gVirtualXRay: Open-source Library to Simulate Transmission X-ray Images

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Franck P. Vidal
Lecturer in Visualisation

School of Computer Science and Electronic Engineering
Bangor University

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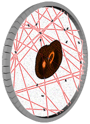
Outline

Parts of this work have been funded by:

- FP7 Career Integration Grant: Fly4PET: Fly Algorithm in PET Reconstruction for Radiotherapy Treatment Planning
  `http://fly4pet.fpvidal.net/`



- FP7 ICT Collaborative project: RASimAs: Regional Anaesthesia Simulator and Assistant
  `http://www.rasimas.eu/`

RASimAs

- The Titan Xp used for this research was donated by NVIDIA.
- Thanks to Dr Jean-Michel Létang, INSA de Lyon, for his support during the data acquisition.

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Outline

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Rational for this Research (in Medical VR)

- Simulation of X-Ray attenuation extensively studied in physics;
- Different physically-based simulation code available;
- Physically-based simulation usually performed using Monte Carlo methods on CPU (often used in dosimetry for radiotherapy);
- Computing an image requires a very very very long time;
- Ray-tracing techniques are an alternative, but still relatively slow on CPU;
- Need for an fast open-source graphics processing unit (GPU) implementation.

Timeline

- N. Freud, "Modelling and simulation of X- and γ-ray imaging systems", PhD thesis, INSA de Lyon, France, 2003
- F. P. Vidal, "Modelling the response of x-ray detectors and removing artefacts in 3D tomography", Master's thesis, INSA de Lyon, France, Sep. 2003
- OpenGL Shading Language (GLSL) included into the OpenGL 2.0 core (2004).
- F. P. Vidal, "Simulation of image guided needle puncture: Contribution to real-time ultrasound and fluoroscopic rendering, and volume haptic rendering", PhD thesis, Bangor University, UK, Jan. 2008
- F. P. Vidal, M. Garnier, N. Freud, *et al.*, "Simulation of X-ray attenuation on the GPU", in *Proceedings of Theory and Practice of Computer Graphics 2009*, Cardiff, UK: Eurographics Association, Jun. 2009, pp. 25–32
- F. P. Vidal, M. Garnier, N. Freud, *et al.*, "Accelerated deterministic simulation of x-ray attenuation using graphics hardware", in *Eurographics 2010 - Poster*, Norrköping, Sweden: Eurographics Association, May 2010, Poster 5011
- Restart as an open-source project, Dec 2013.
- F. P. Vidal and P.-F. Villard, "Development and validation of real-time simulation of x-ray imaging with respiratory motion", *Computerized Medical Imaging and Graphics*, vol. 49, pp. 1–15, Apr. 2016

Fact sheet

- Open-source (created on 01 Dec 2013)
- SVN repository hosted by SOURCEFORGE;

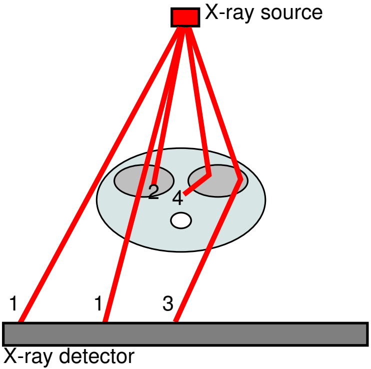
```
svn checkout http://svn.code.sf.net/p/gvirtualxray/code/trunk/
```

- Implemented in C++ using OpenGL ;
- Can also be deployed in python™ applications;
- Provides real-time performance;
- Is accurate (quantitative validation);
- Reproducibility;
- Supports XCOM: Photon Cross Sections Database from NIST;
- Uses polygon meshes to model 3-D geometries

from popular file formats (eg. STL, PLY, 3DS, OBJ, DXF, X3D, DAE)

X-photons/matter Interactions

- X-photons cross matter;
- During their path into the body, they can interact with matter.



1. Directly transmitted photons (no interaction);
2. Absorbed photons;
3. Scattered photons;
4. Absorbed scattered photons.

- For most X-rays imaging modalities, only directly transmitted photons are essential;
- Scattered photons decrease the image quality;
- Absorbed photons do not reach the detector.

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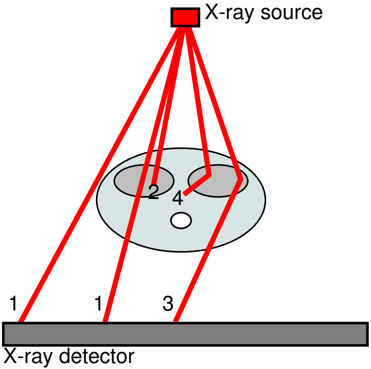

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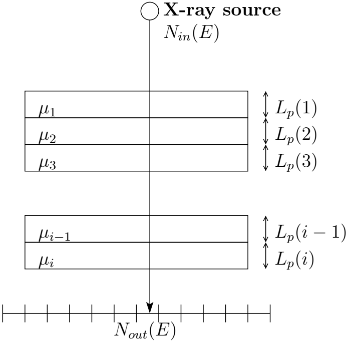
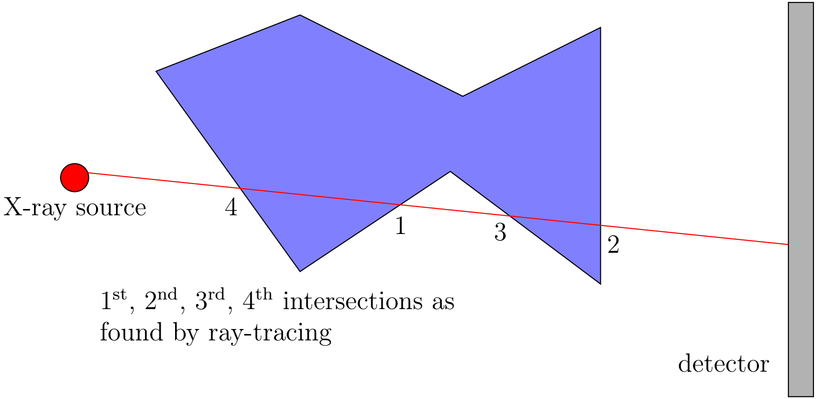
Beer-Lambert Law (Attenuation Law)

- $N_{in}(E)$ the number of incident photons at energy E;
- $N_{out}(E)$ the number of transmitted photons of energy E;
- μ_i the linear attenuation coefficient (in cm^{-1}) of the i^{th} object. It depends on:
  - E the energy of incident photons;
  - ρ the material density of the object;
  - Z the atomic number of the object material.
- $L_p(i)$ the path length of the ray in the i^{th} object.



