Muography in the University and in the Museum

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,[1] João Costa,[4] Paolo Dobrilla,[2] Magda Duarte,[5] Luís Lopes,[2] João Matos,[6] Rui Oliveira,[3] Vanessa Pais,[4] Mário Pimenta,[1] Marco Pinto,[1] João Saraiva,[2] Raul Sarmento,[5] Jorge Francisco Silva,[2] Pedro Teixeira,[3] and Bernardo Tomé[1]

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

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

[3]*ICT - Instituto das Ciências da Terra, Departamento de Física, Universidade de Évora, R. Romão Ramalho 59, 7000-671 Évora, Portugal*

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

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

[6]*LNEG - Laboratório Nacional de Energia e Geologia, 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 team joins together specialists in particle detectors and in cosmic ray analyses, geophysicists and science communicators to muograph an underground gallery of an old mine, now open to visitors of a science museum. The muon telescope is made of Resistive Plate Chambers (RPCs) developed to operate stably and with low consumption at remote locations, and it has been tested in the Coimbra University, before being moved to an underground gallery in the Lousal Ciência Viva Science Center, in Portugal. In parallel to the scientific goals of surveying the geological faults around the gallery, comparing and combining the information from muography and other techniques, and testing and possibly upgrading these detectors for muography, the project aims to engage students at several levels and the public at large. The telescope was thought to operate in front of visitors, all the project phases will be documented, and the muographic data collected in the university building and the mine gallery will be made available for educational use. Providing an almost online update of simple and complex muographies is a challenge but provides an opportunity for a valued interaction of the public with our usually distant work.

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1. THE LOUMU PROJECT

The LouMu project [1] aims to test the usage of muography as a tool for subsurface geophysical survey, with a telescope made of low power and low gas consumption Resistive Plate Chambers (RPC) detectors. The test site is a 20 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 physics experts on RPCs and cosmic ray data analysis, geophysics, geology 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 for 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.

Since its start, the project has thus a strong focus on education, outreach, and science communication, aiming to engage students at several levels and the public at large. The telescope was thought to operate in front of visitors, all the project phases will be documented, and the muographic data collected will be made available for scientific and educational use. A smaller prototype, MiniMu, has been deployed at the mine to test the power and gas feeding and communications, and is now part of the usual visits to the Mine of Science; the larger telescope is installed in a movable and adjustable structure, and is at present under tests at the detector laboratory in Coimbra. It should be moved to the mine in 2022. The project webpage [1] includes information about the preparatory work, including surveys with other techniques, about the detector operation in Coimbra, and the expectations at Lousal.

FIGURE 1: The LouMu project flyer.

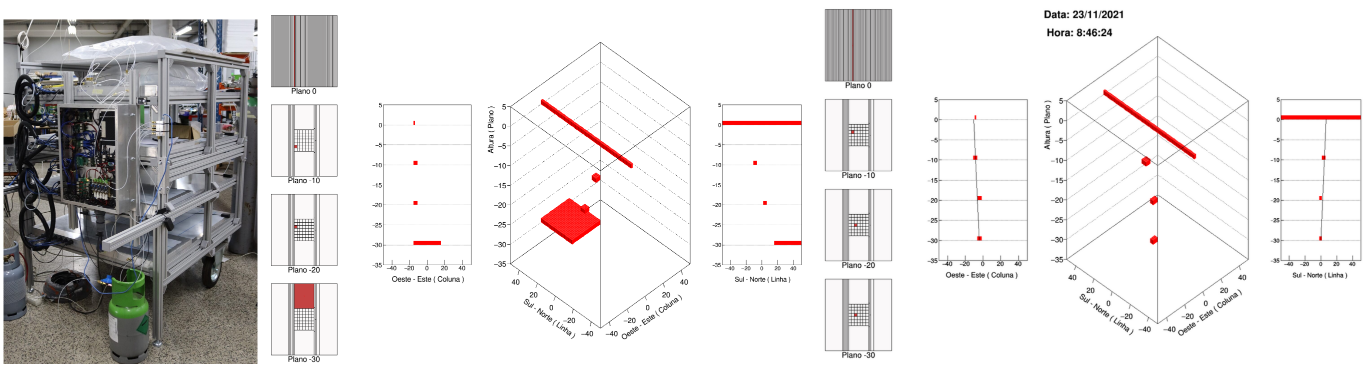


FIGURE 2: The LouMu detector at the laboratory (left), and two muon events, identified by the highest charge channels on each of the 4 planes (next two panels). The distribution of the 64 channels in each plane is shown on the left of the panel for each event. The right side shows how the lines and columns of the CorePix channels are used to reconstruct the muon trajectory in 3D.

