From muography to muon tomography of large structures
CONTENT

• Muon imaging @ CEA
• Going 3D with SART
• Conclusion & perspectives
• Muon telescopes based on Micro-Pattern Gaseous Detectors
  ➢ Robust
  ➢ Excellent spatial resolution
  ➢ Real time
  ➢ Very low gas consumption
  ➢ 3 patents

• Industrial manufacturing – many instruments available
  ➢ 12 telescopes of 50x50 cm²
  ➢ 1 scanner of 1mx1m
  ➢ ~ 8 more telescopes and 1 scanner to come soon

• Operated in many projects, including in harsh environments

Muon tomography of large structures
S. Procureur
IwoRiD| 29/06/2021 | 3
Several projections available for a given structure: 11 for ScanPyramids, 5 for nuclear reactor (~15 by end of 2021)
• Large objects can only be imaged with transmission mode
  ➢ Intrinsically 2D
  ➢ Measures opacity, i.e. 2D density integrated along observation axis

• Muography thus similar to X-ray radiography…
  ➢ Can use algorithms from medical imaging (here SART)

• … with however important differences
  ➢ Size of the volume to image
  ➢ Small number of available projections (a few tens in the best case)

• First implementation in absorption muography (2019):

G. Baccani, JINST 15 P12024 (2020)
GOING 3D - PRINCIPLE

• Same principle in transmission muography…:
  - Split the volume to image in $n_v$ 3D pixels (voxels)
  - Split each muography in $n_m$ independent measurements
  - For a given muography:

\[
\begin{bmatrix} a \end{bmatrix}\hat{\rho} = \hat{\sigma}
\]

- Distance matrix, size $n_v \times n_m$
- Contains mean distance travelled by muons in current voxel
- Calculable

- Density vector, size $n_v$
- Contains density value of each voxel
- Unknown

- Opacity vector, size $n_m$
- Contains opacity value of each measurement
- Indirectly known from data

• … but (much) more complex:
  - Open-sky flux not measured (≠ absorption mode)
  - Much larger objects (~100m vs ~20 cm)
  - Many observation directions are not accessible
  - Need to combine several telescope positions (fixed telescope in absorption)
  - Smaller density contrast ($\Delta \rho \sim 2 \text{ g/cm}^3$ or less vs ~ 11 g/cm$^3$)

⇒ Simulation needed for calibration
⇒ Size of the matrix system

Muon tomography of large structures
S. Procureur
IwoRiD 29/06/2021
• Data should be first converted into opacity measurements
  
  ➢ Calibration with Geant4 simulation
  ➢ Requires very good understanding of telescope performance & muon flux parametrization
  ➢ 1st step: muon flux → transmission factor with open-sky simulation
  ➢ 2nd step: transmission factor → opacity:

\[
o = \rho \times f(T; \theta)
\]

\[
f(T; \theta) = L(\theta) \left( e^{A(\theta)\sqrt{-\ln T}} - 1 \right)
\]

(\(\theta\): zenith angle)
GOING 3D – DISTANCE MATRIX AND MEMORY

• Distance matrix can be calculated once voxels & measurements are defined
  ➢ Need deeply optimized algorithm, e.g. voxel traversal
  ➢ Need special storage method, e.g. YSM (for sparse matrices)

• Just as an example:
  ➢ Volume of 230m x 230m x 140m (pyramid) with 0.5m side voxels
  ➢ Each muography splitted in 200x200 independent measurements
  ➢ 11 projections

⇒ Distance matrix has 26 000 000 000 000 elements!! (ok, many zeros, but still…)

  ➢ After full optimization, CPU to calculate the matrix elements yields ~ 1 day (single thread)
  ➢ Memory (RAM) of 200 Gb
SART algorithm provides update of the density vector at each iteration:

\[ \Delta \rho_v^j = \frac{1}{\sum_{m=1}^{N_m} w_m} \sum_{m=1}^{N_m} w_m \frac{O_m - O_m^{j-1}}{|A_m|^2} A_{m,v} \]

\[ O_m^{j-1} = \sum_{v=1}^{N_v} A_{m,v} \rho_v^{j-1} \]

- Number of effective iterations ~ a few 10,000 for the pyramid case
- CPU time ~ 0.5 day

In practice, limited issue of the initialization of the density vector...

More details in S. Procureur, «Muon tomography of large structures with 2D projections», submitted to Nucl. Inst. & Meth. A
• Framework tested with pseudo-data of a cubic structure with 3 cavities
  - 50m side, concrete material
  - 3 cavities of 10, 7 and 5m side
  - Up to 13 projections below and on the side, 1 month each

Muon tomography of large structures

S. Procureur
• Tomography obtained in the vicinity of the 7m cavity:

Below cavity  Centered on cavity  Above cavity

13 projections

8 projections

5 projections
• Tomography obtained in the vicinity of the 7m cavity:

⇒ Limit of concrete cube very well defined
⇒ Excellent resolution in x-y (transverse)
⇒ Quite good in z (vertical) as well
⇒ Works with only 5 projections
• Using SDvision tool:
• Probably the first SART implementation in transmission muography
  ➢ Most general case in muography (large structures like volcanoes, pyramid, etc.)

• Careful optimization to make the calculation reasonably fast (~1 day)

• Works very well with pseudo-data

• Also successfully tested with pyramid data
  ➢ Requires deep understanding of the instrument (noise, efficiency, acceptance)
  ➢ Added in the ScanPyramids latest paper, submitted to Science recently

• Very recently applied to our nuclear reactor data (only 5 projections so far!)
  ➢ Many internal structures properly localized and reconstructed
  ➢ Probably a paper by the end of the year
THANK YOU FOR YOUR ATTENTION