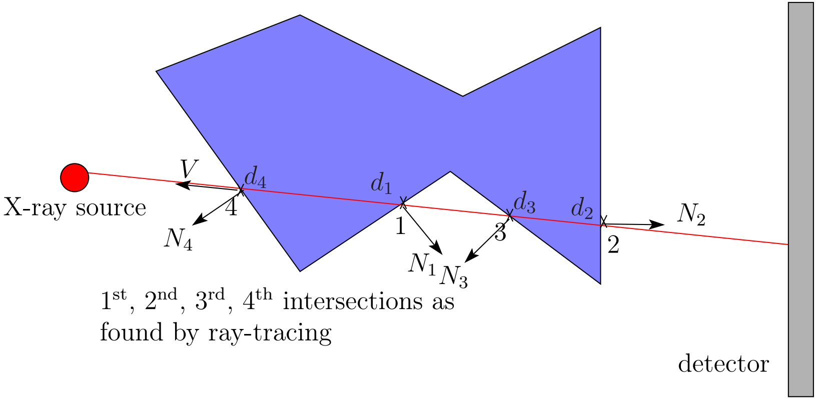
$$N_{out}(E) = N_{in}(E) \exp\left(-\sum_i \mu_i(E, \rho, Z) L_p(i)\right)$$

Path Length: Naive Approach



- Detect every intersection between a ray and the objects;
- Sort intersection (Can be handled by GPUs using depth-peeling, a multi-pass rendering technique for semi-transparent polygonal objects without sorting polygons);
- Compute path length.

Path Length: L-Buffer



- Intersection sorting is not needed!
- By convention normals are outward;
- A ray penetrates into an object when the dot product between the view vector (V) and the normal (N_i) at the intersection point is positive;
- It leaves an object when the dot product is negative.

L-Buffer Implementation

$$L_p = \sum_i -\text{sng}\left(V \cdot N_i\right) \times d_i$$

- i refers to i^{th} intersection in an arbitrary order;
- d_i distance from X-ray source to intersection point;
- $\text{sgn}\left(V \cdot N_i\right)$ stands for the sign of the dot product between V and N_i;
- In a shader program, compute:
    - $\text{sgn}\left(V \cdot N_i\right)$;
    - d_i the distance between the X-ray source and the intersection;
    - Assign $-\text{sng}\left(V \cdot N_i\right) \times d_i$ for the fragment value.
- For each pixel, compute L_p thanks to high-dynamic range and OpenGL blending function (pixel values may not be between 0 and 1).

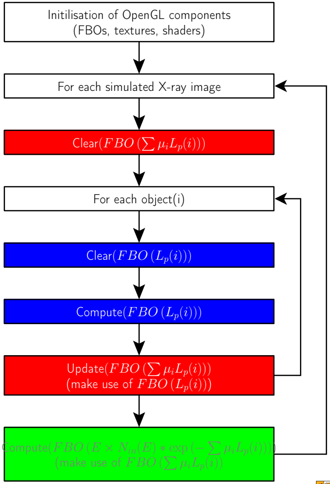
F. P. Vidal, M. Garnier, N. Freud, *et al.*, "Simulation of X-ray attenuation on the GPU", in *Proceedings of Theory and Practice of Computer Graphics 2009*, Cardiff, UK: Eurographics Association, Jun. 2009, pp. 25–32.

Multipass Rendering Pipeline

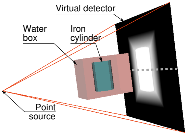
$$pixel = E \times N_{out}$$

$$= E \times N_{in}(E) \exp\left(-\sum_i \mu_i L_p(i)\right)$$

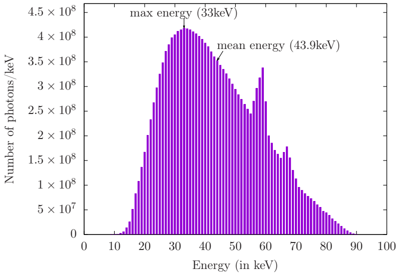
- Needs 3 FBOs with high-dynamic range capability for off-line rendering:
- For each object of the scene:
  1. Compute $L_p(i)$;
  2. Update results of $\sum \mu_i L_p(i)$.
- For the final image only:
  1. Compute *Nout*;
  2. (Optional when direct display only is needed).



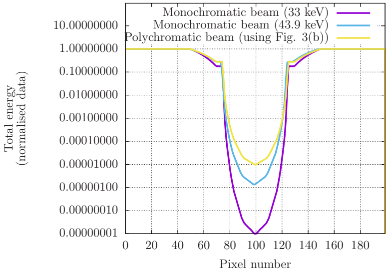
$$pixel = \sum_j E_j \times N_{out}(E_j)$$
$$= \sum_j E_j \times N_{in}(E_j) \exp\left(-\sum_i \mu_i(E_j, \rho, Z) d_i\right)$$



Set up.



Polychromatic beam spectrum for 90kV X-ray tube peak voltage.



Intensity profiles.

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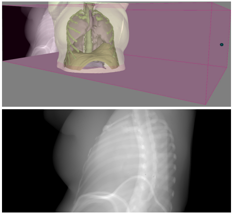
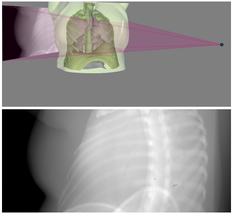
Simulation with Different Source Shapes

Take into account the focal spot of the X-ray source

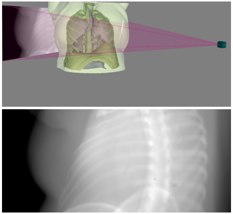
$$pixel = \sum_{k} \sum_{j} E_j \times N_{in}(E_j) \exp\left(- \sum_{i} \mu_i(E_j, \rho, Z) d_i(k) \right)$$



(a) Parallel beam.



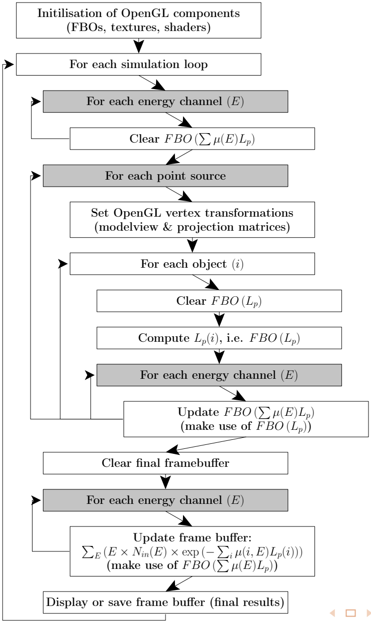
(b) Infinitely small point source.



(c) 1^3mm source.

