Muon Survey Tomography Based On Micromegas Detectors For Unreachable Sites Technology (MUSTˆ2). Principles, Experimental Results And Overlook

Ignacio Lázaro Roche[1]

[1]LSBB CNRS

November 21, 2022

Abstract

Transmission muography is an expanding technique based on the attenuation of the natural-occurring cosmic muons flux due to the opacity of the medium to obtain the distribution of density around the detector. The current work introduces the technology developed by the Temporal Tomography of the Densitometry by the Measurement of Muons (T2DM2) collaboration. The MUST2 camera leans on a thin time projection chamber read by a resistive Micromegas. This new tool presents interesting distinctive features, allowing a wide angular acceptance of the detector with a low weight and volume, well adapted for confined spaces or underground operation. The results obtained from field measurement campaign carried out at the dam overlooking the village of Saint-Saturnin-les-Apt (South-East of France) are presented. The influences of (i) the host rock body of the barrage and dam's structure, (ii) the temporal water level variations of the reservoir and (iii) the effect of the temperature on the muons flux measurements are discussed The main challenge that faces the project is that the muon trajectory reconstruction algorithm cannot infer the arrival angles for a non-negligible number of detected events, with the subsequent loss of information. The data collected during the campaign of measurements, should help improving the algorithm's robustness and reconstruction efficiency. Field transportability and the capability to perform long-term out-of-lab measurements have been demonstrated. The successful proof-of-concept trial makes the MUST2 camera a valuable candidate for transmission muography purposes, particularly in challenging available volume scenarios. The next phase of the T2DM2 project aims at imaging and monitoring the hydrodynamics across the unsaturated zone of the Fontaine-de Vaucluse aquifer. To do so, a network of 20 autonomous detectors will be constructed and deployed within the facilities of the Low Background Noise Laboratory of Rustrel (LSBB), France. The privileged emplacement of the LSBB allows the access to both the surface and to a network of 4 km of underground galleries with depths ranging from 0 to 518 m.

Muon Survey Tomography Based On Micromegas Detectors For Unreachable Sites Technology (MUST²). Principles, experimental results and overlook.

Ignacio Lázaro Roche[1], Adnand Bitri[2], Jean Baptiste Decitre[1], Julien Gance[3], Catherine Truffert[3], Stéphane Gaffet[1,4]

1. T2DM2 COLLABORATION

- ✓ Originally conceived to characterize **local density variations** due to the water motion across unsaturated zones.
- ✓ Develop a new tool based on the **cosmic muon** flux directional measurement for in-situ **imaging and monitoring** the **density** of large volumes of matter.
- ✓ Complementary collaboration between academic and industrial partners towards the creation of a sturdy, reliable, **portable** and ergonomic detector for **ground and underground operation**.

MUST² camera

The MUST² camera is a gaseous detector consisting of a thin time projection chamber read by a resistive Micromegas[1].

I. The muon ionizes the gas blend in several points along its trajectory inside the detector's drift chamber.
II. The electrons so generated drift towards the micromesh thanks to the electric field, and arrive sequentially.
III. This triggers an electronic cascade in the amplification zone and the charge, collected by the resistive layer, induces a signal in the readout planes.

