# Testing Muography for Subsurface Geophysical Surveys at the Lousal Mine

**Luis 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 Instrumentaţão 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 n.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: Sofia Andringa*
*Email: sofia@lip.pt*

## Abstract

The LouMu collaboration was established between the Laboratory of Instrumentation and Experimental Particle Physics (LIP), the Institute of Earth Sciences (ICT), and the Ciência Viva Center of Lousal, to create the conditions for the use of muography as a novel method for subsurface geophysical surveys in Portugal, starting with an end-to-end test at the Lousal Mine. The exploitation of the Lousal Mine, located in the Iberian Pyrite Belt, ended in 1988, and it was then rehabilitated as the core of a science center. An 18-meter-deep gallery was kept accessible, allowing the operation of a muon telescope. Detailed surveys of the gallery and surroundings were done to help establish the muography targets and interpret the first results. In April 2022, the muon telescope was installed at Lousal and soon obtained the image of the first geological target: the Corona geological fault crossing the gallery. The analysis proceeds with the development of the methods for translating these into local density maps and for combined inversion of muography with other datasets. The aim is not only to provide the best knowledge on Lousal, but also to prepare for other geophysical surveys.

*Keywords:* muography, mine gallery, geological fault, RPC detectors
*DOI:* 10.31526/JAIS.2024.484

## 1. THE LouMu PROJECT

The LouMu project [1] aims to test the usage of muography as a tool for subsurface geophysical survey, as in [2, 3, 4], with a telescope made of low power and low gas consumption Resistive Plate Chambers (RPC) detectors. The test site is an 18 m deep gallery of a now closed pyrite mine, which is crossed by known geological faults that provide interesting targets for observation. The mine gallery is now part of a science museum, the Mine of Science. The LouMu team joins particle physicists experts on RPCs and cosmic ray data analyses, geophysicists, geologists, and science communication experts in different institutions in Portugal. The Laboratory for Instrumentation and Experimental Particle Physics (LIP) has a strong compromise with education and outreach programs in particle physics, participates in large cosmic ray observatories, and develops RPC detectors for different applications; the Institute of Earth Sciences conducts geophysical surveys with different methods, of which muography would be a new addition; the Lousal Ciência Viva Science Center houses the project which increases the investment in outreach and communication.

The LouMu muon telescope was installed at the Lousal in April 2022, for a yearlong data-taking campaign. This long campaign has served to certify the operation of the RPC telescope, following gas flow constraints in a confined public space. The first target for geophysical subsurface imaging, the regional Corona geological fault, was successfully imaged by November 2022. Data taking continued with the telescope in a second position, and geosurveys were done by other methods for comparison. The future goal of the project is to compare and combine muography with the independent data sets for a global geological result.

## 2. THE MUON TELESCOPE

The LouMu telescope consists of four 1 m × 1 m detector planes, placed horizontally in a movable structure, which can be tilted up to 30 degrees. The planes can be easily changed, which allows new ones to be tested for further R&D programs, and the vertical distances between them can be adjusted to focus on the muographic images.

The RPC detectors have two 1 mm layers of gas, divided by 2 mm glass plates, the top layer covered with high resistivity paint. The high voltage is automatically adjusted to compensate for changing environmental conditions of temperature and pressure, to keep the reduced electric field in the gas constant. These parameters are, nevertheless, very constant in the gallery requiring variations of less than ±10% around the ±6 kV. The chambers are flushed with pure Tetrafluorethane at flow rates below 5 cc/min [6]. The largest challenge for operation in the mine, in a confined public access space, was to bring the communication and gas flow through a 100-meter-long gallery, to an outside shed. The used gas was also recovered and recompressed into bottles for recycling, in the same outside location. While these RPCs are operated at low gas flux [5], the gas bottles were still exchanged a few times by the local personnel, needing little support from detector experts. The long tubes have introduced some degradation of the performance, which is being investigated [6].

The telescope is triggered by coincidences in two of the planes within 30 ns, strongly reducing random noise. A Raspberry Pi computer writes out the charge measured in each of the channels of each plane. One of the planes has 64 narrow width parallel strips, the others mix strips of varying widths, with large and small squared pads. The central region of three of the planes is occupied by 7 × 7 squares of 4.3 cm side, which set the spacial and angular resolution used in the following analyses. The telescope and a muon event are shown in Figure 1.

