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

Voichița Maxim, Xavier Lojacono, Estelle Hilaire (CREATIS)
Jean-Luc Ley, Denis Dauvergne, Etienne Testa (IPNL)

Université de Lyon, France

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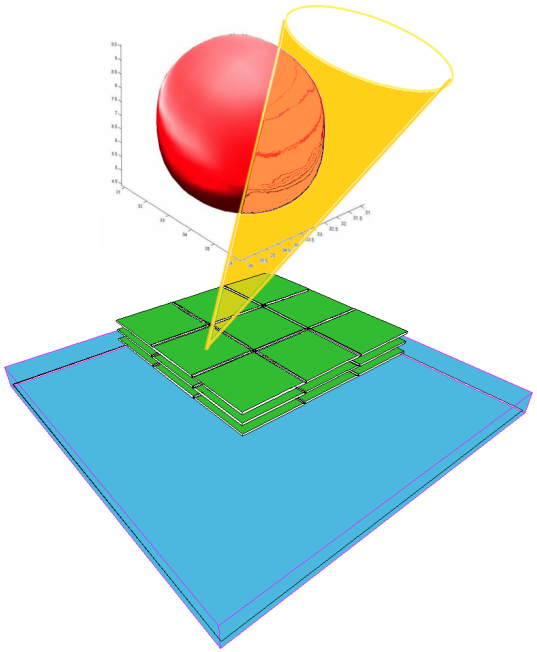
Summary

Summary

SPECT imaging with the Compton camera



- Source of γ particles : 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)

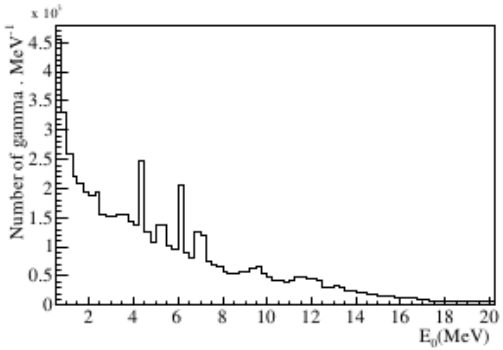
Event $\mathscr{E} = (V_1, V_2, E_1, E_2)$

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

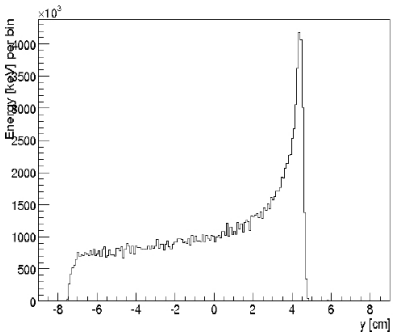
Applications

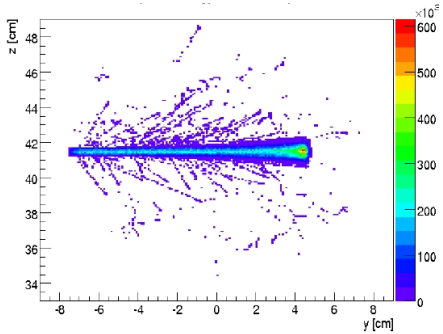
The sensitivity of the Compton camera is superior to the one of the Anger camera by 1-2 orders of magnitude.

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

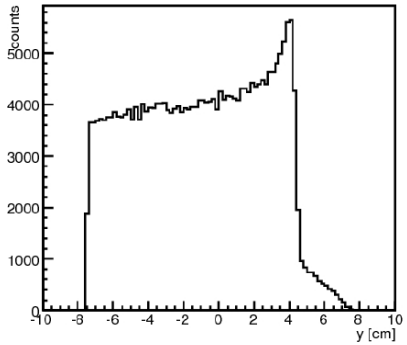


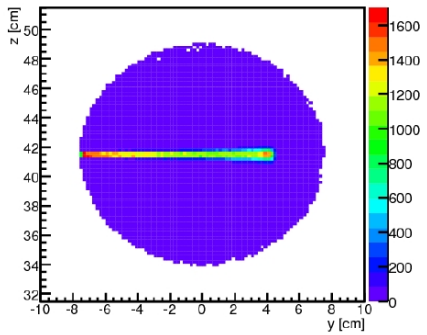
Emission spectrum of prompt-γ particles between 0.5 and 20 MeV obtained with a carbon ion beam at 350 MeV/u irradiating a water phantom with 10^5 ions.





