Technical Report

Muon tomography of the Physics Department of the University of Coimbra

Luís Afonso,[1] Isabel Alexandre,[1] Sofia Andringa,[1] Pedro Assis,[1] Alberto Blanco,[2] Mourad Bezzeghoud,[3] José Borges,[3] Bento Caldeira,[3] Lorenzo Cazon,[4] João Costa,[5] Paolo Dobrilla,[2] Magda Duarte,[6] Josué Figueira,[3] Ines Hamak,[3] Luís Lopes,[2] João Matos,[7] Rui Oliveira,[3] Vanessa Pais,[5] Mário Pimenta,[1] João Saraiva,[2] Raul Sarmento,[6] Jorge Francisco Silva,[2] Pedro Teixeira,[3] and Bernardo Tomé[1]

[1]*Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal*

[2]*Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Departamento de Física (DF), Universidade de Coimbra, Rua Larga, 3004-516 Coimbra, Portugal*

[3]*Departamento de Física (ECT), Instituto de Ciências da Terra (ICT/IFFA), Earth Remote Sensing Laboratory (EaRSLab), Universidade de Évora, Rua Romão Ramalho no. 59 7000-671 Évora, Portugal*

[4]*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Rúa Xoaquín Días de Rábago, 15705 Santiago de Compostela, Spain*

[5]*Mina de Ciência - Centro Ciência Viva do Lousal, Av. Frédéric Velge, 7570-006 Lousal, Portugal*

[6]*Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Universidade do Minho, Campus de Gualtar, CP3, 3.02, 4710-057 Braga, Portugal*

[7]*Laboratório Nacional de Energia e Geologia (LNEG), Campus de Aljustrel, Bairro da Vale D'Oca, Apartado 14, 7601-909 Aljustrel, Portugal*

Corresponding author: Magda Duarte
Email: mduarte@lip.pt

Abstract

The LouMu is the first project of muography in Portugal, more particularly of transmission muography. It has employed an RPC muon telescope to perform the imaging of a building, the Physics Department of the University of Coimbra, and of a geological structure, the Lousal mine. Regarding the muon tomography of the former, data analysis was already carried out to obtain 2D transmission maps that compare well with simulation and efforts are being made to use these maps to reconstruct 3D images of the University building. In this work, three image reconstruction methods are applied: back-projection, analytical inversion, and iterative reconstruction. While the first two were not successful given the muon telescope's spatial resolution and given the type of structures encompassed when imaging a building, the iterative method has led to promising results in simulation and is, now, being applied to real data acquired at the University.

Keywords: transmission muography, simulation, back-projection, analytical inversion, iterative method, image reconstruction
DOI: 10.31526/JAIS.2024.483

1. THE LouMu PROJECT

The LouMu project is the first muography project in Portugal, and it started back in 2019 with the development of a muon telescope by the Laboratory of Instrumentation and Experimental Particle Physics (LIP) in Coimbra. This muon telescope consists of 4 $(1 \times 1)\,\mathrm{m}^2$ Resistive Plate Chambers (RPCs) placed parallel to each other with a varying distance on a trolley that eases the process of transportation and inclination of the telescope—Figure 1 (Left). The 4 RPCs are not identical, the top one has stripped pads, and the bottom three have a more complicated pad configuration, with a $(30 \times 30)\,\mathrm{cm}^2$ central region, the CorePix, composed of 7×7 small square pads—Figure 1 (Center) and (Right), respectively.

After its construction, the LouMu telescope remained in the Department of Physics of the University of Coimbra for two and a half years until April of 2022, having occupied 7 different positions, in one of them with 3 different inclinations up to 28.5° (Figure 2). During this stay, the goal was to study and calibrate the telescope to prepare what would be, indeed, the first experiment of the LouMu project, by which the telescope would be deployed to the south of Portugal to perform the imaging of the Lousal mine [1]. Nevertheless, with the data acquired in the university, it was possible to perform the imaging of the building and develop transmission muography as an imaging tool for the field of civil engineering.

