as a function of interaction depth (z_{DOI}).

In Fig. 4, we illustrate the dMiCE detector geometry considered and a coincidence-collimated source that was used to experimentally calibrate the mean detector response (MDR) of photopeak events as a function of z_{DOI} . We also indicate the model parameters used to simulate a comparable response from SCOUT. Some of the optical-model parameters that we did not have prior information for were selected to minimize the square error of the simulated verses experimental MDR. These parameters included the refractive index of the Melt-Mount® coupling material at 415 nm, the probability of absorption at the interface, the amount of air bubbles in the interface, and the transparency of the mirror film. The resulting parameter values (also shown in Fig. 4) were quite plausible given other anecdotal observations we made concerning these parameters. For instance, the prediction of air bubbles in the interface was initially not expected, but subsequently verified.

In Fig. 5 we show the experimental procedure for identifying the crystal that was *hit* (gamma-ray interacted in) and which was the *abutted* crystal. The photodetector signals that are filtered in this way are then used to calibrate *hit* and *abutted* detector response to 511-keV photoelectric gamma-ray interactions as a function z_{DOI} . Repeating this process in simulation, we then compare simulated to experimental signal spectra in Fig. 6 and depth dependence of the MDR for photopeak events in Fig. 7.

B. Monolithic detector model

We compare SCOUT simulated output of a cMiCE detector [7–8] with experiment. All simulation parameters in this case were selected based on prior knowledge or empirical observation.

A diagram of the detector and its calibration procedure are shown in Fig. 8. The MDR for photopeak events was measured with a physically collimated and coincidence-collimated ^{22}Na point source. We represent this calibration process in simulation with a 0.6-mm-diameter dual-energy (511-keV and 1274-keV) gamma-ray beam that is normally incident as shown in Fig. 8. Twenty thousand events were simulated at each beam position. The ratio of 511-keV to 1274-keV gamma-ray interactions that we simulated was 18:1, which accounts for solid angle subtended by the collimating aperture and the probability ratio for attenuation of these energies. We do not account for collimator penetration or scatter. We compare the resulting signal spectra in Fig. 9 and the MDR of photopeak events verses 3D position in Figs. 10(a-b). Determination of the MDR as a function 3D-position from 2D-calibration data is accomplished by the maximum-likelihood clustering method [7, 8].

IV. Benchmark Comparison

We compared the CPU time per interacting gamma ray of SCOUT with that of Geant4 [9] and Detect2000 [10, 11]. Since the optical track history depends on detector geometry, we examine two scintillator sizes. Also, since Detect2000 does not track gamma rays, we used a fixed gamma-interaction position (crystal center) and forced photoelectric interaction for comparison with Detect2000. However, for comparison with Geant4, we used a random interaction depth and allowed scatter. Results are presented in Table 1.

The majority of CPU time spent in these simulations is due to optical photon tracking (simply because there are so many optical photons generated per gamma ray). Gamma-ray tracking and readout-noise simulation take relatively little time.

The speed improvement in SCOUT is attributed to four reasons. First, since SCOUT assumes a fixed rectangular geometry, intersections of photons with surfaces can be determined by a few trigonometric tests as opposed to iterating over all bounding surfaces. Second, there is no time stepping in SCOUT; bulk attenuation and scatter are randomly sampled for each track segment from a cumulative attenuation distribution as a function of pathlength. Third, when optical photon track data is not requested for output, the number of photons tracked is reduced by a binomial selection of the maximum quantum efficiency (QE) of any one photodetector in the camera (the difference in QE for lower-QE photodetectors is tested later). Finally, SCOUT source code has been heavily optimized to minimize redundant calculations and it diligently uses lookup tables where possible.

V. Discussion and Conclusion

The SCOUT modeling tool has proven to be easily adaptable for the arrayed-scintillator studies we are conducting. Several options and combinations of surface treatments permit significant flexibility and realism in modeling optical transport in a scintillation camera. Furthermore, a comparison with experimental data has validated SCOUT accuracy in modeling the underlying physical processes in scintillation camera signal generation. Simulated results from this model have accurately reproduced measured signal statistics. We have conducted sufficient verification of this modeling tool to proceed with our surface-treatment optimization study.

One current limitation is that SCOUT presently applies only to rectangular scintillator and photodetector geometries. Trapezoidal scintillator and hexagonal photodetector geometries are being worked on for a future release. However, the simplicity of SCOUT's assumed geometric model permits it to run relatively fast. In one second of a single 2.26 GHz Intel Xeon processor, SCOUT tracked 4 gamma rays and ~60,000 optical photons with about 2 million diffuse-surface interactions. This speed will enable us to conduct a wide range of parametric studies on detector design.

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Fig. 1.

The general physical model is a rectangular array of scintillators. An optical spacer (LG) and a regularly spaced rectangular array of Photodetectors (PD) can be placed on the entrance (front) and/or exit (back) scintillator surfaces. The active area of each PD is assumed to be uniform within a support region centered at its PD-grid location. This support region can be circular, square, or an intersection of a concentric circle and square.

