Study of the influence of some key tomography parameters and artifacts resulting from X-ray-material interaction on surface determination used for dimensional measurement

Thesis on uncertainties of measurement in X-CT

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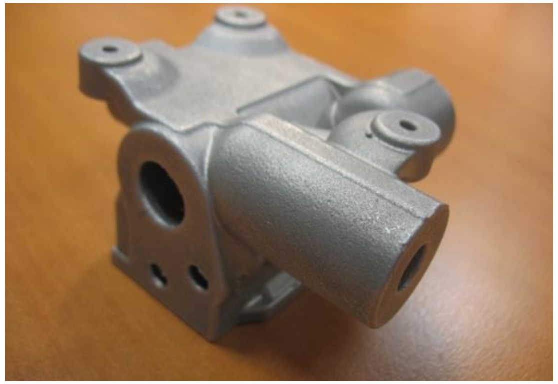
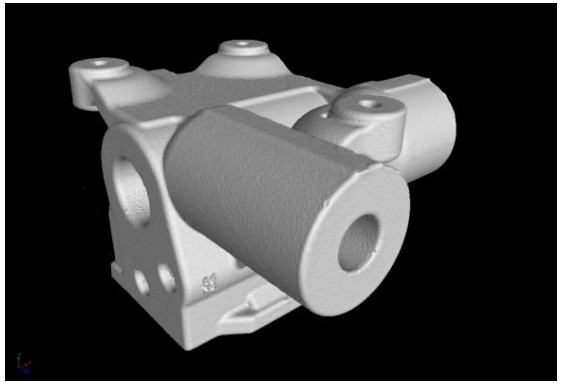
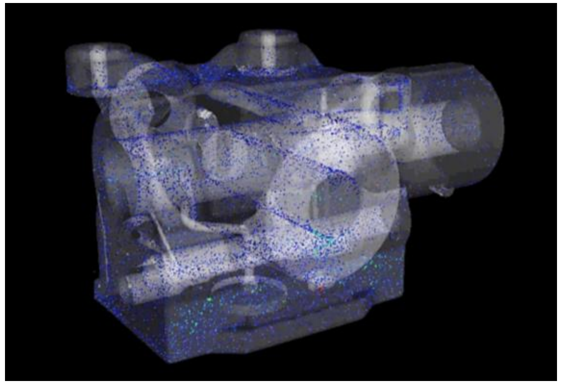
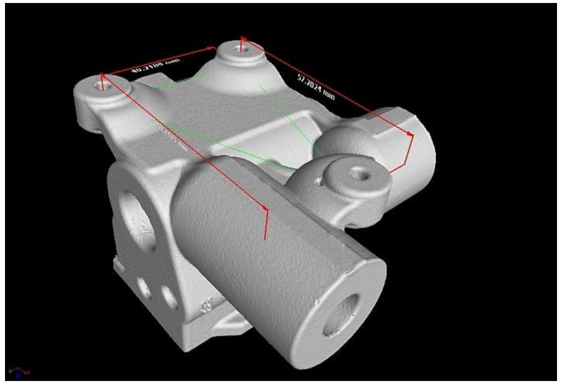
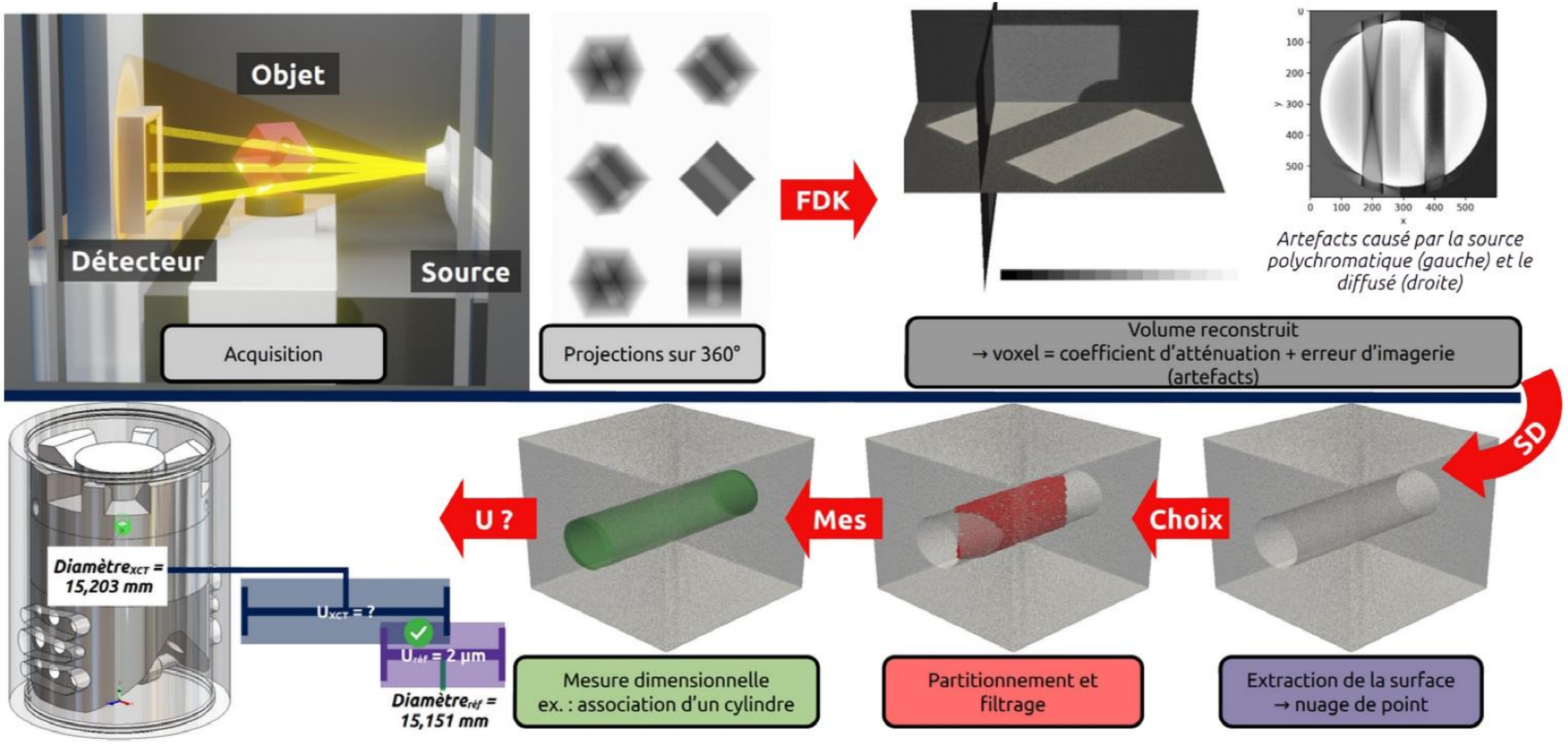
Origin of the study

