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Measurements with cosmic muons to monitor the stability of a civil building on a long time-scale

The EEE collaboration

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Abstract: Due to their penetration capability, cosmic muons may provide a way to monitor the alignment and possible long term deformations of large structures, such as historical or other civil buildings. The basic idea behind this possibility is to look for any misalignment between position-sensitive detectors, fixed to different parts of the structure, relative to the original alignment condition. In this paper we discuss the possibility of employing Multigap Resistive Plate Chambers (MRPC) as tracking devices, operating them in coincidence with additional detectors without tracking capability. One of the MRPC telescopes (size $158 \times 82\,\mathrm{cm}^2$) of the Extreme Energy Events (EEE) project, installed in the underground floor at the Department of Physics and Astronomy in Catania, was used together with a $40 \times 60\,\mathrm{cm}^2$ scintillator-based detector, located at about 16 m vertical distance, on the third floor of the same building. Coincidence measurements were carried out over a period of about two months by shifting the position of the smaller detector, to mimic the movement of the structure. Plans for future studies with different detectors and under different geometrical configurations are also discussed.

Keywords: Gaseous imaging and tracking detectors; Interaction of radiation with matter; Resistive-plate chambers; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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Contents

1 Introduction

Cosmic ray muons are created by high energy primary cosmic radiations, mostly consisting of protons, when striking the Earth's atmosphere. Besides their common use in nuclear and particle physics for detector testing and calibration and for the alignment of detectors in complex apparata, they have also been used since several decades as a powerful probe for many applications [1]. Muons are particles highly penetrating in matter and their average energy is sufficient to penetrate several meters of rock. Thanks to their penetration capability, highly energetic cosmic muons may even be used for absorption radiography of volcanoes and large civil structures, such as Pyramids. The detection of illicit nuclear materials inside containers, through their scattering by high-Z elements, is another promising application.

Muons may also provide a way to monitor the alignment and possible long-term deformations of large structures, such as historical or other civil buildings. The basic idea behind this possibility is to employ a set of position-sensitive detectors fixed to different parts of the structure and reconstruct the muon tracks passing through them. Any misalignment between the positions measured in all detection planes with respect to the original alignment condition would signal, when measured on a long-term data acquisition basis, a mechanical shift of a part of the structure with respect to other parts.

An alternative choice, as exploited in the present investigation, is the combined use of a tracking and a non tracking detector, looking at the detailed angular distribution of tracks, as reconstructed by the tracking device, when crossing also the sensitive area of the non tracking detector. This simplifies somewhat the setup, since it only requires a single tracking detector, although with good angular resolution. As an attempt to employ this technique, we used a telescope consisting of three Multigap Resistive Plate Chambers (MRPC) of the Extreme Energy Events (EEE) project [2] and an additional, scintillator-based, detector. Both were installed in the same building, at about

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16 m vertical distance. Coincidence measurements between the two detectors were carried out over a period of approximately two months by shifting the position of the smaller detector to mimic possible deformations of the building. Plans for additional investigations with a smaller size scintillator under a different geometry are also discussed.

2 Muons as a tool to monitor building stability

The idea of using cosmic muons passing through two far detectors with the aim of monitoring small shifts — of the order of few *mm* — of a structure over long time periods is particularly appealing when traditional methods cannot be easily employed. These methods are usually based either on optical systems, such as the laser alignment technique, or on mechanical devices, as metal wires stretched between various points in the structure. Cosmic muon measurements are particularly indicated when the regions undergoing possible shifts are not optically in view due to interposed materials, such as the concrete layers separating different floors of a building.