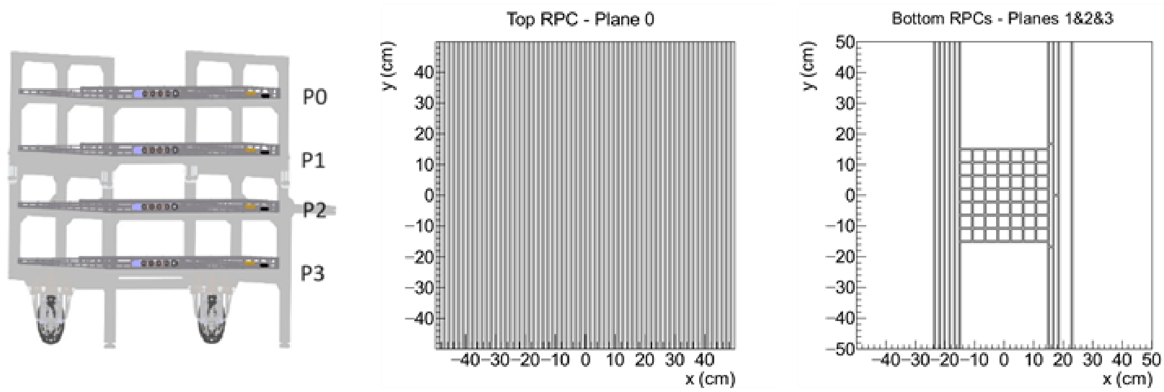

FIGURE 1: (Left) CAD of the LouMu telescope. (Center) Pad configuration of the top RPC. (Right) Pad configuration of the bottom RPCs.

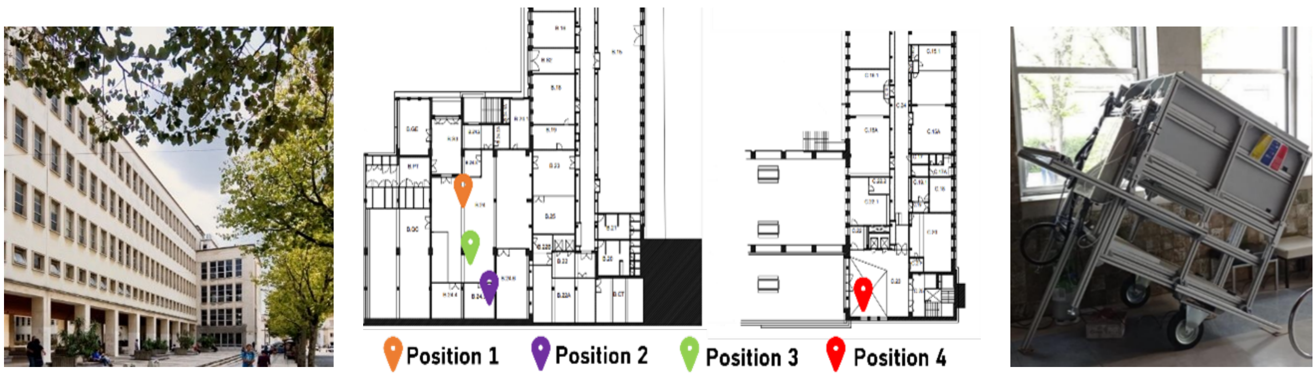

FIGURE 2: (Left) Picture of the Department of Physics of the University of Coimbra. (Center) Construction plans of the underground floor (Center Left) and of the entrance floor (Center Right) of the Physics Department of the University of Coimbra with 4 markers signaling some locations where the detector was positioned. (Right) Picture of the detector in one of the configurations at the university, inclined by 28.5°.

2. TWO-DIMENSIONAL IMAGING

The 2D imaging was performed using only the CorePix of the bottom RPCs, which were distanced by 33.5 cm, and it encompassed two main tasks:

(1) *Development of a simulation* for muography with the LouMu telescope at the Physics Department of the University of Coimbra. The simulation consisted of an algorithm developed specifically for this study.

(2) *Generation of 2D transmission maps from data*, which included the simulation of the expected telescope's muon flux in an open sky configuration and the development of an iterative algorithm to retrieve high-resolution maps.