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





Last interaction of γ particles 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)

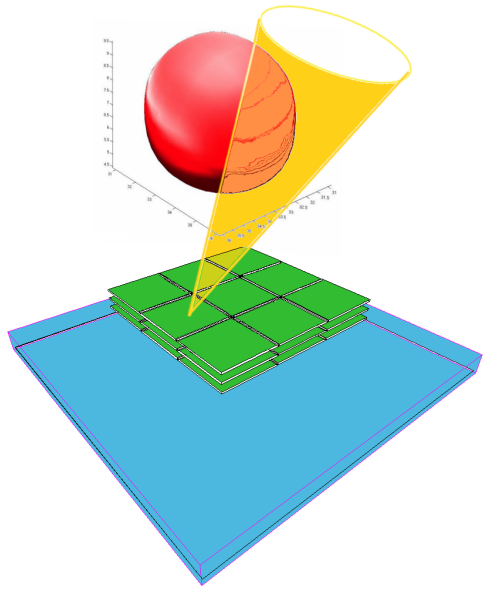
Summary

Challenge : from the events to the image

Requires a model for the conditional probability of $e = (V_1, V_2, E_1, E_2)$ given the emission point V_0,

$$p(\mathscr{E} = e \mid V_0).$$

We choose to focus on the geometrical parameters and to ignore the influence of scattering/absorption probabilities. When real positions of interaction and real energies are supposed to be measured,



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

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

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

$$\beta_{\overrightarrow{V_1 V_2}} := (\widehat{\overrightarrow{V_1 V_2}, \overrightarrow{OV_1}})$$

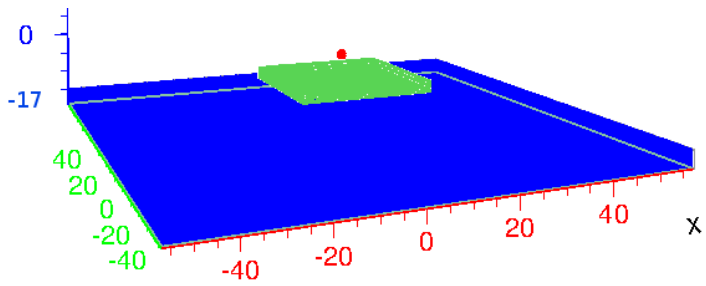
Numerical validation by simulations ?

Simulation setup

Camera : three Si layers, $32 \times 32 \times 0.5$ cm^3, altitude $z \in \{-5, -6, -7\}$, absorber made of $0.5 \times 0.5 \times 4$ cm^3 crystals at $z = -17$

Source : mono-energetic (364 keV) point source in O(0,0,0), 10^8 emitted photons.

Events : $\approx 7 \times 10^6$



Ideal detectors :

- $E_1 + E_2 = E \quad \rightarrow e := (V_1, V_2, \beta)$
- The sequence of interactions is known
- The (x, y) positions of interaction are measured without noise ; the z coordinate is taken at half-depth of the detector.