This method has been studied and tested over the last years by the Brescia-Pavia group, monitoring an important historical building, *Palazzo della Loggia* in Brescia (Italy), as a case study [3]. They carried out simulation studies for this application, demonstrating that a relative shift of the order of a *mm* can be evidenced in about one week data taking with a proper experimental setup. Prototype detectors have been also built and tested for this purpose. Limitations of the tracking detector (space and angular resolution) and the physics mechanisms which govern muon propagation between the two detectors can affect the outcome of such technique. Multiple scattering effects may limit the effective performance of the method, even in presence of an ideal reconstruction of muon tracks by the detectors, and it is an important aspect to be considered when a large amount of heavy material is interposed between them. The effective solid angle and the detection efficiency are also points of concern, since they largely determine the overall acquisition time needed to reach a given uncertainty on the observed angular shift. Also the intrinsic stability of all main detection components (detector tracking efficiency, electronics stability, . . .) over long measurement periods has to be checked, since small variations of the detector parameters could result in a slight change of the angular distribution of the tracks, thus being indistinguishable from real mechanical movements of the detectors position. Since the use of two tracking detectors with good performance may be difficult to achieve, especially for the detector which has to be mounted far from the building basement, an alternative solution is to employ a single, large area, detector with good tracking capabilities, and one or more, smaller area, non tracking devices, to be easily installed over different parts of the structure. We recently tested such possibility [4] using one of the MRPC telescopes of the EEE project [2], in coincidence with an additional scintillator-based detector located at a relatively large distance (16 m) in the same building. Additional measurements are in progress to exploit the potential of using several small area detectors under different geometrical configurations.

3 Experimental setup

The EEE project consists in an extended array of cosmic ray telescopes based on MRPCs, spanning an area of more than $3 \times 10^5\,\mathrm{km}^2$. Most of these detectors are located in high school buildings, whereas few of them are installed in Research or University Institutions. The experiment aims at

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the study of extensive cosmic ray showers by detecting and tracking their muon component, thanks to the good tracking capabilities of the MRPCs.

The basic structure of each telescope used for the EEE project includes three MRPCs, with $158{\times}82\ \mathrm{cm}^2$ sensitive area [5]. The EEE MRPCs have been specifically designed for the requirement of the project, with a low construction cost and easy assembling procedures, which are carried out at CERN by high school teams under the supervision of EEE researchers. Each MRPC has six gas gaps, obtained by a stack of glass sheets, separated by narrow (300 µm) gaps, and coated with resistive painting. A high voltage (around 20 kV) is applied only to the external sheets, while leaving the inner sheets floating. Chambers are usually operated with a gas mixture of 98%/2% of Freon and SF_6, with a continuous flow and at atmospheric pressure. Signals are read via 2.5 cm wide Cu strips, longitudinally by measuring the time delay between the signals arriving at the two ends of a strip. Longitudinal and transverse space resolution were found from beam test measurements to be 0.84 cm and 0.92 cm respectively, in agreement with the expected value, due to the strip pitch. Each event is time stamped by means of the GPS information, with a time resolution of about 40 ns. Detection efficiency of the chambers, which depends on the operational conditions, has been evaluated as a function of the applied high voltage. For most of the chambers, this efficiency is better than 90%. The overall performance of these chambers is adequate for a possible use as muon tracking devices, in coincidence with smaller size detectors placed some distance apart, as it is required by this specific application. For this investigation we employed one of such telescopes, named CATA-01, installed and taking data since more than 10 years in the underground floor of the Physics Department in Catania (see figure 1).