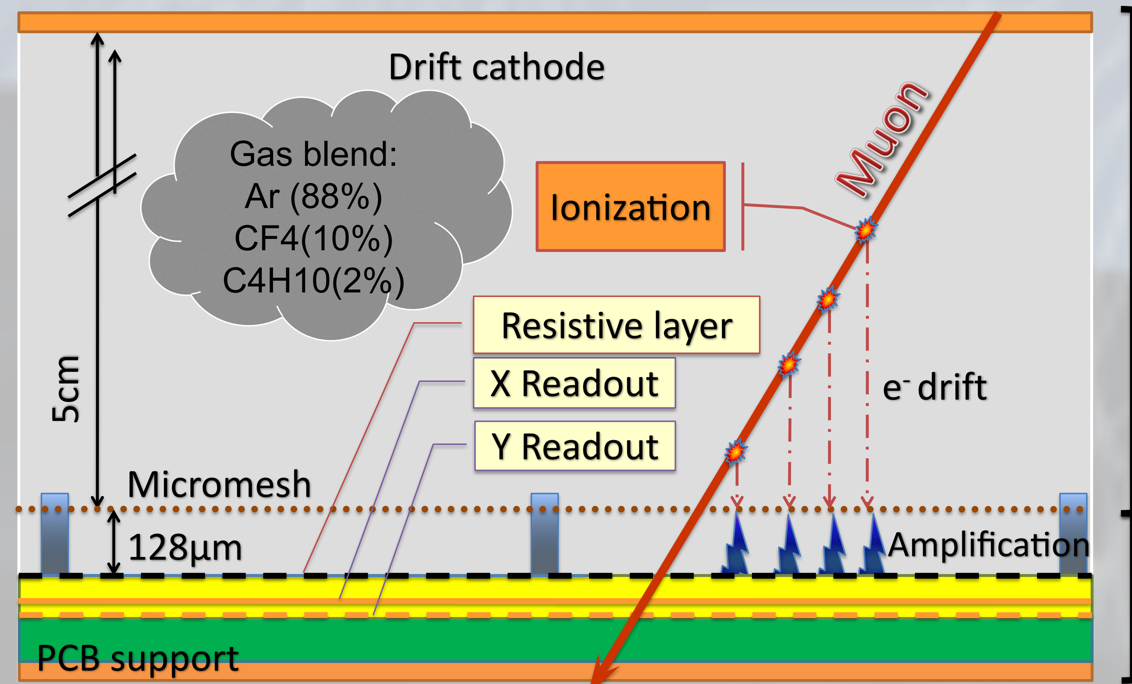


Figure 2.1. Schematic cross-section of the MUST² to illustrate its functioning principle.

The MUST² camera allows retrieving the following information:

- Muon passage time (few ns resolution).
- 2D Position (0.4mm resolution).
- Muon incidental trajectory, characterized by the zenith and azimuth angles.

2. HOW DOES IT WORK?

Muography

- Cosmic muons are a natural, permanent, passive source, capable to penetrate up to several hundreds of meters underground.
- The muon flux scatters and decreases progressively, with an absorption correlated with the medium density and length

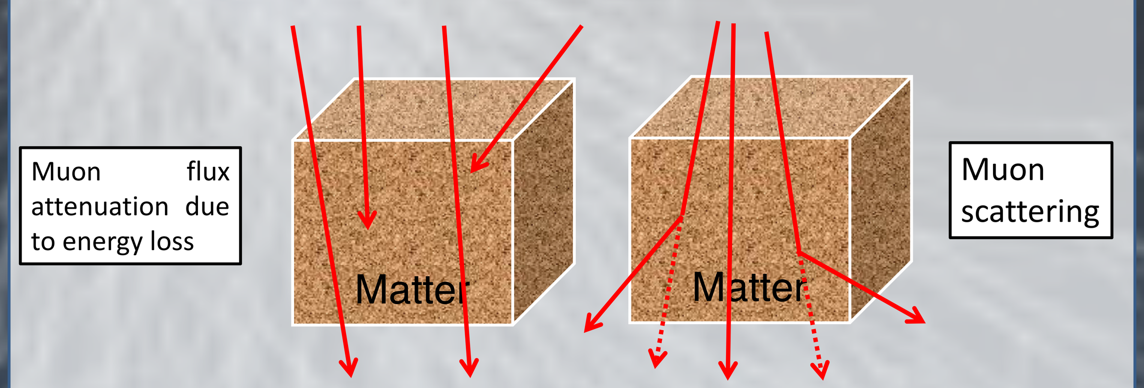


Figure 2.2. (Left) Principle of transmission tomography. (Right) Principle of scattering tomography due to the deviation of the muon.

- The muon flux characterization at ground level and underground is fundamental. The Tang empirical model[2] allows to estimate surficial flux as a starting point for the tomography.
- Figure 2.3.C provides the efficiency distribution of the muon trajectory reconstruction, and is used to correct the measurements.

