A Feasibility Study of Attenuation Correction in the J-PET Scanner Using Detector-Scattered Photons

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On behalf of the J-PET collaboration

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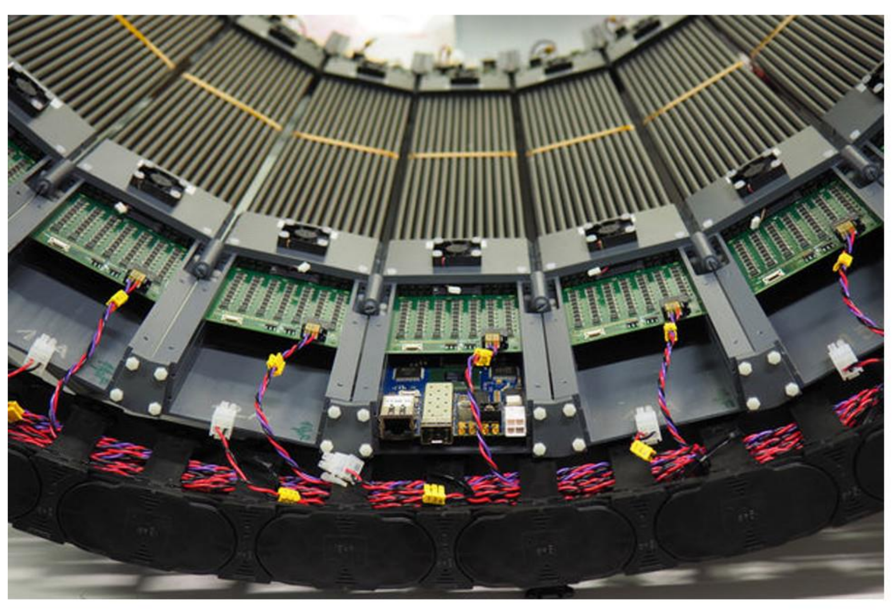
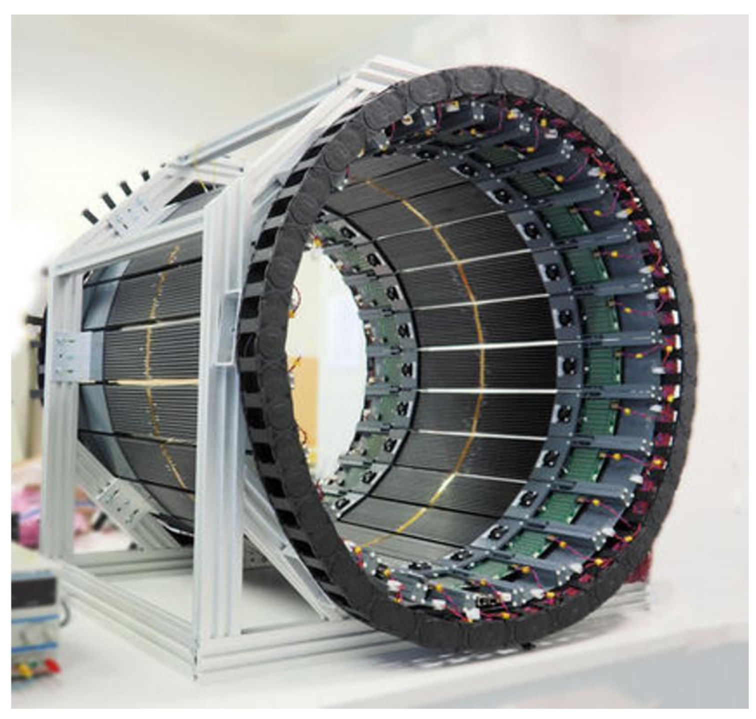
ABSTRACT: Quantitative accuracy in Positron Emission Tomography (PET) depends on reliable attenuation correction (AC) methods [1] , and novel imaging concepts such as positronium lifetime imaging with the Jagiellonian PET (J-PET) system have further highlighted the importance of developing advanced PET methodologies [2]. The clinical standard for AC in PET imaging remains computed tomography (CT). However, this approach **increases patient radiation dose** and **imaging expenses**. In recent years, several CT-less attenuation correction methodologies have been proposed to eliminate the need for CT scans [3]. In this work, we present a feasibility study for a CT-less AC approach that utilizes photons undergoing Compton scattering within the PET detector—data typically discarded in conventional analyses. This method is especially well-suited to the J-PET scanner [4], which is built from long plastic scintillators that inherently produce a significant number of detectable scattered photons [5].