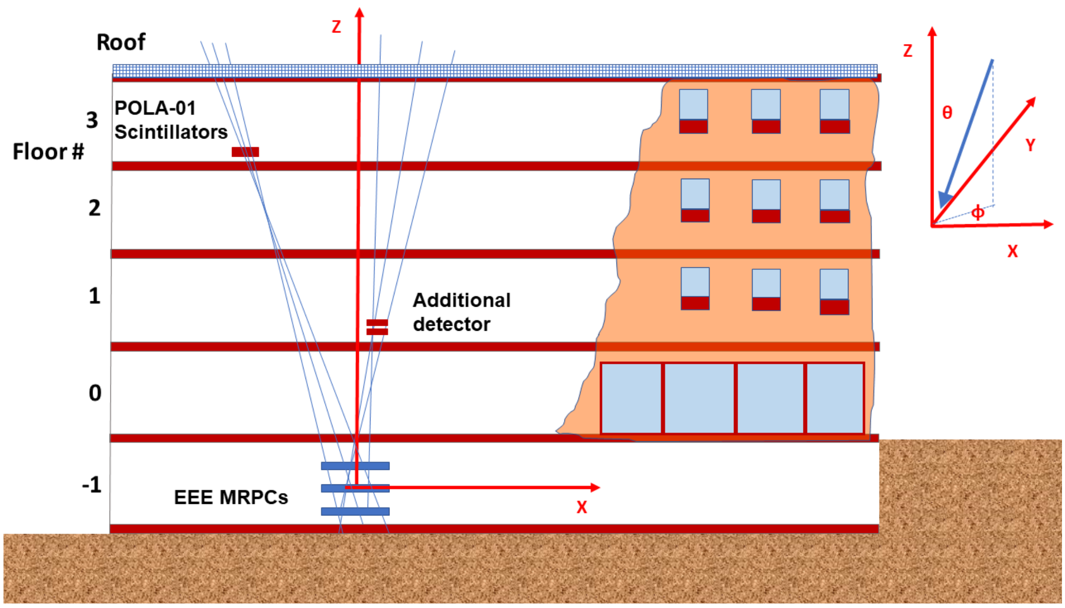

Figure 1. Layout of the detector locations inside the Department building, with the MRPC telescope on the underground floor and the POLA-01 scintillators at the third floor (not to scale). Also shown is an additional detector which is being used for a new set of measurements closer to the vertical and at a smaller vertical distance.

An independent, scintillator-based detector, named POLA-01, was operated during this measurement. It is one of three equal detectors, built by students from Italy, Norway and Switzerland within the Polarquest project [6], to carry out cosmic ray measurements in various conditions in the polar region and elsewhere. This detector is based on two parallel layers of plastic scintillators separated by 10 cm, each segmented into four tiles with individual size of $20 \times 30\,\text{cm}^2$. Each scintillator tile is readout by two Silicon Photomultipliers placed on opposite corners and operating in coincidence. Custom-made front-end and acquisition electronics for this detector includes a discriminator, TDCs and a trigger logic based on a FPGA. The control of the system is achieved by means of a Raspberry Pi 3+ microcomputer. Several sensors to monitor environmental pressure, temperature and humidity, as well as an accelerometer, are also included in the setup. The average count rate of the POLA-01 detector at the sea level is about 30 Hz. More details on the Polarquest measurement campaigns can be found in ref. [7]. Time tagging of the events is performed by its own GPS, which has an intrinsic resolution on the 1 PPS (Pulse per Second) signal around 20 ns. In this analysis however, the time tagging within each second was derived from the internal clock of the board, and due to its poor stability, the effective resolution of the absolute time stamp of each collected event had a value of about 250 ns. Off-line synchronization of the events was then achieved by correlating the event time from the two detectors.

4 Data taking

Measurements were carried out during the spring of 2019. The MRPC telescope and the POLA-01 scintillators were operated independently, each one taking data and time-stamping collected events by means of the GPS time information. Tracks due to the same particle traversing both detectors were selected within a coincidence time window of ±600 ns, and imposing cuts on the χ^2 of the tracks being reconstructed and on the time-of-flight measured between the top and the bottom chambers in the EEE telescope. Single-track events were selected in both detectors for this analysis, to reject events with more than one reconstructed track.