- Computed Tomography scan = 3D digitisation of an object (inside and outside)
- Main applications :
  - NDT
  - Dimensional measurement

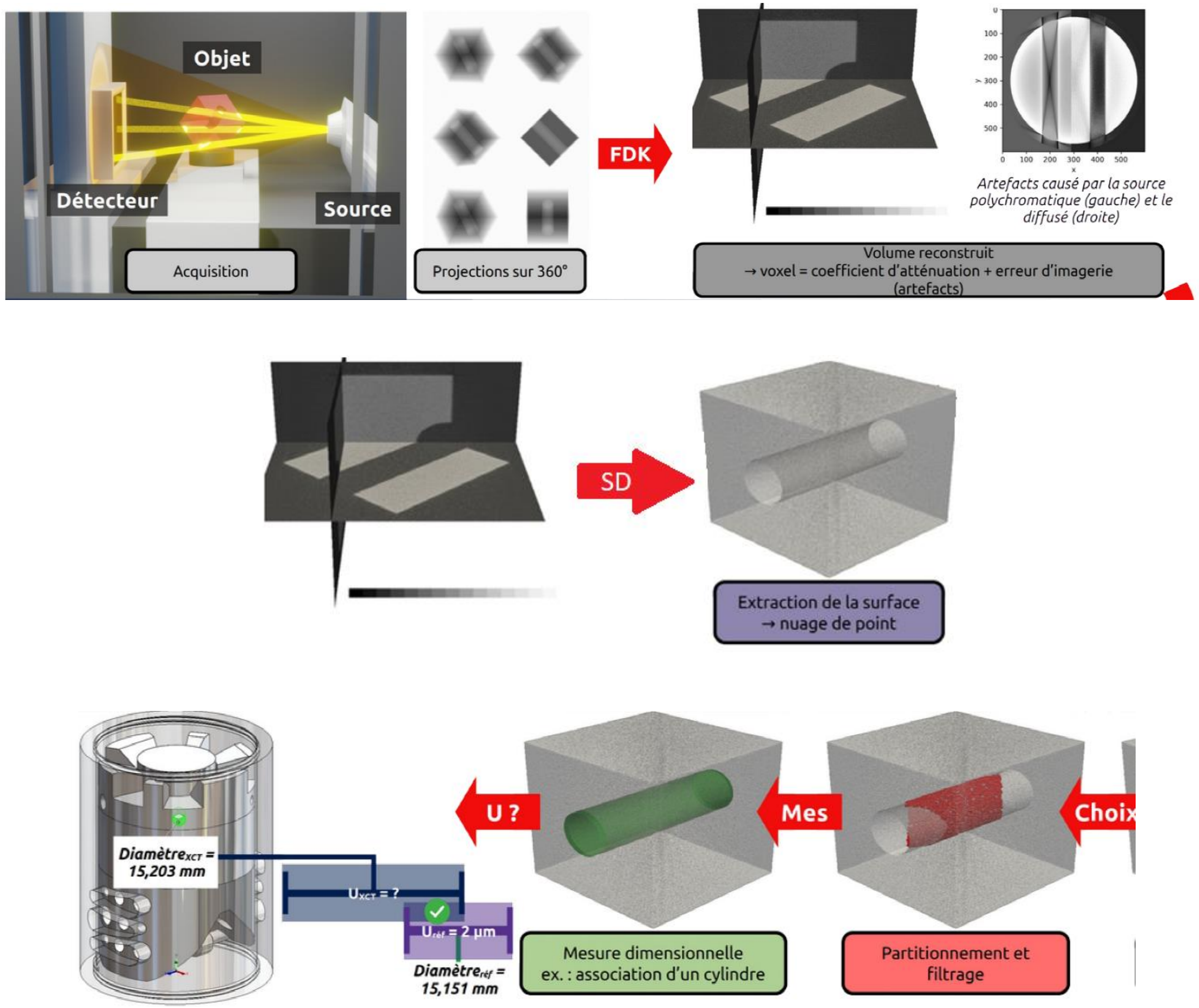





- Uncertainties of dimensional measurement by XCT
  - CT systems available with the maximum permissible error measured on spheres, but not with uncertainties like a CMM
  - Not easy to evaluate in a general frame
  - Artifacts never considered

Dimensional measurement chain by X-ray CT



Dimensional measurement chain by X-ray CT



Acquisition and reconstruction

- Setting not completely standardized
- Quality of the reconstructed volume not the same everywhere, strongly depending on the situation

Surface determination

- Key-step of the dimensional measurement chain
- Black box in commercial software
