A Fast-Converging Maximum A Posteriori Algorithm for 3D Image Reconstruction Using Multi-view Compton Data

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Outline

3D imaging:
A promising concept for waste characterization

To optimize waste storage packaging and costs a 3D map of major isotopes contamination is the best solution

But today this is not realistic economically as 3D scanning systems, based on collimated Germanium are both expensive and slow.

The cost of a 3D scan is a function of:

- The number of views needed for 3D reconstruction. This number depends on:
  - Camera Field of View FOV (nb of views to 2D image an object)
  - How many photons are needed by voxel/by view
- The sensitivity of the camera (how long should we wait to reach a given detection limit?)
- How fast the reconstruction algorithms converges with a limited number of photons & views

Why are Compton cameras uniquely suited for 3D scans?

Compton camera has a wide Field of View (90°x90° here)

→ A limited number of views should fully cover an object

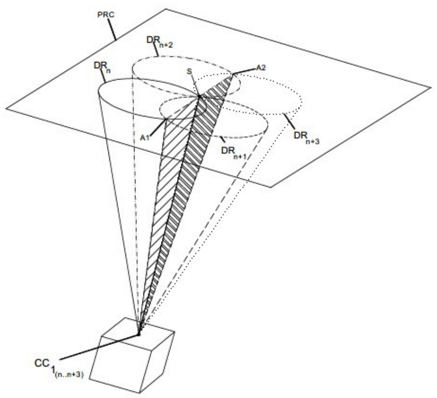
Compton events generate large thick cones : « fuzzy objects »

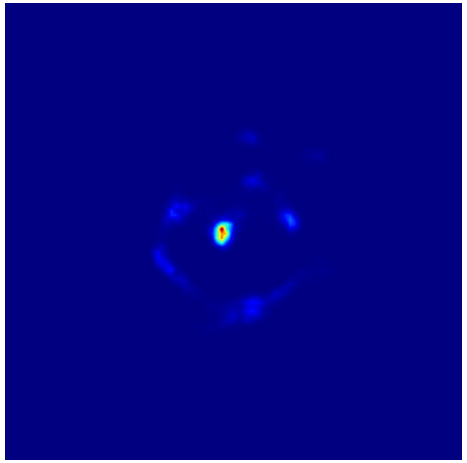
→ In 2D reconstructions High statistics are needed to avoid false positive

→ In 3D the volume of intersection between cone shrinks by an order of magnitude

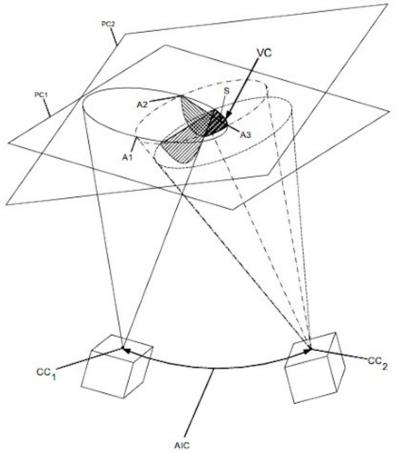
Compton image reconstruction works much better in 3D than in 2D