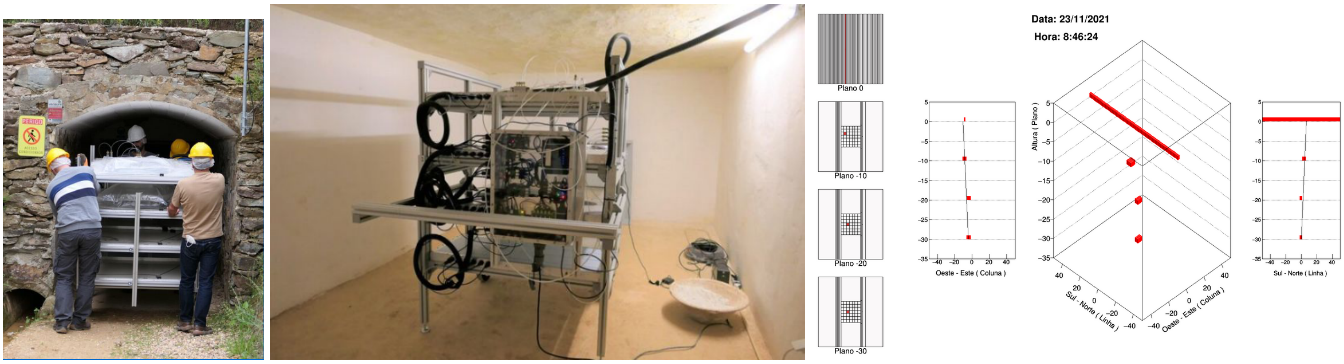

FIGURE 1: The LouMu telescope at the entrance of the Lousal mine gallery (left), and at its first data-taking position (center). Also, the photo shows a UPS used to protect the detector against frequent power cuts, and a preexisting pot of quicklime used to decrease the humidity in the old gunpowder storage room. The image to the right shows the online display of a muon event, exemplifying the reconstruction of a muon track from the lines and columns of the detection planes.

## 3. IMAGING THE FAULT

The telescope was first positioned in a storage room, at a point where it is crossed by the regional Corona fault [7]. Photogrammetry was used to characterize the surface, while a dedicated lidar campaign provided excellent position resolution inside the storage room and the surrounding gallery. Additionally, rock samples were collected horizontally along the gallery and vertically in the mine shaft. The unfractured rocks have densities of around 2.8 $g/cm^3$, while in the fault they had a density similar to what is found at the surface, 2.5 $g/cm^3$. Other geophysical methods used to complement muography are detailed in Section 4.

### 3.1. *Preliminary Muography Analysis*

The muon telescope configuration was set so that the planes were horizontal and separated vertically by 33.5 cm. The 0.3 m × 0.3 m central area with smaller pads from two adjacent planes projects the image on an area of 30 m × 30 m at (the reasonably flat) surface, 18 m above the focal point. The pixels in each plane have a 4.3 cm side, which scales to a pixelization of 2.3 m at the surface.

The first images of the fault were done using only the muon data, with no model dependence and exploring the pixelization of the detector. The muons were counted according to the pair of pads they went through in the top and middle plane, into a 13 × 13 directions map. The number of counts was corrected only for the detection efficiency of each pad. The muon count maps obtained show the rapidly falling pattern from the center (vertical direction, with higher open sky muon flux) to the periphery (inclined directions, with low open sky muon flux). Reference maps, representative of the muon flux distribution under a more homogeneous average overburden, were constructed from data alone, by reflecting the original one along the $xx$ and $yy$ axis.