We performed simulations using the **GEANT4 Application for Tomographic Emission (GATE)** [6] by modeling a modular J-PET scanner with phantoms having varying attenuation profiles. We then analyzed the Lines of Response (LORs) formed between the first interaction at the detector and the subsequent detection of the scattered photon after it passes through the phantom and reaches the detector on the opposite side. Our initial findings show that these LORs contain spatial information about the phantom's attenuation distribution, enabling the distinction between varying attenuation density regions. These results demonstrate that detector-scattered photons can serve as an intrinsic data source for generating attenuation maps.

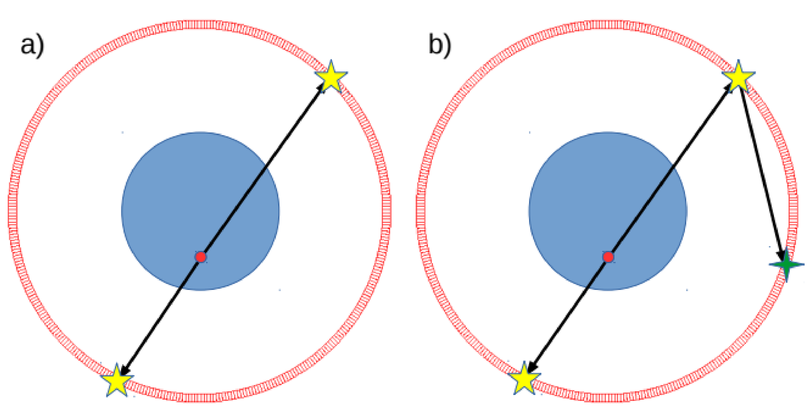
The JPET Advantage: A novel PET system, based on Plastic Scintillators.





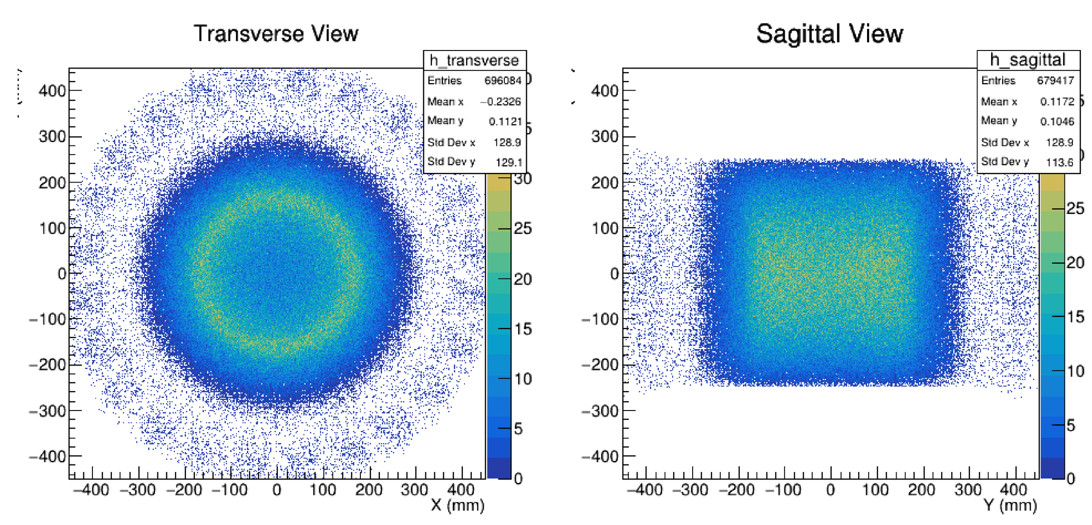
Key Features:

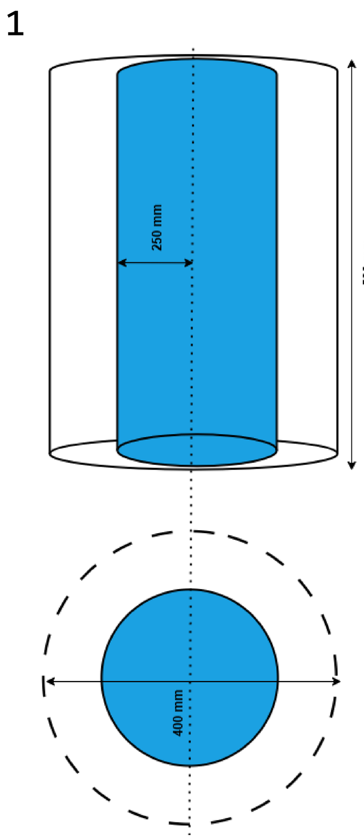
1. Use of Plastic Scintillators ⭐
2. Excellent Time Resolution ⭐
3. Non-Magnetic and Light-weight
4. Multi-photon Detection [7]
5. Positronium Imaging [8]
6. Fundamental Symmetry Studies [9]