F. P. Vidal, M. Garnier, N. Freud, *et al.*, "Accelerated deterministic simulation of x-ray attenuation using graphics hardware", in *Eurographics 2010 - Poster*, Norrköping, Sweden: Eurographics Association, May 2010, Poster 5011

Final Simulation Flowchart



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Outline

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Validation Method

- Simulating an image relies on a Beer-Lambert law implementation;
- Solving the Beer-Lambert law relies on Linear Attenuation Coefficients; (μ)
- μ is not known for given incident energies;
- μ is computed using Mass Attenuation Coefficients $\left(\frac{\mu}{\rho}\right)$ and Density (ρ).

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Are the values used in gVirtualXRay accurate? Compare values computed in gVirtualXRay with those from the literature.

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Are the Beer-Lambert law implementations accurate? Compare values computed in gVirtualXRay with theoretical ones.

Are the simulated images accurate? Compare images computed using gVirtualXRay with those using a state-of-the-art Monte Carlo software from CERN.

Density for Different Materials (human tissues)

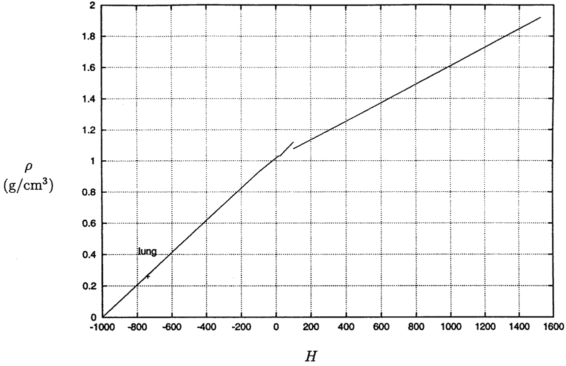

Image from W. Schneider, T. Bortfeld, and W. Schlegel, "Correlation between CT numbers and tissue parameters needed for Monte Carlo simulations of clinical dose distributions", *Physics in Medicine & Biology*, vol. 45, no. 2, p. 459, 2000. DOI: 10.1088/0031-9155/45/2/314

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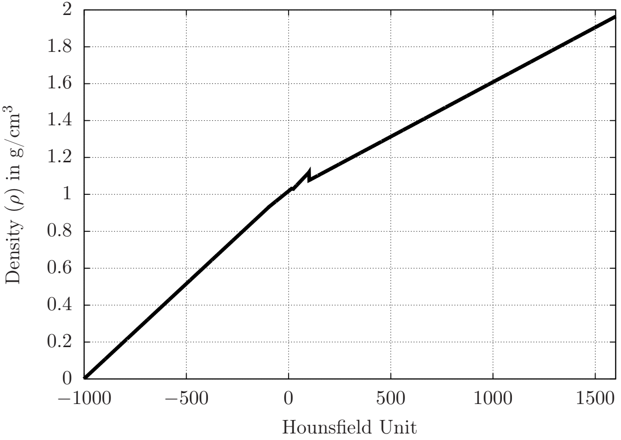

Mass Attenuation Coefficients

- Any tissue can be described by its Hounsfiled Unit (HU):

$$HU = 1000 \times \frac{\mu - \mu_{water}}{\mu_{water}}$$

- Give a HU value to any simulated object;
- If μ_{water} is known for any energy, then μ for any HU and for any energy can be computed:

$$\mu(E) = \mu_{water}(E) \times \left(1 + \frac{HU}{1000}\right)$$

- Mass attenuation coefficients $\left(\frac{\mu}{\rho}\right)$ for various human tissues can be found in the literature;
- The density (ρ) for various human tissues can be found in the literature.

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Mass Attenuation Coefficients: Tissue, Soft (ICRU-44)

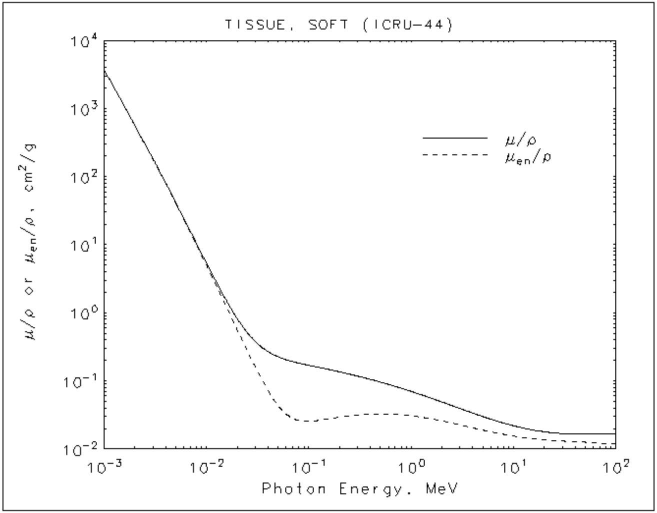
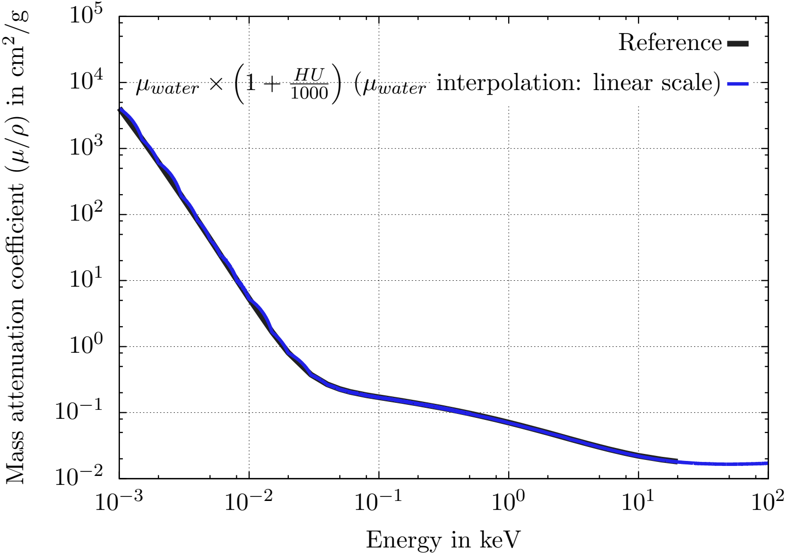


