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Characterization of atmospheric muons at sea level using a cosmic ray telescope

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ABSTRACT

In this work, a portable cosmic-ray telescope was designed, assembled and operated to measure the cosmic-ray induced atmospheric muon flux at ground level. The instrument was entirely characterized and modeled from the point-of-view of detector efficiency, energy detection window and counting rate. Experimental data are reported for the characterization of the muon flux at sea level (43°N of latitude) in terms of vertical muon intensity and zenithal angle dependence.

1. Introduction

A large number of experimental works has been reported in the last decades on cosmic-rays muon intensities at sea level; these data are important for astrophysical standards and contain useful information concerning cosmic-ray interaction processes [1]. In a completely different field of interest, that initially motivated the present work, the metrology of terrestrial cosmic rays is also an essential challenge in modern microelectronics, for the understanding of basic mechanisms and for the characterization, modeling and predictive simulation of single event effects (SEE) in electronics [2]. SEE are radiation-induced errors in microelectronic circuits caused when energetic particles lose energy by directly (charged particles) or indirectly (neutrons) ionizing the medium through which they pass, creating electron–hole pairs at the origin of transient parasitic currents [3]. If the effort has so far focused mainly on the characterization of atmospheric neutrons [4–8], one must not longer neglect muons at ground level that are susceptible to significantly contribute to SEE in current integrated electronics [9–12]. Muons are indeed the most numerous energetic charged particles at sea level. They arrive at sea level with an average flux of about 1 muon per square centimeter and per minute. Their mean energy at sea level is ~4 GeV. For these typical energies and up to a few hundred of GeV, muons mainly interact with matter by ionization, losing energy at a fairly constant rate of about 2 MeV per g/cm^2. Although a large literature exists on muons in the atmosphere, studies are generally oriented "high energy physics" and consider muon energies above the GeV or beyond [11]. In the particular framework of radiation effects in microelectronics, there is an evident lack of data available in the "low energy" range, typically above a few tens of MeV and below a few GeVs. At these energies, muons can easily penetrate packaged ICs but are rapidly slowed or stopped: they can deposit by ionization a significant amount of electric charge along their track and contribute to single-event effects.

In the present work, we developed a cosmic-ray telescope to accurately characterize, in a long-term perspective effort, the atmospheric muon flux at ground level, precisely in this "low energy" range. This paper presents and discusses in details the main characteristics of the instrument and reports the experimental measurements conducted in the region of Marseille (south of France) at sea level.

2. The muon telescope

2.1. Experimental setup

In this work, we developed an experimental apparatus called "cosmic-ray telescope". Fig. 1 shows the front and back views of this setup derived from a real astronomical telescope fabricated by SkyVision (ultra compact Dobson, model 400-UT [13]). The initial telescope has been modified to receive two circular plastic scintillators (diameter 40 cm, thickness 5 cm, housed in 1.5 mm of aluminum plate) in place of the classical primary and secondary optical mirrors. This solution offers the advantage to take full benefits from an alt-azimuthal PC-controlled motorized mount with high precision mechanics and great

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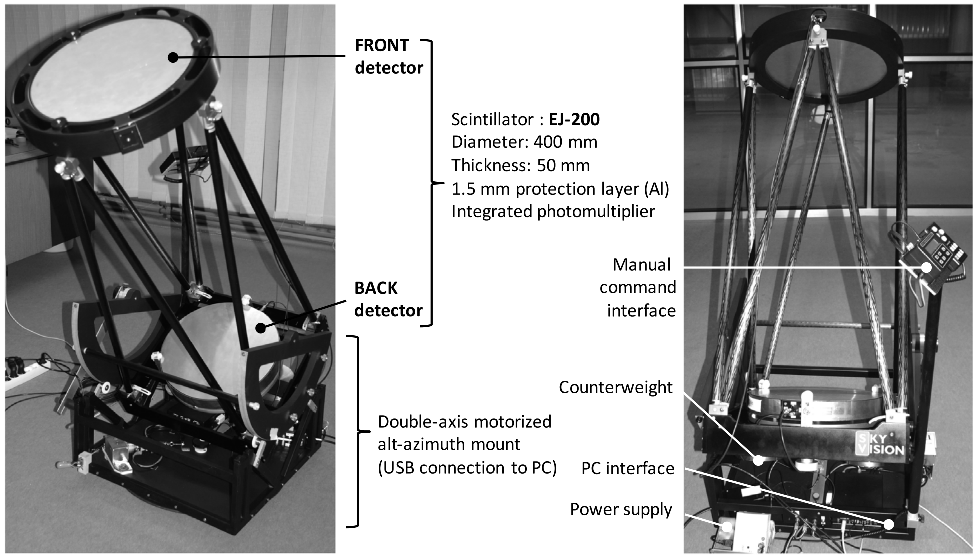

