Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: C Pinto *et al* 2020 *J. Phys.: Conf. Ser.* **1561** 012019

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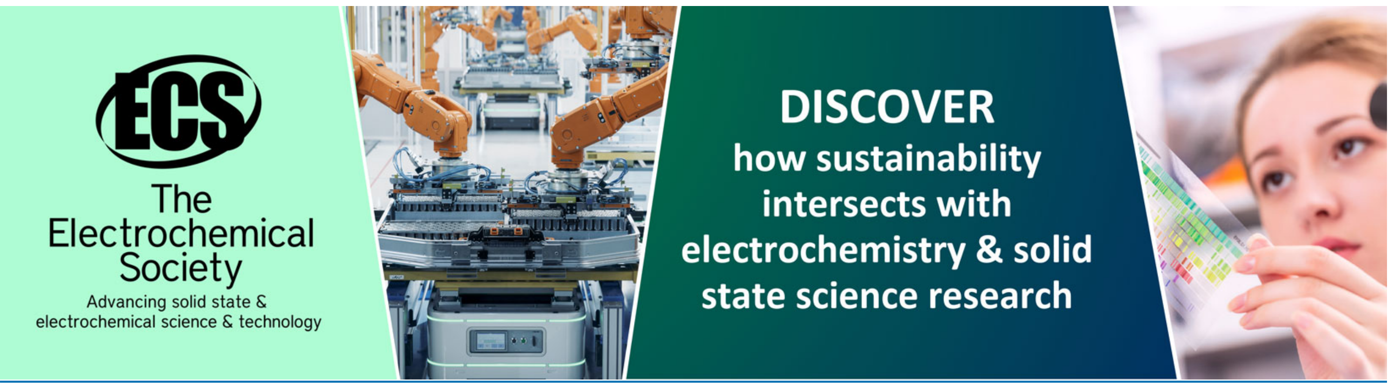

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Monitoring the long term stability of civil buildings through the MRPC telescopes of the EEE Project

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Abstract. Cosmic ray muons are a penetrating component of extensive air showers created in the Earth atmosphere by the interaction of highly energetic primary particles, mostly protons, which continuously bombard our Planet. The secondary cosmic radiation is the result of the

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complex interplay between the production cross section and the interaction mechanisms with the atmosphere (including the energy loss, multiple scattering and particle decay). Cosmic muons have been considered since several decades as a powerful probe to exploit our environment, from muography of volcanoes to absorption radiography of possible hidden rooms inside large structures, such as Pyramids, to the detection of high-Z illicit nuclear materials inside containers and many other applications of social interest.
This paper discusses the possibility to employ the Multigap Resistive Plate Chambers (MRPC) of the Extreme Energy Events (EEE) Project as muon tracking detectors to monitor the long term stability of civil buildings and structures when used in conjunction with additional detectors. For this application the average direction of the cosmic muon tracks passing through the MRPC telescope and an additional detector located some distance apart in the same building may be reconstructed with good precision and any small variation over long time acquisition periods may be monitored. The performance of such setup is discussed and experimental results from first coincidence measurements obtained with a 40 x 60 cm^2 scintillator detector operated in the same building with one of the EEE telescopes, at about 15 m vertical distance from it, are presented. Simple Monte Carlo and GEANT simulations were also carried out to evaluate typical acceptance values for the operating conditions employed so far, to extrapolate to other geometrical configurations, and to evaluate multiple scattering effects.

1. Introduction

Cosmic ray muons are created by high energy primary cosmic radiation, mostly made of protons, coming from the Sun and from the outer Galaxy when striking the Earth's atmosphere. The properties of the secondary cosmic radiation are studied since their discovery a long time ago. As it is well known, in fact, the flux reaching the surface of the Earth is about 10 000 μ/(min m^2) and the mean muon energy a.s.l. is around 3-4 GeV. Besides the common use of cosmic rays in nuclear and elementary particle physics for detector testing and calibration and for the alignment of detectors in the very complex apparata used in this field, cosmic muons have also been considered since several decades as a powerful probe to many applications in physics and engineering fields. Muons are heavy particles and do not undergo nuclear interactions, so they are highly penetrating in matter and their average energy is sufficient to penetrate tens of meters of rock. Thanks to this peculiarity, cosmic muons are used for muography of volcanoes and for absorption radiography of possible hidden rooms inside large structures, such as Pyramids, but also for the detection of high-Z illicit nuclear materials inside containers [?]. One of the most recent applications is the muon tomography, in which the angular scattering that every muon undergoes when crossing matter is exploited. While the absorption technique requires the measurement of the muon position and direction only downstream of the object to be inspected, the technique based on muon scattering requires the measurement of muon position and direction both upstream and downstream, to measure the single muon angular deviation.
Recently, it has been suggested [?] that muons may also provide a way to monitor alignment and possible long term deformations of large structures, such as historical buildings or other large civil structures. 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 could signal a mechanical shift of a part of the structure with respect to other parts. A possible shift in the relative position of the two devices can be investigated on a long-term data acquisition basis, thus allowing to evidence long term instability of the structure.