Regarding the first task, a Monte Carlo simulation was developed. The first two steps of the simulation consist of setting up the geometric configuration of the telescope and setting up the 3D model of the Physics Department of the University of Coimbra. This model is based on the building's construction plants—Figure 2 (Center)—and consists of a simple assembly of parallelepiped volumes with different densities ρ that represent the walls, ceilings, beams, and columns that compose the edifice. After the setup of the telescope and the building, the simulation proceeds to generate muons that reach the telescope with random trajectories.[1] These trajectories are back-projected into the building space to determine the distance d_i the muons travelled in each structure i. These distances are converted into amount of matter, O, by multiplying them by the density of each of the structures ρ_i, $O = \sum_i d_i \times \rho_i$ [g/cm^2].[2] Finally, the amount of matter O is converted into transmission, T, using the exponential model in [2].[3] The values of T obtained for each combination of pads are used to construct 2D transmission maps discretized according to the simulated telescope resolution. The results of the simulation for a telescope with 10x LouMu's resolution and for a telescope with LouMu's resolution are presented in Figure 3 (Center) and (Right), respectively.

[1] In the simulation, when generating the muons and their trajectories, the energy and angular distribution that characterizes atmospheric muons was neglected.

[2] The sum is carried over all structures i that constitute the university building.

[3] This model was derived previously with muography data acquired at the university building. By considering an approximate value for the amount of matter of a ceiling ($O_{\mathrm{ceil}} = d_{\mathrm{ceil}} \times \rho_{\mathrm{ceil}} \approx 40\,\mathrm{cm} \times 2.4\,\mathrm{g/cm^3}$), the muon transmission across a structure characterized by its respective amount of matter O is determined as follows: $T = 0.94^{O/O_{\mathrm{ceil}}}$.

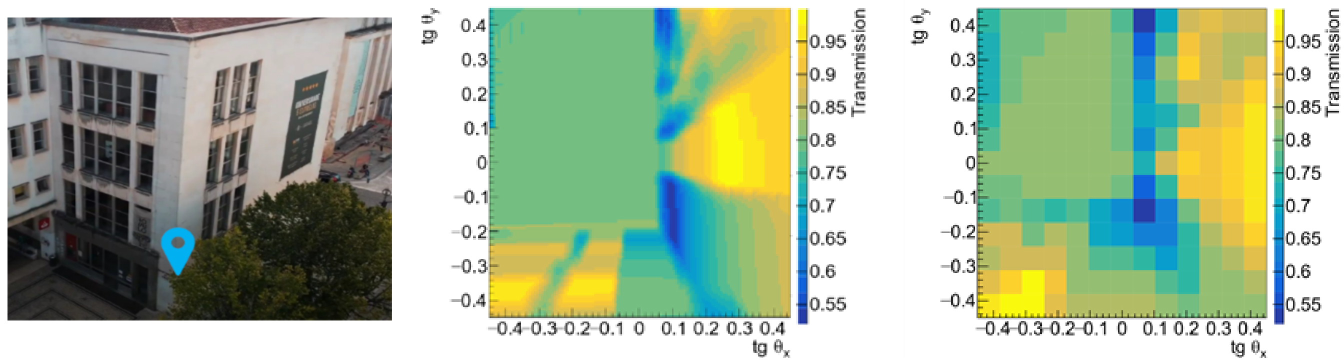

FIGURE 3: (Left) Location of the telescope used for the simulation results exemplified. (Center) 2D Transmission map simulated with 10x LouMu's resolution. (Right) 2D Transmission map simulated with LouMu's resolution.

Then, 2D transmission maps were also determined from the data. The muon transmission T is given by the ratio between the muon rate measured with the telescope placed underneath the imaged structure and the muon rate measured with the telescope placed outside, that is, the atmospheric muon rate. Since a data acquisition campaign with the telescope outside the building was not carried out, it was necessary to obtain a simulation of the atmospheric muon rate. To do this, one other simulation, a Monte Carlo simulation, was developed, considering LouMu's geometry and a cosine-square angular distribution of the atmospheric muon flux. The 2D transmission maps obtained for four of the telescope locations at the university are presented in Figure 4, alongside the respective simulations. Each of the data maps presented in Figure 4, and later in Figure 5, has been normalized to their maximum value. This normalization is justified by the fact that the experimental transmission values are over 1 by a factor that is still being analyzed regarding its origin.[4]

