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Muographying the City

Carolina Sobral[1,a] and Henrique Cunha[1,b]

[1] *Universidade do Minho, Braga, Portugal*

Project supervisors: R. Sarmento, S. Andringa, M. Duarte

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Abstract. A muography simulation was developed to study the subterranean environment of Lisbon, given the opportunity to perform muographic measurements opened by the construction of a drainage tunnel. The simulation accounts for the various underground passages and material densities of the subterranean layers and it is executed computationally, utilizing the ROOT programming framework along with its graphical tools. Despite the simulation being confined to one dimension, and not precisely representing real material densities, it yielded an approximate one dimensional reconstruction. Moreover, it provided valuable insights into the time required by the detector to produce accurate results in specific locations. This project was carried out during the summer internship at the Minho's LIP Pole.

KEYWORDS: Muography, Simulation, Density, Sensitivity

1 Introduction

Our universe is replete with an abundance of high energy cosmic rays and every second the Earth is bombarded by these. Upon colliding with our atmosphere, they initiate a sequence of reactions, yielding various subatomic particles, including muons.

The muon stands as one of the fundamental subatomic particles, closely resembling electrons but distinguished by their substantial mass, which exceeds that of electrons by over 207 times. Muons carry an electric charge of $1e^-$ and possess a spin of $1/2$. These subatomic particles exhibit inherent instability, and only exist for a mere $2.2\,\mu s$ before they decay into an electron and two distinct types of neutrinos. However they reach our detector due to the relativistic phenomenon of time dilation. Muons hit every square meter of Earth's surface, and are capable of penetrating nearly any material.[**?**]

1.1 Muography

This project employed a technique known as muography. Muography entails the placement of a detector beneath or alongside a structure to identify muons, either through electronic or chemical means, as they cross it. This process yields a projection of a target volume, in our case the subterranean landscape beneath Lisbon's city.

Utilizing these detectors - that will be presented later - we acquire the trajectories of muons. Despite the fact that muons hit every square meter of Earth's surface and are capable of penetrating nearly any material, some decay when traversing extended paths within high-density matter. As a result a higher number of muons will reach the detector if they approach from a path where they need to pass through less matter as opposed to a trajectory where it travels through more. Consequently, from directions where more muons are detected we can obtain clear models more rapidly.

It is important to clarify how beneficial muographying a city is. By doing this we can discover new information about the city's underground that might be important to prevent disasters, for example. Consequently, this method can give us access to new information, that might be useful also for various branches of studies (geology, archeology, civil engineering, etc). A very important point to note is that this technique does not damage the city neither the people because we are just detecting natural events. The goal of this project was to simulate the use of the muography technique to explore Lisbon. [**?**]

1.2 Lisbon and the Tunnel

This project originated from the vision of the Lisbon Municipal Council to construct an underground tunnel beneath the city, to facilitate efficient rainwater drainage during the months of increased precipitation.

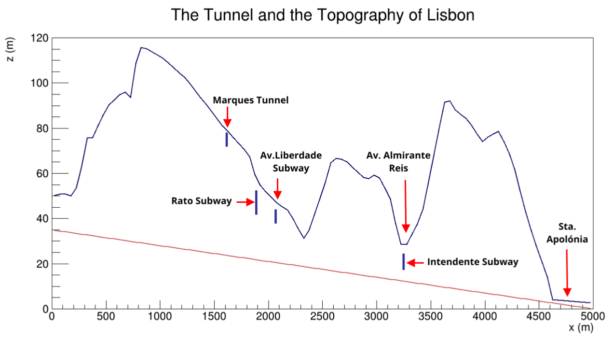


Figure 1: The topographical representation of the city of Lisbon, highlighting the tunnel in red, the four underground passages and significant landmarks.[**?**]

The objective is to place a detector inside this underground tunnel, aiming to perform a soil analysis in the space above it. Several critical factors necessitated consideration:

[a] e-mail: a97116@alunos.uminho.pt
[b] e-mail: a97038@alunos.uminho.pt

- Every location within the city presented a unique composition of materials, comprising either a singular or multiple rock formations characterized by varying densities.
- The tunnel goes underneath four existing underground passages, including three for subways and one called the Marquês Tunnel, which is used by cars.
- Given Lisbon's densely populated urban center, careful attention was directed towards numerous architectural structures, each distinguished by its distinct dimensions.