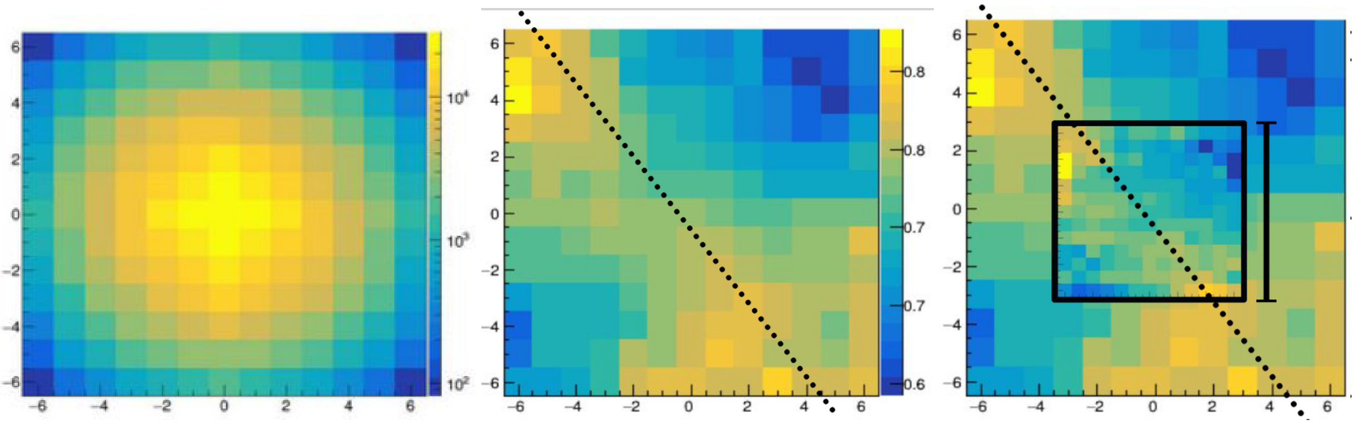

FIGURE 2: The image treatment, from the muon count map (left), after division by a symmetrized map (center), adding the higher resolution map (right, highlighted by the dark line). The dotted line highlights the direction of the fault. The coordinates are a distance in pixels, scaling like $L = Z \cdot \frac{4.3}{33.5}$, for different distances ($L$) at different depths ($Z$). Around 4 months of data were used to produce this figure.

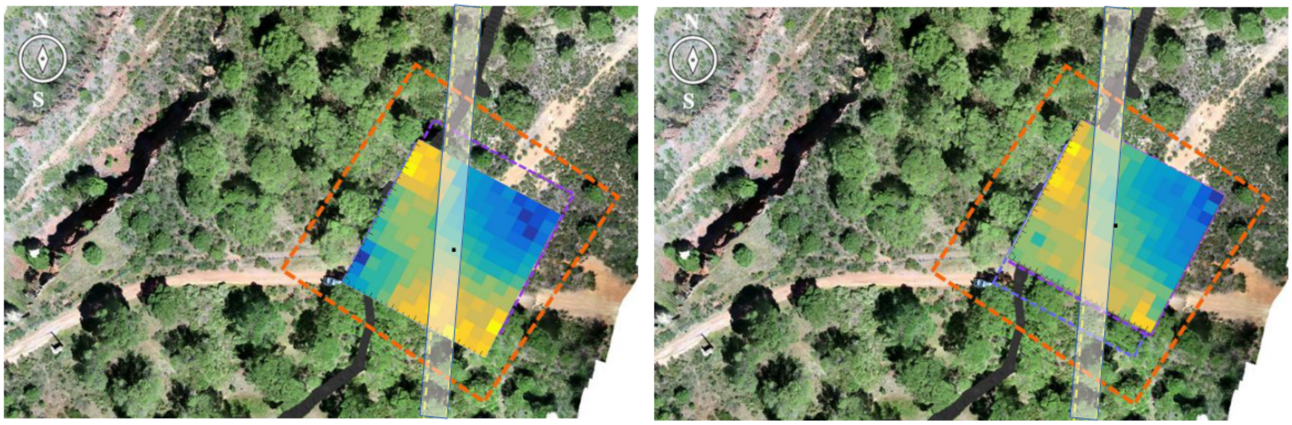

FIGURE 3: The two muographies over the local photogrammetry. On the left, the detector is located inside the fault; on the right, it is moved by 5 m to the front and 1 m to the side. The fault contour is shown as a band, with the expected 5 m width. The dashed regions show the area characterized by muography and different geophysical techniques.

Figure 2 shows the result of dividing the original data by this reference, highlighting an excess of counts following the general direction of the geological fault. Using instead the middle and lower planes leads to very similar results. Repeating the same procedure with the top and lower planes provides maps with higher resolution, which reinforce this pattern at the center of the field of view. Finally, the telescope was moved forward by 5 meter, and 1 meter to its right, such that it is outside the fault region, and images it from the side. The corresponding map is shown in Figure 3 overlaid with the photogrammetry of the area and the expected contour of the fault.

### 3.2. *Further Muography Analysis*

To advance from imaging to measuring, the contrasts in muon numbers need to be translated into crossed matter depth and then, given the distances to the surface, to rock density. In earlier studies in a building at the surface [8], an exponential dependency on crossed depth had been assumed and applied to a flux given simply by a $\cos^2\theta$ dependence, which is not applicable in this case. At Lousal, we tested a fast Monte Carlo model comparing it to both our symmetrized data reference for the flux and a full Geant4 simulation [9]. The model included the parameterization of the open-air flux as a function of muon energy and zenith angle from [10], which highlights that a similar energy threshold is needed for a muon to reach a detector underground shielded by a flat overburden of constant density. Muons with any possible energy and angle at the surface were sampled according to the geometrical acceptance of the detector and accepted only if their energy was above the given threshold as posed by the geology, given the constant energy loss characteristic of minimum ionizing particles. The maps were in good agreement with our symmetrized data maps and also with the full Geant4 simulation. The agreement with Geant4 was also checked in muon energy and angular distributions, allowing the conclusion that scattering effects are negligible in this case.