2. The method: advantages and limitations

The possibility of using cosmic muons to monitor long-term stability of civil structures is particularly useful when traditional methods, for instance based on laser alignment or metal wires stretched between various points in the structure, cannot be easily employed. This may be the case when the regions undergoing possible shifts are not optically in view due to interposed materials or being located in different floors of the building. A detailed study of this method has been pursued over the last years by the Brescia-Pavia group [?, ?, ?, ?] and applied to the problem of monitoring an important historical building, namely Palazzo della Loggia in Brescia (Italy), as a case study. Simulation studies for this application have demonstrated that resolutions of the order of 1 mm could be achieved in about one week data taking with a proper experimental setup, and prototype detectors have also been tested [?].
Possible disadvantages of this technique are associated with the limitations of the tracking detector (space and angular resolution) and with the unavoidable physics mechanisms affecting muon propagation between the two detectors, especially multiple scattering effects. This limits the effective sensitivity 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 the detectors. The effective solid angle subtended by the additional detector with respect to the main tracking device and the detection efficiency of such detectors are also points of concern, since they largely determine the overall acquisition time needed to reach a given angular resolution, hence the sensitivity of the method. 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 detector position.
The Extreme Energy Events Collaboration [?] has built and operated since more than ten years a large number of cosmic ray telescopes based on Multi-gap Resistive Plate Chambers in the framework of a project with both educational and scientific aspects. Most of these detectors, built at CERN by high school teams, are presently installed in high school sites over the Italian territory, whereas few of them are located at CERN and in Physics Departments and INFN sites. Due to the good tracking capability of the EEE MRPC detectors, we recently made a preliminary investigation of the possibility to employ such detectors, in conjunction with an additional scintillator, for applications in this area [?], as described above. To this aim, a set of measurements was carried out with one of the EEE telescopes, located in the underground floor of the Physics Department in Catania and the POLA-01 detector [?], based on two layers of scintillators covering a 40 x 60 cm^2 sensitive area, which was located at the third floor of the bulding, at a vertical distance of about 15.6 m from the EEE telescope, with a large amount of material between the two detectors, due to the concrete layers separating the different floors. Figure ?? shows a sketch of the detector setup used for this purpose. Measurements were performed in various locations during a period of approximately two months.

3. The experimental setup

The cosmic ray telescopes employed by the EEE Collaboration have been described in detail in many previous papers [?, ?, ?, ?, ?, ?]. The basic structure of each telescope includes three Multi-gap Resistive Plate Chambers (MRPC), with 158 x 82 cm^2 sensitive area. MRPCs are a development of Resistive Plate Chambers (RPC), where the gas gap is divided into sub-gaps. Particles passing through the detector may create avalanches in several or all gaps and the signal collected on the external cathode and anode is the analogue sum of avalanches in all gaps, with a time jitter in the rise time smaller than that expected from a single gap. As a consequence, a much better time resolution and detection efficiency are obtained by the use of multi-gap devices. The EEE MRPC chambers have been specifically designed for the requirement of the project,

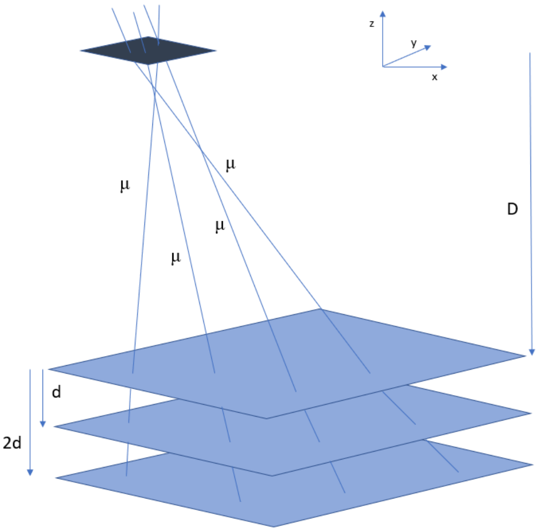

Figure 1. Sketch of the configuration of two detectors used to investigate long-term stability of civil structures. The MRPC-based tracking detector of the EEE project is coupled to an additional one, which is a scintillator-based detector, built in the framework of the Polarquest project.