- Different algorithms available
- Poorly controlled artifact behaviour

From points to measurement

- Same operations as with a CMM
- Many more points to manage than with a CMM, but not all with the same level of quality in terms of accuracy and precision (due to artifacts)

Modelling of dimensional measurement chain by X-ray CT

Acquisition

- CIVA RT/CT

Reconstruction

- CIVA CT

Surface Determination

- Development of our own algorithms

Dimensional measurement

- Polyworks software

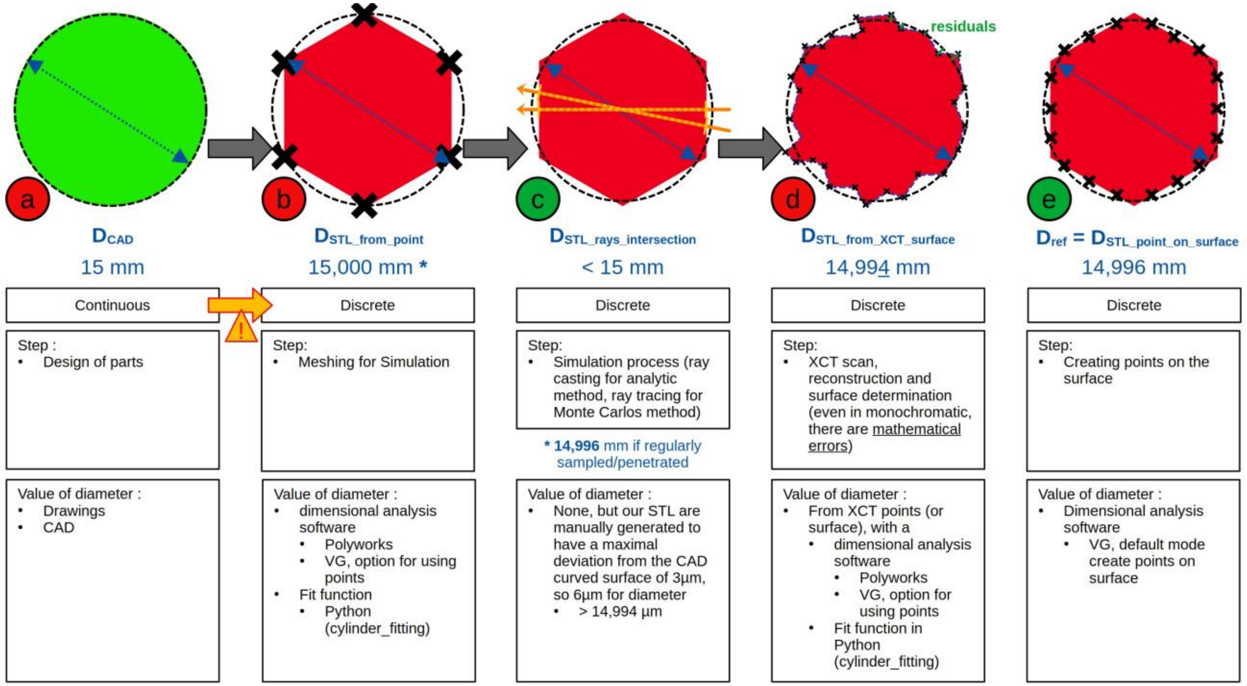
- PC configuration :
  - AMD Ryzen ThreadRipper PRO 5995WX (64 processors)
  - 512BG RAM
  - GPU Nvidia RTX 1080
  - Hard disk SDD PCIe (NVMe)
- Calculation time of a complete scan : from 10min to 7h (depending on whether or not the scattering is taken into account)