2. THE LOUMU TELESCOPE AND FIRST DATA

The LouMu telescope consists of four 1m x 1m 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 during the R&D program, and the vertical distances between them can be adjusted to focus for 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. The main developments were done to minimize maintenance and consumption: they work with 4 c.c./min gas flow and are read out by low power front-end electronics (FEE) so that the full system can be fed by small solar powered stations and a single bottle per year of the gas R-134a (tetrafluorethane). These developments were done for the Pierre Auger Observatory, and after initial tests, a small engineering array is now being installed in Malargüe, Argentina [2, 3].

The RPCs of the LouMu telescope are slightly smaller than the original ones but have the same 64 channels per RPC plane. The telescope is triggered by a coincidence 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. The channels have now much finer granularity, as shown in Figure 2. One of the planes has 64 narrow width parallel strips, the others mix strips of varying widths, with large and small squared pads. The data acquired on these differently shaped pixels will be used to optimize the resolution for future muon telescopes using the same RPCs and FEEs. The central region of three of the planes, named CorePix, is occupied by 7×7 squares of 4 cm side, which provide simultaneous high resolution in two dimensions.

For the first tests, only the CorePix region is used for trigger and reconstruction. The passage of the muon is identified by the pad with the highest charge in each plane. The selected signals in the three planes are required to be compatible with a straight line. The differences between the positions of the pads in the top and bottom plane define simple 13×13 direction maps. With a typical separation of 67 cm, the vertical direction has a 3-degree aperture.

One of the first muographies obtained at the end of 2020 from the detector laboratory in Coimbra is shown in Figure 3(left), together with the representation of the viewing cone projected on the building façade and the observed region as seen at the top of

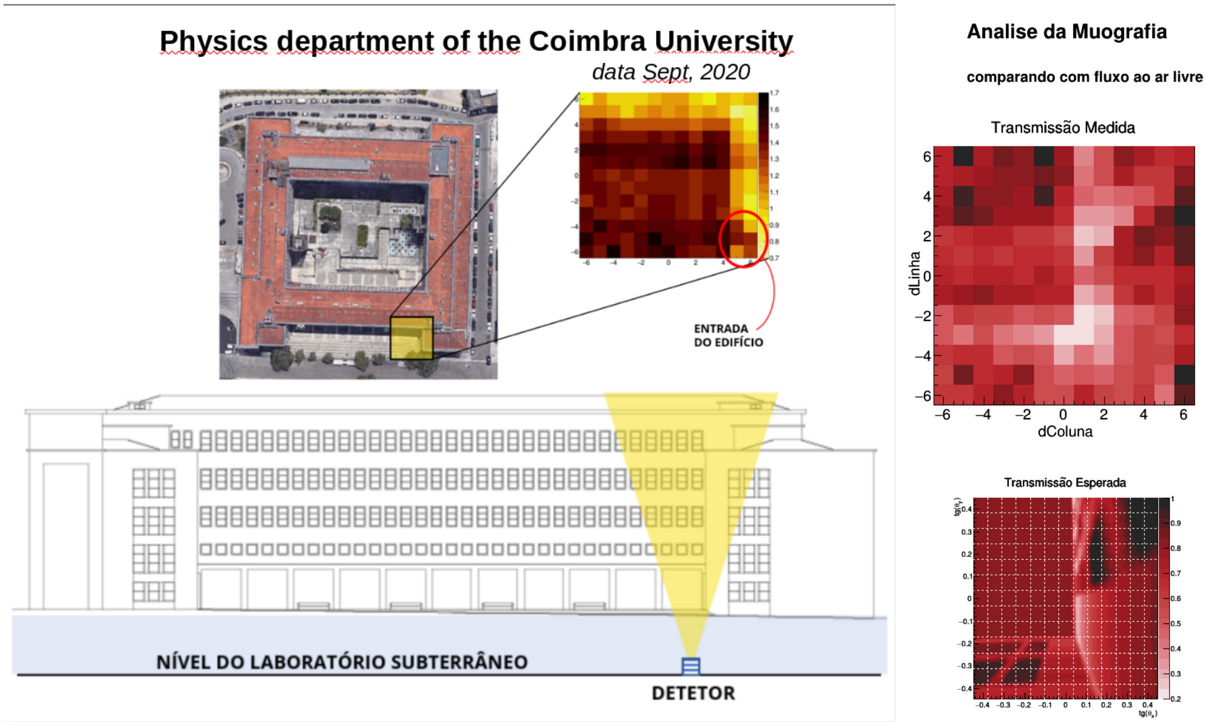


FIGURE 3: Two muographies taken at different locations in the Coimbra University building, in 2020 (left) and in 2021 (right). The left one is shown with a scheme of the part of the building that is being imaged, in early analyses. The right one shows the transmission image as it is being constructed, now compared to the one expected at a near location, with increased resolution.

