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Simulations of the muon flux sensitivity to rock perturbation associated to hydrogeological processes

Fanny Hivert[1,2,3,a], Ignacio Lázaro[1], José Busto[2], Jean-Pierre Ernenwein[2], Jürgen Brunner[2], Jean-Baptiste Decitre[1], Xavier Martin[3] and Stéphane Gaffet[1,3]

[1] LSBB, UMS 3538 Université de Nice, Université d'Avignon, CNRS, Aix-Marseille Université, OCA, La grande combe, 84400 Rustrel, France
[2] Aix Marseille Université, CNRS/IN2P3, CPPM UMR 7346, 13288 Marseille, France
[3] Géoazur, Université de Nice Sophia-Antipolis, UMR 7329, CNRS, France

Abstract. Muon tomography is a method to investigate the in-situ rock density. It is based on the absorption of cosmic-ray muons according to the quantity of matter (thickness and density). Numerical simulations are performed in order to estimate the expected muon flux in LSBB Underground Research Laboratory (URL) (Rustrel, France). The aim of the muon measurements in the underground galleries of this laboratory is to characterize the spatial and temporal density variations caused by water transfer in the unsaturated zone of the Fontaine-de-Vaucluse karstic aquifer.

1. Introduction

Muons are charged particles produced in the atmosphere. Primary cosmic rays, mainly composed of protons [1, 2], interact with the atmosphere and produce a huge number of secondary particles, including muons. These muons are particularly interesting because, due to their important mass (i.e., 200 times that of electrons), they are highly penetrating and they are able to propagate down to several hundreds of meters below the surface [3]. Moreover, the attenuation of their flux is proportional to the quantity of matter they cross. Muography is a method to investigate the subsurface, its principle being based on muon absorption to estimate the density of the rock.

This method has been used in several fields since 1955 [4]. Alvarez et al. [5] used it for archeology, to study the internal structure of the Chephren pyramid. It has been particularly developed in volcanology [6–9]. These last years, the projects using muons have diversified: the CO_2 storage [10], exploration of Mars [11], etc.

2. Muon tomography applied to hydrogeology

The T2DM2 (Temporal Tomography of the Density using the Measurement of Muons) project aims at characterizing the density variations linked to hydrogeological processes. The measurements are

[a] Corresponding author: hivert.fanny@lsbb.eu

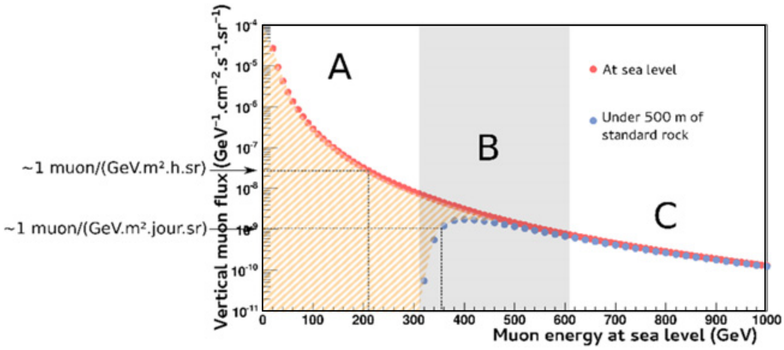

Figure 1. Comparison of the vertical muon fluxes at sea level and at 500 m depth of standard rock. 3 areas are defined: (A) muons are unable to pass through 500 m of standard rock; (B) a part of the muons is attenuated by the rock; (C) almost all the muons can reach 500 m depth of standard rock. The most interesting areas to observe flux variations are A and B (hatched area).

carried out in the low noise underground laboratory of Rustrel (LSBB, France). The galleries of this laboratory have a rock overburden up to 500 m and they are located in the unsaturated zone of the Fontaine-de-Vaucluse karst aquifer. This spring is characterized by an important catchment area that is mostly supplied by rainfall. The 800 m thick unsaturated area has an important role in the storage and the transfer of the water from the surface to the underlying aquifer. The variable permeability allows a duration of water storage ranging from some days to several months [12]. In such a context, the study of the location and the evolution of the density variations caused by water displacement can provide new information on the operation of this complex karstic system. Moreover the porosity can vary between 0% and 25% [13] and consequently the expected density variations may reach 10%.