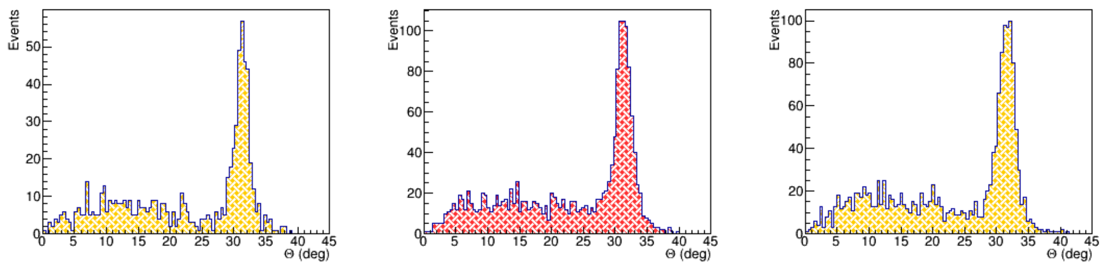

Figure 2. Zenithal angular distributions of muons measured in coincidence by the two detectors: the peaks represent events due to the passage of single muons through both detectors, whereas the rather flat distribution corresponds to two muons from the same shower. Left, middle and right panels show the distributions corresponding to a shift of 5, 10 and 20 cm, respectively, with respect to the reference position. The measurements have been performed with different durations, hence their yields cannot be directly compared.

For each event detected in coincidence by the two detectors, the zenithal (θ) and azimuthal (φ) distributions of the track orientation, as reconstructed by the MRPC telescope, were considered. These distributions depend on the relative position of the movable scintillator detector with respect to the EEE telescope, fixed to ground. Due to the limited geometrical acceptance of the EEE telescope (zenithal angles from the vertical $\theta = 0°$ to about $\theta = 40°$), events originating from the same muon passing through both detectors may be detected only if the scintillators are placed within the acceptance cone of the reference telescope. Two sets of measurements were carried out. In the first measurement set, POLA-01 was located outside the acceptance cone of the EEE telescope, allowing us to detect the background due to correlated muons from the same extensive air shower; in the second set of measurements, as in figure 2, the movable detector was located within the acceptance cone of CATA-01, so that on top of the independent events, also muons intersecting both detectors could be detected. In this latter case we expect a narrow distribution of zenithal (and also of azimuthal) angles around the most probable track direction which intersects both detectors.

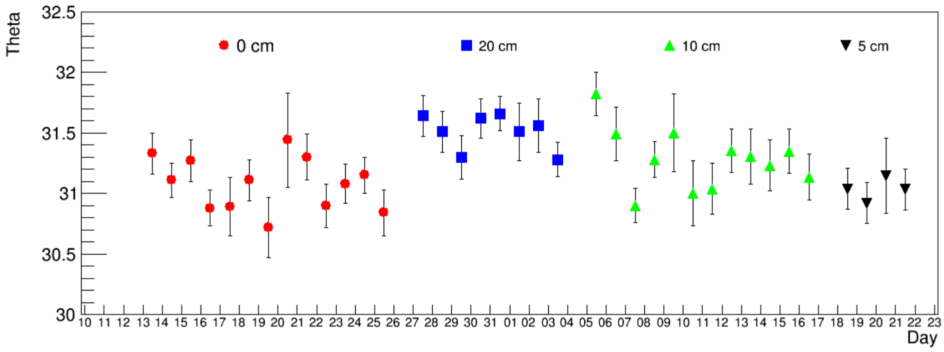

Figure 3. Day by day average values of the zenithal angle, obtained by a Gaussian fit of the narrow peaks (see figure 2) in each daily distribution. Error bars have been also obtained from the fit. Different colours and symbols refer to the different measurements carried out in the four positions, as marked in the legend.

5 Testing the sensitivity of stability measurements

The first position where the POLA-01 detector was located within the acceptance cone of the EEE telescope (with its center at X = -7.69 m, Y = 5.44 m, Z = 15.6 m with respect to the center of the middle chamber of the EEE telescope) was taken as a reference. The choice of this position was largely dictated by practical constraints, since the detector had to stay in a fixed position for a long time and the maximum allowed length of the GPS antenna cable was only 5 m. To mimic the movement of the structure, the POLA-01 scintillators were shifted in various positions along a line (ΔX = 5, 10 and 20 cm). The average values of the zenithal and azimuthal angles were obtained by a Gaussian fit of the narrow peaks in the spectra shown in figure 2.