Approx 17.13% of the detected hits are scattered from the detector

GATE Simulation Setup: `Version 9.1`





Key Features:

1. **Physics List**: `emlivermore_polar`.
2. **Source**: Ge-68 emitting 511 keV back-to-back gammas isotropically with 135 MBq activity.
3. **Cylindrical GATE Phantom**: 25 cm radius, 50 cm height, water (*alternatively air*) material, centered at (0,0,0) cm, attached to PhantomSD.
4. **PET scanner hierarchy**: World → cylindricalPET → 24 × modules (arranged in a ring) → 13 × crystals (stacked in Y) → 200 × Scintillators made of EJ230 (stacked in Z).
5. **Digitizer**: CTW = 600 ps & Energy Resolution = 23.1 % @ 200 keV

Event Selection: Taking care of Space & Time Complexity + More relevant with respect to the experimental data.

"Detector-Scattered (DS) coincidences form a subset of the normal coincidences"

The speed of light in vacuum is ~30 cm/ns. For a detector with ~80 cm diameter, the maximum photon travel time is:

$$\frac{80cm}{30cm/ns} \simeq 2.7ns$$

Thus, a coincidence time window (CTW) of 3 ns is sufficient to include all DS-coincidences.
However, to allow for experimental tolerances, a wider CTW of 5 ns should be chosen.

Steps to get DS-LORs Efficiently

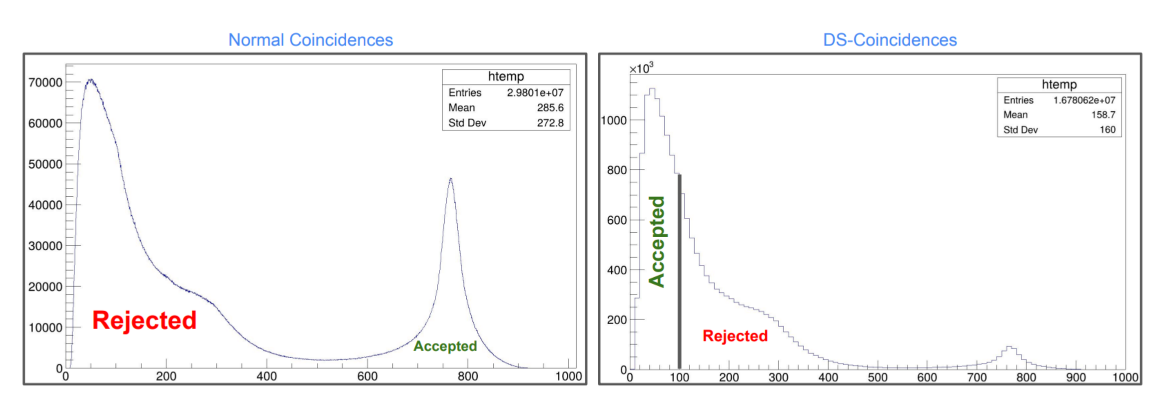
1. Start a Coincidence Time Window (CTW) of 3-5 ns *OR* Group by `eventID.`
2. Energy Deposition Threshold > 50 keV (**WHY?**)
3. Apply minSectorDifference = 1:

$$min(|rsector1 - rsector2|, 24 - |rsector1 - rsector2|) >= 1$$

4. Apply Scatter Test: **`ST <= 100 mm`**.

$$ST = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} - |t_1 - t_2| \cdot c$$

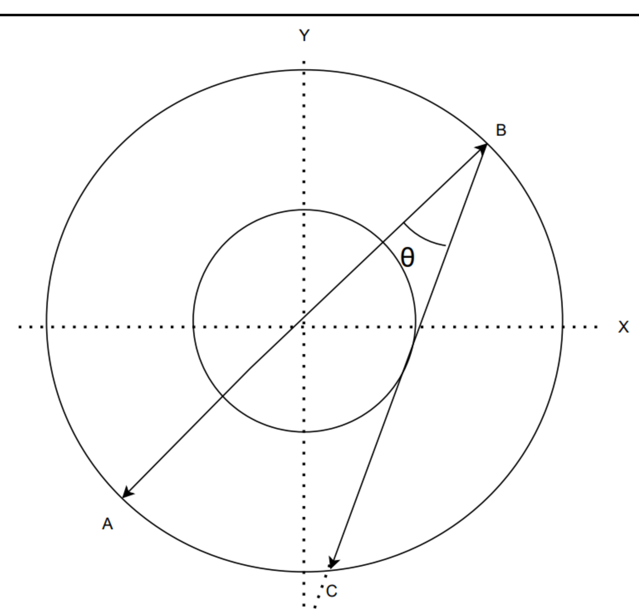
Scatter Test Plots



$$\text{Purity} = \frac{\#\{i \mid \text{comptonCrystal1}_i = 1, \text{comptonCrystal2}_i = 1, \text{comptonCrystal3}_i = 2\}}{\text{Total number of entries}}$$

57.04 % for Water Phantom & 65.14 % for Air Phantom

Data Analysis & Preliminary Results: DS-LORs are getting affected by the Attenuation Values of the phantom.