1.3 The detector

The muon detector simulated possesses two parallel plates separated by a variable distance. Each plate holds the same distribution of pads and when a pad from the upper plate is activated followed by another pad from the lower plate, we detect a muon as well as its direction.

In our simulation we are only going to consider two directions (length and height) since the width of the tunnel is very small when compared with its length. Our plates will be 7x1 even though the code works for a different number of pads in the detector. Besides, in this simulation, each pad is a square with 4.3 cm each side and initially we work with a distance of 33.5 cm between plates. In figure 2 we can see a schematic representation of our detector. As we can see, the muon arrives from above, activates a blue dot from the upper plate (i.e. the pad detects it through physical processes as it crosses) and then it activates another blue dot from the lower one.

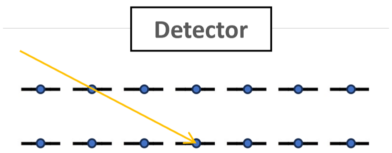


Figure 2: Schematic representation of the detector used in our simulation as well as a muon detection example. It is not to scale.

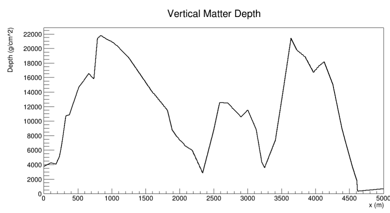
2 Data

The energy distribution of atmospheric muons is stable over the entire surface [?] and these particles lose energy at a constant rate as they pass through matter. From these we acquire the information needed. For simplicity we are going to start considering only vertical muons. In addition we are assuming Lisbon's underground to have constant density.

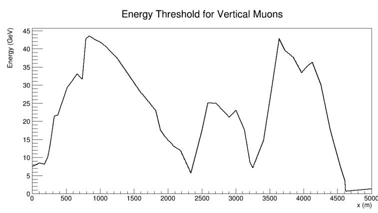
2.1 Matter Depth and Energy Threshold

The first information we obtain is the depth of matter seen by the muon. This is accomplished by multiplying the distance that the muon crossed by the corresponding density. From the topography of Lisbon (with corresponding densities) and considering the subways (and other known information) we are able to predict the matter depth. The product between the constant rate of muons loss of energy (using $2.0 \times 10^{-3}\, GeV/(g/cm^2)$) and the overall matter depth give us the energy threshold, i.e. the minimum energy that the muon needs to possess to arrive into the detector. As stated before we know the energy distribution at surface and now also the minimum energy which the muons need to have. Therefore, integrating the energy distribution from the energy threshold to infinity we obtain, from all the muons, the fraction that will reach the detector.

However, the information the detector will obtain is only the number of muons that pass through the pads. From that muon count acknowledgment we do the inverse process into the matter depth. Comparing our predicted results with matter depth obtained we are able to study the city. Figure 3 represents this information.



(a)



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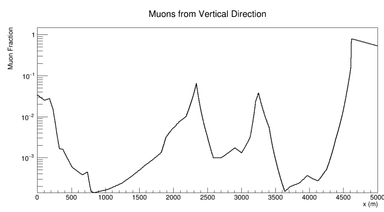


(c)

Figure 3: Matter depth (a), energy threshold (b) and muons fraction (c) graphs of Lisbon considering only vertical muons.

2.2 The Four Underground Passages

As mentioned previously, the tunnel's construction will occur beneath four preexisting underground passages, and when muons traverse such areas, they tend to continue along their trajectory without undergoing significant interactions. Consequently, when estimating the depth of matter in these regions, the findings will differ from those presented in figure 3(a), with specific variations occurring at the precise locations of the four underground passages.