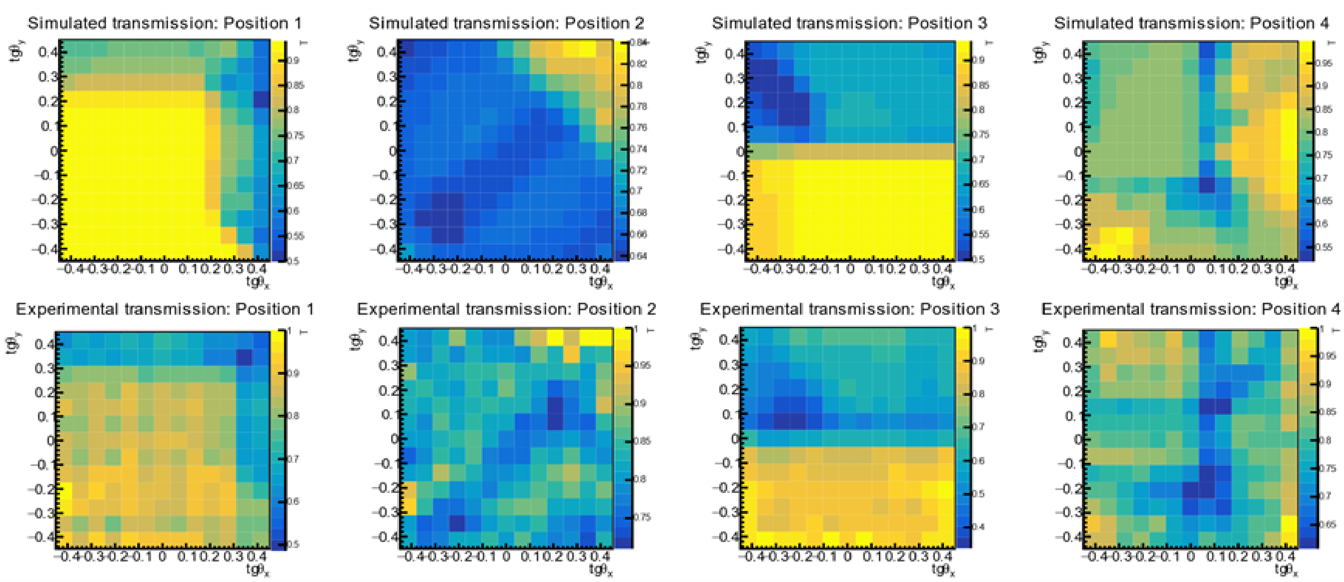

FIGURE 4: Four 2D transmission maps acquired with the LouMu telescope at the Physics Department of the University of Coimbra (simulation at the top row and data at the bottom row).

In Figure 4, only 1 of the 3 transmission maps possible to obtain with the CorePix of the bottom RPCs is displayed. Namely, Map13, the one that results from considering the muons detected by planes 1 and 3, which are the furthest apart—Figure 1 (Left). Taking the data acquisition relative to Position 4 and using another combination of two planes, for example, of planes 1 and 2, a lower-resolution and larger field-of-view transmission map is attained, Map12. Since these two maps share part of their field of view, while perceiving it differently—Figure 5 (Left[5] and Center)—it is possible to combine their information in a higher-resolution transmission map. This process is done iteratively. Initially, a higher-resolution map, MapHR, is initialized and populated with

[4]Regarding this issue, the possibility of the telescope's efficiency having been underestimated is analyzed. Since the muon rates measured are divided by the telescope's efficiency: the underestimation of this quantity would result in an overestimation of the muon rates and, consequently, of the muon transmission. This is a correction that is only applied to the data, since the outcome of the simulation is, by definition, constrained to plausible values of muon transmission (<1).

[5]This Map13 was already presented in Figure 4 as "Experimental transmission: Position 4."

values from Map13 and Map12 weighted by the fraction of their geometrical apertures that coincides with the geometrical aperture from MapHR (refer to Figure 5, Right). Subsequently, the reconstruction of maps Map13 and Map12 is conducted using MapHR, and these reconstructed maps are compared with the experimental ones to determine the residuals. MapHR is then updated with the residuals obtained from this comparison. This iterative updating process is repeated through multiple iterations until a stopping criterion is met, such as reaching a maximum number of iterations. An example of the application of this iterative method to one data acquisition with the LouMu telescope at the university is shown in Figure 6.