Fig. 2.
Control flow diagram of SCOUT model.

Fig. 3. SCOUT optical models. Some of the models depicted (specular, MF diffuse, diffuse cone, isotropic and bidirectional) can either be a reflector or an interface treatment. Each surface can be a weighted mixture of two models.

Side, top, and bottom views of a dMiCE crystal pair are shown to the left. A two-region interface of this pair is shown to the right. The mirror-film region is a depth-dependent mixture, which transitions from one layer of mirror film in the triangular region to two layers in the lower rectangular region. The remaining interface area is specularly coupled with Melt-mount ®. The interface suffers a 50% probability of an air gap (trapped bubbles). The crystals are side-illuminated at a depth, z_{DOI} , with a 2-mm-diameter 511-keV gamma-ray beam (coincidence-collimated Ge-68 source in the experiment). In this arrangement, gamma-ray interactions can occur in either crystal.

Fig. 5.

Hit & Abutted channel identification. Using the setup in Fig. 4, signals of both photodetectors (PD1 and PD2) were recorded for each of 25,000 events at each of several z_{DOI} . Shown in both plots above are the experimental spectra of both photodetectors at $z_{DOI} = 18$ mm; the spectra of both channels are similar aside from a 5% gain difference. To the left, we treat the photopeak-windowed events of PD1 as events where PD1 is the hit channel; we assume that PD2 for these same events is the abutted channel. In the plot to the right, the role of PD1 and PD2 are reversed; we window photopeak events of PD1 and identify PD1 as the hit channel and PD2 as the abutted channel for these events. For the interface treatment used, we find this hit-channel identification method to be unambiguous even for z_{DOI} near the open region of the interface. However, if a truly transparent region of the interface existed, then the crystals might have to be separately illuminated to independently calibrate their responses.

Fig. 6.

Simulated vs. experimental spectra for $z_{DOI} = 2$ mm. Roll-off below 200 ADU of the measured spectra is due to a soft low-level discriminant (we windowed pulse height, but measured integrated charge). We also see Lutetium background counts above the photopeak, which were not simulated. We observe similar agreement of measured and simulated spectra at other z_{DOI} .

Fig. 7.

Mean detector response (MDR) vs. interaction depth of photopeak events in the *hit* and *abutted* detectors from Fig. 3. The refractive index for the melt-mount is specified as $n_c = 1.7$ at 589 nm. However, fitting model parameters to minimize the square error of the simulated MDR, we find $n_c = 1.5$ with a 50% probability of an air gap. A lower index is expected due to the scintillation spectrum (LFS peak wavelength is ~ 415 nm). Also, air was likely trapped in the melt-mount since it was not degassed. The residual difference in simulated and measured depth dependence is due to minor discrepancies in both the mirror film shape and the depth alignment of the coincidence beam.

Fig.8.

Design and calibration of a cMiCE detector ($50 \times 50 \times 8 \text{ mm}^3$) Detector sides are blackened and the top is painted white. All surfaces, except the readout side, are roughened (see [8]). We simulated the sides to be 95% absorptive with 80% air gap and the top to be a MF diffuse reflector. For MDR comparison, interactions are forced photoelectric at fixed depths. Random interaction depth is used for spectral comparison.

Fig.9.

Comparison of SCOUT vs. experiment: sum spectra (top) and single-channel spectra (bottom) of a 1-mm coincidence-collimated ^{22}Na source normally incident at the center of a monolithic cMiCE detector. Differences in these spectra are a result of random coincidences with unmodeled background (e.g. ^{176}Lu) and out-of-detector scatter.

Fig.10(a).

SCOUT vs. experiment comparison of the mean detector response (MDR) as a function of 3D interaction position for several photodetector channels. Slices in an X-Y plane with $Z_{DOI} = 1$ mm are shown at the top and slices in an X- Z_{DOI} plane with $Y = 0$ mm (central slice) are shown at the bottom. To better capture the relative spatial dependence of the photodetector input signals, the MDR for each channel was divided by its gain. Reported values are in units of photoelectrons (p.e.).

Fig.10(b).
SCOUT vs. experimental comparison of 1-D profiles of the same MDR as in Fig. 10(a) for several photodetector channels.

Table.1

CPU time per simulated gamma-ray (sec/ γ) for discrete LSO crystals ($2 \times 2 \times 20 \text{ mm}^3$) and for a monolithic LSO crystal ($50 \times 50 \times 8 \text{ mm}^3$). An average of 27,800 optical-photons/MeV are generated/tracked and a minimum verbosity was used in each case. Note that forced photoelectric interaction results in more optical photons per γ (on average) than when Compton scatter occurs.

sec/ γ	Random DOI & Random scatter		Fixed DOI & Forced photoelectric	
Model	SCOUT	Geant4	SCOUT	Detect2000
Monolithic	0.0042	0.58	0.0095	0.89
Discrete	0.26	10.2	1.1	4.2