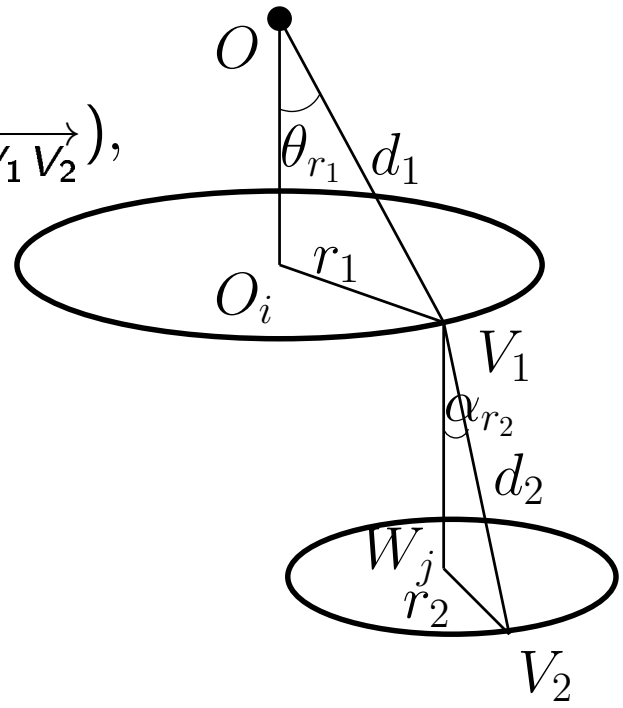
The number of events/bin (≈ 1 mm, $\approx 1^\circ$) is statistically small.

Averaging

1. Selection of events having $z_{V_1} = -5$ cm and $z_{V_2} = -6$ cm.
2. For each $r_1 \in (0, 16\text{ cm})$, selection of $V_1 \in C(O_1, r_1)$ parametrized by $\varphi_1 \in [0, 2\pi)$.
3. For each V_1 and for each $r_2 \in (0, 8\text{ cm})$, selection of $V_2 \in C(W_2, r_2)$ parametrized by $\varphi_2 \in [0, 2\pi)$.
4. For each V_1, V_2 there is one single β such that $V_0 \in \mathscr{C}(V_1, V_2, \beta)$

When

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



$$\sum_{V_1 \in C(O_1, r_1)} \sum_{V_2 \in C(W_2, r_2)} \sum_{\beta} \frac{\widehat{p}(V_1, V_2, \beta \mid V_0)}{K(\beta, E)}$$

should be proportional to

$$M(r_1, r_2) = r_1 r_2 \frac{\cos(\theta_{r_2})}{d_1^2} \frac{\cos(\alpha_{r_1})}{d_2^2}.$$

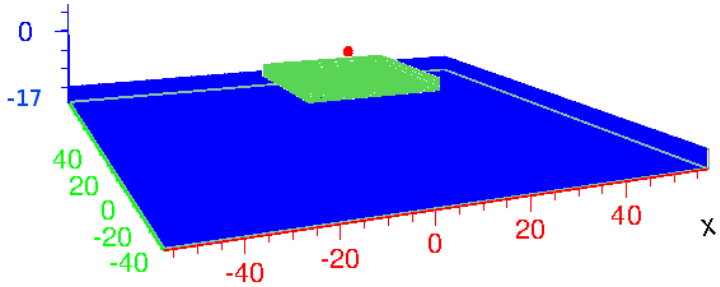
Numerical investigation

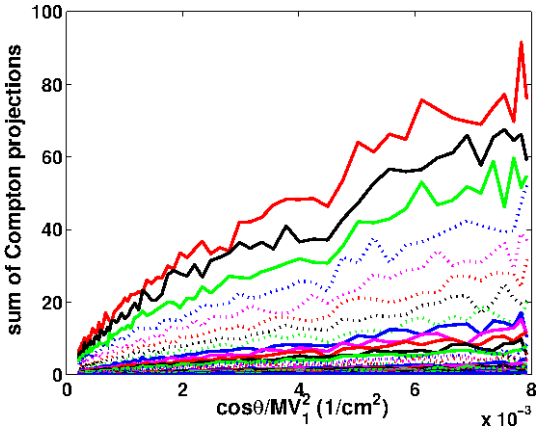
Camera : three Si layers $z \in \{-5, -6, -7\}$, absorber at $z = -17$