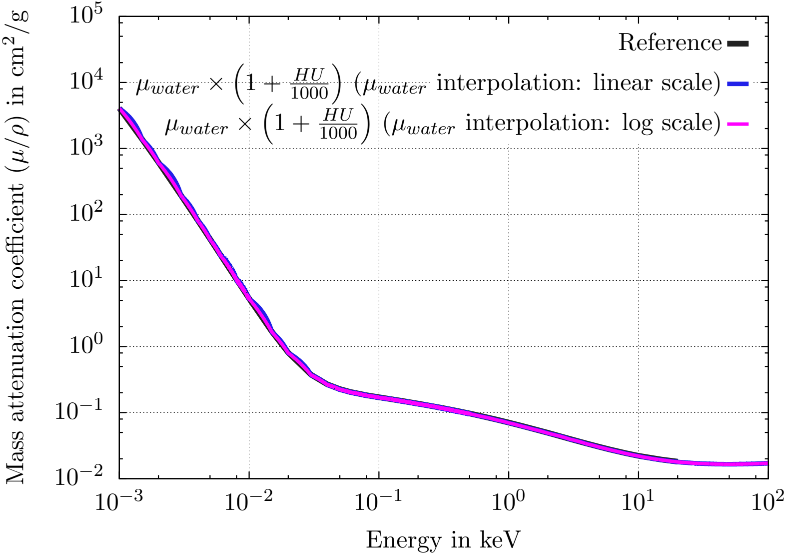
Image from https://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/tissue.html

Mass Attenuation Coefficients: Tissue, Soft (ICRU-44)



μ_{water} from literature is provided at given energies only: Interpolation needed

Mass Attenuation Coefficients: Tissue, Soft (ICRU-44)



Mass Attenuation Coefficients: Bone, Cortical (ICRU-44)

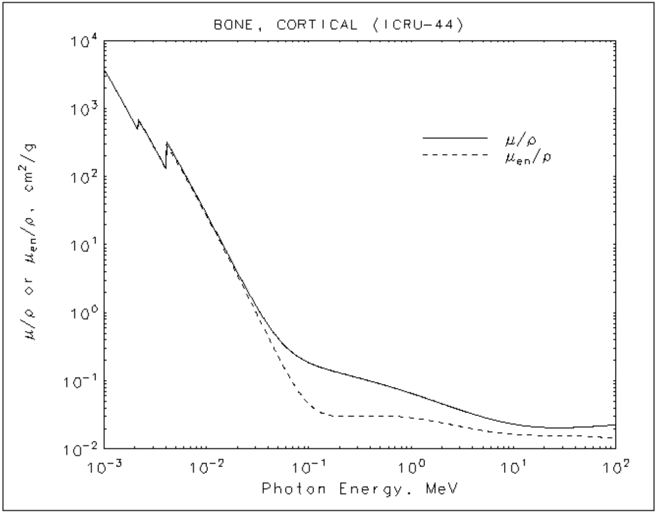


Image from https://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/bone.html

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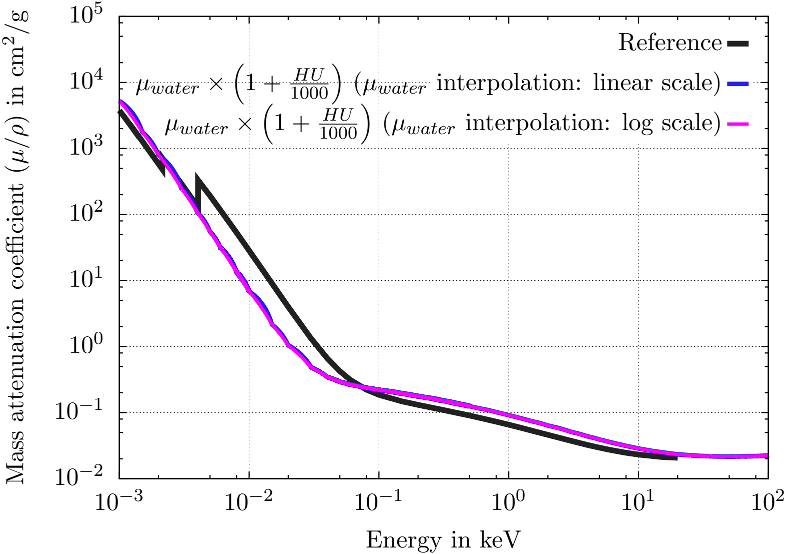

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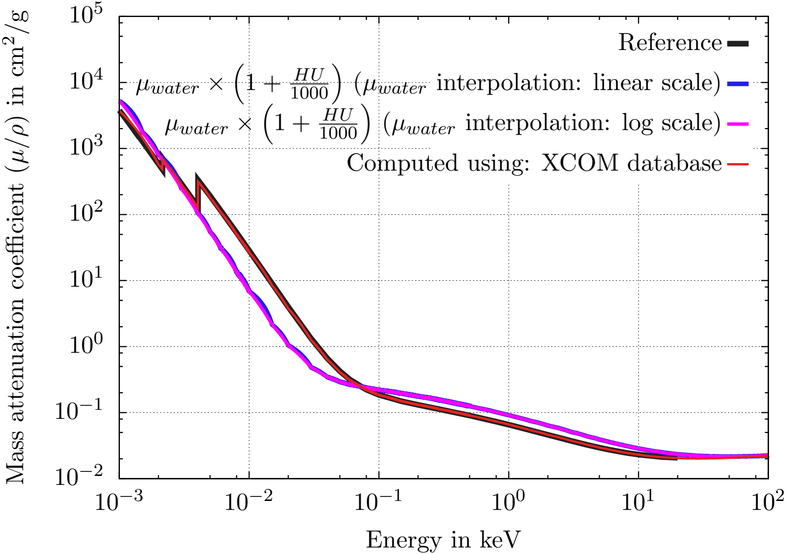
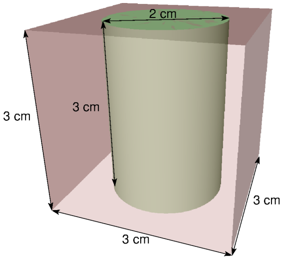


Cube: Edge length of 3 cm, made of soft tissue (HU = 52).

Cylinder: Height of 3 cm, diameter of 2 cm, made of bone (HU = 1330).