the building. The muography is in this case obtained as a ratio of counts to that obtained from a more uniformly covered position in the lab, to avoid using the information on the muon flux and detector response. It shows that at the main entrance of the University buildings, there are less ceilings and walls. In fact, there is a Foucault Pendulum hanging from higher above the ground floor and the telescope is 4 meters below. The global height projected in this muograph is similar to the one that will be seen from the mine gallery, with a depth of $\sim$20 m.

3. IN THE UNIVERSITY

Muographing parts of the University building allowed for optimization of both the detector and the analysis chain leading to more final results. A large part of the tasks has been done in the framework of the LIP Internship Program, which receives undergraduate students from different universities for a few months each summer. Some of them have decided to continue working on the project afterward, increasing the team, and some have gained university prizes for early integration in research.

We have started by creating the muographs by ratios as shown in Figure 3(left) before the detector was fully optimized. Then, proceeded to calibrate the different channels, until achieving uniform vertical rates across the 49 pads. The ratio of vertical rates measured at different locations was used to derive the transmission per ceiling. This practical unit of crossed depth was checked to be compatible with previous measurements and predictions from the known materials.

For the small depths crossed inside the building, the transmission can be obtained as a product of an exponential attenuation over all the objects crossed. Parametric models for the open air flux, the geometry of the building, and the geometry of the detector were used to check the observations and evolved in complexity according to the needs. Particular attention was given to understanding the effects of the inner geometry of the RPC planes (the alignment between pads but also the separation of the two gaps, the pad effective side, etc.) on the detector efficiency. For the transmission, a model of far away ceilings and walls was sufficient for the first muographs; columns and beams were added to the building model as they appeared “by surprise” in other locations. These models were later used to predict the results of data taken from different positions while muographying the building.

There is a lot of work ahead and more complex analyses are ongoing, including the detailed analyses of the response of other channels for the use of the full RPC planes, combination of direction and position information in a single muography, combination of different muographies for a 3D reconstruction of local structures and the preparation of more sophisticated simulation and analyses tools that will be necessary for the underground mine gallery. However, the present simplified analyses are already sufficient to start using the real data for the education and outreach part of the project, which is the focus of this contribution.

During the National Science and Technology week, coinciding with the conference, the detector was placed to collect data at the entrance of the Coimbra University building. The event display shown in Figure 2(right) was run next to the detector. Muon maps were constructed in real time, and compared to the expectations calculated with much higher resolution for guidance, as in

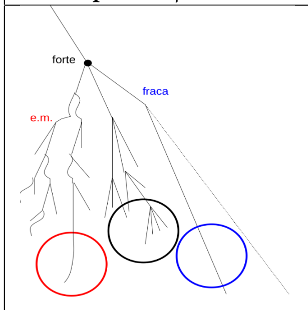
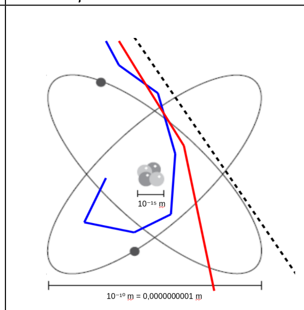
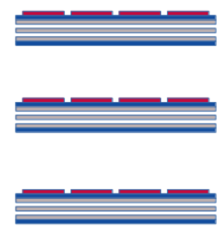
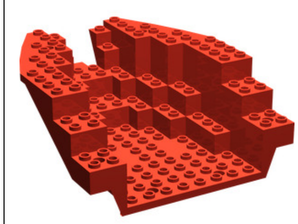
open air μ flux	**μ transmission**	**μ detection**	**muography**
			
Astrophysics	Particle Physics	Instrumentation	Imagiology
cosmic rays	**particle interaction**	**particle detection**	**other ways of seeing**
$\cos\theta$ dependence	$\exp(-\rho.\text{distance})$	ionization and electronics	image reconstruction
...	...	...	...

