

The EEE MRPC telescopes as tracking tools to monitor building stability with cosmic muons

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ABSTRACT: This paper discusses the possibility to employ the Multi-gap 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, to reconstruct the average direction of the cosmic muon tracks passing through both devices and any small variation over long time acquisition periods. The performance of such setup is discussed and preliminary experimental coincidence results obtained with a $40 \times 60 \text{ cm}^2$ 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.

KEYWORDS: Analysis and statistical methods; Gaseous imaging and tracking detectors; Resistive-plate chambers; Simulation methods and programs

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1 Introduction

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 properties of the secondary cosmic radiation are studied since their discovery a long time ago. Apart from a detailed understanding of their energy and angular distributions, which are the result of the complex interplay between the production cross section and the interaction mechanisms with the atmosphere (including the energy loss, multiple scattering and particle decay), secondary muons have also 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 [1].

It has been suggested [2] 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. Variations of this strategy consider a single good tracking muon detector fixed to part of the structure or to the ground, and one or several additional detectors — even without tracking capabilities — fixed to the part(s) of the structure being monitored, and operated in coincidence with the tracking detector. Long-lasting measurements of the angular distribution of the cosmic muons passing through the tracking telescope and one of the additional detectors may give information on

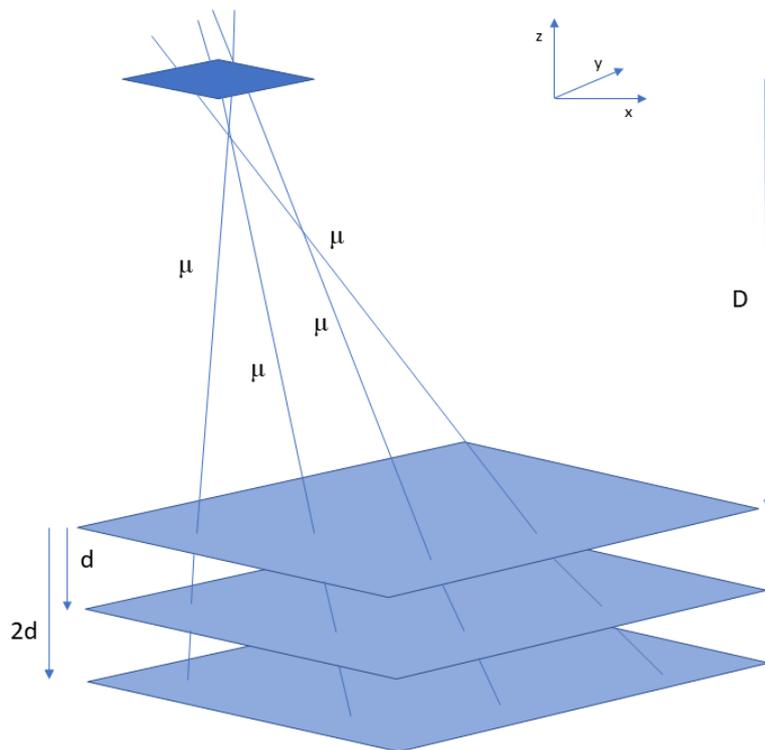


Figure 1. Geometrical sketch illustrating the technique, with coincident muons passing through a tracking telescope made by three position-sensitive planes and one or more additional detectors located some distance apart.

possible shifts in the relative position of the two devices, thus evidencing long term instability of the structure. Figure 1 shows a sketch of a possible implementation of this strategy.

This possibility 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 [3–6] and applied to the problem of monitoring an important historical building, Palazzo della Loggia in Brescia (Italy), built in 1574, as a case study. This site is monitored since several decades by means of different techniques, due to large deformations observed in the wooden vault over the years. 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 recently been tested [6].