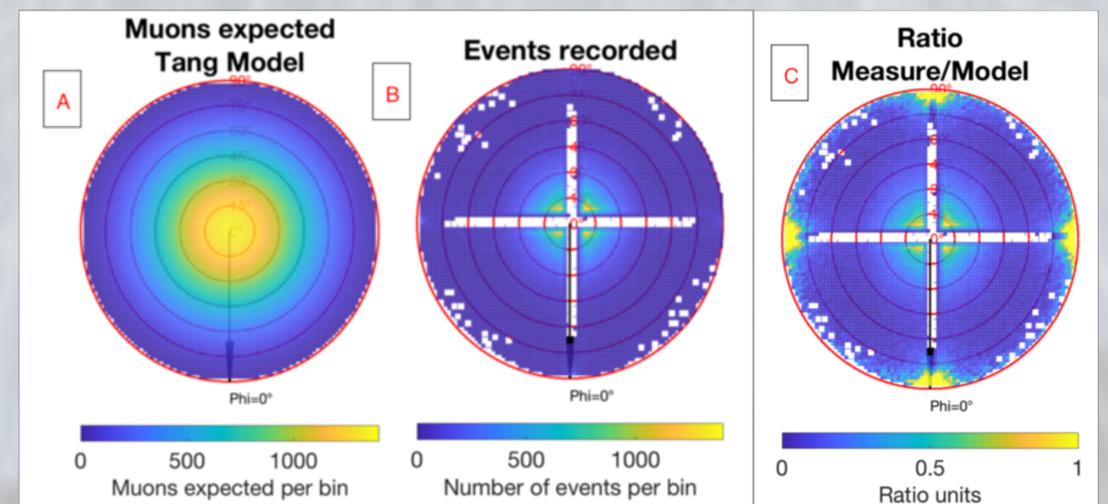


Figure 2.3. Polar chart of the muon arrival distribution according to the Tang model (A), experimental open sky measurement (B) and ratio between them (C).

- The **underground muon flux** can be estimated by multiplying the survival probabilities with the surficial flux.

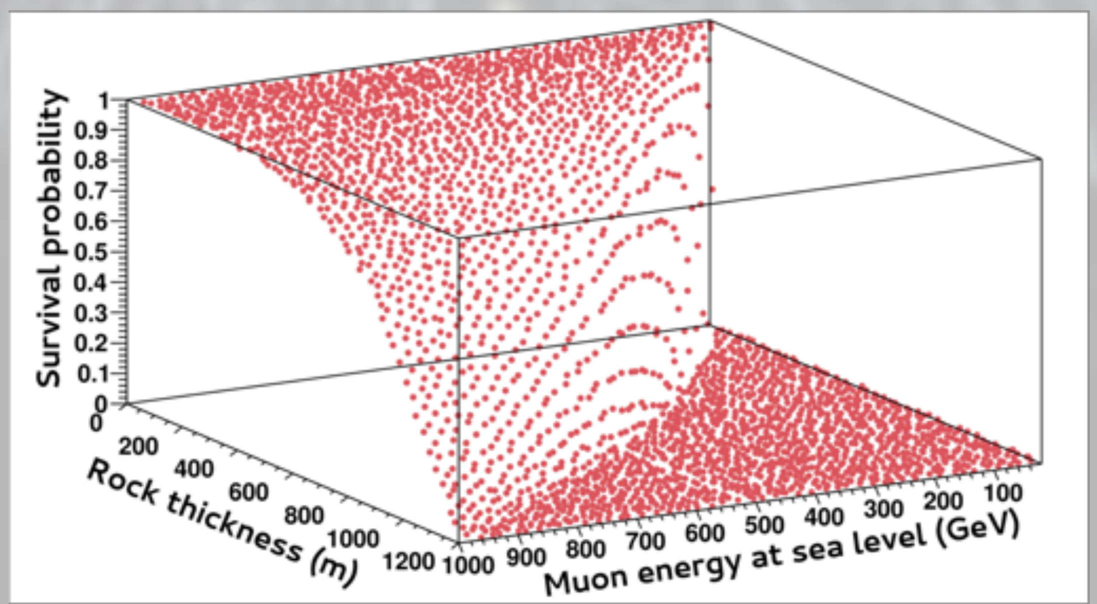
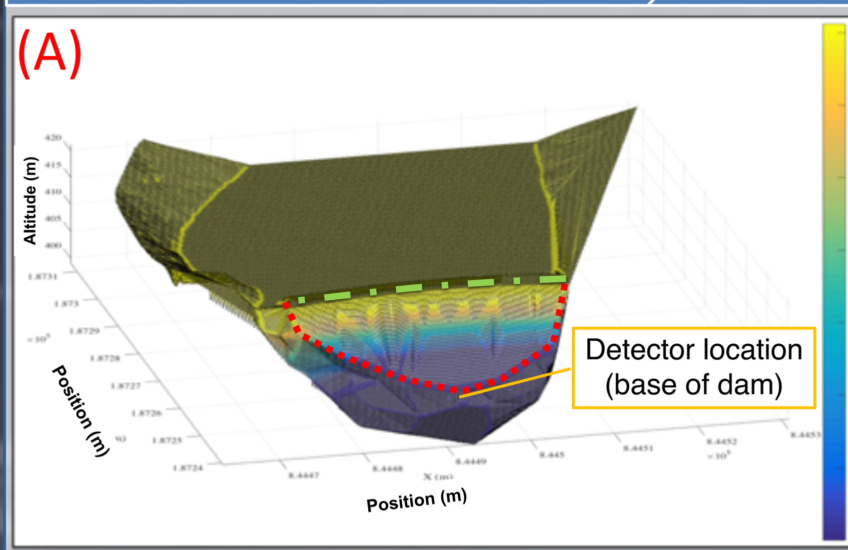