- 3 different algorithms with selectable parameters
- Code written in python

- Software validated for metrological measurement
- Used for the partitioning and measurement by association
- Normalised least squares algorithm

Modelling of dimensional measurement chain by X-ray CT

- Modelling the acquisition step with CIVA:
  - Possibility to create “perfect” source, detector and geometry and degrade their performances independently
  - Possibility to separate scatter and beam hardening effect
    - 5 different levels of scattering and beam hardening artifacts by adjusting the source spectrum and scattering calculations
  - Use of STL format for the part
- Development of surface determination algorithms:
  - Interest only for sub-voxel surface determinations
- Measurement steps:
  - Study on association measurements (diameters of circles or cylinders) :
    - $D_{error} = D_{reference} - D_{XCT}$ and STD of the residuals = dispersion of the points
  - STL discretization considered when calculating the reference measurement



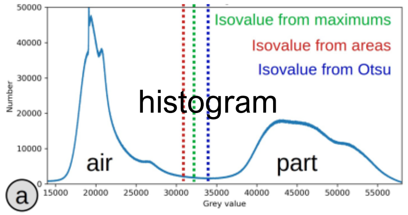
Surface determination : 3 different algorithms

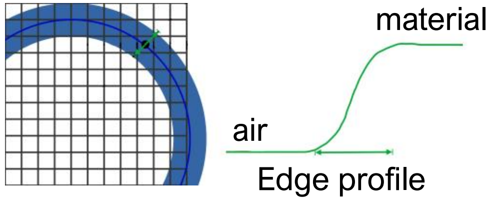
Steps common to all criteria

1. Binary thresholding with a global gray value determined from volume histogram
2. Positioning of points at the frontier of voxels to get an initial points cloud
3. Edge profile orientation computation
4. Edge profile extraction
5. Application of a criterion

Gray value

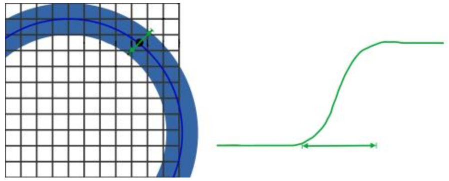
Frontier between air and material delimited by a grey value threshold determined from histogram or edge profile and adjusted by linear interpolation between tow voxels.

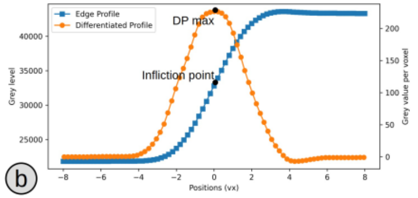




Gradient

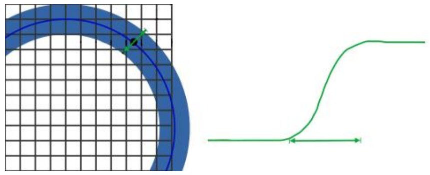
Frontier between air and material delimited by the inflection point of the edge profile determined from the gradient of edge profile.