TABLE 1: The simulation and analysis steps and examples of their use in education and outreach.

Figure 3(right). Showing the data as it is being taken is thought of as outreach to the University students; the same information is also shared online, as is intended to happen during the next phases of the project. In addition to the challenge of showing the almost untreated data, there is the need to test the best ways of presenting the results at different levels of treatment to different audiences.

The data collected in the building will be used for developing tools for outreach, education, and advanced training. The muography analysis was from the start separated into steps that address different parts of the physics we are interested in for those purposes (see Table 1 for an illustration). This is easier to do for the building in which there is not so much material to be crossed and small details can be safely ignored when observing high contrast images with low resolution; undergraduate students can concentrate on the physics aspects. One of the challenges of the interpretation of the muon maps is their projective geometry, for which a layered structure in a building divided into several floors provides better insight. Adapting the data formats and analyses for use with high school level mathematics is the next logical step in its exploration for education activities. For younger students, as for the general public, a more visual approach is needed, and for that our model of ceilings, walls, columns, and beams can be easily turned into a game in which "Lego pieces" (even with different densities corresponding to their color, if needed) are added to reconstruct the muographed object.

The ideas outlined in the previous paragraph create the basis to develop an outreach program that could in the future be incorporated in the masterclasses for high school students promoted by the International Particle Physics Outreach Group (IPPOG). These are based on software that allows very visual analyses, generally dealing with fundamental particle physics. In addition to the general aim of engaging young students with the open challenges in fundamental physics, particle physics applications reach out to others, with the aim of reaching future users and supporters of sciences and technology R&D. The IPPOG masterclasses [4] already offer a program on proton-therapy, and muography is another promising subject.

4. IN THE MUSEUM

The Mine at Lousal [5] is part of a Science Centers' national network "Ciência Viva" [6], which incorporates more than 20 science museums. Many of these are devoted to specific subjects, of interest to the local community. Visitors are from organized high school trips, families, and tourists. The communication is done in both Portuguese and English.

The Lousal center originated from the requalification of a deactivated pyrite mine and its surroundings. At the surface, the old machinery was kept in a mining museum hall, and the old shower rooms were transformed in order to house small hands-on modules devoted to mining, geology, biology, chemistry, and physics. The environmental recovery of the acid water lakes is also shown in the visits. The deeper galleries of the mine were flooded, but the upper one was kept. The Mine of Science welcomes projects, namely (but not only), scientific ones, which make use of this 300 m long and 20 m deep gallery, with easy access and infrastructures. Presently, wine is kept to age underground in a closed room, while the next one houses one of the seismographers of the national network of the Portuguese Institute of the Sea and Atmosphere (IPMA).

A large poster at the main entrance of the Science Center describes the techniques of muography and in more detail the scientific project designed specifically for Lousal. The main goals of the project are to first test the muography technique by comparing its results against already existing records and with data acquired with more standard geophysical techniques and second to combine the new results to improve the knowledge about the site, to be shared with the scientific community and the Lousal Science Center. This poster, as other printed materials, has been developed with input from the education, communication, and outreach (ECO) group at LIP.

The project aims to create at Lousal a point of dissemination for muography, which can extend after the data taking campaign ends. It should be framed by the other existing exhibitions (e.g., a module on gravimetry) and eventually extend towards related