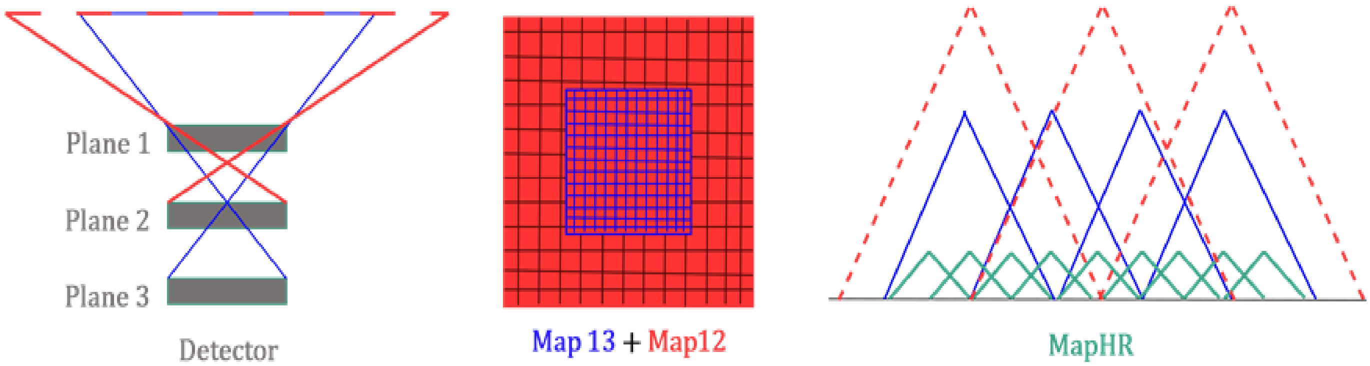

FIGURE 5: (Left and Center) Superposition of Map13 and Map12 fields of view. (Right) Schematics of the contribution of the values of Map13 and Map12 for MapHR.

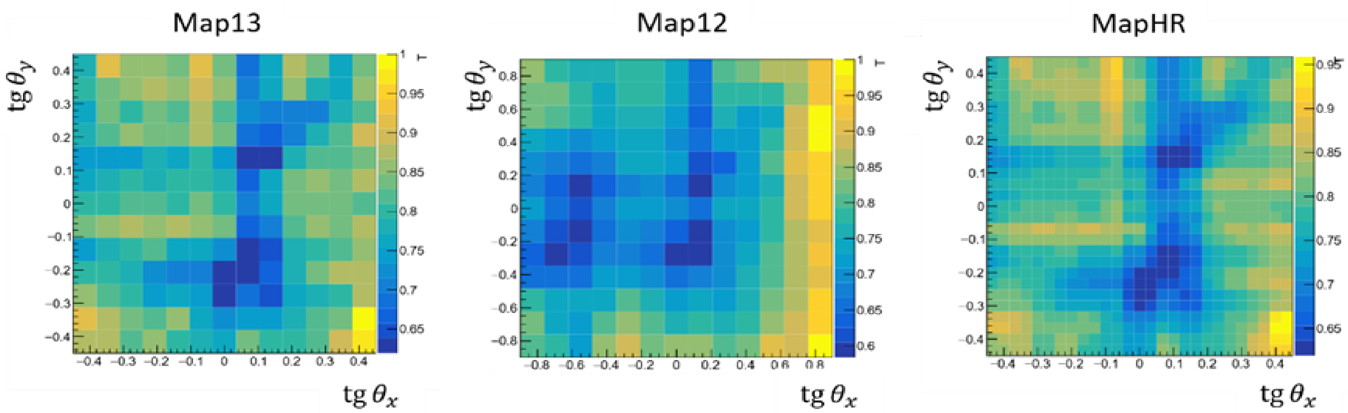

FIGURE 6: Example of the application of an iterative method to attain higher-resolution maps to a set of data acquired by the LouMu at the Physics Department of the University of Coimbra: (Left) Transmission Map13, (Center) Transmission Map12, and (Right) Transmission Map HR.

3. THREE-DIMENSIONAL IMAGE RECONSTRUCTION

In the 2D analyses, the physical extension of the telescope is ignored, and only the directions of the muons are considered. Exploring the physical extension of the telescope may allow the retrieval of 3D information. Concerning the three-dimensional imaging of the university building, three image reconstruction algorithms are studied in simulation. For all of them, the case study consists of a simple setup: a beam placed at different distances above the detector, which was inspired by a specific data acquisition at the university where the detector was below a beam oriented 45° to the detector (second column of Figure 4).

