Degradation Mechanisms of Photon-Counting Detectors

Notes

This assignment is performed in teams with 2-3 members. Each team should hand in a separate report, you cannot copy (part of the report) from other teams. A plagiarism check will be performed to check if this is your own work explained in your own words. Cite all literature that you use. It is important that this is a technical report, so if I ask for equations you should provide them and explain them in-depth (I really want to see that you understand them). Please make sure that the symbols you use throughout the report are consistent, also if you obtain equations from different literature sources. Every symbol you use has to be explained.

You should first give an introduction of the topic (don't forget the abstract), then a few sections that describe your literature search, then a section on the experimental evaluation, and in the end a discussion/conclusion. Please don't copy the questions literally and then give an answer. The answers to the questions and your results should somehow be put together in a logical story.

You must also provide the code that you used for evaluation separately; you may use the language of your choice. Code without sufficient documentation will not be accepted.

Assignment

Your report should cover the following points:

- Explain the working principle of (direct conversion) photon counting and energy integrating detectors, and how they differ.
- The pixelated photon-counting detectors suffer from several effects that cause correlations between pixels or multiple counts for one incoming photon in several pixels. List the various effects and explain them. You have to be able to understand them in order to evaluate their influence on performance.
- How do these effects relate to the pixel size of a photon counting detector (PCD)? Think about what happens when you e.g. decrease the pixel size: which of the effects will increase in severity, which will decrease?
- Which effects influence the spatial resolution of a detector, and which influence the spectral performance of a PCD (which can also measure the photons' energy), or both?
- The detectors that are used in X-ray imaging so far are of course also pixelated detectors, but they are (almost exclusively) energy-integrating detectors. Do they suffer from the same degradation effects? If yes, why are the degradation effects much more of a concern in photon counting detectors? If not, why do these effects not happen in energy-integrating detectors?

Note: In this report you can limit yourself to direct-conversion photon counting detectors.

Practical work

For the ‘practical’ part of this assignment, you are going to work with simulated data.

Task 1

In this task, you are going to compare an energy-integrating detector with a photon counting detector based on the contrast between two tissues.
The setup is really simple: A parallel 140 kVp (140 kV source peak voltage) X-ray passes through an object (called the “phantom”) consisting of a single material, and the remaining X-ray intensity is captured by an idealised detector which is able to capture each incoming photon with perfect energy resolution. The detector consists of only one pixel, and only the X-rays that incident the pixel orthogonally are accepted (scatter is hence rejected).
The dataset consists of two sets: The registered intensity of the X-ray beam with 33 mm of water inserted, and with 33 mm of fat inserted. The actual data is a histogram of registered counts over energy [MeV].
Please see the README file in the dataset for detailed descriptions of the data. The histograms are saved as Python numpy arrays, Matlab arrays (not tested) and plain text files.

Calculate contrast between the fat and water tissues for:

- An energy-integrating detector,
- A purely photon counting detector (that is, a detector which can count the number of incident photons, but cannot distinguish their energy),
- A photon counting detector with spectral resolution. The photon counting detectors today have a limited amount of energy bins. For this example, assume its lower energy bin ranges from 20 keV to 50 keV, and the higher energy bin from 50 keV to infinity. In order to enable comparison with the first two detector types, the measurements from the two energy bins are added, giving the lower energy bin a weight of 80%, and the higher energy bin a weight of 20%.

Explain how you obtained the results for the various detector types and explain your findings.

Note: Base your calculations of contrast on the detector signal.

Task 2

The setup is the same as in Task 1, however, the photon counting detectors now exhibit a finite response time to incoming events, and hence suffer from pile-up effects which vary with the fluence rate of the beam. Calculate again the contrast between fat and water tissues for:

- A purely photon counting detector (that is, a detector which can count the number of incident photons, but cannot distinguish their energy),
- A photon counting detector with spectral resolution. Its lower energy bin ranges from 20 keV to 50 keV, and the higher energy bin from 50 keV to infinity. The lower energy bin is weighted with 80%, and the higher with 20%,

and for all the available fluence rates. Explain your findings.

Details of the simulation: The dead time of the photon counting detector is assumed to be 34 ns, the pulse shape is assumed to be Gaussian with a FWHM of 20 ns, and its triggering threshold is at 20 keV. The counting model for the pile-up was assumed to be non-paralysable. The filenames refer to rate of photons in the total X-ray beam (# photons/second), measured after the X-ray source and before the phantom. Both the X-ray beam and the detector have a cross section of $2 \cdot \pi \cdot (5\text{mm})^2$.

Task 3

So far, we only considered a single, isolated pixel of a more or less idealised detector. Now, we will consider a pixel of a realistic material (cadmium telluride, CdTe) as part of a two-dimensional pixel array.

For this dataset, monoenergetic X-rays of 100 keV directly hit the pixelated detector, without passing through a tissue in advance. This helps to assess the influence of various effects on the registered spectral shape.

The simulation realistically models the transport of X-rays through matter, and the response of a material to X-rays. The simulation assumes that each time energy is deposited within a pixel, the created charge is proportional to the deposited energy and focused in a point. The simulation skips the steps of modelling charge transport in a semiconductor and their collection at electrodes. It does, however, assume a finite response time of the detector to events. Based on this information, which degradation effects of photon counting detectors should be visible in this dataset?

The dataset contains histograms for different pixel sizes and fluence rates. Please note that the histogram was created for one of the pixels in the 2d array, where the whole pixel array is homogeneously illuminated by X-rays. Your task is to compare the histograms, explain their spectral shape and explain the changes with pixel size/fluence rate. (Please note that in reality a photon counting detector provides you only with a very limited number of energy bins.)

Details of the simulation: The dead time of the photon counting detector is assumed to be 34 ns, the pulse shape is assumed to be Gaussian with a FWHM of 20 ns, and its triggering threshold is at 20 keV. The counting model for the pile-up was assumed to be non-paralysable.

Task 4

In this task you are going to simulate the effect of charge sharing yourself, again in a very simplified way. Assume the following:

- A 2d array of square pixels is homogeneously irradiated by X-rays of 60 keV,
- Every X-ray deposits its energy fully in the detector,
- The detector has an infinitely fast response time,
- After the deposition of energy, the charge cloud that is created by the events is of circular shape with homogeneous charge area density, and has a diameter of 100 µm.

Simulate the following pixel sizes: 1000 µm, 500 µm, 250 µm, 200 µm. For each pixel size, ideally simulate a flux of 1E6 events per pixel size (or less if it takes a long time to compute), and create a histogram of the registered spectrum (energy bins from 20 to 65 keV, with 1 keV bin width).