Source : mono-energetic (364 keV) point source in O(0,0,0), 10^8 emitted particles

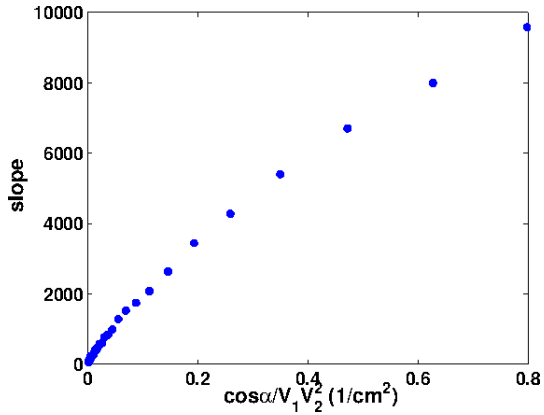
Events : $\approx 7 \times 10^6$

Binning : $d_{r_1} = d_{r_2} = 2$ mm, $d_\beta = 3°$

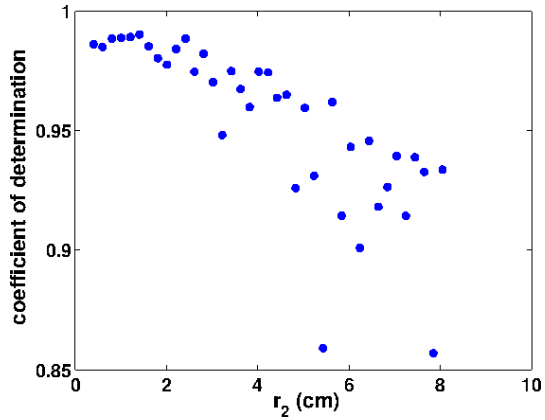




Variation of $\frac{M(r_1,r_2)}{r_1 r_2}$ w.r. to $\frac{\cos\theta_{r_1}}{d_1^2}$; Each r_2 : a curve



Slope from regression as function of $\frac{\cos\alpha_{r_2}}{d_2^2}$; Each r_2 : a point



Quality of the regression. Degrades as V_2 moves tw. the border.

Summary

Image reconstruction : LM-MLEM algorithm

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

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

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

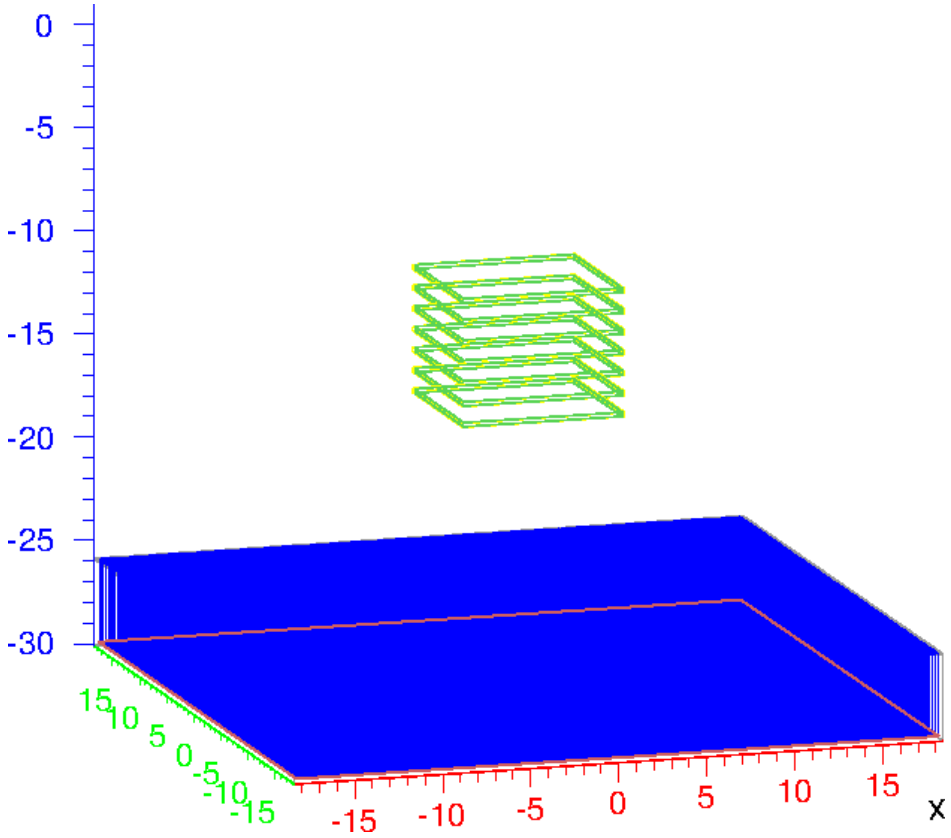
and s_j is the probability for a photon emitted by the voxel j to be detected. Thus,