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. The detector structure has six gas gaps, obtained by a stack of glass sheets, separated by narrow (300 μm) gaps, and treated with resistive painting. A high voltage 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 the atmospheric pressure. High voltage to the chambers is provided by DC/DC converters, with most of the chambers operating in the range 18 to 20 kV. The (anode and cathode) strips collect the signals induced by the particles, providing position information along one direction. The information along the other coordinate is obtained by the time difference between the arrival of the signal at the two strip ends. Signals from left and right front-end cards are used to build a six-fold coincidence between the three chambers to provide the trigger to the data acquisition. Each event is time stamped by means of the GPS information, with a time resolution of about 40 ns. Time and space resolution of the MRPC chambers were measured by a comparison between the information provided by the bottom and top chambers with that extracted by the middle chamber. The average time residuals (over all the telescopes in the network) from this comparison gave a $\sigma_{\Delta t}$ of 238 ps. The longitudinal (along the strip direction) space resolution is 0.84 cm, while the transverse space resolution was found to be 0.92 cm, in agreement with the expected value, due to the strip pitch. 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 then more than 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. Figure **??** (left) shows a picture of this MRPC telescope.

A scintillator based detector, named POLA-01, was employed for these measurements as

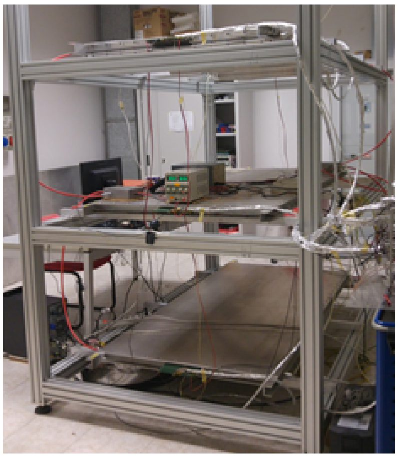


Figure 2. *Left.* Picture of CATA-01 EEE telescope, consisting in three MRPC chambers. It is located in the underground floor of the Physics Department at the University of Catania. *Right.* Scintillator-based detector built in the framework of the Polarquest project, named POLA-01. For the measurements described in this paper, the POLA-01 detector was located in various parts of the third floor of the Physics Department.

additional detector. POLA-01 is one of three equal detectors, built by students from Italy, Norway and Switzerland within the Polarquest project, to carry out cosmic ray measurements in various environments around the world. 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 x 30 cm^2, as shown in the sketch of Fig. **??**. The overall dimensions of the detector, which is enclosed in a light-tight metal box, are about 56 x 78 x 19.5 cm^3, with a weight of about 65 kg. 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. Time tagging of the events is performed by a GPS, providing absolute time stamp of each collected event with a resolution of about 20 ns. The average count rate of the POLA-01 detector at the sea level is about 30 Hz. Further details on this detector and the measurement campaigns where such detector was or will be used may be found in Ref. [**?**].

4. Data taking

During the set of measurements carried out in the spring 2019, the MRPC telescope and the POLA-01 scintillator were operated independently, each one taking data and time-stamping collected events by means of the GPS time information. Time correlation was achieved by offline analysis of the data provided by the two detectors in the same acquisition period. The absolute time of each event in the time-stamping procedure is usually obtained by the number of clock cycles elapsed since the last Pulse Per Second (PPS) precision signal derived from the satellites.

Tracks due to the same particle traversing both detectors were selected by means of cuts on the zenithal and azimuthal angles taking into account the size of the two detectors and their relative position, within a coincidence time window of $\pm$ 600 ns. Additional track quality conditions were also introduced, imposing realistic cuts on the χ^2 of the tracks being reconstructed in the EEE telescope and on the time-of-flight measured between the top and the bottom chambers.

Single-track events were selected in both detectors for this analysis, to avoid the possibility to introduce events with more than one reconstructed track. Moreover, the availability of a reliable GPS information was also imposed in both detectors.