Incident energy:

N **: Number of photons**	***E*** **: Energy (in MeV)**
10	0.1
20	0.2
10	0.3



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Beer-Lambert Law: Polychromatism Case

- Use material properties from the literature;
- The energy, I_{out}, (in MeV) transmitted orthogonally throw the middle of cube and cylinder should be:

$$
\begin{aligned}
I_{out} &= I_{out}(0.1) + I_{out}(0.2) + I_{out}(0.3) \\
I_{out}(0.1) &= 10 \times 0.1 \times \exp\left(-\left(3.346\text{E}{-01} \times 2 + 1.799\text{E}{-01} \times 1\right)\right) \\
I_{out}(0.2) &= 10 \times 0.1 \times \exp\left(-\left(2.361\text{E}{-01} \times 2 + 1.443\text{E}{-01} \times 1\right)\right) \\
I_{out}(0.3) &= 10 \times 0.1 \times \exp\left(-\left(2.008\text{E}{-01} \times 2 + 1.249\text{E}{-01} \times 1\right)\right) \\
I_{out} &= 4.359
\end{aligned}
$$

- On GPU, the energy, I'_{out}, is: 4.353.
- The relative error is:

$$\frac{|I'_{out} - I_{out}|}{I_{out}} = 0.1\%$$

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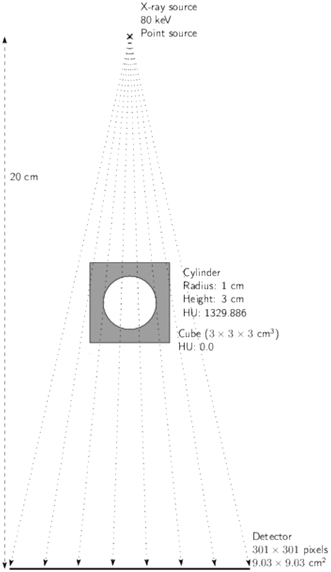
We simulate a test case twice:

- Using a Monte Carlo method for particle physics implemented in GATE[1];
- Using our GPU implementation.

[1] GATE is an opensource software developed by an international collaboration. Its focus is on Monte Carlo simulation in medical imaging and radiotherapy. GATE makes use of the Geant4 libraries. Geant 4 is CERN's Monte Carlo simulation platform dedicated to particle physics in nuclear research. CERN is the European Organization for Nuclear Research.

Gate vs. gVirtualXRay: Point Source



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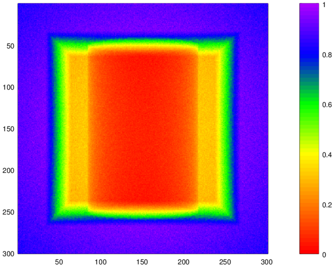
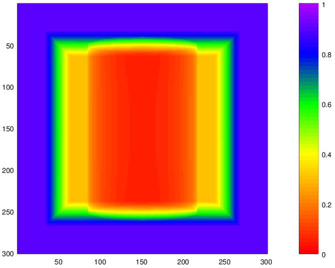




GATE gVirtualXRay

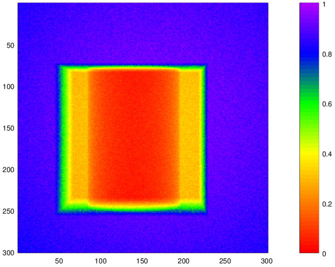
(13.8 days of computations) (less than 1 sec. of computation)

Normalised cross-correlation (NCC) = 99.747%

Gate vs. gVirtualXRay: Uncentered Source

The source has been translated by a vector: -5.0 0.5 0.5 cm.

Gate vs. gVirtualXRay: Uncentered Source

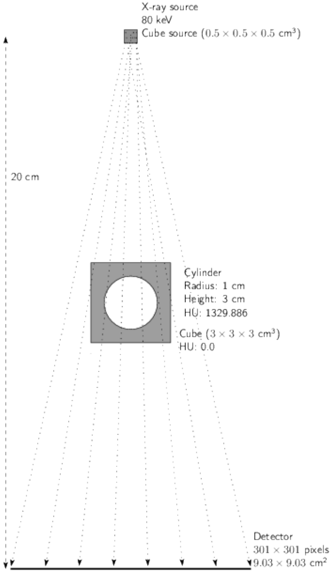


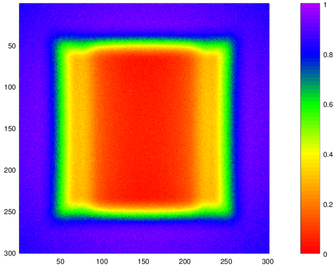
GATE gVirtualXRay

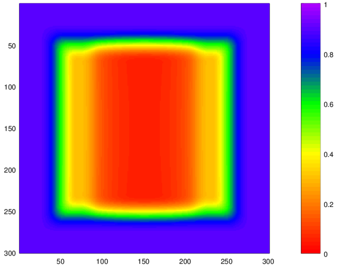
(12.9 days of computations) (less than 1 sec. of computation)

Normalised cross-correlation (NCC) = 99.656%

Gate vs. gVirtualXRay: Cube Source







GATE | gVirtualXRay

(14.4 days of computations) (less than 1 sec. of computation)

Normalised cross-correlation (NCC) $= 99.743\%$

Outline

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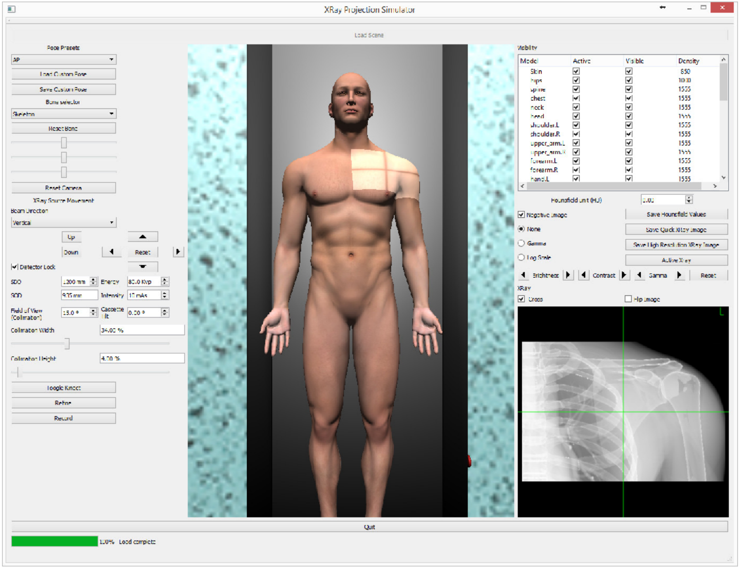
Outline

Projectional Radiography is a medical imaging diagnostic tool :

- **Anatomical variations:** Requires a specific patient pose;
- **Settings:** X-ray machines need a specific set up in each case.