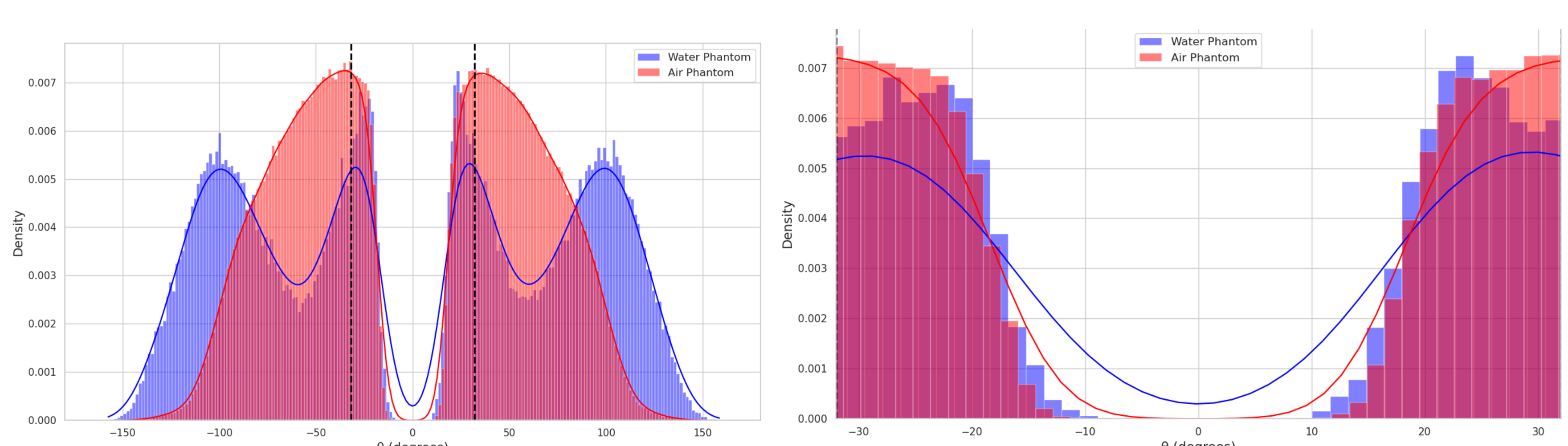
$$\theta_c = \arctan\left(\frac{25}{40}\right) \cdot \frac{180}{\pi}$$

$$\theta^\circ = \frac{180}{\pi} \operatorname{atan2}\left(\left(\frac{v_1}{\|v_1\|} \times \frac{v_2}{\|v_2\|}\right) \cdot a,\ \frac{v_1}{\|v_1\|} \cdot \frac{v_2}{\|v_2\|}\right)$$

Noise Propagation Analysis:

- DS Event Fraction = 40 %
- Total DS Events (in 10 mins) = 40,000,000
- Counts per bin (120,000) = 333
- Projection Noise ($\sigma_p \approx 1/\sqrt{\#}$) = 0.055 cm^{-1}
- Reconstructed Noise ($\sigma_\mu \approx \sigma_p/\sqrt{N}$) = 0.0032 cm^{-1}
- SNR for Water (SNR ≈ μ_{Water} / σ_μ) = **30**

In case of Crystals, SNR for water is 3.4



Conclusion: The above **θ-distribution plots** show that the Detector Scattered LORs are influenced by attenuation from the phantom. This indicates that such information can be valuable for reconstructing the attenuation map using detector-scattered photons.

Challenges:

1. **Low Statistics:** This limitation could be addressed by employing a total-body J-PET.
2. **High Noise & Accidental Coincidences:** These effects are evident from the purity analysis.
3. **Standard Reconstruction Algorithms:** Conventional methods such as MLEM are not directly applicable in this case.

Next Step:

<UNDER CONSTRUCTION…>

The next step is to develop an iterative approach that integrates information from the Normal Coincidence Events with detector-scattered photon data, with the goal of progressively refining and deriving a reliable attenuation map.

Future Goal:

1. Validate this approach with **real J-PET Experimental Data.**
2. Integrate the validated approach into a **deep learning architecture**.
3. Deploy the final form for **clinical use**. It would be particularly beneficial for **Pediatric Patients**.

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