5. Measurements and results

For each event detected in coincidence by the two detectors, the track orientation (θ, ϕ) - as reconstructed by the MRPC EEE telescope - was considered. The distribution of these variables depends on the relative position of the movable scintillator detector with respect to the EEE telescope, fixed to ground. We have to consider that due to the geometrical acceptance of the EEE telescope, i.e. zenithal angles from the vertical (θ=0) to about $\theta = 40°$, events originating from the same muon passing through both detectors may be detected only if the scintillator is placed within the acceptance cone of the reference telescope. In Fig. **??** a sketch of the relative position of detectors located in the Physics Department in Catania University is shown. 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. However, due to the possibility of detecting also two correlated muons from the same extensive air shower, we expect an additional broad angular distribution which spans a much larger angular range. This is actually observed in Fig. **??** (right), which shows the zenithal angular distribution measured with the POLA-01 scintillator 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). As it is seen from Fig. **??** (right), the main peak located at about 31° originates from the same muon track intersecting both detectors, whereas the broad distribution which extends from 0 to about 40 degrees is the contribution of two individual, time correlated muons from the same shower. When the scintillator is moved outside the acceptance cone of the EEE telescope, only the broad component may be seen, while the narrow peak disappears. An example of such situation is shown in Fig. **??** (left), corresponding to a location of the POLA-01 scintillator in the position X = -19.82 m, Y = 5.44 m at the same height Z = 15.6 m.
After a few preliminary tests, a first set of measurements was performed over a period of several weeks, with the POLA-01 scintillator shifted in various positions (ΔX = -5, -10 and -20 cm) with respect to the original location (X = -7.69 m, Y = 5.44 m). For each measurement, the number of coincident events was extracted after applying cuts in the time difference spectrum ($\pm$600 ns with respect to the centroid), in the zenithal and azimuthal angle spectra ($28° < \theta < 34°$, $200° < \phi < 230°$) and on the quality of tracks as reconstructed in the EEE telescope. The average values of the zenithal and azimuthal angles were obtained by a Gaussian fit of the narrow peaks in these spectra. To monitor possible day-to-day variations in these centroids, we

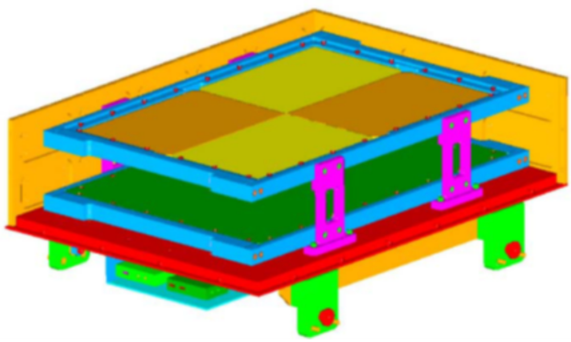

Figure 3. CAD drawing of a Polarquest detector. As described in the Text, the POLAR detectors consist in two parallel layers of plastic scintillators, each one segmented in four tiles.

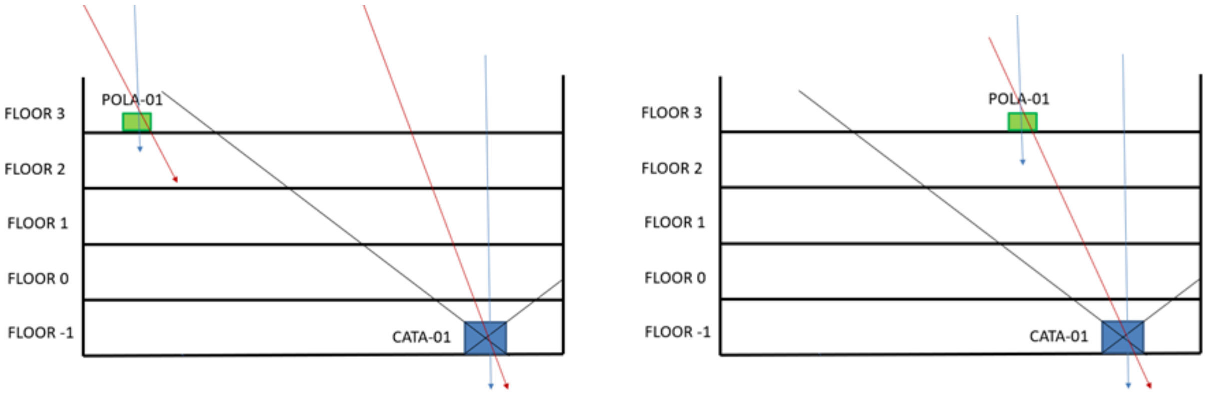

Figure 4. Sketch of the two possible configurations for the data acquisition: on the left POLA-01 is located outside the acceptance cone of CATA-01 whereas on the right it is located inside.

