ProSPECTus: A Compton Camera for Medical Imaging

Amina Patel

Science & Technology Facilities Council

UNIVERSITY OF LIVERPOOL
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• Compton imaging
• ProSPECTus system
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• Future plans
• Summary
Motivation: Medical Imaging

- Obtain functional images from nuclear medicine imaging techniques
- ProSPECTus designed to overcome limitations in conventional Single Photon Emission Computed Tomography (SPECT) systems

Main Gamma Camera Components

- NaI(Tl)
- PMTs
- Electronics
- Collimator

Radioisotopes:
- $^{99m}$Tc – 141 keV
- $^{123}$I – 159 keV
- $^{131}$I – 364 keV

Prevents co-registry with Magnetic Resonance Imaging (MRI) scanners
Multiple Scans
High dose or Long scans
Compton Camera: Principles

1. Gamma ray interacts with both detectors
2. Energy deposited used to determine scattering angle via Compton scatter formula
3. Conic represents all possible source locations
4. Position interactions create cone axis
5. Many events lead to overlap of conics revealing source location

\[
\cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)
\]

Source Location

Number of events
Figure 6.1: Pictures of the frame designed to mount the Compton camera system for work at Aldermaston. The frame is made from aluminium cross section and mounted on wheels to enable the detectors to be moved easily. The mounting positions are designed to hold the detectors parallel to one another with the detectors aligned co-linearly. Using the 121.78, 244.70, 778.90 and 964.08 keV peaks.

The ProSPECTUs System

ProSPECTUs

Prototype System

Scatter Cryostat

Absorber Cryostat

ProSPECTUs Preamplifier readout from each channel

ScaVer
**ProSPECTus System**

### Scatter Detector
- Diameter: 71 mm
- Height: 8 mm
- Position resolution: (5 x 5 x 8) mm

### Absorber Detector
- Height: 60 mm
- Width: 60 mm
- Position resolution: (5 x 5 x 20) mm

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The ProSPECTus System provides a low noise level. The strips are arranged orthogonally on either side of the detector. The AC side has a p-type contact (strips 1-13, termed AC01 to AC13) while the DC side has a n-type contact (strips 14-26, termed DC01-DC13). The strip layout can be seen in Figure 4.1a.

The detector is contained within a purpose-built cryostat which Canberra designed to have a minimum of shielding materials while providing a large number of outputs. A cross-section of the cryostat can be seen in Figure 4.1b with the detector unit as a whole shown in Figure 4.1c.

Figure 4.1: Schematic diagram of the strip configuration of the SiLi detector used as a scatterer (a) along with pictures of the detector unit itself (b) and (c). Images (a) and (c) are reproduced from [32]. Image (b) was provided by Canberra France.

4.1.2 DC01 and AC13

One channel of the SiLi detector was found to be not working. Channel DC01 produced no output when connected to an oscilloscope, and replacing the preamplifier for this channel did not correct this. The fault appears to be on the cold side of the feed through which would require the detector to be opened to atmosphere for an investigation to take place, which would lead to the loss of valuable time and the possibility of further damage to the detector's performance following any repair work. As the strip affected is an edge strip and there were only 24 channels of electronics available to instrument the Si(Li) detector, the decision was taken to use the detector but not instrument DC01 and AC13, removing two of the small edge strips which should have a negligible effect on the efficiency of the detector.

4.2.1 High voltage (HV) and preamplifier power

To provide the bias voltages to the detectors, two HV units were used. Two Ortec 671 amplifiers were used to provide the preamplifiers with power. The four units are NIM powered and placed into one high power crate, allowing for simple grounding and easier transportation.

The two detectors require different bias shutdown methods. A bias shutdown prevents HV being applied in the event that the detector warms up, preventing any damage that may occur due to contaminants being released into the vacuum from the molecular sieve. Typically, this out-gassing will result in a spark across the crystal if the HV is still applied, leading to the FET on the preamplifiers blowing or in extreme cases the crystal itself cracking.

To provide the correct bias shutdown methods, a Canberra 3106D HV supply was used with the SiLi detector, while an Ortec 659 HV supply was used with the HPGe detector.