Possible drawbacks 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. Last, but not the least, the intrinsic stability of all main detection components (detector tracking efficiency, electronics stability, . . .) over long measurement periods is also 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 [7] 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. Few of them are also operating at CERN and in Physics Departments and INFN sites. The work organized by the use of such extended array is contributing to advanced educational activities involving thousands of students and high school teachers every year. Physics analyses of the collected data have also been carried out, to investigate several aspects of the secondary muon flux, including the study of Forbush variations [8, 9], the detection of extensive air showers [10, 11], the investigation of possible anisotropies at the sub-TeV scale [12], the measurement of upward-going particles [13] and the search for long distance correlations between detectors located hundred km apart [14, 15].

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 $40 \times 60 \text{ cm}^2$ sensitive area, which was located at the third floor of the building, 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. Measurements were performed in various locations during a period of approximately two months.

The present paper reports the results obtained from this preliminary investigation, together with Monte Carlo simulations to understand and improve the experimental running conditions. Section 2 describes the experimental setup, briefly recalling the working principles and the parameters of the EEE MRPC telescopes, which have been already presented in detail in other papers, and the basic operation of the additional scintillator (POLA-01) used for this investigation. Section 3 reports the experimental results and their analysis, while section 4 shows some results from Monte Carlo basic and GEANT calculations for the operating condition of this investigation. Some conclusions and outlook is discussed in the final section of the paper.

2 Experimental setup

2.1 The EEE MRPC telescopes

The cosmic ray telescopes employed by the EEE Collaboration have been described in detail in many previous papers [16–21]. Recently, a review of the overall performance of such devices has been published [22]. The basic structure of each telescope includes three Multi-gap Resistive Plate Chambers (MRPC), with $158 \times 82 \text{ cm}^2$ 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, 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. Fire-retardant epoxy glass fabric laminate (FR4) panels with 24 copper strips (25 mm wide, separated by 7 mm) are placed at the two outer surfaces. 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, which is measured by commercial VME TDCs, with a time bin of 100 ps. 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 was measured during a beam test performed at CERN, obtaining a value of 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 depend 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 2 (left) shows a picture of this MRPC telescope.

2.2 The POLA-01 detector

A scintillator based detector, named POLA-01, was employed for these measurements carried out in the same building as for the EEE telescope. POLA-01 is one of three equal detectors, built by students from Italy, Norway and Switzerland within the Polarquest project [23], 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 $20 \times 30 \text{ cm}^2$. The overall dimensions of the detector, which is enclosed in a light-tight metal box, are about $56 \times 78 \times 19.5 \text{ cm}^3$, with a weight



Figure 2. Pictures of the EEE telescope employed for the present investigation (left) and of the POLA-01 detector (right), while taking data during an outdoor session.

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 [24]. 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. Due to its low power consumption, the detector may be operated with a backup battery (with a few hours autonomy) when used far from the electrical power. Data are transmitted over the Internet wherever available and are collected in the INFN CNAF computer center, as for all the data collected by the EEE network. 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. [25].

The POLA-01 detector was actually employed in 2018 during a two-months scientific expedition on board of a 18 m-long special boat (Nanuq), circumnavigating the Svalborg archipelago, after leaving from Isafjoudur (Iceland) and arriving in Tromso (Norway). Presently, POLA-01 has also been employed for a variety of measurements in a wide range of geographical latitudes, from 82° N to 35° N [25] and at different altitudes above the sea level. Moreover, the installation of this and the two twin detectors for long duration measurements of extensive air showers in the Ny Alesund base (Norway), is in progress, as part of a long term educational and scientific activity of the EEE Collaboration.

3 Measurements and analysis

3.1 Running conditions

During this set of measurements, 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 off-line analysis of the data provided by the two detectors in the same acquisition period. The absolute time of each event in the time-stamping

