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Journal of Physics: Conference Series **718** (2016) 052016 doi:10.1088/1742-6596/718/5/052016

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Abstract. Muon tomography is a potential non-invasive technique for internal structure scanning. It has already interesting applications in geophysics and can be used for archaeological purposes. Muon tomography is based on the measurement of the muon flux after crossing the structure studied. Differences on the mean density of these structures imply differences on the detected muon rate for a given direction. Based on this principle, Monte Carlo simulations represent a useful tool to provide a model of the expected muon rate and angular distribution depending on the composition of the studied object, being useful to estimate the expected detected muons and to better understand the experimental results. These simulations are mainly dependent on the geometry and composition of the studied object and on the modelling of the initial muon flux at surface.

In this work, the potential of muon tomography in archaeology is presented and evaluated with Monte Carlo simulations by estimating the differences on the muon rate due to the presence of internal structures and its composition. The influence of the chosen muon model at surface in terms of energy and angular distributions in the final result has been also studied.

1. Introduction

Among the different applications that muon tomography can have, the scanning of archaeological structures is one of the most innovative one. The principle of the method is straightforward. By detecting the muons that cross the studied object and reconstructing their directions, it is possible to identify the existence of significant differences in the muon rate for a given direction. These differences, consequence of a variation of the mean density of the object traversed by the muons, indicate the possible existence of an internal structure inside the object. The reconstruction of these internal structures by the analysis of the directions of the registered muons is frequently called inverse method.

Some features of muon tomography are specially interesting for archaeology. It is a passive method since it is based on the detection of the atmospheric muons, which are naturally produced. Moreover, it is a non-invasive technique since the detector would be placed outside the object to study or, if possible, inside it if internal corridors and halls already exist, as is the case of several archaeological monuments. In any case, no disruption of the archaeological monument is needed.

Potential candidates to be studied by muon tomography are the so-called tumuli. They are man-made hills grown to cover one or more tombs and burial structures, that can be located at ground level or inside the hill. They usually also contain corridors driving to their interior. Other non-invasive techniques, such as seismic tomography (ST) or electrical resistivity tomography (ERT), have been already used to study several of these tumuli [1]. Muon tomography can represent a complementary method to develop alone or together with other techniques as ST or ERT, to improve the results of the tumuli scanning.

The aim of this work is to perform a first evaluation of the muon tomography capabilities as scanning method for archaeological structures. In this case, the study is particularly focused on the described tumuli. To do that, different simulations have been performed taking into account two relevant issues: the parametrization of the muon flux at Earth's surface, and the particular geometry of the tumuli and the position of the internal structures inside them. The dependence of the muon rate variation on these factors has been taken into account for this evaluation.

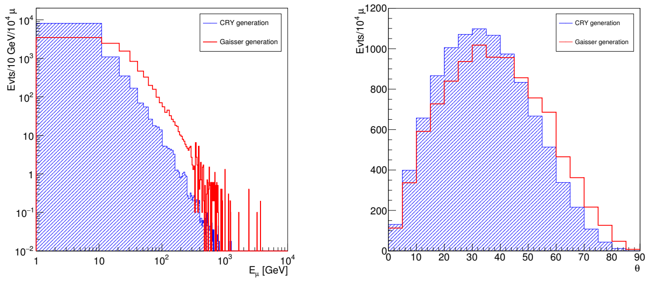
2. Simulation definition

Monte Carlo simulations have been performed developing a framework which implements the MUSIC software [2]. This FORTRAN - based code allows the 3-D transport of muons through the matter simulation taking into account the energy loss due to four main processes: ionization, pair production, bremmstrahlung and inelastic scattering. Information about the energy loss, angular deviation and lateral displacement is provided as output. Two main set of information should be supplied for the simulation performance: the geometry and composition of the studied object and the initial muon distribution in terms of energy and incident angles.

There exist tumuli with a wide range of dimensions, although rarely exceeding two hundreds metres diameter in the basis and few tenths of metres height. The tumulus model generated for this study is based on the Kastas Amfipoli Macedonian Tumulus [3]. Its dimensions are described in Figure 2. Different compositions have been considered for the tumulus and the structures inside it: standard rock, standard soil (based on [4]) and $CaCO_3$ (as marble main component). These three materials will provide the required information for the particular cases evaluated in the study.