4.2.2 GO Box

The dynamic range available on the CAEN V1724 card is 2.25V. This is very large compared to the output voltages per 1MeV of energy deposited that the detector preamplifiers provide. To better match the dynamic range of the cards to the energy range...
Data Processing

**Optimisation**
- $^{139}$Ce -165 keV
- Average intrinsic silicon timing resolution ~ 22 ns
- Average intrinsic germanium timing resolution ~ 27 ns
- ProSPECTus system ~ 45 ns
- Coincidence window: 150 ns
- Thresholds:
  - Scatter detector ~ 8 keV
  - Absorber detector ~ 15 keV

**Data Collection**
- Point sources
- Phantom

**Digitiser Cards**
- Offline Processing

**Data Sorting**
- MT sort

**Image Reconstruction**
- Analytical
- Iterative

[Image link: http://ns.ph.liv.ac.uk/~dsj/web/] - image reconstruction manual
Data Processing

Optimisation

- $^{139}$Ce - 165 keV
- Average intrinsic silicon timing resolution ~ 22 ns
- Average intrinsic germanium timing resolution ~ 27 ns
- ProSPECTus system ~ 45 ns
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Digitiser Cards
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Data Sorting
- MT sort

Image Reconstruction
- Analytical
- Iterative

http://ns.ph.liv.ac.uk/~dsj/web/ - image reconstruction manual
Image Quality : Phantom

- Source: $^{139}\text{Ce}$ (165 keV)
- Rod diameter: 16, 12.4, 11, 10 mm

Medical Imaging quantitative assessments:
1. Resolution
2. Noise
3. Sensitivity
4. Contrast

sjc@ns.ph.liv.ac.uk - SPECT data acquisition, phantom holder design
Phantom Simulations

Simulations in GAMOS (GEANT-4 based Architecture for Medicine Oriented Simulations)

A Compton camera application for the GAMOS GEANT4-based framework, L.J. Harkness, NIMA
Phantom Simulations

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A Compton camera application for the GAMOS GEANT4-based framework, L.J. Harkness, NIMA
Experimental Data: Subset of Phantom Rods

16.4 mm diameter rods

10 mm diameter rods
Experimental Data: Subset of Phantom Rods
Phantom Simulations

Experimental Data: Subset of Phantom Rods

- 10 mm rods placed perpendicular to detector (one in clamp stand, one on scanning arm)
- Separation increased by 10 mm each time
- Minimum centre to centre separation 1.6 cm
- Maximum centre to centre separation 10.6 cm

16 mm
26 mm
36 mm
46 mm
56 mm
66 mm
76 mm
86 mm
96 mm
106 mm
Phantom Simulations

Experimental Data: Subset of Phantom Rods

- 10 mm rods placed perpendicular to detector (one in clamp stand, one on scanning arm)
- Separation increased by 10 mm each time
- Minimum centre to centre separation 1.6 cm
- Maximum centre to centre separation 10.6 cm

Start

Step 1

Step 2

Step 3

Step 4

Step 5

Step 6

Step 7

Step 8

Step 9

16 mm

26 mm

66 mm

76 mm

86 mm

96 mm

106 mm
Future Work

• Establish resolving limitations

• Apply basic Pulse Shape Analysis (PSA)

• Image using Technetium-99m

• Quantitative analysis of image quality

• Comparisons to SPECT images

• Multi isotope imaging
Summary

• ProsPECTus system designed to overcome the limitation of SPECT imaging
• Optimised for low energies
• Custom made Phantom designed to assess image quality
• Data taking currently in progress
• Limitations of system under investigation
• Quantitative assessment and comparison to SPECT data
Collaborators

L.J. Harkness-Brennan¹, A.J. Boston¹, H.C. Boston¹, S.Colosimo¹, J.R. Cresswell¹, J.Dormand¹, T.Hughes¹, D.S. Judson¹, P.J. Nolan¹, C.Reid¹, J.A. Sampson¹, N. Clague², J.Groves², J.Headspith², A.Hill², I.H. Lazarus², J. Simpson², W.E. Bimson³, G.J. Kemp³, and D.Gould⁴

¹ Department of Physics, The University of Liverpool, UK,
² STFC Daresbury Laboratory, UK
³ MARIARC, The University of Liverpool, UK
⁴ Royal Liverpool University Hospital, Liverpool, UK
Image Quality: Pulse Shape Analysis (PSA)

Principle: Manipulates signals generated from contact strips to determine position of interaction

Two types:
1) Parametric
2) Generate a database of pulse shapes for each interaction position
Pulse Shape Analysis: Parametric

Two main PSA techniques:

A) Parametric: works with real charges produced and image charges.

1. Real charges (position in depth):
   - Charge collection time for the pulse is a function of the distance that the charge carriers have to travel to the electrodes.
   - Rise time parameters $t_{30}$ and $t_{90}$ can provide information on the interaction position in depth.