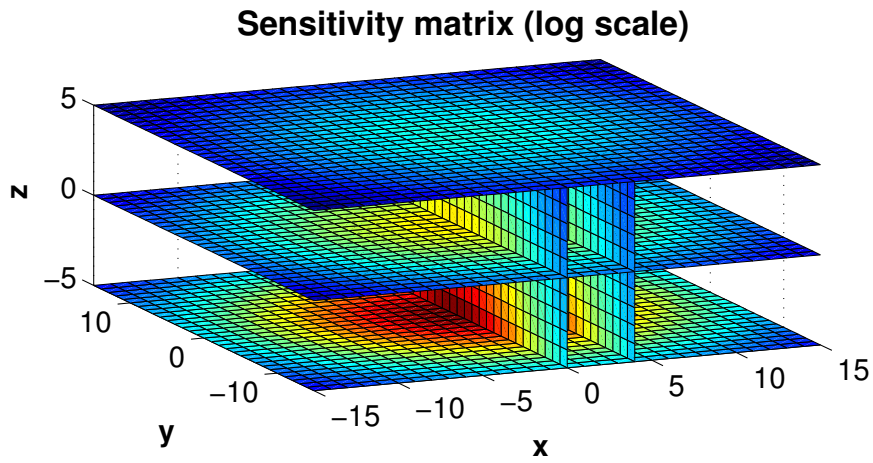
$$s_j = \sum_i t_{ij}$$

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

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

Sensitivity matrix





- Si scatterers, $9 \times 9 \times 0.2$ cm^3, 128×128 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 particle, 31 keV @ 1 MeV.

Summary

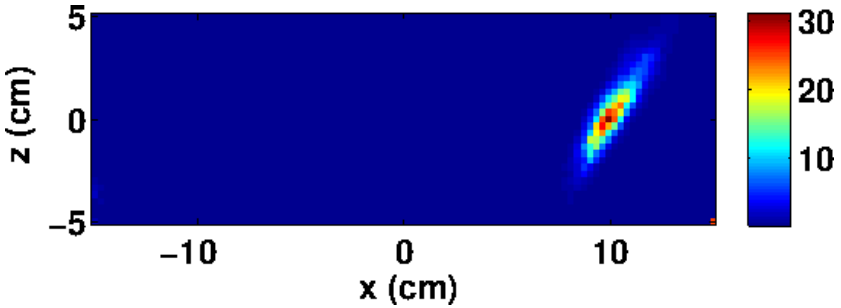
Aim

1. Role of the parameters of the system matrix
2. Role of the sensitivity matrix
3. Joint influence of the system matrix and of the sensitivity