First, the *back-projection* method was applied as explained in [3] with the goal of determining the distance between the beam and the telescope using only one data acquisition. From this analysis, it was expected that by back-projecting the 2D transmission maps and measuring the reconstructed angular signal width at different distances from the telescope, a minimum would be found at the distance the beam was positioned relative to the telescope. While this turned out to be true in simulation for a telescope with 10x the LouMu's resolution—Figure 7 (Top row)—using LouMu's resolution, a minimum could not be well resolved—Figure 7 (Bottom row)—and, thus, the back-projection method as presented in [3] proved inadequate in this experiment.

The second image reconstruction method applied to the beam case study is more similar to what was used in the construction of higher-resolution maps, shown in Figure 6. It is an *iterative method*, more particularly, the Simultaneous Algebraic Reconstruction Technique (SART) presented in [4]. For this method, one admits that it is possible to convert transmission T into the amount of matter O and that the latter can be given by a linear equation $O = A\rho$, where A is a matrix with entries in distance units and ρ is a vector where the densities of the voxelized image are concatenated. This matrix is determined, and the iterative process, similar to the determination of MapHR, starts with the initialization of the voxelized image, which is subsequently updated with the O values according to the SART's algorithm. In simulation, for the LouMu telescope and for the beam's case study, the results in Figure 8 were obtained: the reconstruction correctly signals the presence of a denser volume at the height the beam was placed.

The third image reconstruction method used was the *analytical inversion*, usually employed in the field of geophysics and previously employed in muography, as well, for the reconstruction of volcanoes. Admitting that it is possible to convert transmission T into the amount of matter O, the analytical inversion subset of methods studied in the context of the LouMu project relies on the capability of mathematically describing the muography measurements by the previously mentioned linear equation $O = A\rho$. Given O and A, the method described in [5] consists of using the errors associated with O and *a priori* information regarding the imaged structure to determine ρ. Although the applicability of this method to the problem of reconstructing the beam is still under study, we anticipate difficulties given the fundamental differences between the beam and the structures that are usually imaged with this method, which are continuous and smooth-varying density structures, such as geological structures.