2. Image charges (X and Y position beyond segmentation):
   - Movement of charge carriers induces signals in neighbouring contacts.
   - The magnitude of the signal in a neighbouring contact is dependent on how close the interaction position is to it.
   - If interaction occurs in the centre, the neighbouring strips signal is equal. If closer to one side than the other, the signal in that neighbouring strip is larger relative to the other.

B) The generation of a database containing pulse shapes for various interaction positions within a detector is the second main PSA technique.

### Depth: Charge Collection

![Graph showing normalized pulse height with depth markers](image)

- Normalized Pulse Height
- Depth:
  - 10%
  - 30%
  - 90%
  - $t_{30}$, $t_{90}$

The graph illustrates the normalized pulse height with depth markers indicating 10%, 30%, and 90% points, along with $t_{30}$ and $t_{90}$ for the pulse shape.
Pulse Shape Analysis (PSA): Parametric

Parametric PSA has two components:

a) Depth - Charge Collection
b) Precision in X and Y direction – Image charges

a) Depth: Charge Collection

R. Cooper, Thesis
b) Precision in X and Y – Image Charges

\[
\text{Asymmetry} = \frac{\text{Area}_{left} - \text{Area}_{right}}{\text{Area}_{left} + \text{Area}_{right}}
\]
Position Resolution Investigations

**Depth Position Resolution Investigation: Absorber**

![Graph showing depth position resolution investigation for absorber. The x-axis represents position resolution in depth (Z) in mm, and the y-axis represents image resolution (mm). There are two sets of data points: blue crosses represent position resolution, and red pluses represent position resolution including physics effect.](image-url)
Position Resolution Investigations

- Exact Position on Scatter with normal segmentation on Absorber (no physics effect): 26 mm

- Exact Position on absorber detector with normal segmentation on Scatter detector (no physics effects): 19 mm

- **Position sensitivity most important in the absorber detector**

- Simulations used to investigate lateral and depth position precision independently
Conclusion

• Position resolution has significant influence on image quality
• Pulse shape analysis techniques will be applied to the ProSPECTus absorber detector to improve image resolution
• Phantom will be used to compare the ProSPECTus system to current SPECT systems

Current Work

• Acquiring experimental images with point sources and phantom
• Apply parametric PSA to data

Future Work

• Generate a pulse shape database for the absorber detector
• Develop PSA algorithms
• Images with Technetium (141 keV) to be compared to SPECT images
Analytical back projection – projects full cone – high background

Iterative imaging

Generates arbitrary starting state - randomly chose a point on cone surface
Select 1st event, randomly move point to new location
If new event density is greater, leave in new location, if not put back where it was
Repeat for all events = 1 iteration

Maximum Likelihood Expectation Method (MLEM)
Ordered Subset Expectation Method (OSEM)
Geant3 simulations have been reported showing that energy gates are highly effective in restricting data analysis to only single site interactions; only 55% of scattered coincidences interact at single sites in each detector compared with over 85% with energy gates.

Secondary collimation is used in all three reported coincidence experiments [Pet03][Mil05][Vet03]. However, these experiments all suffered from low statistics. Therefore, based on a high probability of single-site interactions with the utilization of energy gates, a judicious removal of secondary collimation has been made for a number of experiments in this thesis. This also provides a fair comparison with previous work [Tur06].

Figure 3.5 shows the geometrical arrangement of the coincidence experiments performed, in which an axis connecting the two auxiliary detectors sits perpendicular to the collimated primary detector. Coincidence is performed with two auxiliary detectors angled at 90° to the primary detector (represented as blue volumes). Secondary collimation can be performed to define the interaction in three dimensions, or the secondary collimators can be removed and the interaction is defined in two dimensions. See Fig. 3.6 for a photograph of the experiment.

**Coincident events:**

- $^{137}\text{Cs} – 662 \text{ keV}$
- Absorber Detector : 374 keV
- Scintillator detector : 288 keV
Position Resolution Investigations

Lateral Position Resolution Investigation: Scatter

Image Resolution (mm)

Pixel dimensions in X and Y (mm)

- + Position Resolution
- + Position resolution including physics effects
Position Resolution Investigations

**Depth Position Resolution Investigation: Absorber**

- **Image Resolution (mm)**
- **Position Resolution in Depth (Z) mm**

- Including physics effect
- Position resolution
Position Resolution Investigation

Conclusions

• Improvement in position resolution will improve image resolution
• Position resolution in depth has more impact than that in X and Y
• Position resolution most important in absorber detector
Image Quality : Phantom

Characteristic Position resolution

1mm³ Position resolution in absorber
Compton Efficiency: Previous Work

Absolute Compton Efficiency

- Factor of 3 difference between simulated and experimental data.
- GAMOS\(^2\) Monte carlo simulations previously validated against Compton data and matched.