Due to the dimensions of the tumulus, high energy muons will cross the object independently of its composition, so no muon detection rate difference will be induced by them. On the contrary, low energy muons (with energies below $\sim$110 GeV) have more probability of being stopped while they traverse the tumulus, being the most important for the muon tomography study. It is for low energy muons that muon parametrizations present bigger disagreements. To evaluate the influence of the muon parametrizaton considered, all the simulations of the study have been performed using two different models: an extension of the Gaisser parametrization [5] adequate for the simulation of low energy muons and the whole zenith angle range (as described in [6]), and a muon sample generated by the CRY software [7, 8], which generates muons based on the data tables coming from full MCNPX [9] muon simulation. Differences between both parametrizations for the energy and incident angle distributions can be observed in Figure 1.

With these features, two main scenarios have been defined for the simulations to study the differences in the muon rate after crossing the tumulus (see Figure 2). In the first one the detector is placed besides the tumulus with a marble box of $2 \times 2 \times 2\ m^3$ simulating a tomb at the centre of the tumulus (labelled as *Side Detector*). In the second case, the detector is placed at the centre of the tumulus basis, using an eventual corridor (labelled as *Centred Detector*), with the marble box with a relative zenith angle of 0° and 45°. For all the cases the tumulus is considered to be an homogeneous standard soil object.



(a) (b)

Figure 1: Muon energy (a) and angular (b) distributions at surface provided by the two models used in this study: the Gaisser parametrization and CRY muon generation software.

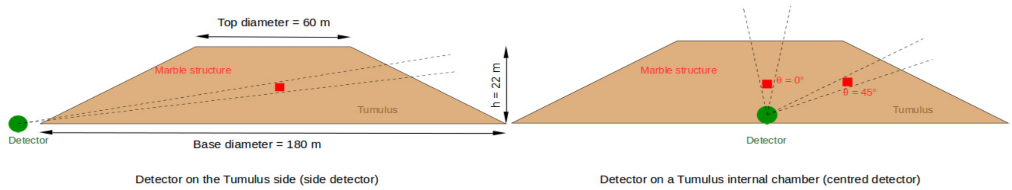


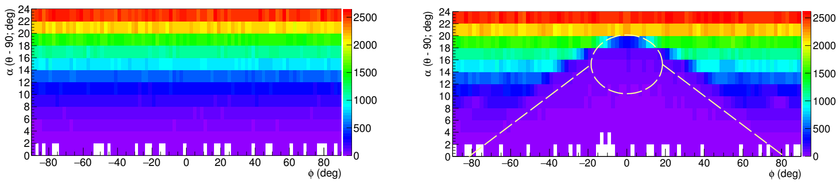
Figure 2: Schema of the different scenarios considered for the study, indicating the dimension of the tumulus and the position of the detector and the marble structure inside the tumulus.

3. Simulation results: variation on the detected muon rate

For each detector position (previously defined as *Centred Detector* and *Side Detector*) the propagation of muons through the tumulus has been done considering the three main elements mentioned in Section 2. For all the performed simulations is possible to evaluate the muon rate and angular distribution that reach the detector after crossing the tumulus. The reconstruction of the angular distributions allows the identification of the tumulus shape if compared with the same distribution at open air, as showed in Figure 3 for the *Side Detector* case. To evaluate the difference on the detected muon rate, two values are extracted from the simulations: the detection probability, defined as the percentage of detected muons with respect to the initial generated events, and the comparison of this probability with the case of standard soil, defined as normalization to soil (δ_{Soil}). The obtained values for these parameters in the different simulations are presented in Table 1. Based on these parameters, it is possible to estimate the difference on the expected muon rate (δR_μ) due to the presence of an internal marble structure (with length $L_{Tumulus}$) placed along the full muon path across the tumulus (L_{Marble}), using Equation 1:

$$\delta R_\mu = \frac{L_{Marble}}{L_{Tumulus}}(1 - \delta_{Soil}) \tag{1}$$

However, the difference of detected muons per day due to the existence of an internal structure ($\delta\mu$), is the magnitude which allows to evaluate the potential of this technique to identify its presence. This value is obtained by multiplying the muon rate difference by the expected muon flux for the studied direction. It is for the estimation of this muon flux that the muon model at surface chosen is most important, since for different models, the muon flux for a given direction could vary significantly. Table 2 shows the differences of the muons detected per day for the different cases studied, together with the other parameters required to estimate it.



(a) (b)

Figure 3: Density plot of the angular distribution of the muons detected at Earth's surface: a) at open air, that means, without the presence of any object in front of the detector. b) With the detector placed behind a homogeneous tumulus with the dimensions used for this study. Dashed yellow lines indicates the tumulus contour.