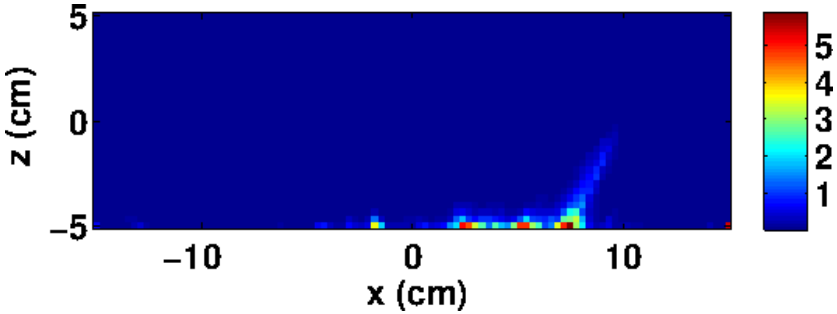
Joint influence of the model and sensitivity

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

- System matrix from the model :

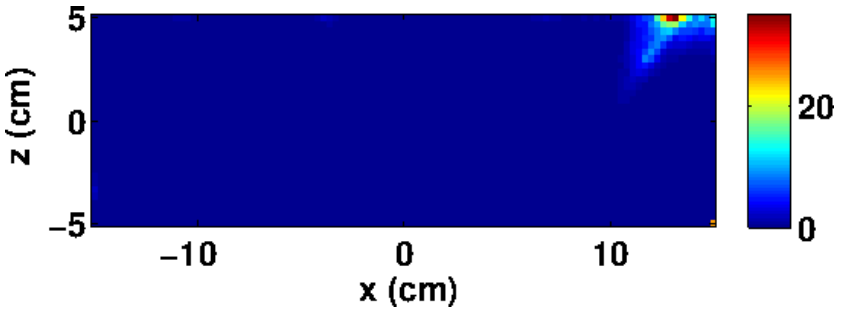


s_j from MC simulation

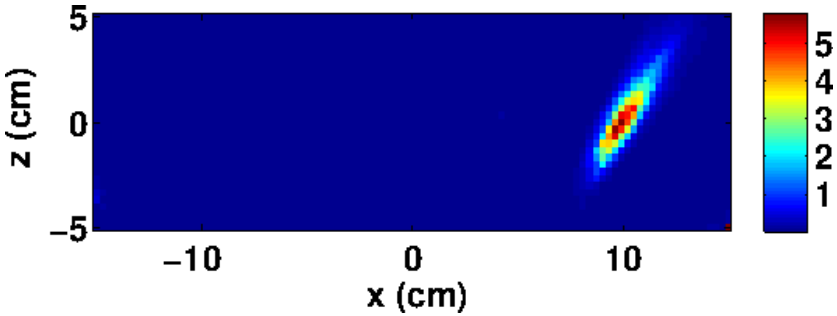


$s_j \equiv 1$

- Elements of the system matrix set to one :