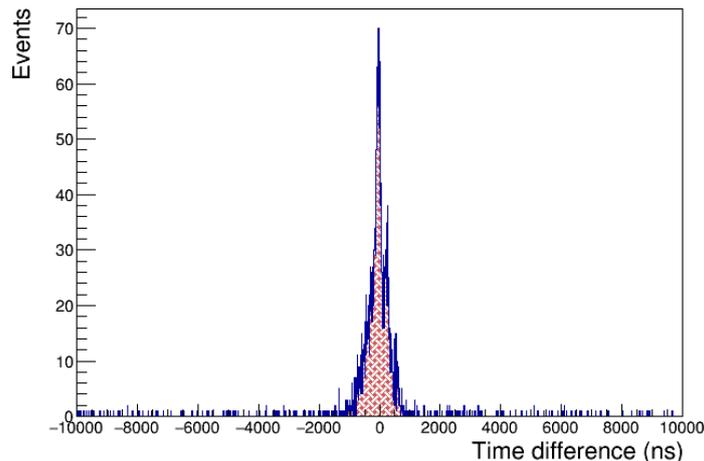


Figure 3. A typical time difference spectrum between the POLA-01 scintillator and the CATA-01 MRPC telescope, after correction for the drift of the internal clock of the Raspberry microcomputer and track selection (see text). A Gaussian fit of the overall distribution gives a σ of about 250 ns.

procedure is usually obtained by the number of clock cycles elapsed since the last Pulse Per Second (PPS) precision signal derived from the satellites. This signal, which is present in most of the GPS timing units, allows to synchronize, through its sharp rising or falling edges, the internal clock of the board being used, aligning it once per second to the UTC time provided by the satellites. The precision in the time stamp assigned to each event will be then determined within each second by the performance of the local clock. The time resolution of the difference between the two coincident signals is largely determined in this case by any variation in the clock frequency, which should be checked every second. To partly compensate the drift of the clock, a linear correction has been introduced for the events being collected by the POLA-01 scintillator, considering the average measured drift of the clock between each synchronized PPS provided by the satellite information. This allowed to reduce the intrinsic resolution (about 3 μ s) by a factor larger than 10. Figure 3 shows a typical spectrum of the corrected time difference between the EEE telescope and the POLA-01 scintillator, placed at about 15 m vertical distance in different floors of the building. 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.

3.2 Experimental results and analysis

To correlate the events collected by the two detectors, a coincidence time window of ± 600 ns was considered. 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.

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 depend on the relative position of the movable scintillator detector with respect to the EEE telescope,

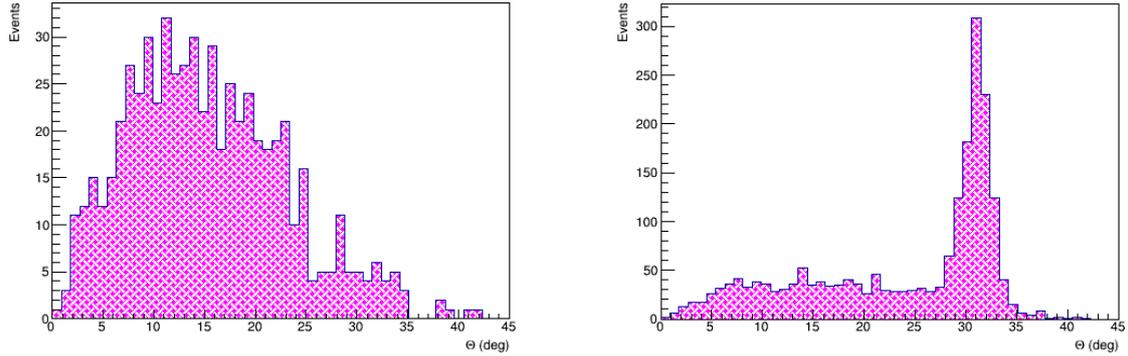


Figure 4. *Left:* zenithal angular distribution of two independent tracks measured in coincidence by the two detectors. The relative position of the POLA-01 scintillator was ($X = -19.82$ m, $Y = 5.44$ m, $Z = 15.6$ m) with respect to the center of the middle chamber of the EEE reference telescope, i.e. outside its acceptance cone. Only a broad distribution is seen, with a shape which reflects the zenithal angular acceptance of the EEE telescope. *Right:* zenithal angular distribution of coincident tracks. The relative position of the POLA-01 scintillator was ($X = -7.69$ m, $Y = 5.44$ m, $Z = 15.6$ m) with respect to the center of the middle chamber of the EEE reference telescope, within the acceptance cone of the EEE telescope. The main peak located around $\theta = 31^\circ$ originates from tracks passing through both detectors.

fixed to ground. We have to consider that due to the geometrical acceptance of the EEE telescope, i.e. zenithal angles from the vertical ($\theta = 0$) to about $\theta = 40^\circ$, 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 such a 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 figure 4 (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 figure 4 (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° 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 figure 4 (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. The two measurements shown in figure 4 have been performed with different durations, hence their yields cannot be directly compared. Similar considerations apply also to the azimuthal angular distributions measured outside and inside the acceptance cone of the EEE telescope, shown in figure 5.