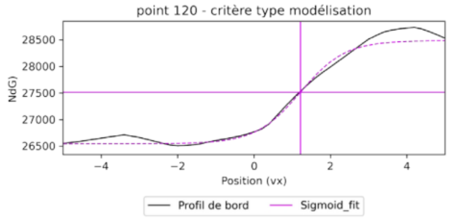




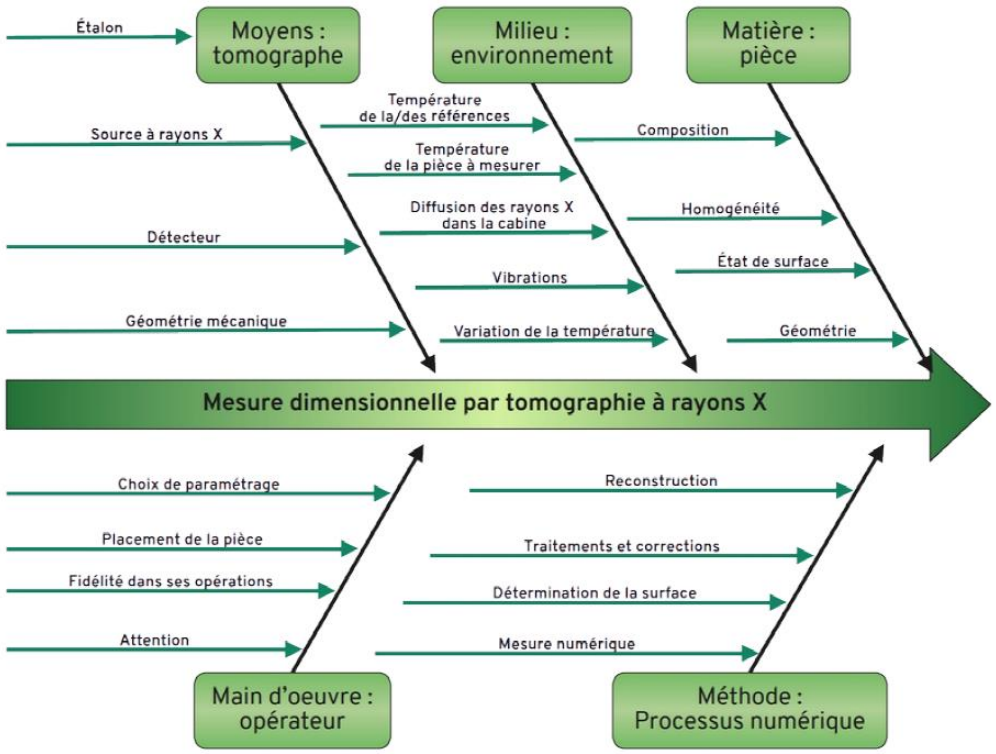
Sigmoid

Frontier between air and material delimited by the inflection point of the edge profile determined from the fitted sigmoid function.





Influent parameters and artifacts

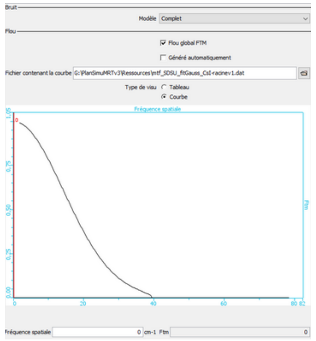


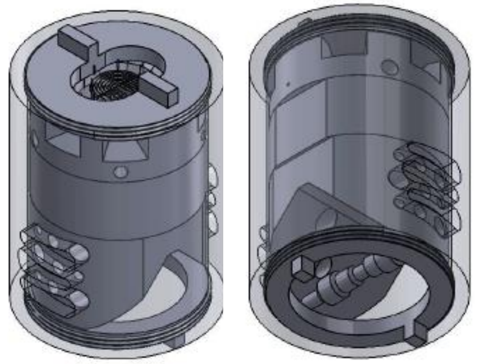
<u>Parameters studied using modelling</u>

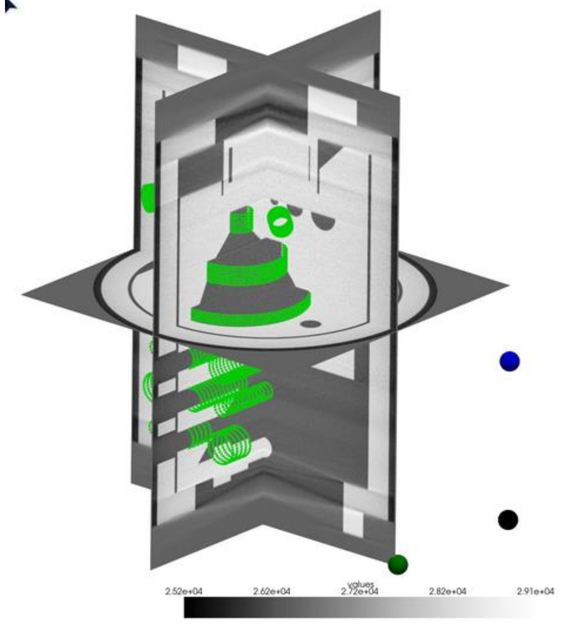
- Focal spot size
- Beam filtering
- Detector noise
- MTF detector
- Pitch of the detector
- Geometry of the system (positioning of the detector ad the turning table)
- Positioning of the scanned part and measurand
- Magnification
- Material (aluminium, steel)
- Thickness of material
- Number of projections
- Beam hardening
- X-ray scatter
- Tuy/FDK artifact (conical projection on the detector)
- EEGE artifact