The model was then used for a preliminary translation to 2D vertical depth maps, in $\rho \cdot H\,[\mathrm{g/cm^2}]$ and rock density maps $\rho\,[\mathrm{g/cm^3}]$, from the measured muon counts. The first operation has highlighted the need to further correct small detector disuniformities that affect equally the muon counts in the top and bottom pixels, resulting in too low opacity. Correcting for the local topography highlighted even better the fault region but with a reduced relative contrast. In fact, the fault profile is also signaled at the surface, as a track of slightly lower altitude compared to the surrounding area.

At present, we are developing the use of iterative methods to provide a 3D density map starting from the original 2D maps at different positions and checking for their compatibility. The method is being tested in simulation before it is applied in data.

## 4. OTHER SURVEY METHODS

As hinted before, the photogrammetry information will be crucial to the full quantitative analyses of the Corona fault and is closely complemented with a millimetric lidar scan of the gallery and the direct measurement of the density of local rock samples. Furthermore, other data will be used for geophysical characterization of the inaccessible rock profiles between the gallery and the surface.

The geophysics team of the LouMu project has collected more data for this purpose, namely, localizing the borders between regions by analyzing different dielectric constants and the compactness and homogeneity of different rock layers through linear surveys with a ground penetrating radar and seismic refraction, respectively. Both methods found consistent results on unexpected anomalies, which seem to be correlated with secondary faults that can be extended from smaller ones identified in the mine geological map. The detailed geological analysis is ongoing.

More recently, the team conducted a new seismic refraction tomography survey. For this case, the signals are generated at the surface now in a larger grid, encompassing the area imaged by muography, and are recorded by geophones located next to the muon telescope and along the mine gallery, as illustrated in Figure 4. The goal is to obtain 3D data that can be directly compared with that coming from the combination of the muographies taken in two positions.