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 ($\Delta X = -5, -10$ and -20 cm) with respect to the original location ($X = -7.69$ m, $Y = 5.44$ m). Table 1 shows a summary of

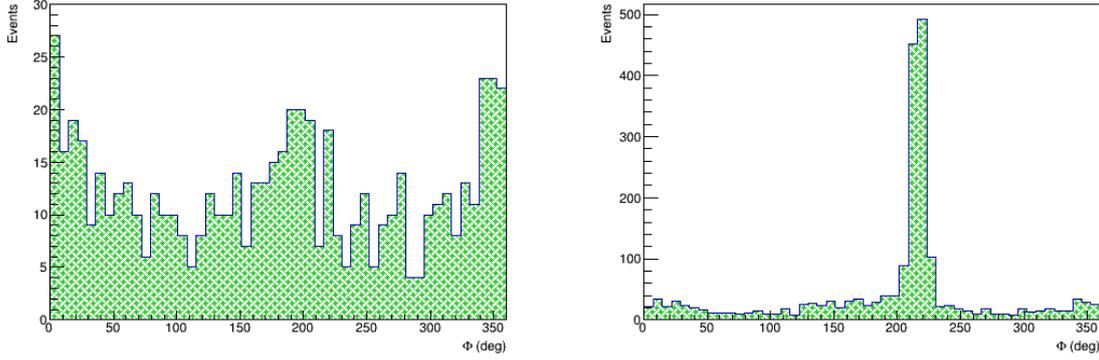


Figure 5. As in figure 4, for the azimuthal angle distribution. *Left:* zenithal angular distribution of two different tracks measured in coincidence by the two detectors, outside the acceptance cone. *Right:* zenithal angular distribution of coincident tracks, showing also the contribution of muons passing through both detectors.

Table 1. Summary of the measurements performed by moving the POLA-01 scintillator with respect to the EEE telescope. In the first column, the location reports the shift with respect to the original position ($X = -7.69$ m, $Y = 5.44$ m). Columns 4 and 5 report the observed shifts in the zenithal and azimuthal angle distributions, as obtained by a Gaussian fit of the corresponding peak. Last column shows the value of the 3D relative angle shift between the average direction of all tracks measured for each location.

Δx shift w.r.t original position (cm)	Measure time (hours)	Number of coincident events	Average zenithal angle (degrees)	Average azimuthal angle (degrees)	Relative 3D angle shift w.r.t. original position (degrees)
0	311.1	990	31.03 ± 0.05	216.39 ± 0.16	n/a
-5	141.7	309	31.18 ± 0.07	215.88 ± 0.33	0.31 ± 0.16
-10	288.9	705	31.36 ± 0.08	215.98 ± 0.30	0.24 ± 0.12
-20	191.7	716	31.45 ± 0.06	215.67 ± 0.20	0.44 ± 0.12

these measurements. For each measurement, the number of coincident events was extracted after applying cuts in the time difference spectrum (± 600 ns with respect to the centroid), in the zenithal and azimuthal angle spectra ($28^\circ < \theta < 34^\circ$, $200^\circ < \varphi < 230^\circ$) 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 extracted the daily average values of the zenithal angle, which are shown in figure 6.