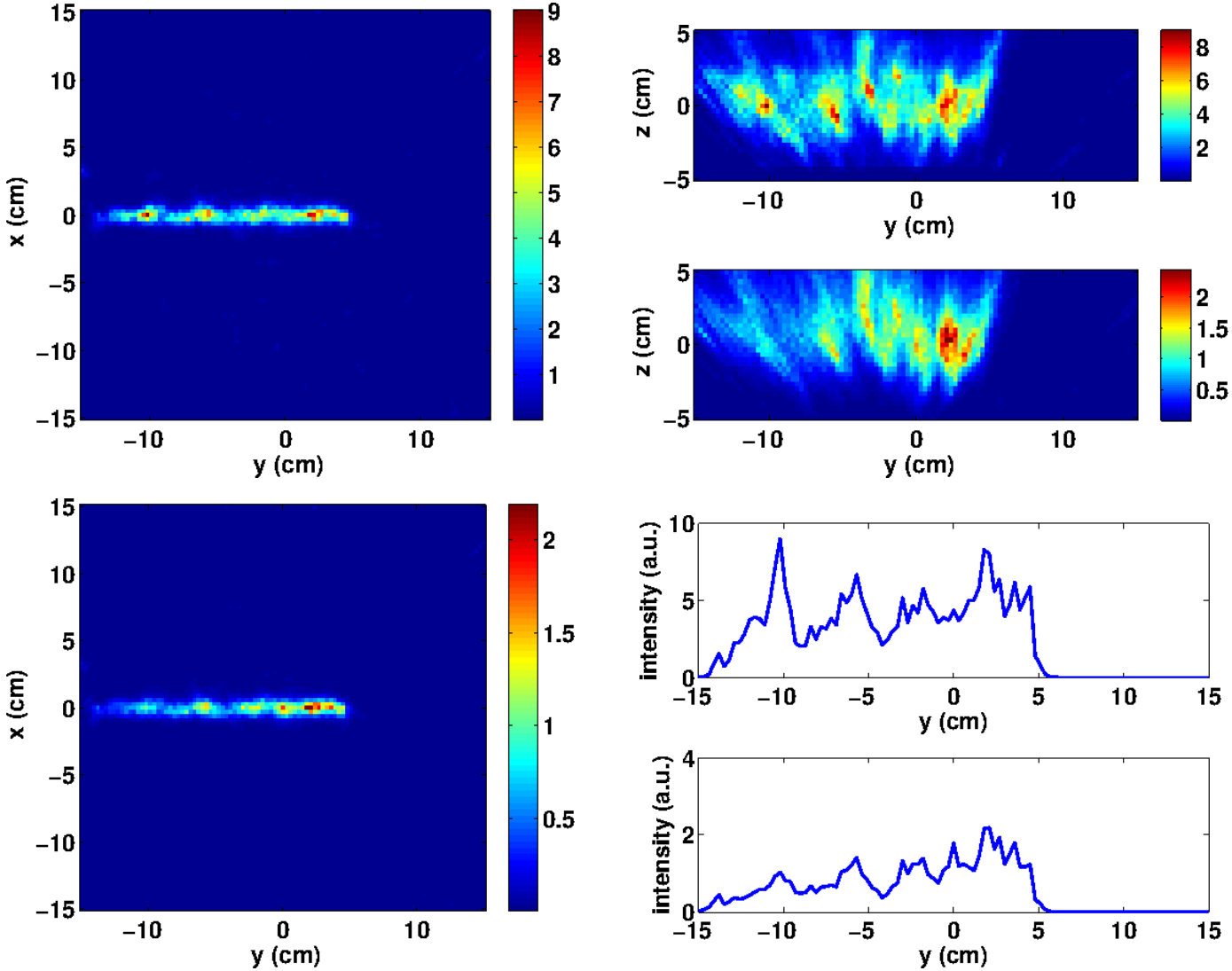
s_j from MC simulation



$s_j \equiv 1$

Is the model of the system matrix gainful ?