To monitor possible day-to-day variations in these centroids, we extracted the daily average values of the zenithal angle, which are shown in figure 3. As it is seen, while the day-to-day variations are not negligible (with an RMS in the reference position of 0.24°), the average values obtained after only one week for each position shows some difference, at least in the zenithal angle,

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even for a shift of the order of 5–10 cm. To combine the zenithal and azimuthal angle differences into a single information, the vector sum of all selected tracks for each given position was evaluated and the 3D relative angle with respect to the reference orientation in the original position was considered. In table 1 the results of such relative 3D shifts with respect to the original position are reported. Column 2 reports the live time, i.e. the effective time during which both detectors were properly operating and coincidences were collected. A clear shift is observed in the relative angle when a linear shift of 10 cm is introduced (from $\Delta X = 10$ cm to $\Delta X = 20$ cm), while, also due to the limited statistics (less than 4 days) for the measurement carried out at $\Delta X = 5$ cm, comparable values of the relative angle are obtained for $\Delta X = 5$ cm and 10 cm. This first set of measurements allows then to roughly estimate the sensitivity of the method in the present conditions, i.e. the angular shift which may be expected for a given difference in the position of the movable detector. This turns out to be of the order of 0.02°/cm in the present conditions. This quantity however depends on the geometry (size of the two detectors and relative location). From an experimental point of view, measuring angular differences versus controlled linear shifts helps to obtain the effective $S + \Delta\theta/\Delta X$ under real detection conditions (performance of the detectors, material interposed between the two, . . .), a sort of calibration of the technique under specific conditions. The experimental uncertainty on S, assuming ΔX is well known, depends on the uncertainty in $\Delta\theta$, which can be reduced with larger statistics, i.e. larger data taking periods during the calibration phase. Once S has been estimated, the observation of an angular shift $\Delta\theta'$ over long periods (with all other conditions fixed) should give information on the shift $\Delta X'$, with an uncertainty which depends both on the uncertainty on the calibration factor S and on the uncertainty in the measured $\Delta\theta'$. In our preliminary measurement, if we take into account only the two extreme measurements, taken in the reference position and at $X = 20$ cm, we have roughly $\Delta\theta/\Delta X = 0.02°$/cm, although with a large error (about 27%). Longer data taking periods during the calibration phase could reduce the uncertainty in S to a negligible contribution to the overall error. For the geometrical configuration of these measurements we checked that uncertainties in $\Delta\theta'$ of about 0.1° may be achieved in about one week. Under the assumption of a negligible uncertainty in the calibration, one week data taking in such conditions would then give the possibility to evidence linear shifts of about 10 cm. Better geometrical configurations could be however explored, which would enhance both the solid angle and the sensitivity.

Table 1. Results of the relative 3D angle shifts with respect to the original position, obtained by moving the POLA-01 detector along the X direction.

ΔX shift (cm)	Live time (hours)	3D angle shift (deg)
5	89.4	0.31 ± 0.16
10	243.8	0.24 ± 0.12
20	175.5	0.44 ± 0.12

An important role in the performance of this technique is played by the material interposed between the two detectors, due to the amount of multiple scattering suffered by the muons. In our case muons had to traverse four layers of concrete. Multiple scattering effects were evaluated by GEANT simulations, assuming a realistic composition of the material, for several muon momenta

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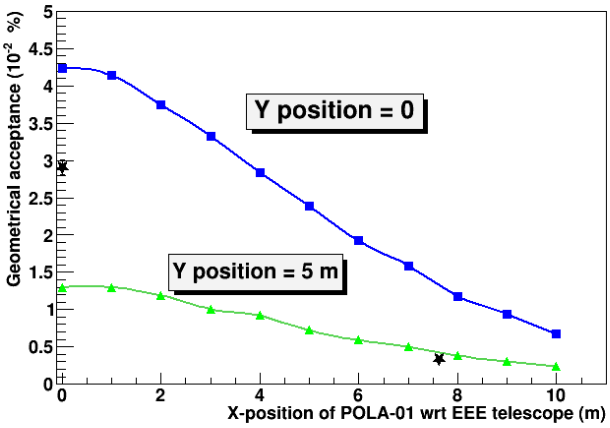