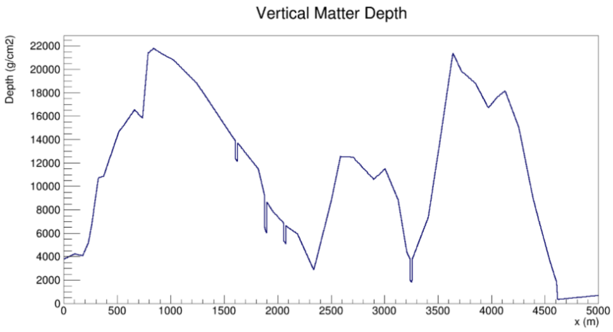


Figure 4: Vertical matter depth, taking into account the presence of the four underground passages while assuming constant density for the soil.

When we perform identical calculations for the graph displayed in figure 3(c), we now observe varying muon counts across the four passages locations. This differences suggests that when there are an excess of muons, there will be regions with the absence of substantial matter above the detector,which can be discerned through muography.

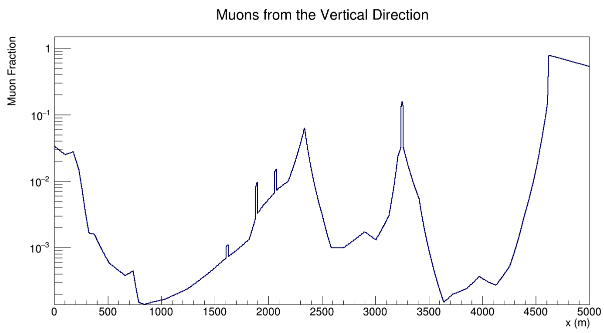


Figure 5: The fraction of vertical muons that reach the detector when assuming a constant density for the soil and the four underground subways.

When using the detector in these areas, it's important to be aware that the readings from the detector may not provide a completely accurate picture of the city's underground environment because there is a lack of significant material within these tunnel areas.

2.3 Incorporating Layers with Different Densities

It's important to mention that when we created the graph showing the depth of materials underground, we initially used a fixed value for material density, which was $2.7\, g/cm^2$. However, we acknowledge the presence of diverse density layers within the soil[**?**]. The subsequent step involved dividing the underground space into distinct sections, considering all the different layers that we were

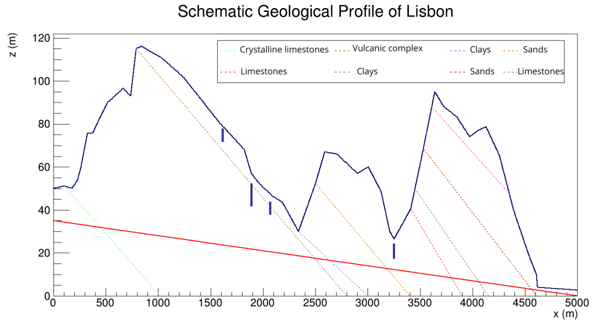


Figure 6: A schematic geological profile of the city of Lisbon, delineating the presence of eight distinct layers with varying material densities.

aware of. Then, we devised a function that takes into account the density value in each position.

As a consequence, we have discerned areas where the detector can yield more rapid and accurate results, as a larger number of muons can reach the detector in a shorter amount of time. In regions composed of sand, characterized by a lower density, muons undergo less energy loss. Conversely, in clay-rich areas with greater density, a considerably higher rate of muon decay is observed.

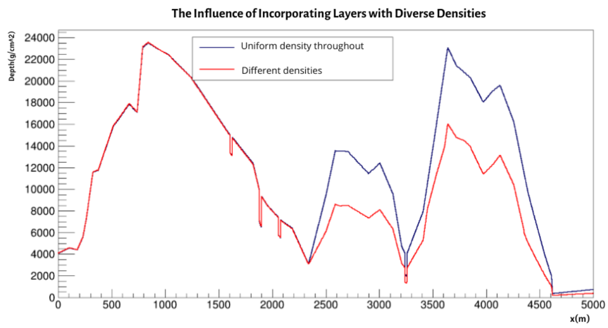


Figure 7: Matter Depth of vertical muons for two cases: the blue one assumes uniform density throughout the area, while the red one considers multiple layers.