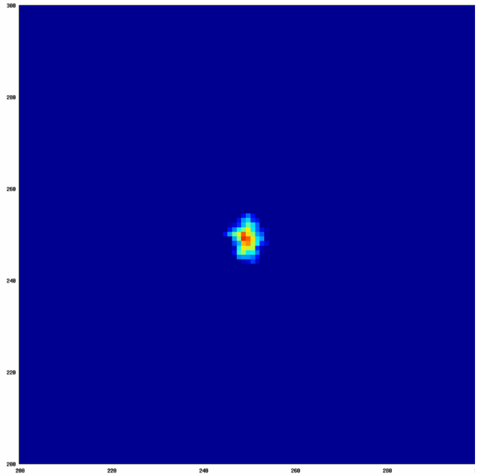
One view



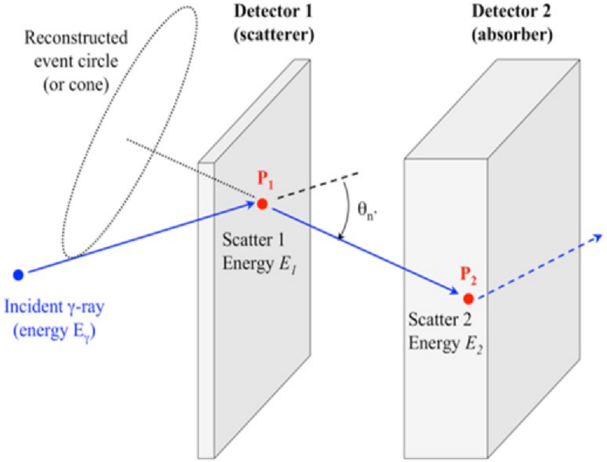


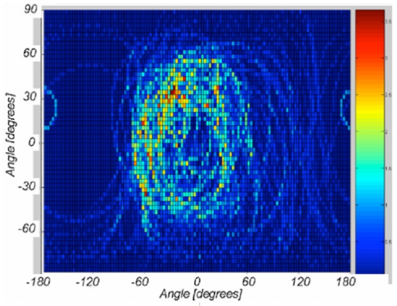
2 or more views





Temporal imaging Compton camera $CeBr_3$:
A technology well suited for 3D imaging





Low noise level

- Two fast CeBr3 scintillating crystals plates
- Low natural background
- <500 ps Coïncidence veto on Compton events

High angular resolution

- <8° vs < 20° for CZT cameras

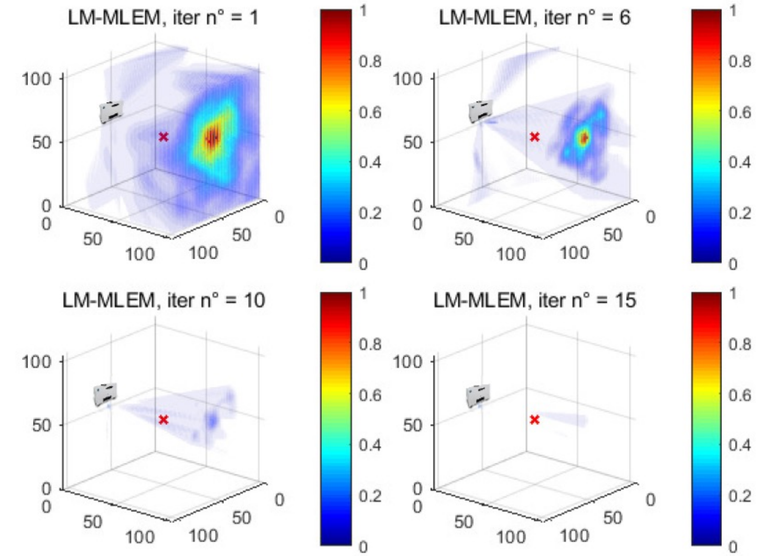
Large Field of View

- 90° x 90°

3D Compton image reconstruction: *Problem statement*

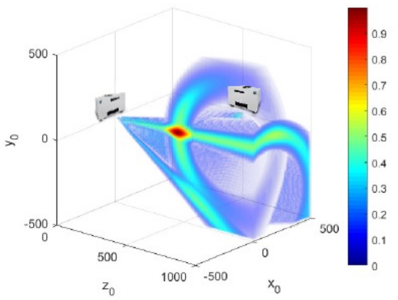
Single-view reconstruction

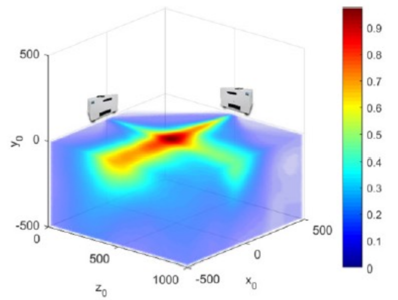
- 2 approaches: analytical, iterative
- 2 classes of models: deterministic, probabilistic
- Reconstruction is marginal if parallax is sufficient (large detector, near field)
- 3D reconstruction Fails if parallax is low (compact camera, far field)