Figure 4. Geometrical acceptance (defined as the ratio between the number of tracks passing through both detectors and the overall number of generated tracks in the upper hemisphere) as a function of the position of POLA-01 (along the X-direction) with respect to the EEE tracking telescope, for two different Y positions (Y = 0 and Y = 5 m). A vertical distance of 15.6 m was assumed in the simulation. The black stars show the two positions investigated experimentally during the measurements, showing an increase of roughly a factor 8 between the two acceptance values.

(from 1 to 4 GeV/c), as a function of the traversed thickness. It can be estimated that 60 cm of concrete-equivalent thickness corresponds to traversing four layers. For an average momentum of 3–4 GeV/c, as for cosmic muons at sea level, this corresponds to about 0.1°–0.2°. We observe however that due to the location of the tracking telescope, with several concrete layers above it, the fraction of low energy muons is higher than for the open sky, so larger effects due to multiple scattering are expected. The expected increase in statistics which can be obtained by a proper positioning of the two detectors was further investigated by means of geometrical simulations and an additional measurement carried out in a different position of the POLA-01 scintillator, still keeping the same vertical distance, as discussed in the next section.

6 The role of the relative position between detectors

Basic geometrical simulations of the correlated passage of particles through both detectors, located at various relative positions, were carried out in order to better understand the detection conditions and the sensitivity of the method. Muon tracks were generated assuming a simple $dN/d\theta = \sin\theta\cos^2\theta$ dependence upon the zenithal angle, as a first approximation to a more detailed dependence on the muon energy and altitude [8], and a generation vertex uniformly distributed along the active surface area of $1.58 \times 0.82\,\mathrm{m}^2$ of the middle chamber of the EEE telescope, whose center was assumed as the origin.

For each location, the geometrical acceptance, here defined simply as the ratio between the number of tracks passing through both detectors and the number of generated tracks over the upper hemisphere, was extracted. Typical examples are shown in figure 4, which reports values obtained as a function of the shift along the X-position, for two different Y-positions (Y = 0 and Y = 5 m). Also marked in the same plot (black stars) are the locations of the two experimental measurements,

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which are coherent with the expected increase in the geometrical acceptance. Choosing an even closer X-Y position of the scintillator with respect to the EEE telescope, i.e. closer to the vertical, could easily result in a factor 10 increase in the acceptance with respect to the original position. This means the possibility to evidence a shift of a few cm in just one day data taking, hence of a few mm in data taking periods of the order of months, even at a non-negligible vertical distance between the two detectors.

In order to test the predictions of the simulations, an additional short measurement was carried out moving the POLA-01 detector in a different position (X = 0, Y = -2.5 m) but in the same floor, thus keeping the same vertical distance. Comparing the results of the two measurements, roughly a factor of 8 increase in the coincidence rate was obtained, in agreement with expectations from simple geometrical simulations. Further measurements are in progress with a smaller size detector, placed close to the vertical with respect to the center of the tracking detector and at a smaller vertical distance.

7 Conclusions

In this work the possibility of monitoring the stability of civil structures on a long time-scale with the use of a tracking detector and an additional, non tracking, detector has been experimentally investigated by the analysis of the angular distributions of cosmic muons crossing both detectors. For this purpose one of the MRPC telescopes of the EEE project has been used as tracking device, and a scintillator detector as a movable detector. The sensitivity and performance of the method have been evaluated with a first set of measurements carried out inside the Physics Department building of the University of Catania. Although the detection configuration in the present experiment was not optimal, due to the large vertical distance between the two detectors, to the horizontal offset between their centers and to the presence of several concrete layers between them, first results point out the possibility to evidence a shift of a few cm in one day data taking (and correspondingly smaller for longer data taking periods), once the detection geometry is properly optimized.

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