Fig. 1. Front and back views of the portable experimental setup (total weight 48 kg) composed of two circular scintillators (400 mm diameter) mounted in place of the primary and secondary mirrors of a real astronomical telescope with an alt-azimuthal double-axis motorized mount. The distance between the two scintillators is 102 cm.

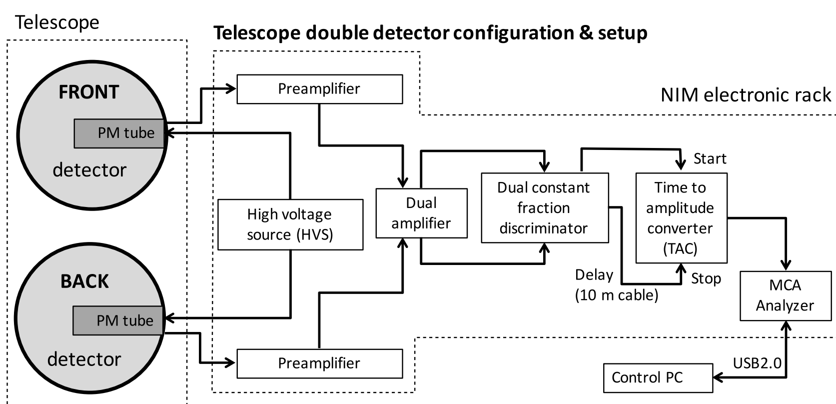

Fig. 2. Schematics of the electronics acquisition chain for measuring the time-of-flight of coincidence muons between the two detectors of the telescope.

transportability. The polymer base material of the two detectors is polyvinyltoluene (PVT) fabricated by Eljen Technology (EJ-200) [14]. This plastic is highly sensitive to charged particles: its typical stopping power for 1 GeV muons is 2.132 MeV/cm [15]. The two scintillators have photomultipliers (PM) directly integrated in their volume and optically coupled using a high refractive index optical coupling medium. The PMs are ADIT model PB29 with 1.125″ diameter, 2π photocathode and 11-stage photomultiplier. The assembly (PM + scintillator) is mounted in an aluminum housing (thickness 1.5 mm) that ensures a permanent light sealing. The two PMs are connected to the measurement and acquisition chain shown in Fig. 2.

The electronics chain trigs the muons traversing the front scintillator and measures, using a coincidence detection procedure, their time-of-flight between the front and back detectors separated by a distance of 1.02 m (in air). PM signals as well as time-of-flights converted in voltage pulses using a time-to-amplitude converter (TAC) are digitalized using multi-channel analyzers (MCAs based on 16k ADCs).

2.2. Instrument calibration

In order to be sure that the telescope detects and counts only atmospheric muons, a careful characterization and calibration of the instrument has been performed in several steps, described below.

2.2.1. Single detector characterization and γ rays rejection

In addition to muons, the two scintillators coupled with PMs of the telescope detect gamma rays, which are particularly present at low incident energy. Fig. 3 shows the telescope counting rate as a function of the MCA channel number. This curve shows two peaks: (i) a first low-energy peak that consists of a mixture of PM noise and the contribution of ambient gamma radiation; (ii) a second peak corresponding to the contribution of charged atmospheric muons. Note that the integral of this second peak (1200–1300 counts/min) corresponds perfectly to the product of the surface of the detector (1256 cm^2 in this case) with the integrated average muon flux at ground level (about 60 muons per square centimeter and per hour), demonstrating that this second peak is due almost exclusively to the contribution of muons in the count rate. In order to minimize the influence of gamma rays in measurements, a detection threshold of approximately 130 mV (corresponding to ADC channel 3500) was considered, as shown schematically in Fig. 3. Since this threshold is very dependent on the PM tube, a threshold value has been separately determined for each of the two (front and back) telescope detectors.

2.2.2. Detector efficiency

The raw counting rate of the telescope needs to be corrected to take into account the detection efficiency of both front and back