The carried out simulations, which reflect the LSBB configuration, have a duration fixed to one month, a detection surface to 1 m^2 and an angular aperture to 10°.

3. Simulations of muon flux

The simulation of muon flux is divided into two parts: it is estimated at sea level and after crossing rock of variable thickness. The surface muon flux is simulated from the Gaisser analytical model [14]. The characteristics of the standard atmosphere constitute the input of the program (notably the opacity of the atmosphere, the altitude of muon production, etc.). The surface muon flux strongly decreases when the particle energy grows (Fig. 1). The survival probabilities of muons inside the rock are calculated with the MUSIC code [15], an open access Monte Carlo code dedicated to the simulation of muon propagation through rock or water. Muon survival probabilities are calculated according to the matter characteristics (thickness, density, atomic composition and radiation length) and the particle energy. They reduce with rising amount of crossed matter as well as with decreasing initial energy. Thus, is needed a higher critical energy to pass through the rock. Consequently, the integral muon flux decreases as well. The flux can be reduced by several orders of magnitude (Fig. 1) and that's why the most important limitation in muon tomography is the accumulated muon statistics. The flux variations that can be distinguished with reasonable statistic significance have to be studied.

4. Sensitivity to density variations of rocks

In order to estimate the sensitivity of muography, various rock densities are tested. They are compared to the standard rock defined in MUSIC with a density of 2.65 g.cm^{-3} and an atomic composition Z = 11

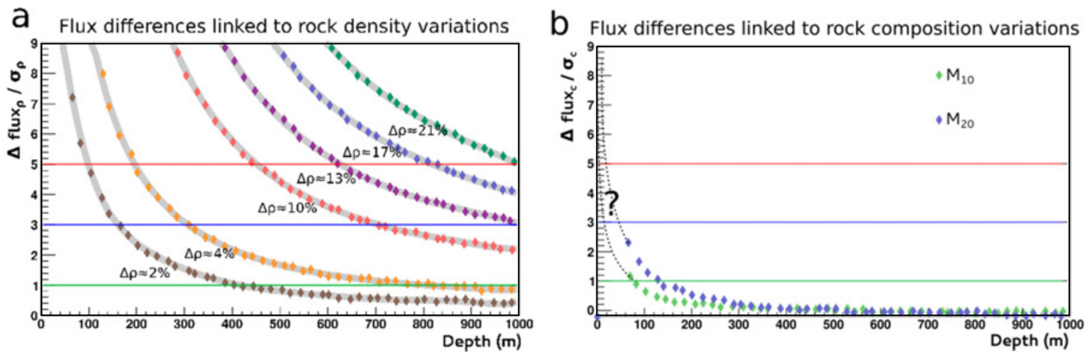

Figure 2. Influences of density (a) and composition (b) variations on the muon flux. The red, blue and green straight lines are respectively the values 1σ, 3σ, and 5σ of significance. (a) The flux differences caused by density variations (in percentages) are fitted by the shaded curves. (b) The muon flux variations are studied for 3 rock compositions (0%, 10% (M_{10}) and 20% (M_{20}) of H_2O) with a constant density (2.40 g.cm^{-3}). These muon fluxes are calculated for a duration of one month, a detection surface of 1 m^2 and an angular aperture of 10°. The results for depths lower than 60 m are extrapolated from deeper simulations (dashed lines).

and A = 22. The flux variations are computed for several density variations between this standard rock and rocks with other densities. The following equation 1 represents the variations of the flux ($\Delta(\Phi_\rho)$) divided by the errors of this flux (σ_ρ).