An example that illustrates the impact of this code change is in the vicinity of $x = 3250\, m$, precisely where the Intendente's Subway is located. In this particular region, muons encounter relatively less material to traverse due to the tunnel's proximity to the surface. The presence of the subway also results in the removal of some material. With the incorporation of the various layers, we have now identified an area predominantly comprised of the material "areolas". It's worth noting that this material is significantly less dense than the material we were initially utilizing. The number of muons, taking into account the new material, has increased by a factor of eight compared to the previous conditions, as shown in Table 1.

Consequently, in regions like this one, the time required to obtain results from the detector will be significantly shorter than our initial expectations.

x = 3250m	Number of Muons
Surface	106156
Matter with constant density	3287
Matter with different densities(without tunnel)	8293
Matter with different densities(with tunnel)	27518

Table 1: Vertical Muon Counts in Various Scenarios in the Intendente Subway

3 Muons from generalized directions

We have been only considering muons form vertical direction, nevertheless they do not restrictly come from there. Therefore we need to treat muons in a generalized way considering all the possible directions. For a detector with n pads there are a total of $2n - 1$ directions. In figure 2 we can visualize an example of a muon direction in a 7-pad detector.

In figure 8 we can visualize where the muons we detect come from, for a 7-pads detector, in position $x = 1615.80\,m$. That same figure makes it clear that muons from different directions pass through different densities as well as different distances which means distinct energy threshold. Besides, there is a subway in this example thus some muons pass through it while others do not.

In order to accomplish this objective we used a code strategy that works with a sum of small hypotenuses. We traverse all the path of muons considering very small distances of x (horizontal direction) and the small height they moved, y (vertical direction). With that we obtain the small hypotenuse the muon traveled and with an auxiliary density function we know the density it passed. To this end we sum all those values. In order that each distance is very small, the method has a precision much higher than the simulation data (topography, subways and layers) used. Thus it is very efficient for this case.

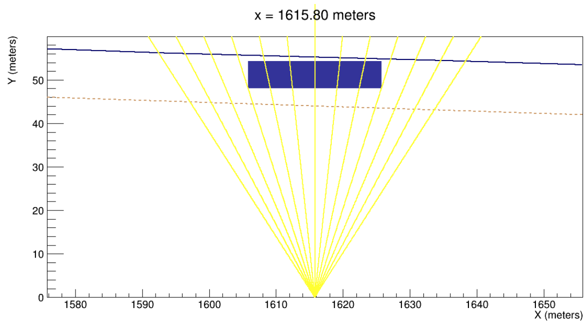


Figure 8: Paths that muons travel into a 7-pad detector at $1615.80\,m$.

3.1 Detection of the Four Underground Passages

With the ability to identify the origins of all 13 muon directions, we were able to conduct a more precise examination of the tunnels. For instance, let us consider the Intendente Subway. After just 12 hours of study, our detector provided valuable insights, and indicated that there was a void of matter along the muons' path. This insight is evident in figure 9, where the detector recorded 13 red points slightly below the dark blue line, representing the city's true elevation.

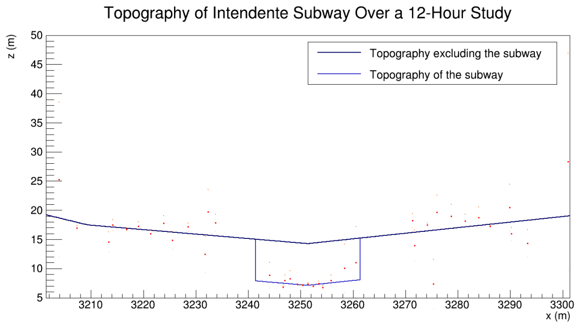


Figure 9: Reconstruction of the Intendente Subway, featuring 13 red dots corresponding to the detector's 13 directions.

We carried out similar assessments for all four underground passages. Given that the Intendente Subway has the least obstructing material to traverse, it yielded results more quickly. For Av. Liberdade Subway, approximately 15 days were required to obtain a clear image confirming the tunnel's presence. Rato's Subway demanded around 20 days of study, and finally, for the tunnel with the longest distance to cover and the highest density of material, the Marquês Tunnel, it took us 30 days to detect a noticeable deviation in the image. However, this detection was not as pronounced as what we observed in the Intendente Subway, as shown in Figure 10.