Multi-view reconstruction

- Improve the parallax of detected events
- Methods to be developed





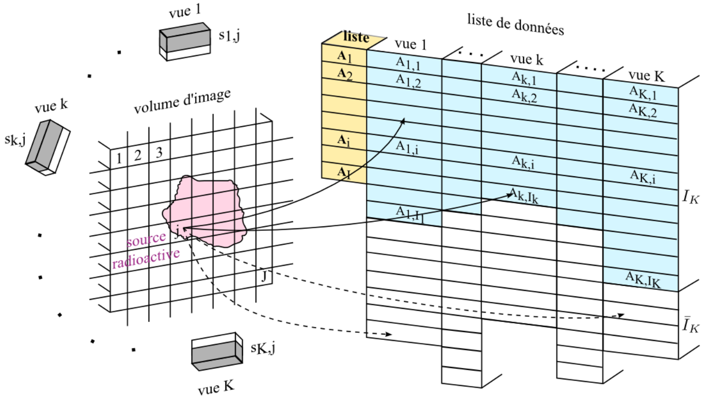
Reconstruction 3D – Extended LMMLEM algorithm

Ordinary LMMLEM

$$\hat{f}_j^{(t+1)} = \frac{\hat{f}_j^{(t)}}{s_j}\sum_{i=1}^{I}\frac{t_{ij}}{\sum_{l=1}^{J} t_{il}\hat{f}_l^{(t)}}$$

(failed due to lack of parallax)

new list-mode data

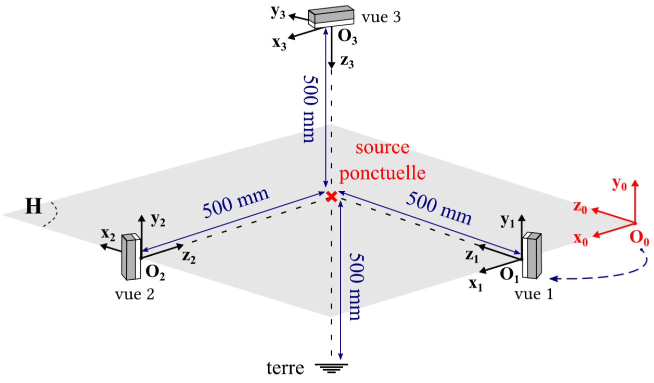


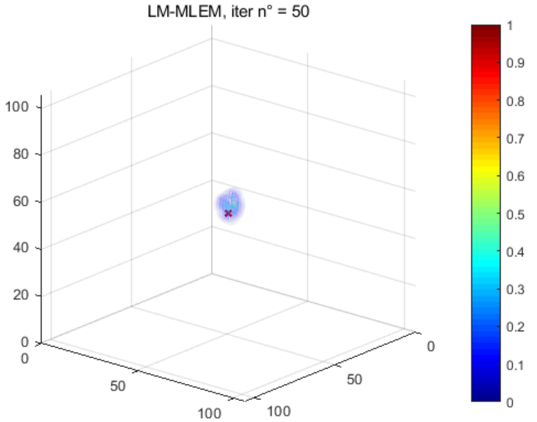
extended LMMLEM

$$\hat{f}_j^{(t+1)} = \frac{\hat{f}_j^{(t)}}{\sum_{k=1}^{K} s_{jk}}\sum_{i=1}^{I}\frac{\sum_{k=1}^{K} t_{ijk}}{\sum_{l=1}^{J} t_{il}\hat{f}_l^{(t)}}$$

(improved parallax)

Result given by extended LMMLEM algorithm





Problem

- Convergence is slow
- Large number of data is needed

Solutions

- Using a priori knowledge of source
- Bayésian reconstruction
- Optimisation algorithm

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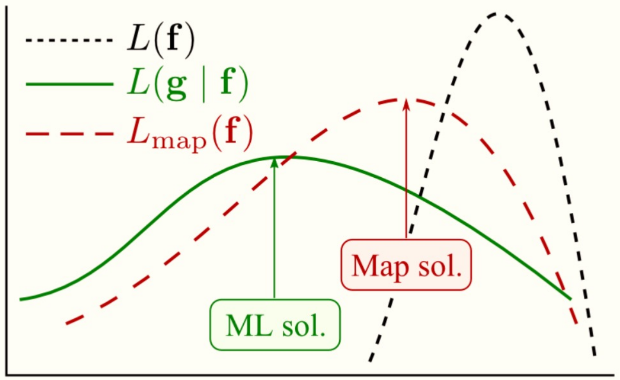
Markov Random Field MAP algorithm (LM-MRFMaP)