$$\Delta(\phi_p)/\sigma_p = |\phi_{standard} - \phi_{\Delta p}|/\sqrt{\sigma^2_{standard} + \sigma^2_{\Delta p}}. \quad (1)$$

Where $\Phi_{standard}$ and $\Phi_{\Delta\rho}$ are the muon fluxes in GeV$^{-1}\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1} for the standard rock and the rocks with other densities respectively, $\sigma_{standard}$ and $\sigma_{\Delta\rho}$ are their respective errors. The density differences are presented in percentages and for depths ranging from 60 m to 1000 m (Fig. 2a). The minimum depth is fixed to 60 m because lower depths require a more specific study that is not in the context of this paper. The simulations are performed until 1000 m to take into account the non-vertical incidence muons at the deepest part of the LSBB (~500 m). The results are compared to 1σ, 3σ and 5σ of significance. The maximum depth limitation range is defined when the significance of the flux variations is between 3σ and 5σ. For example, density variations of about 2% can be detected with 3σ significance until ~160 m. The same significance is reachable until ~320 m for 4% and ~720 m for 10%. Density variations higher than 15% are observable until the maximum tested depth: 1000 m.

5. Sensitivity to slight variations of the atomic composition

The nature of rock atoms may also have an influence on the muon flux. The atomic composition variations are applied by changing the Z (atomic number) and A (mass number) mean values of rock elements in MUSIC code. Three rock compositions have been tested: a dry rock and rocks with 10% (M_{10}) and 20% (M_{20}) of H_2O. For these simulations, the density is kept constant at 2.40 g.cm^{-3}. The simulations focus on composition variations only associated to water saturation conditions. In the same way as for the density tests, the flux differences ($\Delta(\Phi_C)$) between the dry rock and the rocks with 10% and 20% of H_2O are divided by their errors (σ_C) and compared to 1σ, 3σ and 5σ (Eq. (2)).

$$\Delta(\phi_c)/\sigma_c = |\phi_{dry} - \phi_{10/20}|/\sqrt{\sigma^2_{dry} + \sigma^2_{10/20}}. \quad (2)$$

Where Φ_{dry} and $\Phi_{10/20}$ are the muon fluxes in $GeV^{-1} \cdot cm^{-2} \cdot s^{-1} \cdot sr^{-1}$ for the dry rock and the rocks with 10% and 20% of H_2O, σ_{dry} and $\sigma_{10/20}$ are their respective errors. No flux differences higher than 3σ are obtained for the tested rocks, at depths ranging from 60 m to 1000 m (Fig. 2b). Compared to the density effect, the composition influence on muon flux is negligible. This conclusion is suitable only for classical rocks, the presence of high-Z materials leading to important variations of the muon flux.

6. Discussion and prospects

The hydrogeological processes that take place in karstic aquifer are complex and not well known. The LSBB URL provides a perfect location in the unsaturated area of Fontaine-de-Vaucluse to study these processes. Numerical simulations prove that muography is suitable to image the spatial and temporal density variations caused by water transfer. The insensitivity to rock composition variations, compared to the density, demonstrates that muography is a direct measurement of the in-situ rock density.

Currently, a particular attention is paid on the scattering of the muons inside the rock. The idea is to estimate the scattering processes and their impact on the muon flux in order to avoid mistakes on the measurement interpretations. These processes must be studied especially because Micromegas – TPC (Time Projection Chambers) telescopes will be used for the T2DM2 project [16]. These detectors have the spatial and angular high resolutions needed to image the thin geological structures.

Since December 2013, the first muon flux measurements are performed in the LSBB underground galleries with liquid scintillator tanks. This detection system will then be used to calibrate the Micromegas telescopes.

Muography is here applied to hydrogeology but it has already been used in several fields and a lot of others are expected in the next years. Tomography based on cosmic-ray muons is a complementary technique to the standard geophysical methods (e.g., seismic imaging, electric prospection or gravimetry) and can be used for coupled inversions.

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