Data models for the Compton camera acquisition and their influence on the reconstructed images

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Summary

1. SPECT imaging with the Compton camera

2. From the events to the image : list-mode MLEM algorithm

3. Numerical results and conclusions

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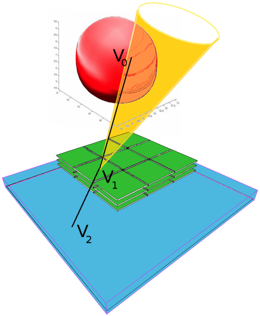
3. Numerical results and conclusions
   - Role of the parameters of the system matrix
   - Role of the sensitivity matrix
   - Joint influence of the system matrix and of the sensitivity

SPECT imaging with the Compton camera



- Source of γ photons : emission at some point V_0 and initial energy E
- Scatterer : first interaction (Compton scattering) at some V_1 and energy transmitted to an electron denoted E_1
- Absorber : second interaction at some V_2 (photoelectric absorption) and energy E_2
- Projection pattern : integral on the surface of a cone

For multiple scatterings, V_2 is the second Compton interaction and E_2 estimates $E - E_1$.

$$\cos\beta = 1 - \frac{m_e c^2 E_1}{(E - E_1)E}$$

(Compton scattering angle)

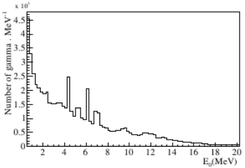
Event $\mathscr{E} = (V_1, V_2, \beta)$

associated to a Compton cone $\mathscr{C}(V_1, V_2, \beta)$

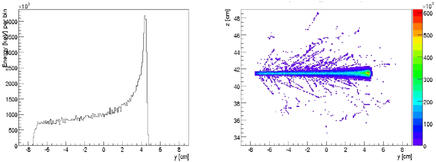
Applications

The Compton camera surpass in sensibility the Anger camera by 1-2 orders of magnitude.

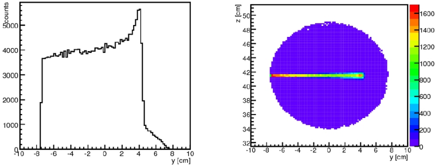
- Imaging of poly-energetic sources
- Imaging of sources with energies $\sim$ 1 MeV
- 3D imaging with a single camera



Emission spectrum of prompt-γ particles between 0.5 and 20 MeV obtained with a carbon ion beam at 350 MeV/u irradiating a water phantom with 10^5 ions.



PMMA-sphere irradiated by a proton beam (140 MeV), Edep.



Last interaction of γ photons that escape the phantom.

("A tracking Compton-scattering imaging system for hadron therapy monitoring", M. Frandes, A. Zoglauer, V. Maxim, R. Prost, IEEE TNS, 2010)

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Image reconstruction : LM-MLEM algorithm

$$\widehat{\lambda}_j^{(\ell+1)} = \frac{\widehat{\lambda}_j^{(\ell)}}{s_j} \sum_i t_{ij} \frac{1}{\sum_k t_{ik} \widehat{\lambda}_k^{(\ell)}}$$

where t_{ij} is the probability for a photon emitted by the voxel j to be detected as event e_i,

$$t_{ij} = p(\mathscr{E} = e_i | v_j)$$

and s_j is the probability for a photon emitted by the voxel j to be detected. Thus,

$$s_j = \sum_i t_{ij}$$

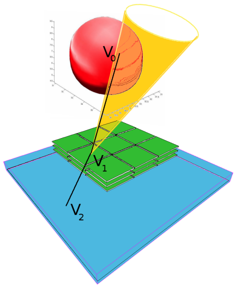
where the sum is taken on all possible events, not only on the realized ones.

Challenge : calculation of the system matrix

Which model for the conditional probability

$$p(\mathscr{E} = e \mid V_0), \quad e = (V_1, V_2, \beta) \ ?$$

We choose to focus on the geometrical parameters. When real positions of interaction and real energies are supposed to be measured,



$$p(\mathscr{E} = e \mid V_0) \propto K(\beta, E) \frac{|\cos(\theta)|}{V_0 V_1^2} \frac{|\cos(\alpha)|}{V_1 V_2^2} \delta(\beta - \beta_{\overrightarrow{V_1 V_2}}),$$

$$\theta = (\widehat{\overrightarrow{V_1 V_0}, \vec{n}})$$

$$\alpha = (\widehat{\overrightarrow{V_2 V_1}, \vec{n}})$$

Numerically verified by MC simulations.

$$\beta_{\overrightarrow{V_1 V_2}} := (\widehat{\overrightarrow{V_1 V_2}, \overrightarrow{V_0 V_1}})$$

Challenge : calculation of the system matrix

Which model for the conditional probability

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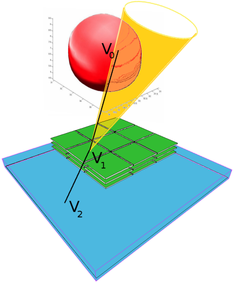
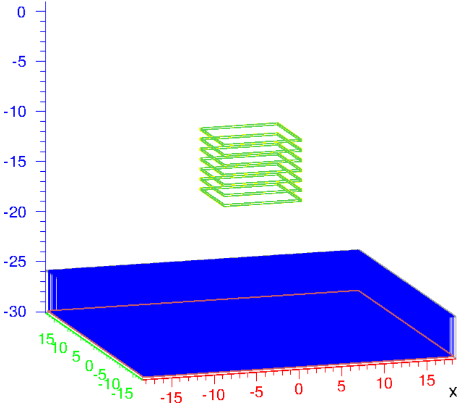