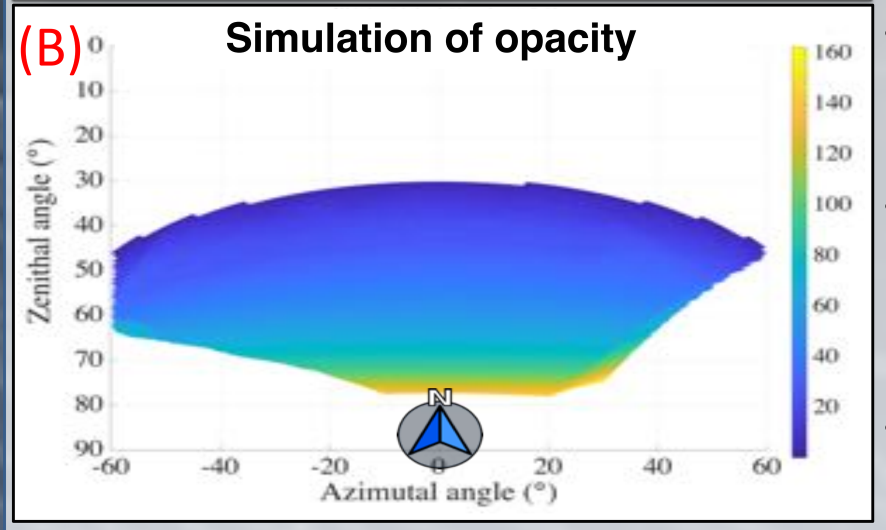
Figure 2.4. Muon survival probabilities as a function of the muon's energy for a standard rock density (2.65 g/cm-3), from Hivert[3].

3. STUDY CASE: DAM

Digital model (A) | Opacity simulation (B) | Experimental measurement (C) | Temporal monitoring (D)



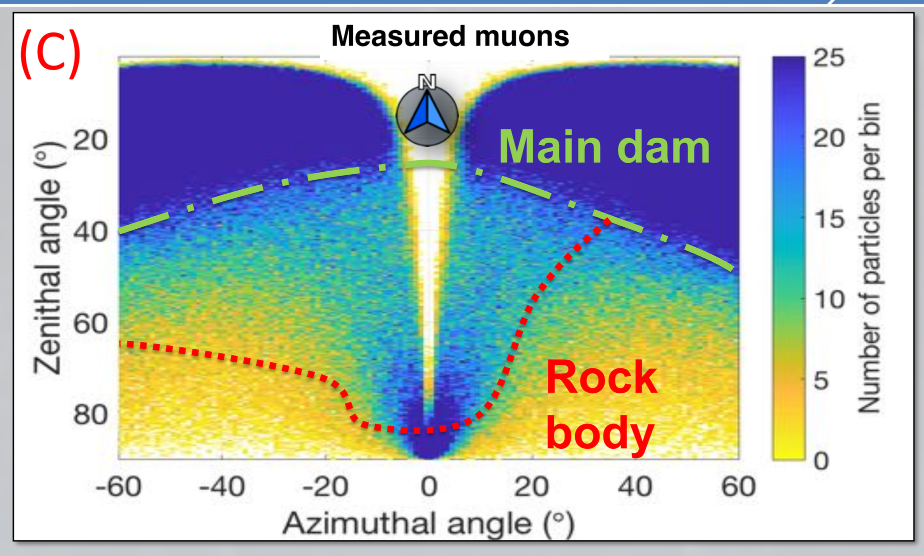
- Two superimposed models considering the medium heterogeneity:
  - Water ρ=1.000 kg/m^3.
  - Geology and dam* ρ=2.400 kg/m^3.
- Customizable water level.