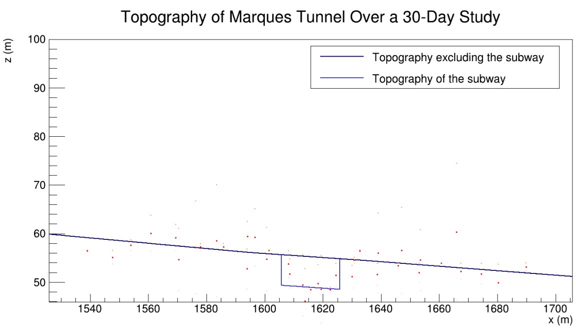


Figure 10: Reconstruction of the Marquês Tunnel, featuring 13 red dots corresponding to the detector's 13 directions.

We had intended to conduct an analysis to calculate the precise number of days required to definitively confirm the presence of these tunnels.

3.2 External matter

The simulation have been only considering the topography of the city as well as its underground passages, however there is exterior matter that will be certainly detected. As a result, data will be deviated from the prediction being the buildings the most responsible for that since they are the most common exterior matter in Lisbon. Even though, depending on the disparity of those values, we might be detecting known materials such as those buildings or we might obtain some new and useful information about the city.

As we mentioned before our detector only counts the number of muons that arrived as well as its directions and from that we know its energies threshold. Previously, we could know the expected values and for this reason we can verify and quantify the deviation obtained. We are going to use an example.

Consider that we place the detector on position $x = 3263\,m$. Some muons will indeed pass through the subway. However, imagine that in real life we have a three-story building that we do not know about. In figure 11 we illustrate this situation where the brown rectangles represent the construction materials that contain the floors, the blue rectangle is the subway and the yellow lines are the different directions the muons reach the detector. We can see that the three leftmost muons are the only ones that pass through the building and as further to the left the more it impacts. However, we are not considering this building so we would predict lower energies threshold for those three directions.

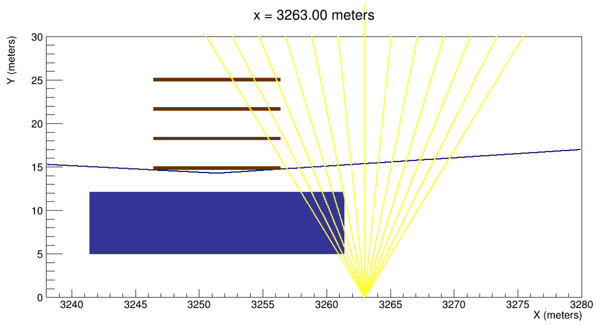
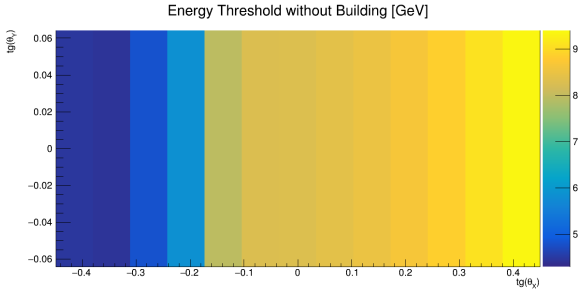
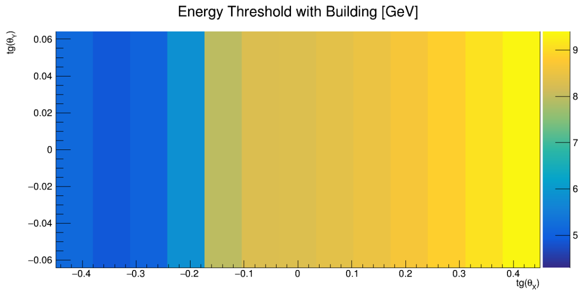


Figure 11: Example of a 3-floor building placed near $x = 3263\,m$.

In figure 12 we can see the energy threshold expected (without the building) and the energy threshold obtained (with the building). From these we verify that the data for every muon matches except for the three bins at the left, for which the energy threshold is increased.. Consequently, a difference is detected and we can even quantify this deviation, indeed, it can be easily done later. From that value we will be able to analyse if it corresponds to an anomaly or not.