Users can train without use real patient and suffer X-Ray radiation



https://www.youtube.com/watch?v=sXB-9fG2AbU

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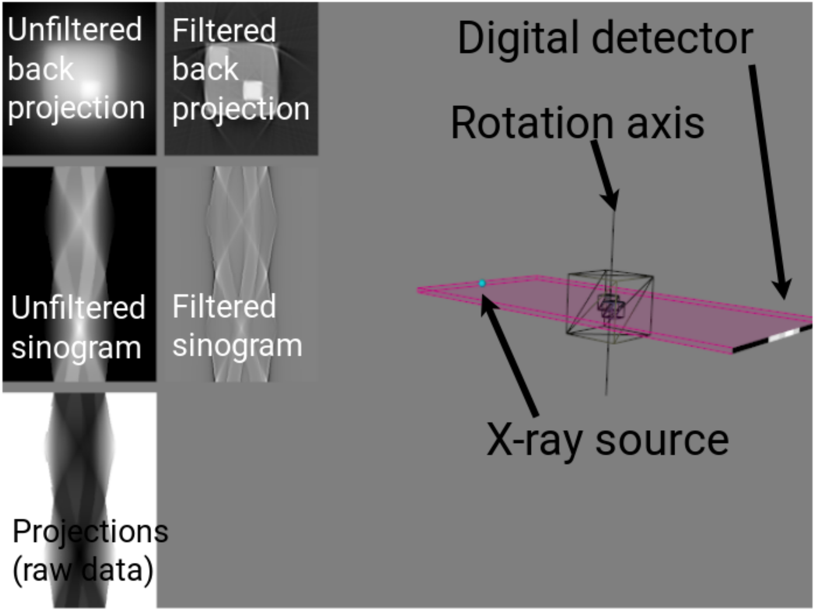
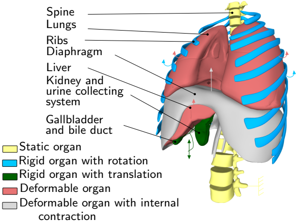


https://www.youtube.com/watch?v=852C4VdWrfc

Outline

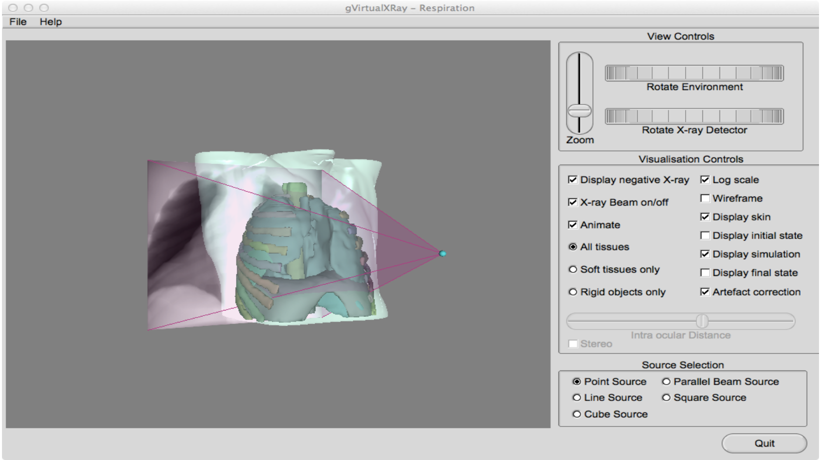
Simulation of respiration motion

- **Aim:** simulating the respiration motion and corresponding X-ray images;
- **Method:** reproducing the real action of the muscles (diaphragm and intercostal muscles);
- Each organ is geometrically defined by a triangular mesh extracted from a segmentation of patient CT scans;
- Soft-tissues are deformed in real-time using 3-D Chainmail.



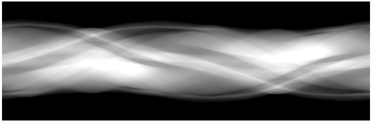
F. P. Vidal, P. Villard, and É. Lutton, "Tuning of patient specific deformable models using an adaptive evolutionary optimization strategy", *IEEE Transactions on Biomedical Engineering*, vol. 59, no. 10, pp. 2942–2949, Oct. 2012. DOI: 10.1109/TBME.2012.2213251

Fluoroscopy simulation

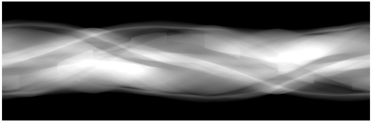


https://www.youtube.com/watch?v=fC1b1rGbtag

Motion artifacts

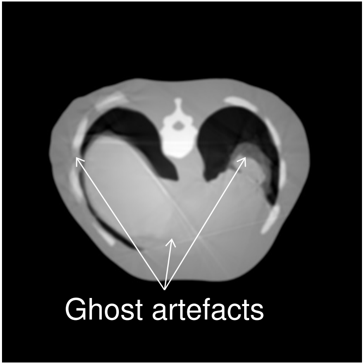


(a) Sinogram without respiration.



(b) Sinogram with respiration.

(c) CT reconstruction of (a).



(d) CT reconstruction of (b).

Outline

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Example of Python Application (1/3)

```
#!/usr/bin/env python3
import numpy as np
import matplotlib.pyplot as plt
import gvxrPython as gvxr

# Create an OpenGL context
gvxr.createWindow();
gvxr.setWindowSize(600, 600);

# Set up the beam
gvxr.setSourcePosition(-20.0,  0.0, 0.0, "cm");
gvxr.usePointSource();
#gvxr.useParallelBeam();
gvxr.setMonoChromatic(80, "keV", 1);

# Set up the detector
gvxr.setDetectorPosition(10.0, 0.0, 0.0, "cm");
gvxr.setDetectorUpVector(0, 0, -1);
gvxr.setDetectorNumberOfPixels(640, 640);
gvxr.setDetectorPixelSize(0.5, 0.5, "mm");
```

Example of Python Application (2/3)

```
# Load the data
gvxr.loadSceneGraph("welsh-dragon-small.dae", "mm");

# Set the material properties
for mesh in gvxr.getMeshLabelSet():
    gvxr.setAttenuationCoefficient(mesh, 0.5);

# Move everything to the centre
gvxr.moveToCentre();

# Use GPU artefact filtering
gvxr.enableArtefactFilteringOnGPU();

# Compute an X-ray image and
# retrieve the image in Numpy's 2D array format
np_image = gvxr.computeXRayImage();

# Run an interactive loop
gvxr.renderLoop();
```

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```
# Save the image
np.savetxt("x-ray_image.txt", np_image);