Bayesian approach: maximum a posteriori (MAP) estimate



$$\hat{\boldsymbol{f}} = \arg\max_{\boldsymbol{f} \geq 0}\{p(\boldsymbol{f} \mid \boldsymbol{g})\} = \arg\max_{\boldsymbol{f} \geq 0}\{L(\boldsymbol{g} \mid \boldsymbol{f}) + L(\boldsymbol{f})\}$$

MAP with Markov random field (MRF) prior

$$\hat{\boldsymbol{f}} = \arg\max_{\boldsymbol{f} \geq 0}\left\{\underbrace{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\frac{t_{ij}f_j'}{\sum_{s=1}^{J} t_{is}f_s'} - t_{ij}f_j\right)}_{\text{surrogate of Poisson log-likelihood}} - \sum_{j=1}^{J}\underbrace{\sum_{\{j,l\}\in C} \beta_{jl}\rho(f_j - f_l)}_{\text{enery of MRF prior}}\right\} = \arg\max_{\boldsymbol{f} \geq 0}\{L_{\text{map}}(\boldsymbol{f})\}$$

Iterative maximization scheme for a concave $L_{\text{map}}(\boldsymbol{f})$

$$\hat{\boldsymbol{f}}^{(k+1)} \leftarrow \hat{\boldsymbol{f}}^{(k)} + \sum_{j=1}^{J} a_j^{(k)} \boldsymbol{e}_j^{(k)} \quad \text{with} \quad a_j^{(k)} \leftarrow \arg\max_{a_j \geq -f_j^{(k)}} \left\{L_{\text{map}}\left(\hat{\boldsymbol{f}}^{(k)} + a_j \boldsymbol{e}_j^{(k)}\right)\right\}$$

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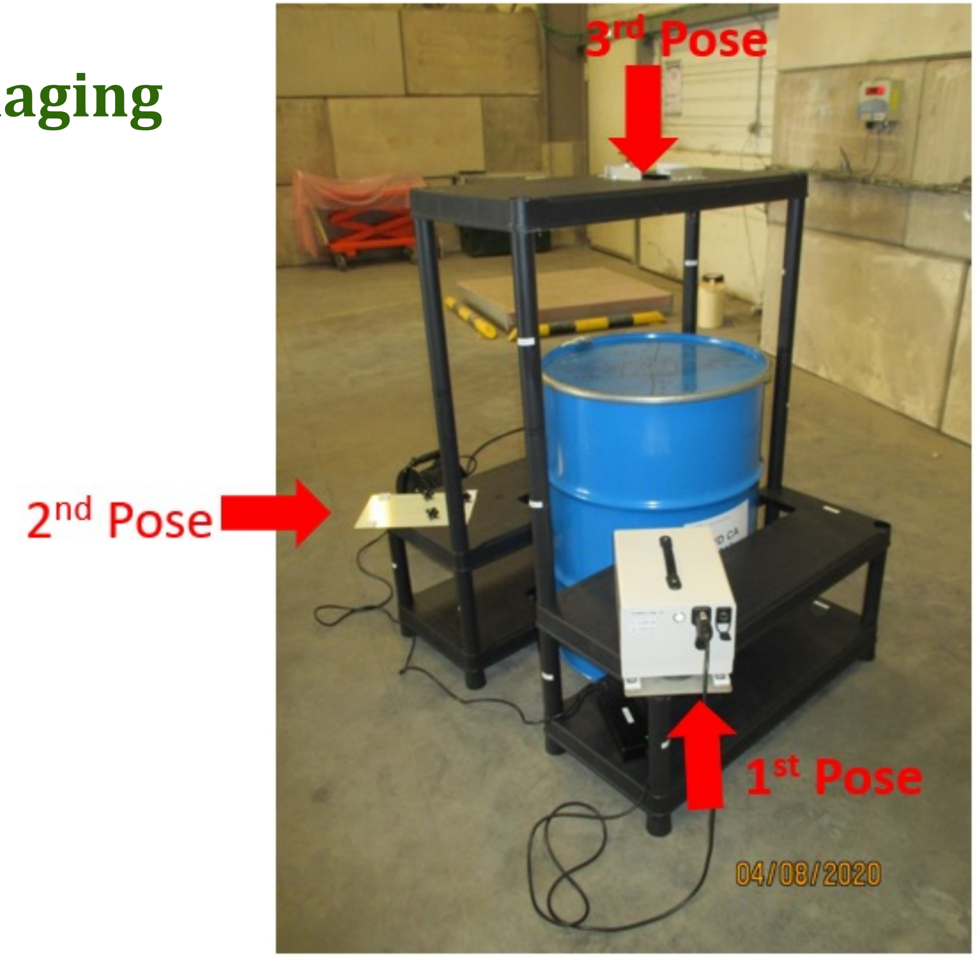
Numerical experiments on real data