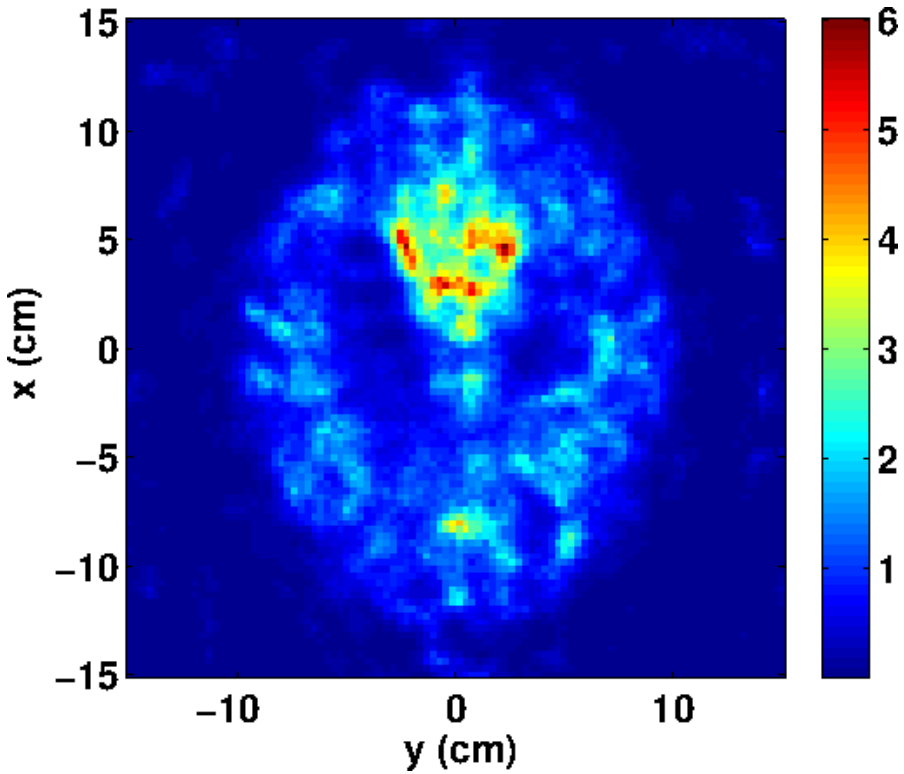
Mono-energetic (1275 keV) line source ($y \in [-14, 5]$) at 10 cm from the camera. Energy selection (20%), 6000 events, 20 iterations.



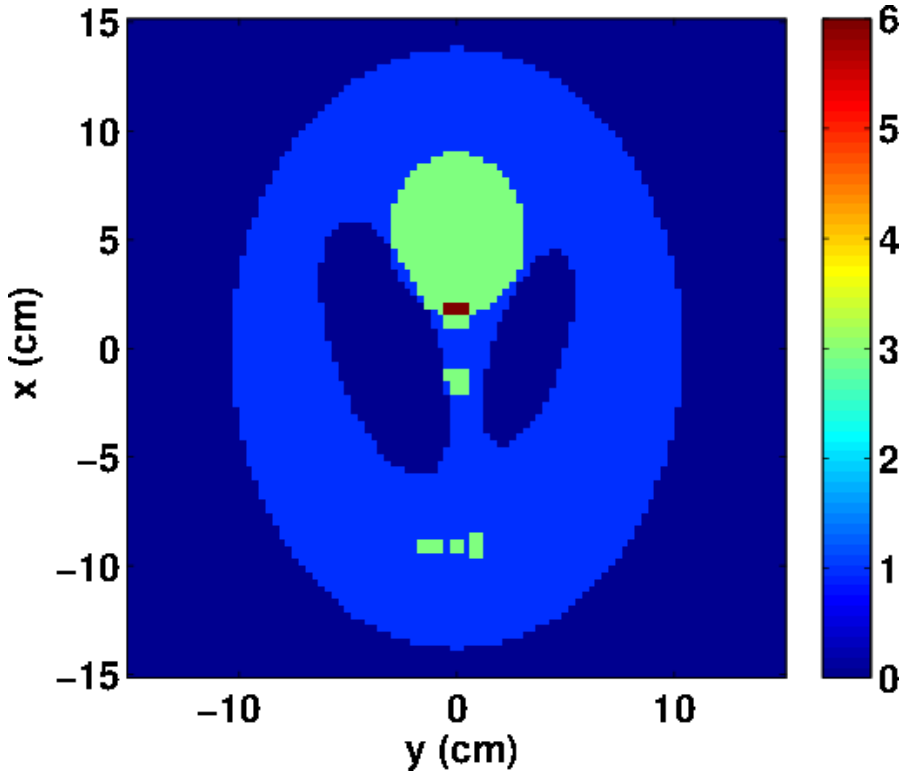
The 3D image of the source was calculated on the base of the proposed model (upper image from each pair), then with $t_{ij} \equiv 1$ and $s_j \equiv 1$ (lower image from each pair).

Examples

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



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



Original phantom (2D)

Conclusions

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

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