Muography in MODE

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What is muography

Mu(o(n radio))raphy or muo(n tomo)graphy

In a nutshell: exploiting the natural and abundant flux of muons of cosmic origin to map the interior of a (large) object of interest, taking advantage of either muon absorption (left) or muon scattering (right)

Huge variety of use cases; see Bonechi, D'Alessandro, A.G., Rev. Phys. 5 (2020) 100038
Absorption and scattering

- Opacity measurement
  - Sensitive to $\rho$
  - Observable: deficit with respect to free sky
  - Intrinsically 2D, can get 3D by using multiple points of view
  - No limit on size of target

- Deflection measurement
  - Sensitive to $Z$ and $\rho$
  - Observable: RMS of deflection
  - (can be combined with absorption)
  - Intrinsically 3D
  - Size of target limited: must fit between the two detectors
MODE ⋂ muography?

- I am in MODE and I am active in muography
  - I would be pleased to marry the two
  - But I need collaboration from MODE: I know nothing about differential programming etc.

- In the next slides:
  - Summary of the general arguments in Section 4.2 of the current white paper draft (overleaf)
  - The CP3 muoscope project, based on RPC
  - The EU H2020-RIA project "SilentBorder", based on scintillating fibers
Versatility

Suppose that you have the budget for exactly 6 position detectors:

- You may maximize redundancy (A)
- … or statistics (B)

Suppose you need a 3D image:

- Scattering method (C)
- Absorption-based tomography (D)
- Absorption-based stereoscopic vision with single tracker (B)

Best arrangement depends on the use case, and often not obvious a priori

*Nice thing of muography wrt HEP: after you finish an experiment, re-arranging the detectors for the next use case is quick and cheap!*
What has to be optimized?

- Most of the parameters to be optimized are the same as in any tracker for particle / nuclear / medical applications: area, strip/pixel pitch, distance between layers, etc.

- Quite specific of muography (but similar to e.g. the MUonE exp) is the presence of passive slabs, whose optimal material, size and position may be not obvious a priori.
Figures of merit

- Not guaranteed a priori that one size fits all

<table>
<thead>
<tr>
<th>Application area</th>
<th>Goal</th>
<th>FOM for optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Archaeology</td>
<td>Look for unknown voids, without assumptions on size, shape and location</td>
<td>Sensitivity to localized excesses in muon flux</td>
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<tr>
<td>Glaciology</td>
<td>Find surface separating ice from rock in a glacier</td>
<td>Precision of the measured surface</td>
</tr>
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<td>Nuclear waste inspection</td>
<td>Identify materials of different atomic number</td>
<td>Classification errors &amp; Sharpness of the borders of the identified objects</td>
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<tr>
<td>Cargo scanning</td>
<td>Fire alarm if a forbidden material is present</td>
<td>False negative rate (*)</td>
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</tbody>
</table>

(*) False positive rate, and acquisition time, are fixed as constraints set by the border authority: time is money, and false positives demand lengthy inspections
Types of parameters

- Of course, changing the parameters of the detector units (e.g., the strip pitch) means rebuilding them from scratch, and very often we simply want to recycle the existing ones.
- Hence, a full optimization may only happen at the start of the lifecycle of a project, and several re-optimizations may only be limited to the "global" parameters.

<table>
<thead>
<tr>
<th>Example of local parameter</th>
<th>Example of geometrical parameter</th>
<th>Example of passive material parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip/pixel number</td>
<td>Number of layers</td>
<td>Material</td>
</tr>
<tr>
<td>Strip/pixel pitch</td>
<td>Total length, area, ...</td>
<td>Number of slabs</td>
</tr>
<tr>
<td>Active thickness</td>
<td>Distance / orientation with respect to target</td>
<td>Size and position of the passive slabs</td>
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CP3 portable muoscope project
About portable detectors

- Many archaeology or geoscience use cases where the optimal location of the detector is hard to access and in a confined space
- A few groups are developing portable muon telescopes whose key design considerations include compact size, light weight and autonomous operation
- Most popular detection technology: scintillators
- Gas detectors can be cheaper (for same performance), but usually disfavoured for safety considerations
Examples

Kyushu detector:
- Scintillating fibers (bundled)