Temporal Imaging Compton camera V3 developped by Damavan Imaging

Radioactive sources :

- Sodium ^{22}Na
- 0,2 MBq of total activity
- Acquisition times: 20mn/view

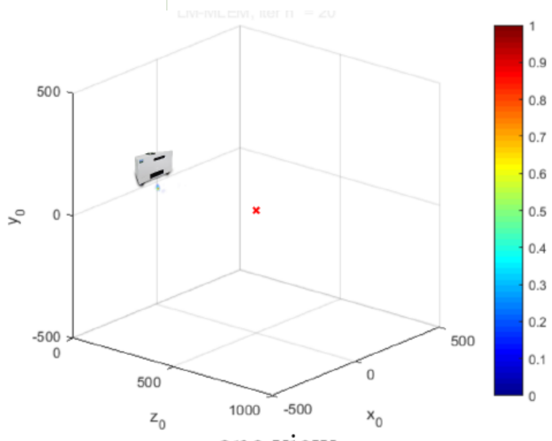
Real experiment setting



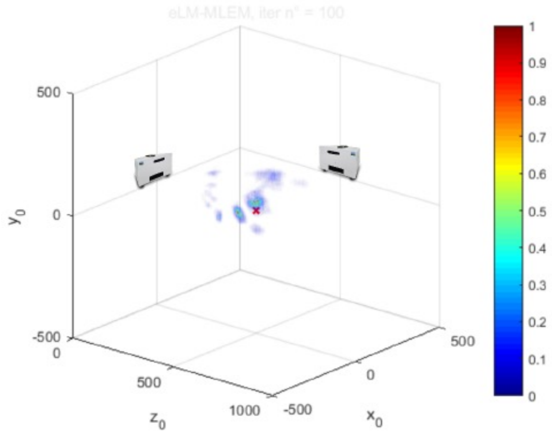
3D Reconstruction results – eLMMLEM algorithm

Reconstruction information

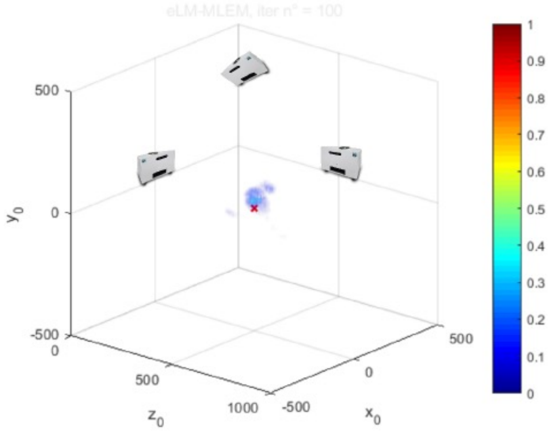
- Source volume: 1000 x 1000 x 1000 mm
- Energy range: 1.1 MeV – 1.3 MeV
- Iteration number: 100