(a)



(b)

Figure 12: Energy threshold without (a) and with (b) the building.

4 Data Study Strategies

4.1 Sensitivity

To calculate the precise number of days required to achieve a clear image from the detector of the subway, we employed the following formula:

$$\sigma = \frac{\mu(z) - \mu(z - dz)}{\sqrt{\mu(z)}}$$

The variable $\mu(z)$ represents the total number of muons arriving at the detector when considering the existence of the subway, while $\mu(z - dz)$ represents the same value but without taking the subway into account.

We conducted this calculation repeatedly over varying time periods, consistently producing varying muon counts. This level of statistical significance gives us assurance that the observed effect is genuine and not merely a consequence of statistical uncertainties.

We are presenting our results for only two cases, as they represent the most distinct scenarios among the studied cases. In the case of the Intendente Subway, we achieved a σ value of 5 merely with 0.10 days, which equates to approximately 2.4 hours of data acquisition. Consequently, we conclude that the 12-hour duration, in the graph above, in figure 9, was not necessary for obtaining reliable results.

In contrast, for the Marquês Tunnel, where we initially allocated 30 days of study and did not secure optimal results, we now understand that a more extensive period of approximately 75 days is necessary to thoroughly investigate the subway.

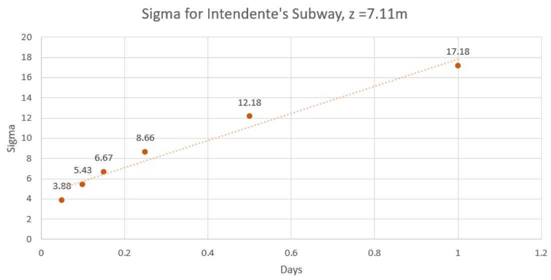


Figure 13: σ values within the context of Intendente's Subway and its linear curve.

Intendente's Subway	σ
1 day	17.18
12 hours	12.18
6 hours	8.65
3.6 hours	6.67
2.4 hours	5.42
1.12 hours	3.88

Table 2: Table containing the calculated values of σ for Intendente's Subway.

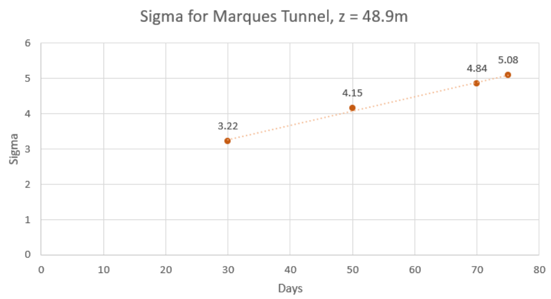


Figure 14: σ values within the context of Marquês Tunnel and its linear curve.

Marquês' Tunnel	σ
75 days	5.08
70 days	4.84
50 days	4.15
30 days	3.22

Table 3: Table containing the calculated values of σ for Marquês Tunnel.

5 Conclusions

From our results we can notice that in some places we will be able to obtain a clear profile in some hours, while in others we would require more than a month. As a result we will need to adjust the detection time in each place according to the total time available for it. Depending on that

it is also important to list priorities according to position relevance for detection.

It's crucial to acknowledge that Lisbon is a city rich in buildings, therefore it is imperative that we consider and account for this diversity in the future detector usage and analysis. As we verified, those building will have an impact in the data obtained. When acquiring the information we can estimate a deviation *a priori* or we can simply calculate the mean deviation over the entire tunnel *a posteriori* and that will certainly be a good approximation. This acknowledgment is very important so that we can be able to detect anomalies.

A next step for the simulation would be to consider more than just one direction of detection, i.e. consider that muons do not only come from the plane perpendicular to the tunnel but also from all around. This expansion in dimensions will enable us to capture a more comprehensive view of the data, as our current approach is limited to one-dimensional data analysis.

Acknowledgements

We are thankful to LIP for the opportunity to work in this project. This experience enabled us to know such a prodigious technique as muography is and it caused us to know more about the physics behind elementary particles. We would like to thank our supervisors Raul Sarmento, Sofia Andringa and Magda Duarte for their time and effort with us.

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