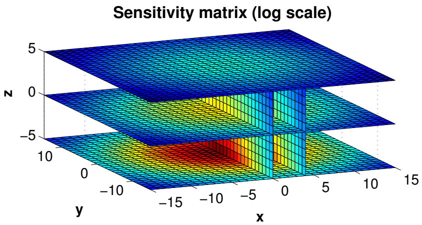
In order to account for measurement uncertainties, we take

$$t_{ij} = \frac{|\cos(\alpha_i)|}{V_1 V_2^2} \int_{M \in v_j} K(\beta_M, E) \frac{\cos(\theta_M)}{V_1 M^2} g(\beta_M | \beta_i, \sigma_{\beta_i}) dv.$$

Summary

Simulation : MEGAlib/GEANT4



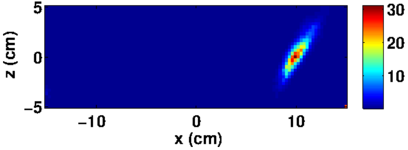


- Si scatterers, $9 \times 9 \times 0.2$ cm^3, 2×128 strips, energy resolution 2.35 keV FWHM
- Absorber in LYSO crystals, $0.5 \times 0.5 \times 4$ cm^3, energy resolution function of the energy of the incident photon, 31 keV @ 1 MeV.

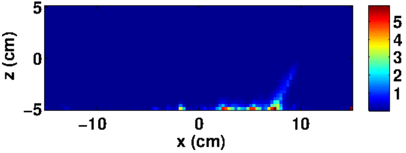
Joint influence of the model and sensitivity

Mono-energetic (1275 keV) simulated point source in (10,0,0).
3500 events, no energy selection, 20 iterations.

- System matrix T from the model :

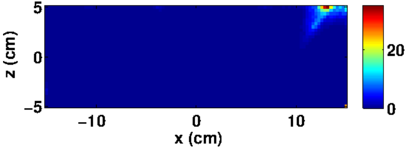


s_j from MC simulation (right model)

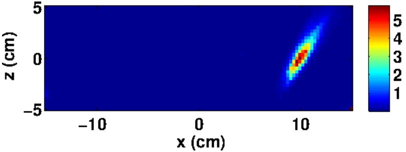


$s_j \equiv 1$

- Elements t_{ij} do not account for the solid angles :



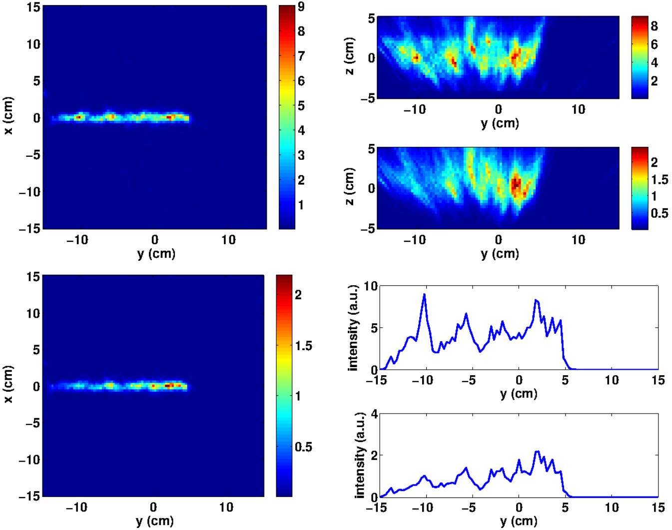
s_j from MC simulation



$s_j \equiv 1$ (trivial model)

Is the model of the system matrix gainful ?

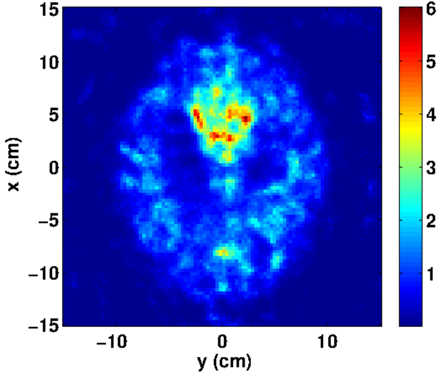
Mono-energetic (1275 keV) line source ($y \in [-14, 5]$) at 10 cm from the camera. Energy selection (20%), 6000 events, 20 iterations.



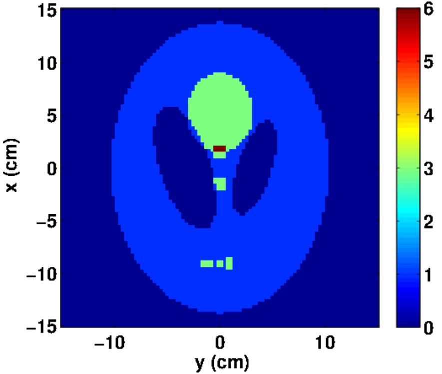
The 3D image of the source was calculated on the base of the proposed model (upper image from each pair), then with the trivial model (lower image from each pair).

Examples

Mono-energetic (1275 keV) Shepp-Logan phantom at 10 cm from the camera. 80000 events, energy selection (20%), 20 iterations.

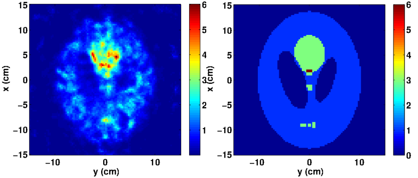


Reconstructed image.
Horizontal slice
at 10 cm from the camera.



Original phantom (2D)

Conclusions



- The quality of the Compton images is strongly related to the model chosen for the system matrix and to the sensitivity matrix.
- The proposed theoretical model of the system matrix for ideal detectors was confirmed by simulations.
- Variants of the iterative reconstruction algorithm may improve the quality of the images.

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