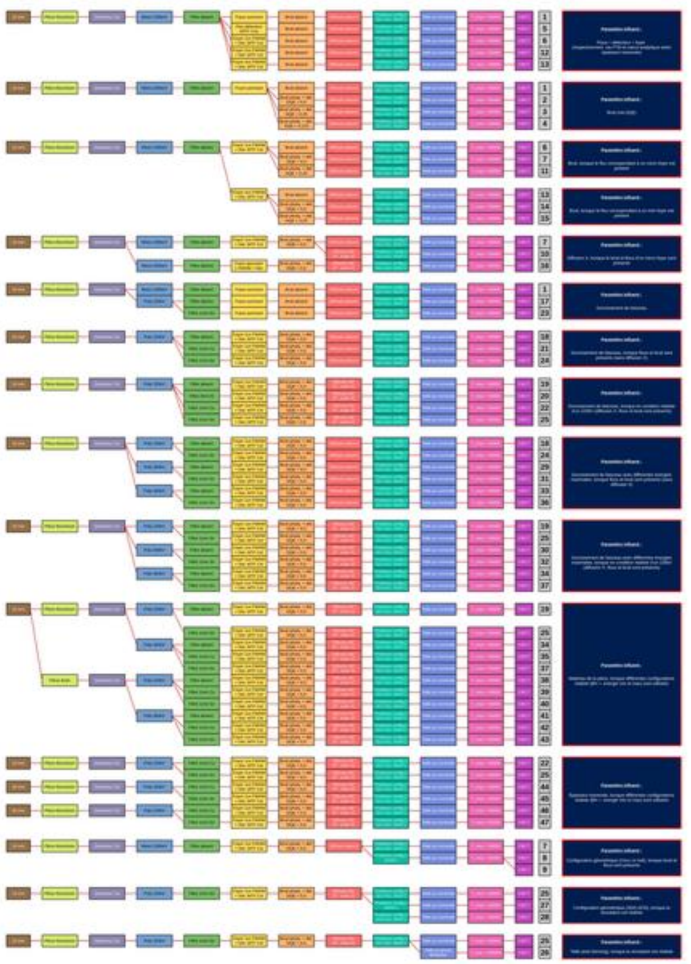
Implementation

- 46 simulations of CT scans
- Design of a reference part with several measurands
  - 32 cylinders with different orientations and lengths
- CIVA Settings
  - Primary beam : analytic
  - Secondary beam : MC accelerated by analytic (10^9 photons)
  - Detector :
    - 1400 x 1024 pixels
    - Pitch 127µm
    - DQE = 0,5
    - Scintillator Csi
    - FTM measured on a real DDA
  - Use of batch mode to distribute calculations more evenly across processors



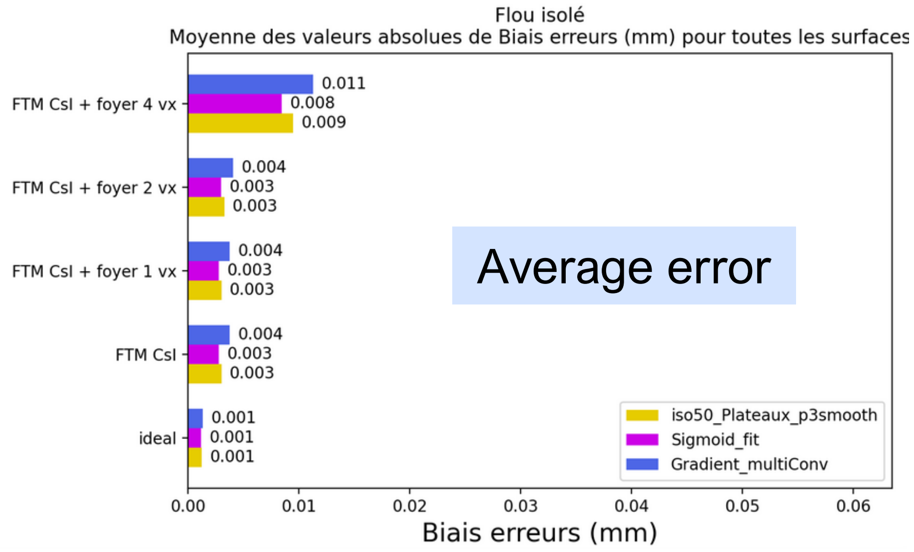


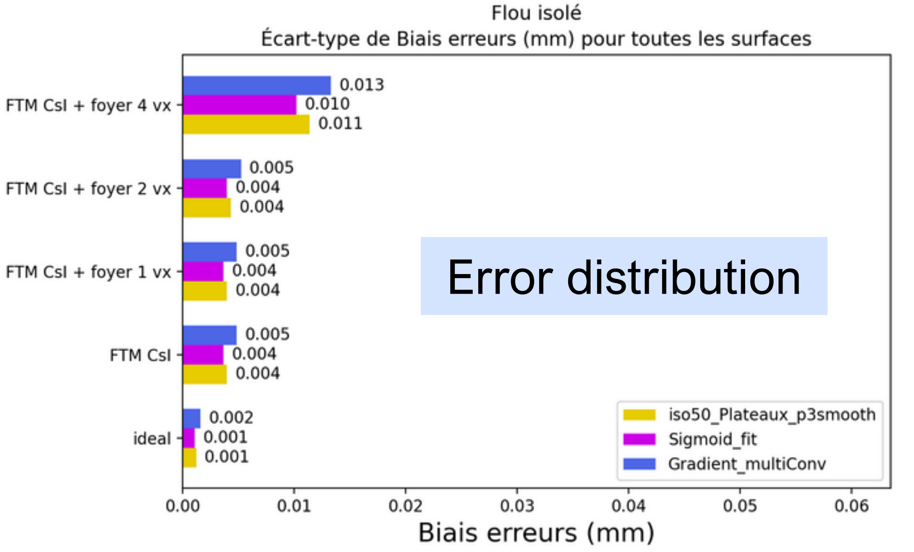




Influence of the blurring (focal spot size and MTF of the DDA)

- Detector blurring is predominant when the focal spot of the X-ray source remains below 2 voxels.
- The focal spot becomes predominant when its size exceeds 2 voxels.
- Gradient-based surface determination is more sensitive to blurring than others.
- The best surface determination is the sigmoid fit, meaning that the edge profile is not deformed by blurring.