# Plot the X-ray image using Matplotlib
imgplot = plt.imshow(np.log(np_image.T), cmap="gray");
plt.show();
```

3D μ-tomography of tungsten fibre

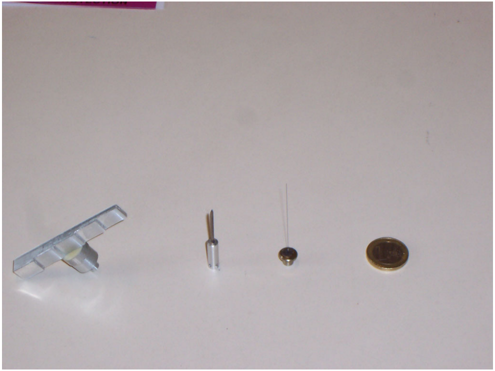
using synchrotron radiation at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France

View from Mount Jalla on the ESRF and ILL in Grenoble.

Source: Photograph by German Wikipedian Christian Hendrich, October 2004.

3D μ-tomography of tungsten fibre

using synchrotron radiation at the ESRF in Grenoble, France



Some volumes reconstructed using tomography by synchrotron radiation, obtained at ESRF, did not contain artefacts, others did.

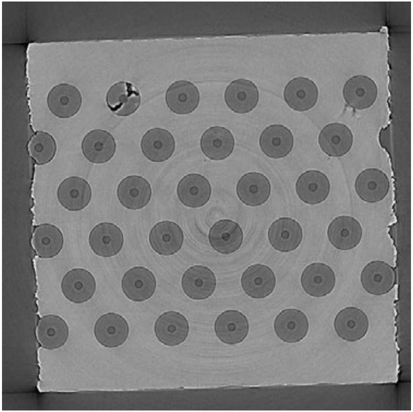
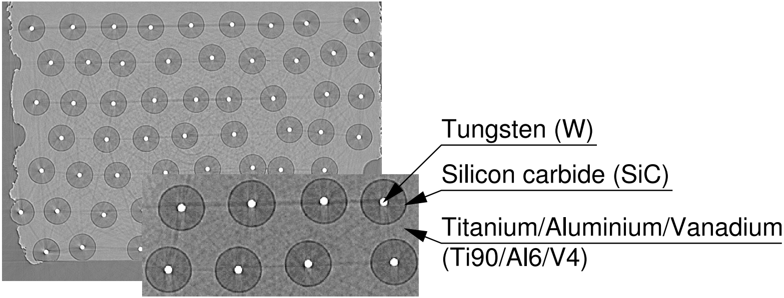


Image courtesy of Dr. Éric Maire and Prof. Jean-Yves Buffière

With artefacts

Almost the same material: Replacing the carbon cores with tungsten cores.

Data courtesy of Dr. Éric Maire and Prof. Jean-Yves Buffière



Reconstructed tomographic slice.
1.9 μm pixel size.
Synchrotron radiation, 33 keV in energy.

Purpose: determining the cause of artefacts and removing them.

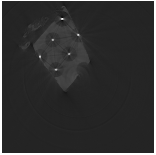
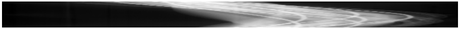
- Take a real μ-CT slice (f). 
- Use its sinogram ($Y = \mathbf{P}[f]$).

- Optimise the position (x, y), orientation (α), and size (u, v) of a parallelepiped using either:
  - $\hat{Y} = \underset{x,y,\alpha,u,v}{\arg\min} \left\| Y - \hat{Y}(x, y, \alpha, u, v) \right\|_2^2$, or
  - $\hat{f} = \underset{x,y,\alpha,u,v}{\arg\min} \left\| f - \mathbf{P}^{-1}\left[\hat{Y}(x, y, \alpha, u, v)\right] \right\|_2^2$
- We use our own simple evolutionary algorithm (EA) written in python™

Image registration: Cube (2/2)

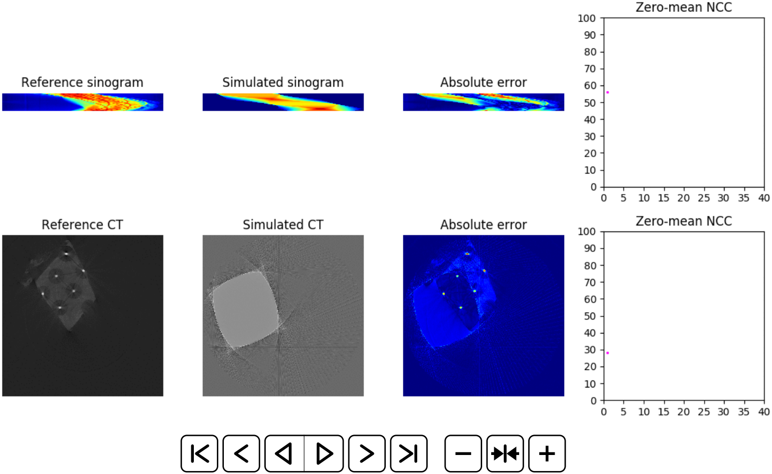


Image registration: Cylinders (1/3)

- Use x, y, α, u, v from previous step.
- Minimise the same functions using Fly algorithm (a cooperative coevolution algorithm).
- Optimise the position of N points representing the centres of cylinders.
- In selection, the fitness of individual i is based on the leave-one-out cross-validation using either:
  - $F_m(i) = \left\| Y - \left(\hat{Y} \setminus \{i\} \right) \right\|_2^2 - \left\| Y - \hat{Y} \right\|_2^2$ or
  - $F_m(i) = \left\| f - \mathbf{P}^{-1} \left[\hat{Y} \setminus \{i\} \right] \right\|_2^2 - \left\| f - \mathbf{P}^{-1} \left[\hat{Y} \right] \right\|_2^2$

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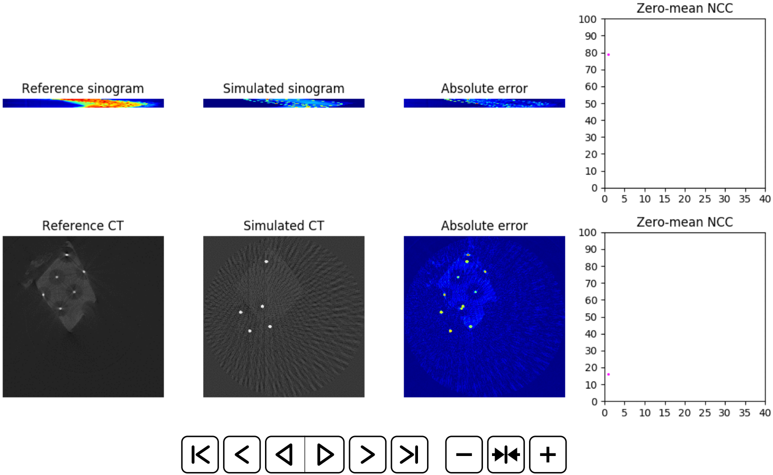
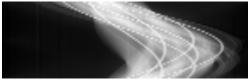
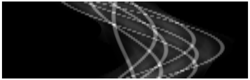
Image registration: Cylinders (2/3)



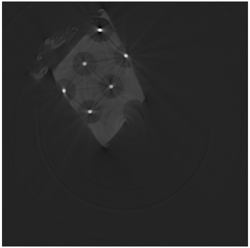
Recursively extract points with $F_m(i) > 0$

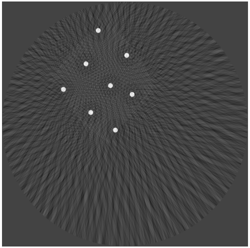
Reference | **Estimated** | **Squared error**

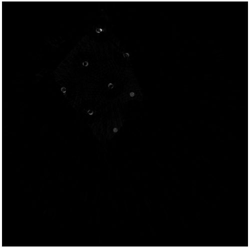




$(Y = \mathbf{P}[f])$ $\left(\hat{Y}\right)$ $\left(\left\| Y - \hat{Y} \right\|_2^2\right)$





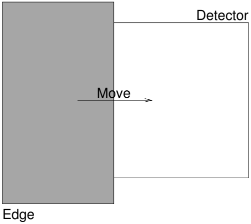


(f) $\left(\hat{f} = \mathbf{P}^{-1}\left[\hat{Y}\right]\right)$ $\left(\left\| f - \hat{f} \right\|_2^2\right)$

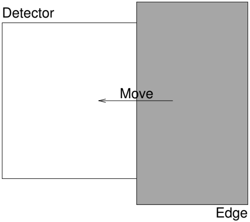
Response of the detector (1/2)

Getting the Edge Spread Function (ESF), experiments performed at ESRF.

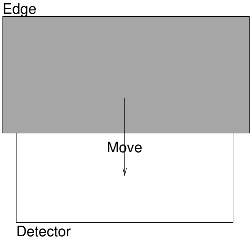