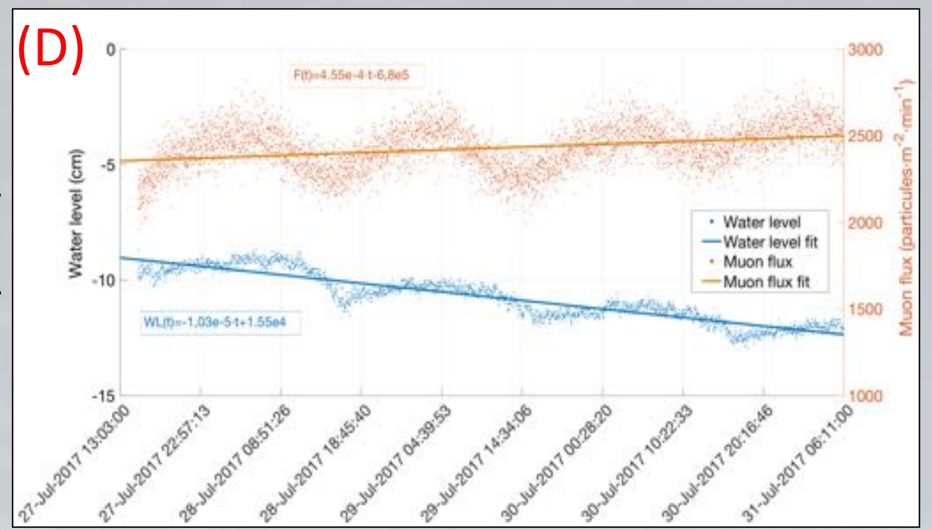
- The digital model of 3.A allows to simulate the opacity of the targeted volume.
- The opacity is defined as the density integrated over the path's length and measured in meters of water equivalent.
- Provides an estimation of target's muon flux attenuation power.

Figure 3.A. Digital model of Saint-Saturnin-lès-Apt (Fr) dam and water reservoir

Figure 3.B. Simulated opacity of the dam from the point of view of the MUST² camera



- Integration time ~90h.
- It is possible to recognize the following elements:
  - Frontier between open sky and dam structure (green dot-dashed line).
  - Rock body of the water reservoir(red dotted line).



- Small density contrast (<1%) due to the water level variation during the measurements.
- Two superimposed behaviors:
  - Influence of the inverse of temperature in the muon trajectory reconstruction performance and the water level measurement (sinusoidal oscillations).
  - The emptying trend of the dam (33 mm in four days) leads to a rise of the reconstructed muon flux as expected.

Figure 3.C. Muons measured coming from the direction of the dam

Figure 3.D. Temporal evolution of (blue) water level of the dam and (orange) recorded muon flux.