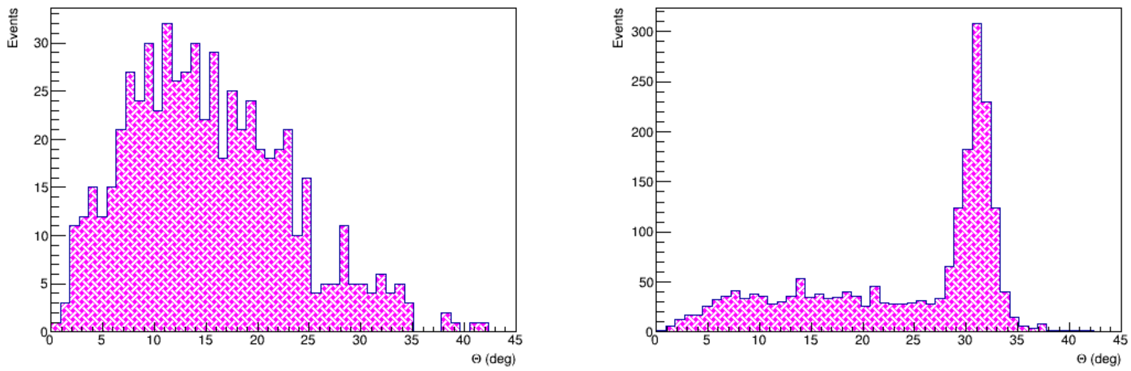

Figure 5. Zenithal angular distribution of coincident events collected using both the tracking detector CATA-01 and the scintillator POLA-01. On the left the background due to independent muons is shown, whereas on the right the peak due to events passing through both detectors lays on the background.

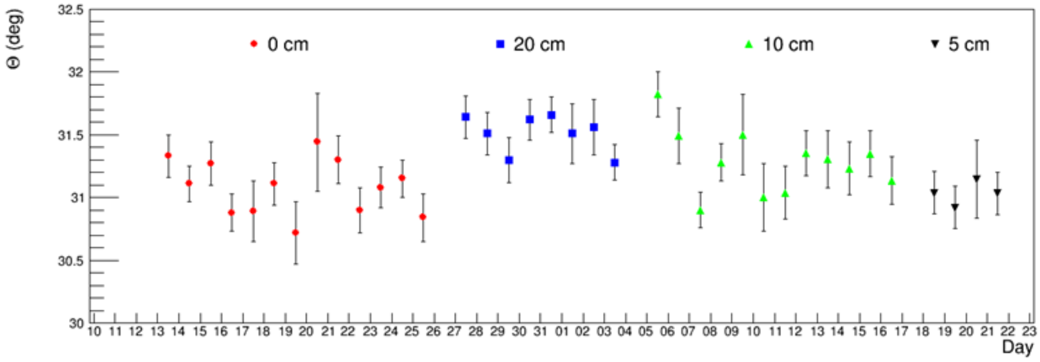

Figure 6. Day by day variation in the zenithal angular distribution.

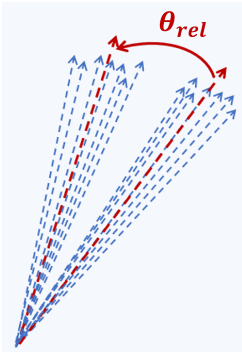

Figure 7. Sketch of the relative angle estimate.

extracted the daily average values of the zenithal angle, which are shown in Figure **??**. As it is seen from Figure **??**, while the day-to-day variations are not negligible (of the order of 0.2°), the average values obtained after only one week for each position allow to evidence some promising difference, at least in the zenithal angle, 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 (see Fig. **??** for a sketch of this relative angle estimate). In Table **??** the results of such relative 3D shifts with respect to the original position are reported. A clear shift is observed in the relative angle when a linear shift