one view



two views

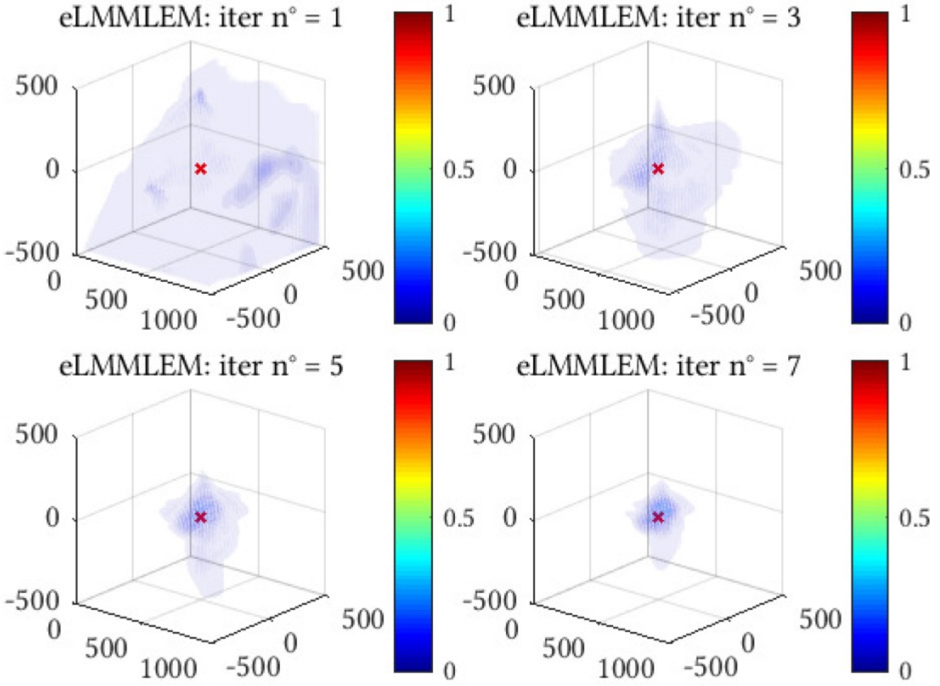


three views

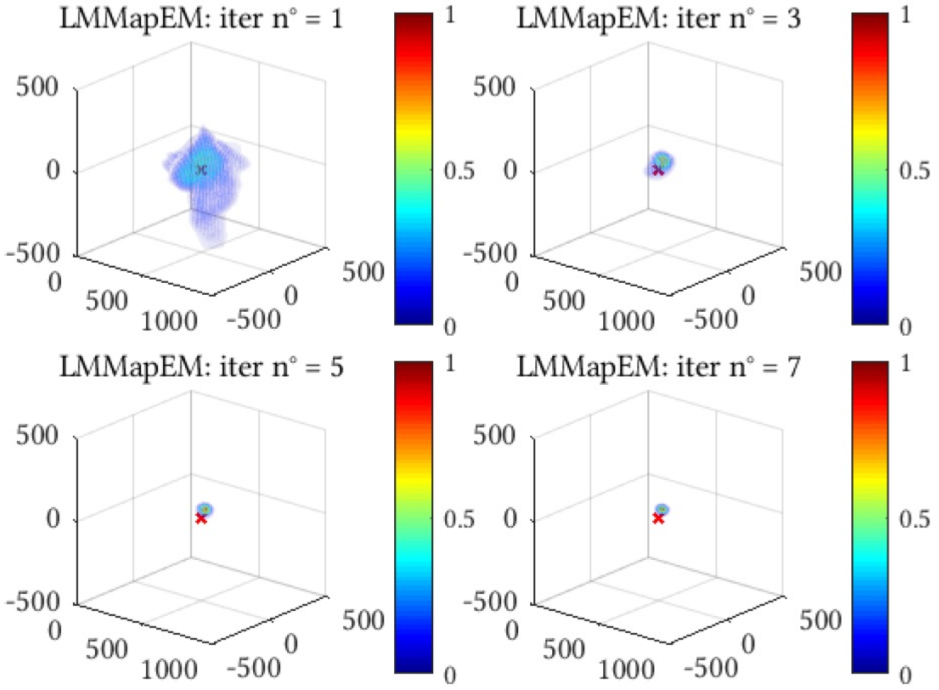
The higher the view number, the more the reconstruction result given by the eLMMLEM algorithm is better