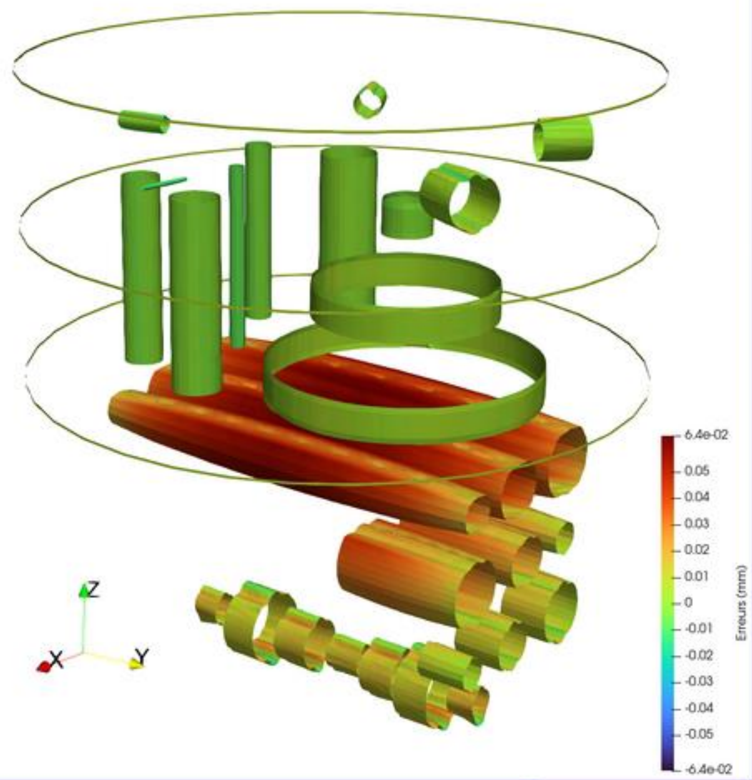




Influence of the geometrical blurring (focal spot size and FTM of the DDA)

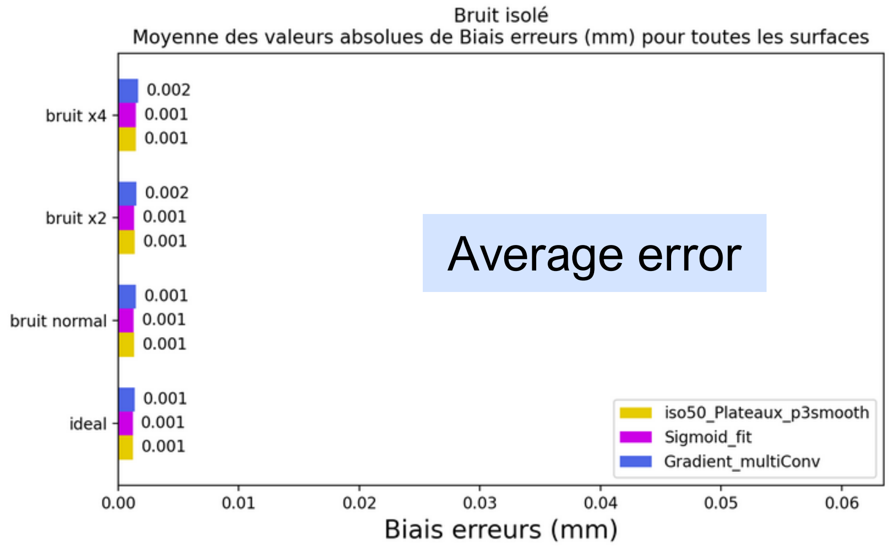
- The error caused by blurring is not uniform on all surfaces.
- Horizontal cylinders are much more affected than the vertical ones.
- The error is always in the same direction: towards the material.
  - Hollow cylinders diameters are measured larger than they actually are.
  - Full cylinder diameters are measured smaller than they actually are.

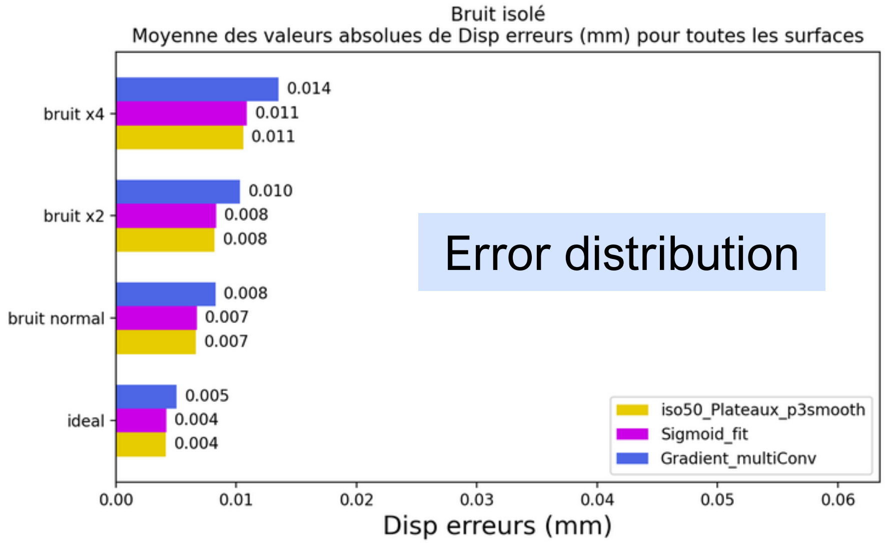
Errors distributed over all 32 cylinders surfaces