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)	**Acquisition time (hours)**	**Relative 3D angle shift (deg)**
-5	141.7	0.31 ± 0.16
-10	288.9	0.24 ± 0.12
-20	191.7	0.44 ± 0.12

of 10 cm is introduced (from ΔX = -10 cm to ΔX = -20 cm), while, also due to the limited statistics (4 days) for the measurement carried out at ΔX = -5 cm, comparable values of the relative angle are obtained for ΔX = -5 cm and -10 cm.
This first set of measurements allows then to roughly estimate the sensitivity of the method (5–10 cm) in such (non-optimized) conditions, i.e. with a limited data taking period of the order of one week for a given position, and with a relatively small solid angle subtended by the scintillator, due to the large vertical distance and with a large X- and Y-offset between the geometrical centers of the two detectors.
The possible increase in statistics (hence improved sensitivity) 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. Optimisation of relative position

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 improve the sensitivity of the method. Muon tracks were generated with a

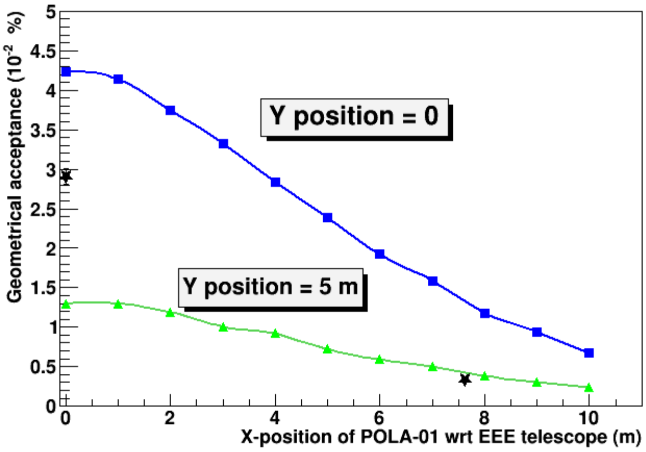

Figure 8. Detection acceptance as a function of the position of POLA-01 (along the X-direction) with respect to the EEE tracking telescope, for two different Y positions (Y = 0 and Y = 5 m). A vertical distance of 15.6 m was assumed in the simulation. The black stars show the two positions exploited during the measurements, showing an increase of roughly a factor 8 between the two acceptance values.

realistic dN/dθ = sinθ cos$^2\theta$ dependence upon the zenithal angle [**?**], and a generation vertex uniformly distributed along the active surface area of 1.58 x 0.82 m^2 of the middle chamber of the EEE telescope, whose center was assumed as the origin. For each location, the geometrical acceptance, defined as the ratio between the number of tracks passing through both detectors and the number of generated tracks, was extracted. Typical examples are shown in Figure **??**, 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, 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 exploited position. In terms of sensitivity, this means the possibility to reach a sensitivity 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, increasing the statistics of the measurement and the sensitivity of the method, an additional measurement was carried out moving the POLA-01 detector in a different position but in the same floor, thus keeping the same vertical distance. In the original location (X = -7.69 m, Y = 5.44 m) several small shifts in X (-5, -10, and -20 cm) were considered, while the second measurement was carried out for a single position (X = 0, Y = -2.5 m) of the scintillator with respect to the geometrical center of the EEE telescope, again at Z = 15.6 m (third floor of the building). Comparing the result of this measurement, which gave a number of coincident tracks of 4030 in a time interval of about $6 \cdot 10^5$ s, i.e. a rate of 6.72 mHz, with that obtained at (X = -7.69 m, Y = 5.44 m), giving an overall number of 2720 events in a time interval of about $3.4 \cdot 10^6$ s, i.e. a rate of 0.81 mHz, roughly a factor of 8 increase in the coincidence rate was obtained, in agreement with expectations from simple geometrical simulations.

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 coupled to an additional one is investigated. For this purpose one of the MRPC telescopes of the EEE project has been used as tracking detector and coupled to the scintillator detector built in the framework of the Polarquest project, i.e. POLA-01. The performance of such method has been evaluated with a first set of measurements carried out in the Physics Department of the University of Catania. Additionally, geometrical Monte Carlo simulations have been carried out in order to estimate the effect of the relative position between the detectors. It turned out that the optimal position between detectors is such that the additional detector is located closer to the vertical of the fixed tracking detector. This allows to increase the statistics by a factor at least 8 and therefore to improve the sensitivity of the method even for shorter data taking periods. In conclusion, the sensitivity of the method has been roughly estimated of the order of few mm for a data taking period of several weeks, if the relative position between the detectors has been optimized.

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