Reconstruction results - LM-MRFMaP algorithm

eLMMLEM algorithm



LM-MRFMaP algorithm



LM-MRFMaP algorithm converges much faster than the extended eLMMLEM algorithm

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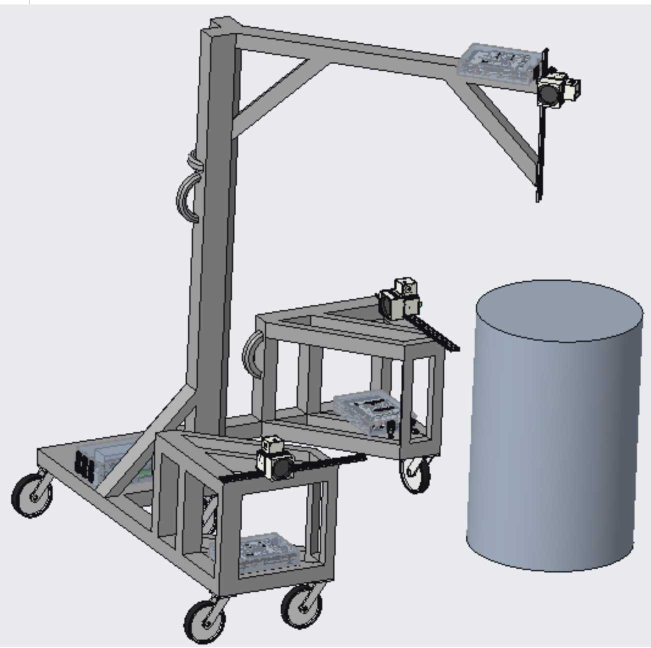
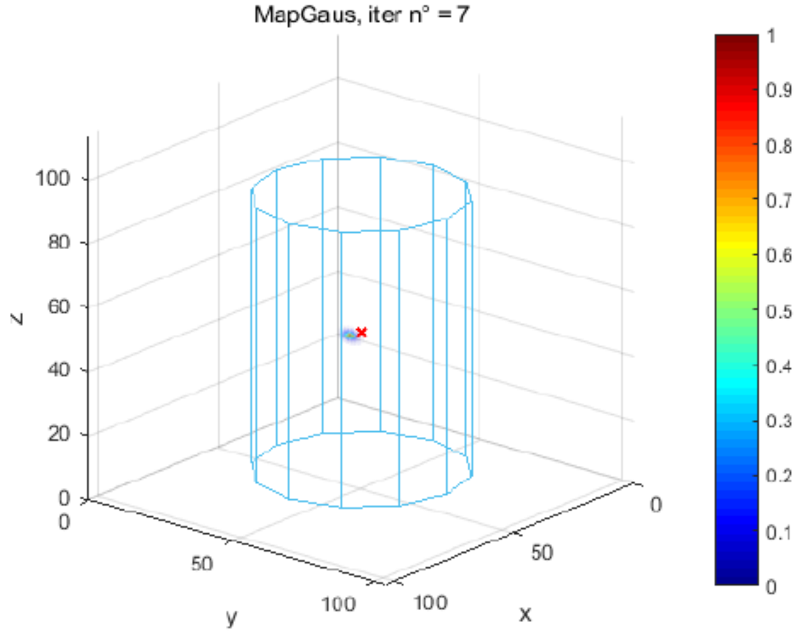
Application to the Dream Scanner project

This reconstruction technology will be implemented on Dream scanner prototype

This scanner is a joint project with Orano DS

- 3 Compton camera heads
- The scanner moves, not the drum
- Will Implements the new algorithm
- Our target is to reach 10 minutes for a 3D scan of a low density 225 l drum





Conclusions & perspectives

Conclusions	Building a new list-mode data space, adapted system response function & sensitivity
	eLM-MLEM 3D reconstruction algorithm extended to multi-view Compton data
	Proposing a new maximization scheme for MRF MAP algorithm
	Numerical tests on real datasets show the outperformance
	More advanced tests on reconstruction of extended sources underway
Perspectives	Extending the proposed algorithm for other kinds of MRF-based priors
	Experiment on other radioactive sources (multi-point source, extended source, …)

Thank you for your attention!

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