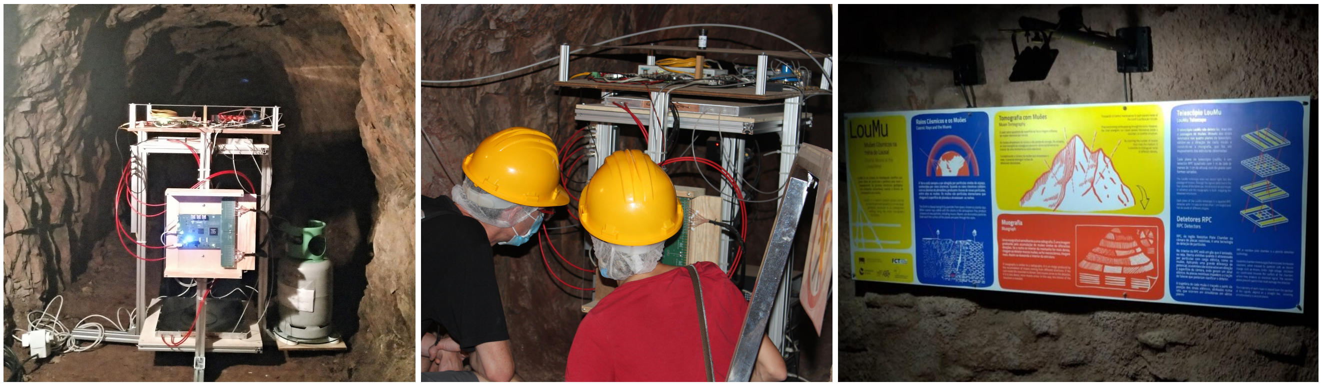


FIGURE 4: The prototype detector, before the gas system was moved outside the gallery (left) and, already in 2021, with visitors (center), and the accompanying poster inside the gallery (right).

FIGURE 5: Some aspects of the gallery, which may serve as targets for geophysical usage of muography, in the LouMu project.

subjects (like cosmic rays). A group of users, composed of school teachers and students, is now being gathered to work with the researchers and the science center members, to build new hands-on modules on muography for the permanent exhibition at Lousal.

A small prototype RPC muon telescope, the MiniMu, with much lower resolution and only two planes, has already been installed at the underground gallery for testing the logistics, namely, the installation and communication of the data to the laboratory. Special importance was given to the gas feeding and recovery, which is now done from and to outside the gallery, as required in a closed space open to visitors. Since its installation, the MiniMu has been working in front of the visitors, to whom the guides describe the project and the detector with the help of a dedicated poster, as shown in Figure 4. A few visits centered on the project have been organized, in which introductory talks focus on muography, particle detectors and the geophysical work done with other techniques for constructing the reference model of the gallery. Some of the inside and outside geological structures have been already included in the reference model for detailed simulation and geophysical analyses [7]. Other geological and geophysical surveys are still planned to improve on the details.

The larger muon telescope will be installed in 2022, and from then on the data taking will be followed by the visitors locally and shown and explained online, as before. The results will be more difficult to interpret than the ones in the building, and so a few high contrast and observable targets need to be defined. The points of interest inside the gallery include the vertical access shaft, a fault separating different geological species (for which the density can change with the phreatic levels), and regions of iron-rich minerals to contrast with lower density rock, creating a diversity of targets to muograph with different levels of precision (see Figure 5).

The use of the muographic data for education and outreach will need to be adapted to explore the more interdisciplinary side of muography. Visits to possible future users, namely, in the mining industry, are also planned. The description of the data and methods should be robust enough to be understandable by students of different courses and different kinds of visitors to the site, as well as for those following the results online. If the possibilities (and limitations) of muography are clear enough, they can even propose applications we had not foreseen before.

5. OUTLOOK

The LouMu project has defined science communication as one of its main goals from the start. The project is designed to test the application of muography for a geophysical survey of an underground gallery of a Science Center, so that data taking is done in front of visitors, to whom also the detector techniques and the first analyses should be conveyed. The final results will be shared with the scientific community but also the Science Center and the general public.

Muography is a great tool for science communication and outreach, with the inherent interdisciplinary of many of its applications, in the case of LouMu for geosciences, and can be easily explored for engagement on particle physics. Being an imaging technique makes it especially easy to first show and then explain to students and the general public the related science and technology. Using a natural radiation produced by cosmic rays, it bridges to astrophysics and cosmology; by exploring the attenuation in matter, it bridges to our underground laboratories dedicated to rare event searches, including neutrino observatories.

The preparation and optimization of the detector at the laboratory, located in an underground level of the university, are done in parallel with the development of simple analysis techniques designed to be easily understandable by students at all levels, while they allow the team to gain insight on the muography techniques and prepare for more complex analyses needed for geophysical survey. At this point, we concentrate on imaging simple structures of a building, which can also be directly seen and easily recognized. The goal is to make muography understandable by all: if school children can understand it, then also possible end users will.

The muon telescope will be moved to an underground mine gallery in 2022. That operation was preceded by the deployment of a smaller prototype that already attracts the interest of the many visitors to the Lousal Ciência Viva Science Center. The project intends to do open science and R&D, working in a public setting and communicating the practical issues, partial results, and end results to an enlarged community. The mine serves as an ideal test case for muographic geophysical survey, testing its possibilities and limitations, and continuing R&D on autonomous RPC-based muon telescopes.

Communication is a fundamental piece to make muography a more standard tool, and we contribute by putting together an interdisciplinary scientific team with a group of experts in science education and outreach, which can make its possibilities and limitations in different settings clear.

CONFLICTS OF INTEREST

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

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