MIMA detector (Florence):
- Scintillating bars

Right: from G. Baccani et al., Universe 5(1) (2019), p. 34
Our project is based on small RPC (a type of gaseous detector)

- Portability
  - Sealed; particular care in making gas-tight boxes ($10^{-9}$ mbar l/s)
  - Small (active area: $16 \times 16$ cm$^2$)
  - Light: thin aluminum casings
  - Robust (made trip to Utah desert and back, still working)

- Versatile: modular geometry
  - Cheap and easy to assemble
  - First full prototype built entirely @ CP3 with UGent's support
    - 4 planes (x-y, x-y)
    - Eventually we intend to increase number of channels
(If funded) EOS project, 2022-2026

- We are applying to a national funding scheme (EOS) together with a museum and X-ray tomography experts
  - Deadline for 3-page pre-proposal in Feb., outcome in Apr., if positive we can apply with a detailed proposal by July
- Project centered around the CP3 muoscope project; concrete use: currently thinking about an ancient fountain
  - Large multi-metallic object, unknown inner structure
  - Need 3D tomography $\rightarrow$ multiple detectors
  - Very little room to install equipment $\rightarrow$ compact detectors
  - We may get permission only in specific time slots (e.g., out of visiting hours) $\rightarrow$ portable, autonomous detectors
- A work package will be on simulation-based optimization
SilentBorder
(Funded) SilentBorder, 2021-2025

- EU H2020-RIA project for border control applications
- Goal: muon tomography scanners to identify illicit materials in vehicles and luggages (including low-Z, e.g. drugs, explosives)
- Detection technology: scintillating fibers (not RPC)
- A work package will be on simulation-based optimization

<table>
<thead>
<tr>
<th>Participant No.</th>
<th>Participant organisation name</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>University of Tartu (UT)</td>
<td>Estonia</td>
</tr>
<tr>
<td>2</td>
<td>GScan OÜ (GSCAN)</td>
<td>Estonia</td>
</tr>
<tr>
<td>3</td>
<td>Université Catholique de Louvain (UCL)</td>
<td>Belgium</td>
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<td>4</td>
<td>German Aerospace Center (DLR)</td>
<td>Germany</td>
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<td>5</td>
<td>Costruzioni apparecchiature elettroniche nucleari spa (CAEN)</td>
<td>Italy</td>
</tr>
<tr>
<td>6</td>
<td>University of Sheffield (USFD)</td>
<td>UK</td>
</tr>
<tr>
<td>7</td>
<td>Société Générale de Surveillance (SGS)</td>
<td>Switzerland</td>
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<tr>
<td>8</td>
<td>LEA: Estonian Tax and Customs Board (ETCB)</td>
<td>Estonia</td>
</tr>
<tr>
<td>9</td>
<td>LEA: Directorate General of Customs Enforcement (DGCE), Ministry of Trade of Turkey</td>
<td>Turkey</td>
</tr>
<tr>
<td>10</td>
<td>LEA: Finnish National Board of Customs (TULLI)</td>
<td>Finland</td>
</tr>
</tbody>
</table>

(Note: Tommaso is in the SilentBorder Advisory Board)
Conclusion

- Impact of MODE on muography can be visible
- General impression that muography practitioners tend to like MODE more than HEP detector builders
- Some of our activities align very well with MODE
- A pre-requisite is a complete (fast) simulation chain, that we are still lacking

Possible personpower with my supervision:

- PhD students: Marwa Moussawi (CP3), Samip Basnet (CP3), Ilker Topuz (SilentBorder), NN (SilentBorder)
- Postdocs: Raveendra Karnam (CP3), NN (SilentBorder)
- Note: only the two "NN" can be 100% on this
Extra slides
SilentBorder

Figure 2 A tomography system with inner scanning chamber dimensions 3x3x10m. The tomography has been integrated using $1 \times 2 \text{ m}^2$ hodoscope.
SilentBorder: detector

*Figure 1* An example of the sandwich type of hodoscope module with the side length of 1050 mm.

*Figure 5* The detector plate constructed of two double-fibre orthogonally adjusted $x$ and $y$ planes using 1 mm round scintillation fibre. Right: the constructed prototype system with the dimensions indicated on the model.