2. L.J. Harkness, A Compton camera application for the GAMOS GEANT4-based framework, NIMA 2012
CHAPTER 5. Compton Camera Optimisation

Energy (keV)

Counts

Threshold ~15keV

Singles Scatterer

Singles Absorber

( L.J.Harkness, Thesis 2010)
5.4.3 Detector Separation

All previous analysis has been carried out using GEANT4 simulations for Compton camera configurations with a constant separation between the closest faces of the detectors. It is useful to investigate the influence on sensitivity of varying the separation distance between the scatter and absorber detectors, so that this can be taken into consideration during the design phase of the detector cryostats. To this end, data has been generated using GEANT4 simulations of the optimum detector configuration with various detector separations from 1 cm to 10 cm.

The separation was 22.5 mm and 20 mm during the scatter detector and absorber detector investigations, respectively.

≈ 30% of single/single events being removed from the data set.

The corresponding threshold level attainable when the detector is furnished with a cooled FET is 3 keV, as advised by the manufacturer [Sem10a]. The cooled FET configuration would be expected to remove ≈ 15% of the single/single events.
ProSPECTus Image Resolution Capabilities

- Voxel size position resolution
- Exact position of interaction

Image Resolution (mm) vs. Gamma–Ray Energy (keV)

- LEHS
- LEHR
CHAPTER 5. Compton Camera Optimisation

Energy (keV)

Counts

Thresholds

Singles Scatterer

Singles Absorber

Threshold ~ 6 keV

( L.J. Harkness, Thesis 2010)
Compton Efficiency: Coincidence Window

Sodium Iodide Detector → Timing Filter Amplifier → Constant Fraction Discriminator

Start → Stop

Time to Amplitude Converter

Germanium Detector

\( ^{22}\text{NA} \text{ Source} \)

Done for energy range 80 keV – 511 keV

Example TAC spectrum from

FWHM = Time Resolution ~ 15 ns
Coincidence Window Results
Pulse Shape Analysis (PSA)

- **Principle:** Manipulates signals generated from contact strips to determine position of interaction
- **Two types:**
  1. **Parametric:** works with real charges produced and image charges
     - **Real charges (position in depth):**
       - Charge collection time for the pulse is a function of the distance that the charge carriers have to travel to the electrodes.
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  2. **The generation of a database containing pulse shapes for various interaction positions within a detector is the second main PSA technique.**

![Diagram with labels $t_{30}$ and $t_{90}$]
• Principle: Manipulates signals generated from contact strips to determine position of interaction
• Two types: 1) parametric 2) generate a database of pulse shaped for each interaction position
Image Quality : Pulse Shape Analysis

PSA investigations
GAMOS Simulated data (141 keV)
Absorber position resolution dominant
  Position resolution  1mm³

Plan
Develop pulse shape analysis algorithms
Develop pulse shape database for Germanium detector
Motivation: Single Photon Emission Computed Tomography (SPECT)

- Medical imaging
- SPECT

Radioisotopes:
- $^{99m}$Tc (141 keV)
- $^{123}$I (159 keV)
- $^{131}$I (364 keV)

Figure 1
Analytical back projection – projects full cone – high background

**Iterative imaging**

Generates arbitrary starting state - randomly chose a point on cone surface
Select 1\textsuperscript{st} event, randomly move point to new location
If new event density is greater, leave in new location, if not put back where it was
Repeat for all events = 1 iteration

**Maximum Likelihood Expectation Method (MLEM)**

**Ordered Subset Expectation Method (OSEM)**
Current Work: Simulations

Aim: To predict image resolution capability of the ProSPECTus system

Gamos (GEANT4-based Architecture for Medicine Oriented Simulations):
- Geant 4 based toolkit, Compton camera plug in.
- Allows definition of position and energy sensitive detectors
- Provides information on interaction position (which voxel hit)
- Provides information of energy deposited in both detectors by gamma ray for single-single event
- Output file created containing $E_1$, $x_1$, $y_1$, $z_1$ and $E_2$, $x_2$, $y_2$, $z_2$. File used by C++ reconstruction code to create images

C++ Image Reconstruction code:
- Input Gamos data or experimental data ($E_1$, $x_1$, $y_1$, $z_1$ and $E_2$, $x_2$, $y_2$, $z_2$) – single-single interactions
- Takes 2D image slices which are created in the $x$–$y$ plane, through depth $z$
- For e.g. cone perpendicular to detector face, size of conic deduced by $r = z \tan \theta$. Position in $x$ and $y$ same as position in detectors

Figure 3