Table 1: Summary of the two evaluated parameters (detection probability and δ_{Soil}) for all the simulated configurations (see text for details). Performed simulations have enough statistic to consider the corresponding errors as negligible.

		Side Detector		Centred Detector	
		Detection Probability (%)	Normalization to Soil (δ_{Soil})	Detection Probablitiy (%)	Normalization to Soil (δ_{Soil})
CRY	Standard Soil	59.87	1	94.28	1
	Standard Rock	37.50	0.63	65.97	0.70
	$CaCO_3$	35.40	0.59	61.11	0.65
Gaisser	Standard Soil	97.74	1	97.77	1
	Standard Rock	81.10	0.83	77.35	0.79
	$CaCO_3$	78.20	0.80	72.64	0.74

Results present the relative position between the detector and the internal structure as the most influential parameter on δ_{μ}, obtaining quite different results for the three scenarios considered. The most favourable case, when the detector is located inside the tumulus, leads to differences in δ_{μ} that can be significantly identified with measurements of few days. On the other hand, if the detector is placed besides the tumulus, these differences are smaller, being necessary longer measurement times to identify them. Results also reveal, as expected, the influence of the muon model at surface chosen. Specially for the *Side Detector* case, for which horizontal muons, those less precisely characterized by the models, are the detected ones. In order to reduce the uncertainty due to muon parametrizations, the selection of the proper model, specially focused in low energy muons, is necessary.

4. Summary and prospects

Results of first simulations, based on the MUSIC muon propagation code, to evaluate the feasibility to use muon tomography as a method to study archaeological structures are presented in this work. The study is based on three particular cases taking the Kastas Amfipoli Macedonian Tumulus as reference, and considering the presence of a $2 \times 2 \times 2$ m^3 marble object inside it. The capabilities of the method have been evaluated for this particular case. This technique

Table 2: Summary of the main parameters used for the estimation of the difference of muons detected per day ($\delta\mu$) due to the presence of a marble box inside a standard soil tumulus for the different scenarios considered (see text for details). L_{Marble} and $L_{Tumulus}$ corresponds to the main distance traversed by muons for each case of marble and soil respectively, which are necessary to estimate the mean density. δR_μ indicates the expected muon rate difference due to the differences in the man density while ϕ_μ represents the absolute muon flux for the studied direction.

		L_{Marble}[m]	$L_{Tumulus}$[m]	δR_μ[s^{-1}]	ϕ_μ[cm^{-1}s^{-1}]	$\delta\mu$[day^{-1}]
CRY	Side Detector	2	140	5.86 10^{-3}	3.41 10^{-9}	0.02
	Centred Det. ($\theta = 0°$)	2	22	3.18 10^{-2}	3.60 10^{-5}	989.10
	Centred Det. ($\theta = 45°$)	2	35	2.00 10^{-2}	1.63 10^{-5}	281.66
Gaisser	Side Detector	2	140	2.86 10^{-3}	3.86 10^{-8}	0.10
	Centred Det. ($\theta = 0°$)	2	22	2.36 10^{-2}	3.59 10^{-5}	732.01
	Centred Det. ($\theta = 45°$)	2	35	1.49 10^{-2}	2.03 10^{-5}	261.33

turns out to be specially interesting if there exists the possibility to place the detector inside the tumulus using an internal corridor, if it exists.

Furthermore, the development of a high-precision simulation model is interesting not only for the general evaluation of the difference in the detected muon rate, but also for further comparison between simulation and real data for better interpretation of the latter. This implies the use of an accurate muon model at surface to perform the simulations, specially for low energy muons. Trying to have a first evaluation of the influence of the muon model, the comparison of the results for two different muon parametrizations has been also performed. The differences induced for the muon model can be important, specially when the studied muons have low energy and high incident angles (*i.e.* horizontal muons).

Following this work, some improvements for the simulation framework are planned. They comprise the performance of new simulations based in Geant4, which allow the definition of more detailed geometry, including the internal structures. These simulations could also allow to take into account the performance of the detectors considered to carry out the measurements. In parallel, deeper studies and cross-checks for the different muon parametrizations at surface, are being also considered, trying to find the most precise muon paramterization to be used as simulation input and for the normalization of the flux variation using the direction information.

Acknowledgments
Authors would like to acknowledge the financial support from the UnivEarthS Labex program of Sorbonne Paris Cité (ANR-10-LABX-0023 and ANR-11-IDEX-0005-02).

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