4. WHAT'S NEXT ?

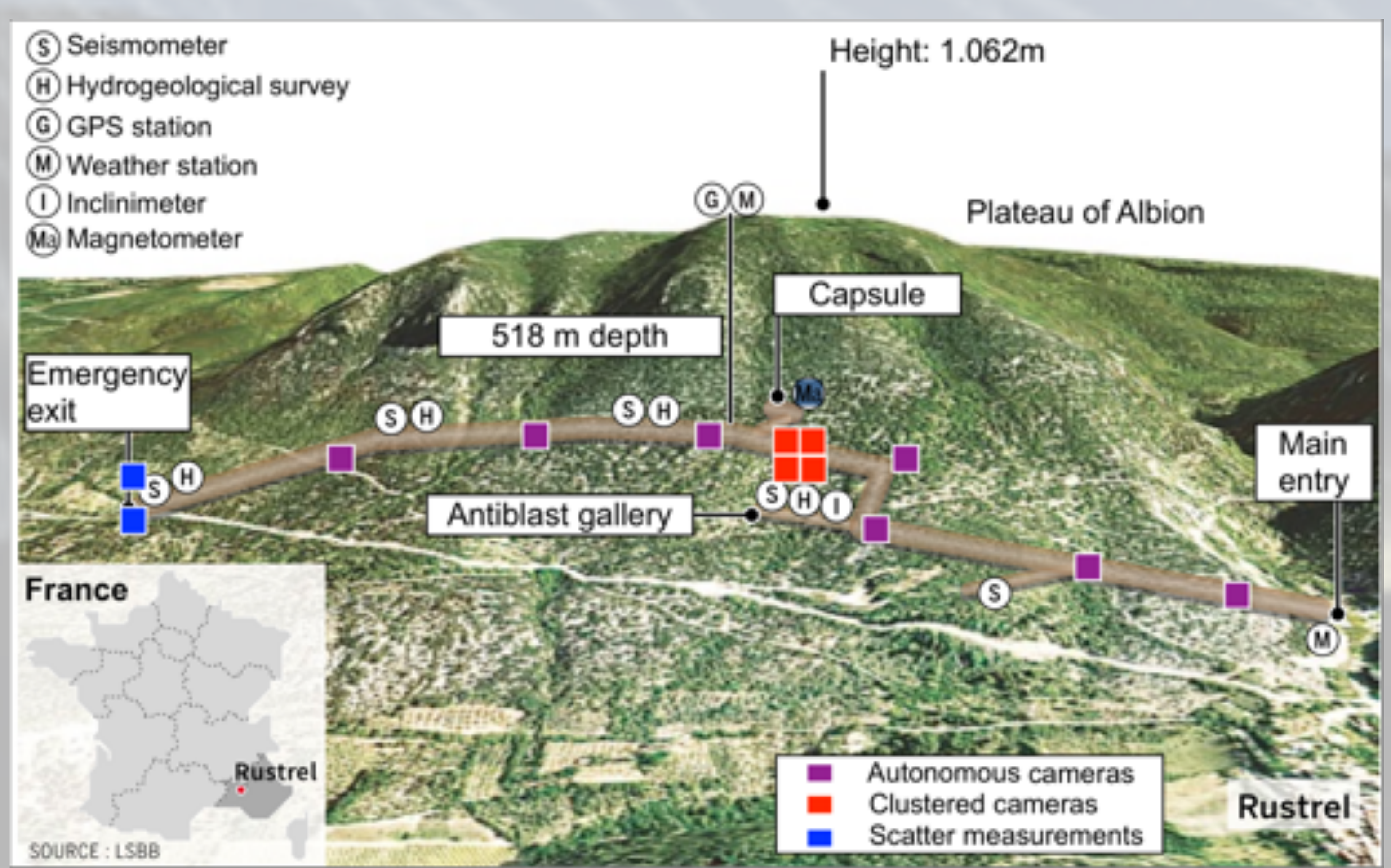


Figure 4.1. Visualization of the Low Background Noise Laboratory (LSBB) galleries underneath the mountain and scheme with the detector's location.

- ✓Minimize performance variability of MUST² due to temperature fluctuations: adaptive gain.
- ✓Test the new muon trajectory reconstruction algorithm, completely new approach
- ✓Construction and deployment at the LSBB of a network of 20 autonomous cameras integrating all the improvements (funded by FEDER LSBB2020). Versatile setup configurations:
  - ➢Monitoring: network of stand-alone cameras.
  - ➢Deep measurements: clustered cameras to increase detection surface.
  - ➢Scatter measurements: trackers upstream/downstream object (different scales).
  - ➢Multilayer operation: stacked detectors to improve angular resolution.

5. CONCLUSIONS

- ✓MUST² is a useful tool for the direction-sensitive measurement of the muon flux towards muographic applications.
- ✓More data required to fully validate temporal monitoring capability due to small density contrast and gain fluctuations during outdoor experiment.
- ✓Field transportability and reliability validated during outdoor measurements.
- ✓The network of cameras, soon deployed at the LSBB, will allow versatile configurations to enhance the cosmic muon absorption/scattering measurements.

Affiliations and contact

Corresponding author Email : ignacio.lazaro@lsbb.eu

[1]LSBB, Aix-Marseille Univ. CNRS, Univ. of Avignon, Univ. of Nice; Rustrel, Fr. [2]BRGM, Orléans, Fr. [3]Iris Instruments, Orléans, Fr. [4]GEOAZUR, Univ. of Nice, CNRS, IRD, OCA; Sophia-Antipolis, Fr.

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Collaborators

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