- 4 acquisitions,
- 50 projections of an edge in a gallium arsenide crystal,
- Translation of the edge, by a constant vector, between each projection.



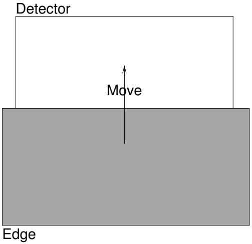
1^{st} *horizontal acquisition*



2^{nd} *horizontal acquisition*



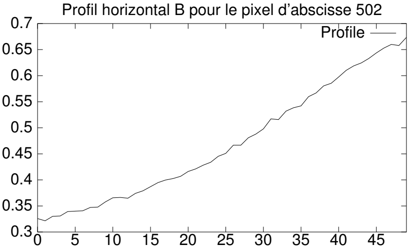
1^{st} *vertical acquisition*

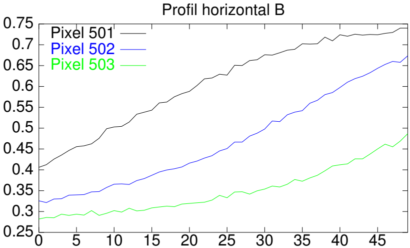


2^{nd} *vertical acquisition*

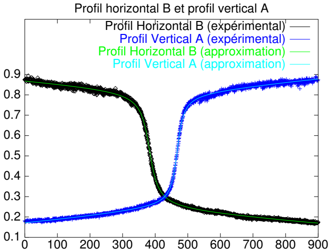
Extracting a profile for an acquisition

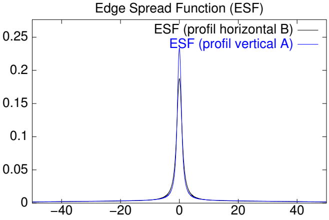
Considering a particular pixel, $p(x, y)$, and extracting its intensity for each projection.





ESF estimation: Reconstructing a complete profile





- Approximation of the profiles:

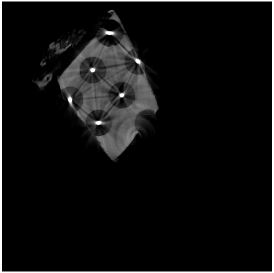
$$\text{profile}(x) = a + b \times (\arctan((x-c)/d) + \text{erf}((x-c)/e))$$

- Approximation of the ESF:

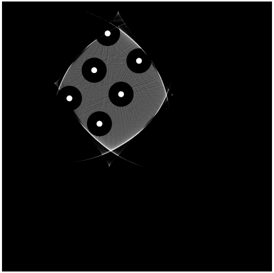
$$\text{esf}(x) = \text{profile}(scaling \times (x - 0.5) + c) - \text{profile}(scaling \times (x + 0.5) + c)$$

Simulation: Tomography acquisition + ESF

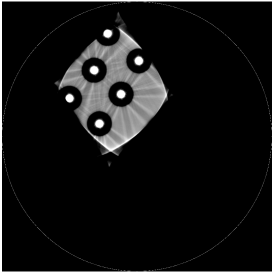
- Simulation of tomographic slices using gVirtualXRay with monochromatic radiation;
- All projections of the sinogram are convolved by the ESF.



Real μ-CT slice



Simulation without convolution



Simulation with convolution

Conclusion: Artefacts due to the camera response, obtained by simulation, are similar to artefacts observed on experimental data.

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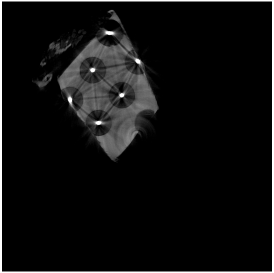
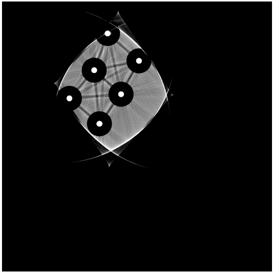
Determining the effect of harmonics using tomographic scans simulated using gVirtualXRay.

a priori data, in the worst case:

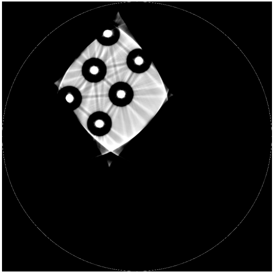
- fundamental component, 33 keV, 97% of the incident beam,
- 1st harmonic component, 66 keV, 2% of incident the beam,
- 2nd harmonic component, 99 keV, 1% of incident the beam.



Real μ-CT slice



Simulation with polychromatic beam and without convolution



Simulation with polychromatic beam and with convolution

Conclusion: artefacts due to harmonics, obtained by simulation, are similar to artefacts observed on experimental data.

Outline

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Conclusions

- C++ X-Ray simulation library:
  - Open source;
  - Realtime;
  - Portable;
  - Validated.
- Incident beam:
  - Shape:
    - Point source;
    - Cube source;
    - Parallel beam.
  - Monochromatic;
  - Polychromatic.
- Fast and accurate:
  - Can be used in an optimisation framework;
  - ...
- Various applications:
  - Teaching radiography;
  - Virtual Reality Simulation;
  - Virtual Testing Lab;
  - ...

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Future Work

- Material properties
  - Add full support to Element/Compound/Mixture Selection
  - exhaustive validation
- Software engineering
  - Unit testing;
  - Consistent coding standard.
- Increase awareness amongst potential users:
  - in various fields of science.
- Volumetric mesh
  - Tetrahedron.
- User requests?
  - New language plugins? C, Ruby, R, Matlab, Octave?
- New applications/Collaborations:
  - ...

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