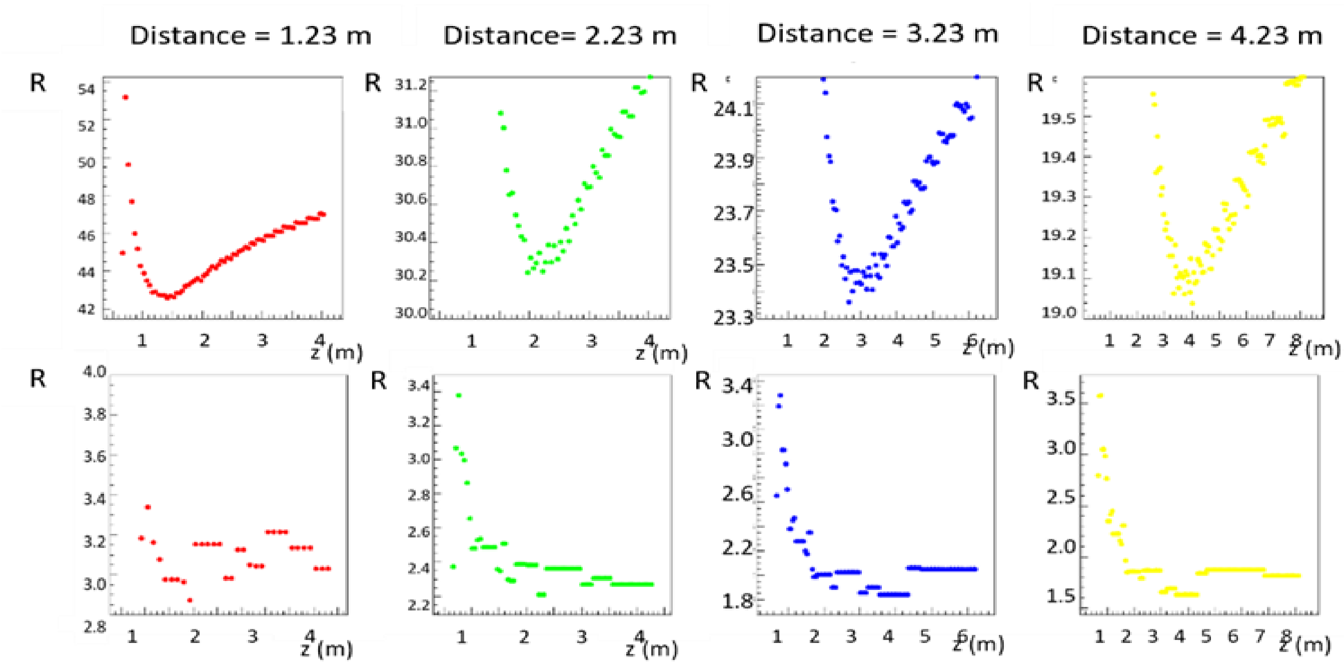

FIGURE 7: Plots of the angular width of the signal region (R) versus the distance from the telescope (z) for 4 different beam positionings relative to the telescope. (Top row) Using 10x LouMu's resolution. (Bottom row) Using LouMu's resolution.

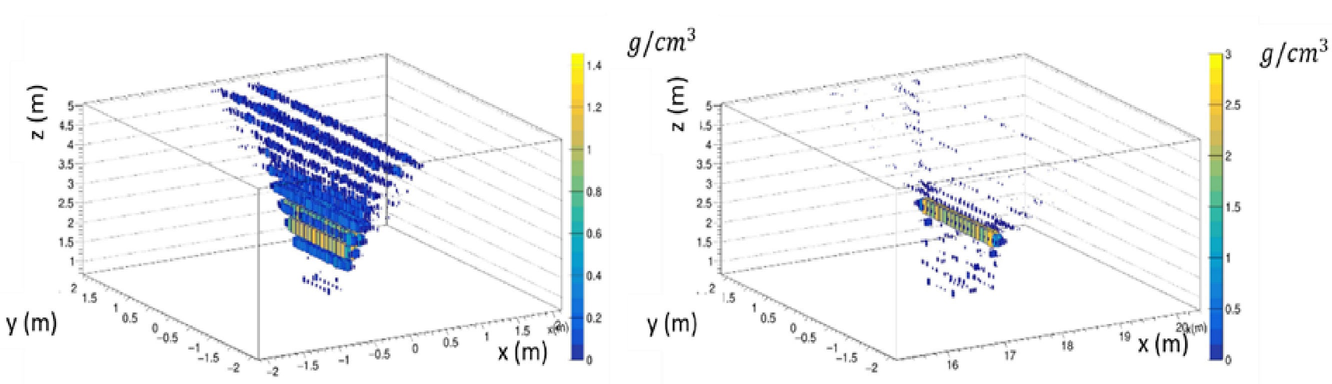

FIGURE 8: Results of the iterative reconstruction of a beam placed at 2.6 m height. (Left) Using one telescope position. (Right) Using three telescope positions.

4. CONCLUSION

The imaging of the Physics Department of the University of Coimbra has been the first application of muography in Portugal. Having started as an exploratory project that aimed to test the LouMu telescope, it has resulted in 2D transmission maps that compare well with simulation, and it has propelled the investigation of 3D reconstruction algorithms. While back-projection and analytical inversion have, so far, proven inadequate for the LouMu telescope and the imaging of a building, iterative reconstruction performed well in simulation. Efforts are currently being made regarding the application of the iterative method to real data.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

ACKNOWLEDGMENTS

This work was made possible due to the contributions of the LouMu project's LIP groups, along with valuable input from ICT, LNEG, and Mine of Science during the general meetings. The project is partially funded by FCT under reference numbers EXPL/FIS-OUT/1185/2021, and CERN/FIS-PAR/0012/2021, which has been instrumental in advancing the LouMu project's research endeavors. FCT also provided funding for M. Duarte under the fellowship UIDP/50007/2020.

References

[1] S. Andringa, L. Afonso, I. Alexandre, P. Assis, A. Blanco, M. Bezzeghoud, J. Borges, B. Caldeira, L. Cazon, et al., Muography in the University and in the Museum, Journal of Advanced Instrumentation in Science, (2022).
[2] L. Amorim and M. Duarte, Muography of a building, LIP 2020.
[3] L. Bonechi, R. D'Alessandro, N. Mori and L. Viliani, A projective reconstruction method of underground or hidden structures using atmospheric muon absorption data, J. Inst. 10, (2015) P02003.
[4] S. Procureur, Muon tomography of large structures with 2D projections, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1013, (2021) 165665.
[5] A. Tarantola and B. Valette, Generalized nonlinear inverse problems solved using the least squares criterion, Rev. Geophys. 20, (1982) 219.