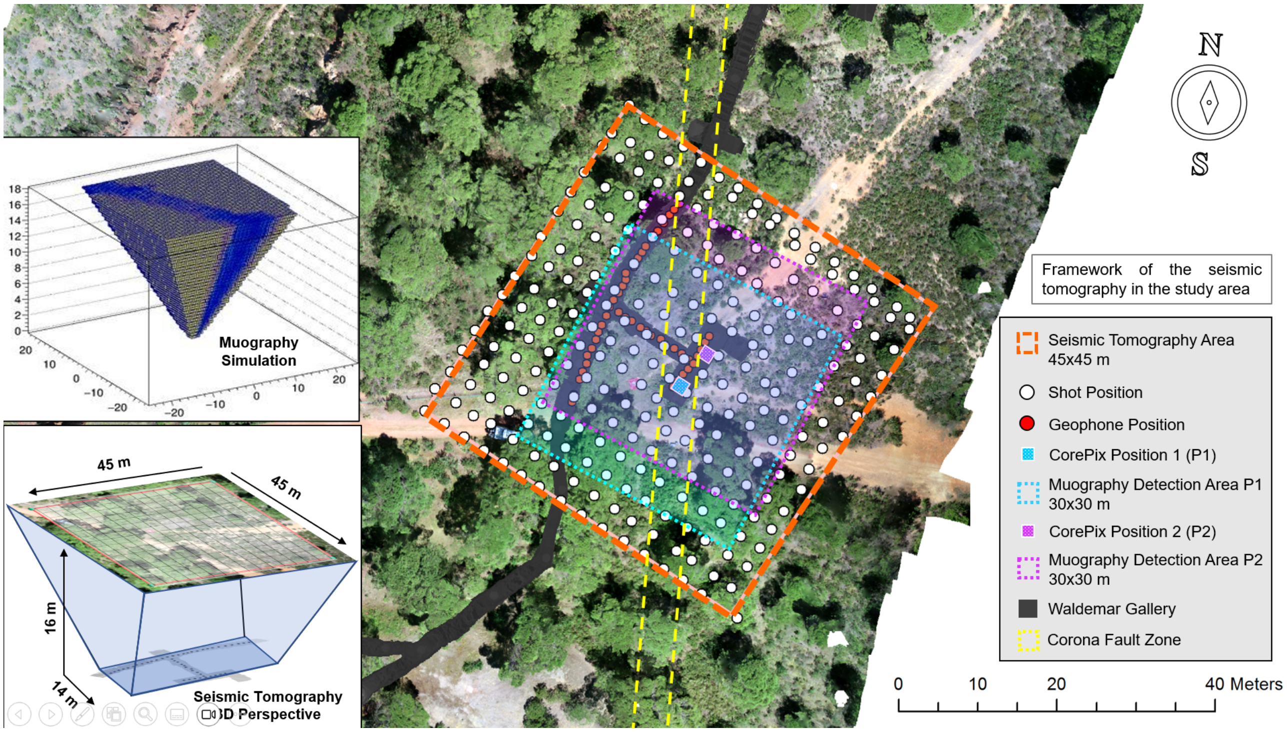

FIGURE 4: Left: simulated muon tomography (top) and expected volume for the seismic tomography (bottom). Right: projected areas on the surface covered by the different methods: signal grid for seismic tomography (white circles), geophone locations (red circles), the two muography positions (shaded areas), overlayed to the photogrammetry and the sketch of the mine gallery from lidar measurements (in black), the storage area is visible, with a blue square showing the first position of the muon telescope.

## 5. OUTLOOK

The LouMu telescope was operated for one year at the Lousal mine providing the first data for muographic analysis for geophysical survey. One of the main characteristics of operating in a mine is the constraints on gas handling, with only small degradation seen even when using 100 m long tubes. At the same time, the LIP RPC team conducted a standalone test of a sealed RPC (with no gas flux) in the lab, showing good results after one year[6]. We expect to avoid the complication on long tubes, by using sealed RPCs in future telescopes.

The regional Corona geological fault had been set as the first geological target at Lousal and was successfully imaged from two different positions. The methods for further quantitative analyses—and in particular, for the 3D density mapping of the rocks between the telescope and the surface—are being consolidated based on this large data sample.

Input from other geophysical methods indicates the probable presence of secondary faults to be measured. A first data analysis is done separately for muography and for the other surveys, for comparison of independent results. A seismic refraction tomography survey was recently performed to be used for a more direct cross-check of the 3D muon tomography results.

The final analysis will aim at combining all the data for the best results for the users at Lousal. The developed methods and conclusions from these comparisons and combinations are expected to be useful also for other muography users.

## CONFLICTS OF INTEREST

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

## ACKNOWLEDGMENTS

The LouMu project would not be possible without the support of the Mine of Science - Centro Ciência Viva do Lousal. LIP supported the first steps of the project with funding and human resources from several groups. The project is partially funded by FCT - Fundação para a Ciência e Tecnologia, Portugal, EXPL/FIS-OUT/1185/2021 and CERN/FIS-PAR/0012/2021.

## References

[1] LIP and LouMu Collaboration, "LouMu - Muon Tomography in Lousal Mine," https://pages.lip.pt/loumu, (2023).
[2] H. K. M. Tanaka et al., "Cosmic muon imaging of hidden seismic fault zones: Raineater permeation into the mechanical fracture zone in Itoigawa-Shizuoka Tectonic Line, Japan," Earth Planet. Science Letters, 306, 156 (2011).
[3] N. Lesparre et al., "3-D density imaging with muon flux measurements from underground galleries," Geop. J. Int. 208(3), 1579 (2017).
[4] D. Schouten et al., "Muon geotomography: selected case studies," Phil. Trans. R. Soc. A. 377, 0061 (2018).
[5] L. Lopes et al., "Outdoor field experience with autonomous RPC based stations," Journal of Instrumentation, Volume 11, September (2016).
[6] L. Lopes et al., "Outdoor systems performance and upgrade," NIMA 1054, 168446, September (2023).
[7] J. X. Matos et al., "Geophysical surveys in the Portuguese sector of the Iberian Pyrite Belt," Comunic. Gol. 107(III)41 (2020),
[8] M. Duarte et al., "Muon Tomography of the Physics Department of the University of Coimbra," proceedings of Muographers 2023.
[9] P. Teixeira et al., "Muography for Underground Geological Survey: ongoing application at the Lousal Mine (Portugal)," JAIS 2022 287, proceedings of Muographers 2021.
[10] L. Bogdanova et al., "Cosmic muon flux at shallow depths underground," Phys. Atom. Nucl. **69** 1293 v (2006).