Influence of the noise (photonic and detector noise)

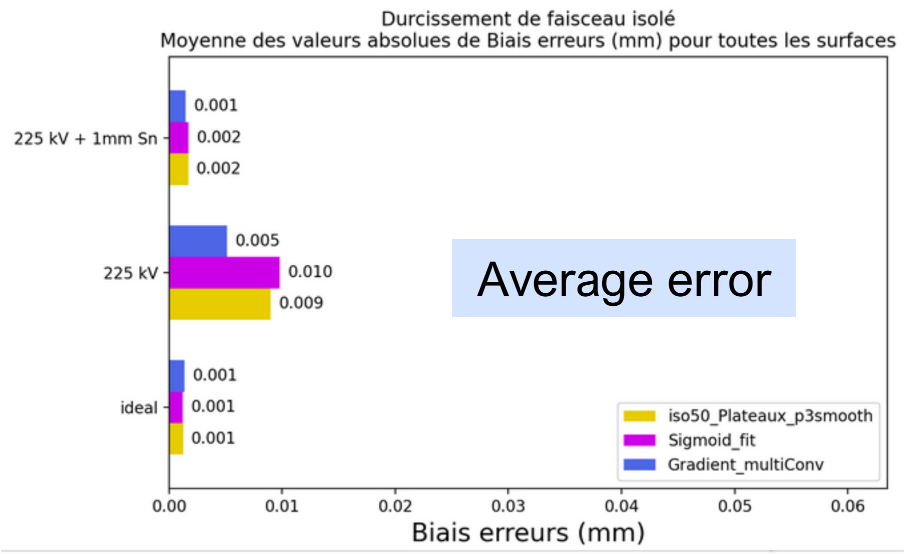
- Photonic and electronic noise do not increase measurement errors, only their dispersion.
- Gradient-based surface determination is more affected by this type of noise than the other surface determinations.
- Error dispersion is greatest where material thicknesses are greatest.

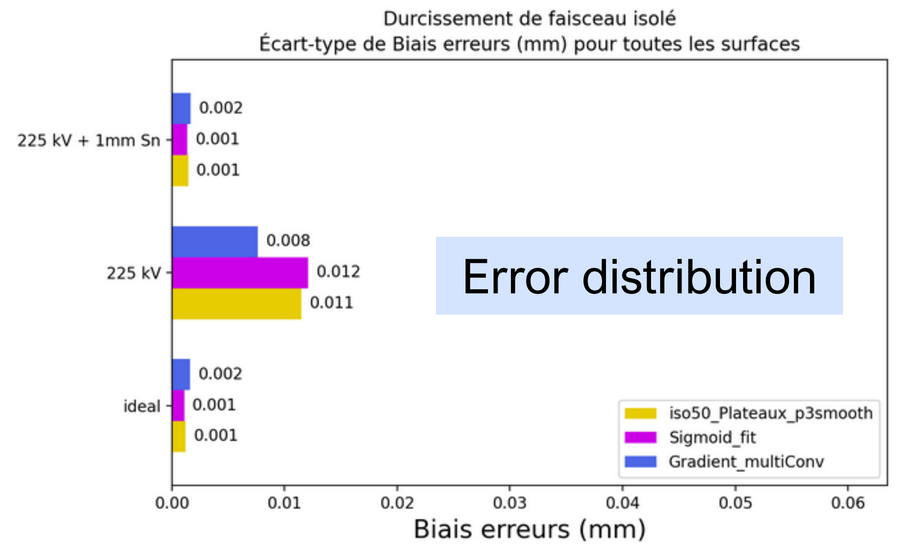




Influence of the beam hardening

- Beam hardening leads to increased measurement error
- The error is always in the same direction: towards the air (the opposite of the bias caused by blurring)
- Gradient-based surface determination is less sensitive to beam hardening than others
- Filtering the X-ray beam reduces measurement errors due to hardening





Conclusions

Study by modelling the complete chain of XCT has shown the following points:

- The points generated during surface determination do not all have the same bias in a scan.
- Different surface determination algorithms respond differently to artifacts and influencing factors, but none seems better than the others in all situations.
- The various physical phenomena involved in tomography generate biases that can be opposed and thus compensate for each other:
    - Optimization of setting parameters to reduce the uncertainties could be more complex than expected
- Measurement errors appear to be highly dependent on the part being scanned (material, dimensions, positioning, measurands) :
    - Simulation might enable us to optimize scan parameters by independently quantifying the errors caused by each phenomenon, and to find a setting that best compensates for these errors.

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