As it is seen from table 1 and from figure 6, 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, we evaluated the vector sum of all selected tracks for each given position k , identified by (θ_k, φ_k) and considered the 3D relative angle with respect to the reference orientation (θ_0, φ_0) in the original position:

$$\Theta_{\text{rel}} = \sin \theta_k \sin \theta_0 + \cos \theta_k \cos \theta_0 \sin(\varphi_0 - \varphi_k)$$

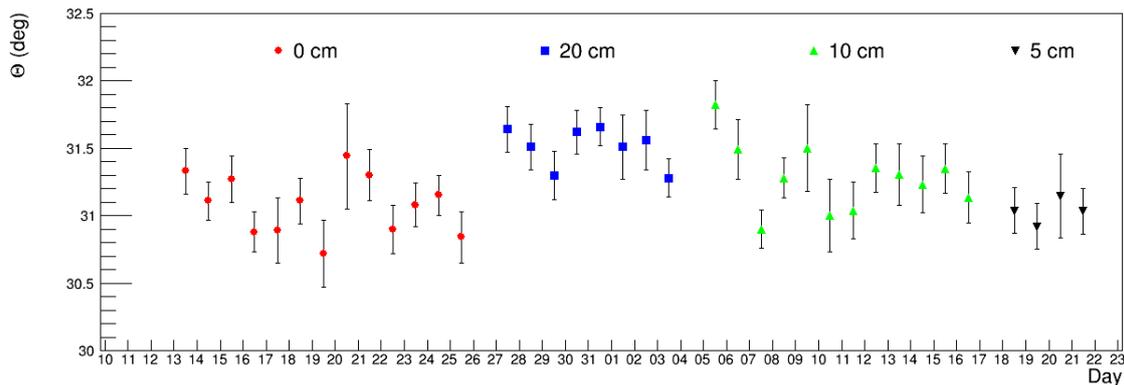


Figure 6. Daily variation of the average value of the zenithal angle. The different datasets refer to the measurements carried out for several positions (along X) of the POLA-01 scintillator with respect to the original location ($X = 0, -5, -10$ and -20 cm).

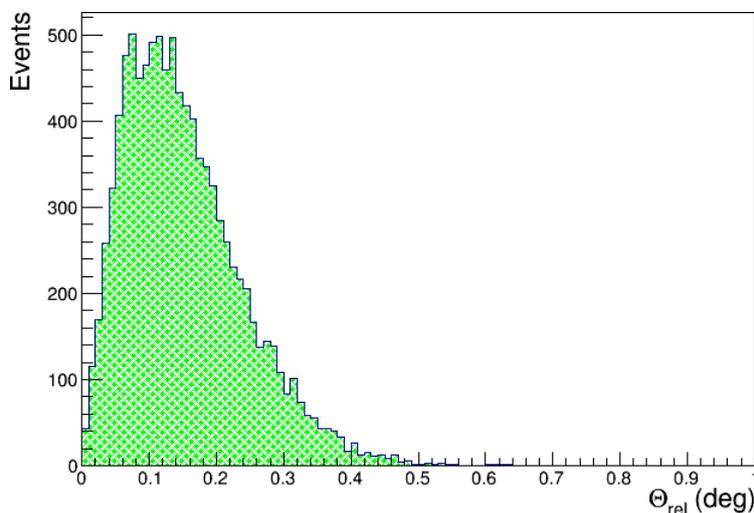


Figure 7. Distribution of the relative angle between the average direction of the tracks, as estimated from two independent subsets of the dataset obtained in the original position, each containing 50% of the tracks.

The values of these relative angles are reported in table 1 (last column). To estimate the uncertainty in this relative angle, for each location we split the overall set of N reconstructed tracks into two subsets, each containing half of the tracks ($N/2$), and evaluated the average direction of the tracks belonging to each subset. Considering the difference between the two directions, as independently estimated from the two subsets, and randomly generating a large number (10^4) of such subsets, we built the distribution of these differences (figure 7), which allows to estimate the error, taking into account the average value of such distribution and the number of tracks $N/2$ belonging to each subset.

From the results shown in table 1 (last column) it may be seen that 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 (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 (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 an additional measurement carried out in a different position of the POLA-01 scintillator, still 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 6×10^5 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 3.4×10^6 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 (see next section).

4 Simulation results

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 realistic $dN/d\theta = \sin\theta \cos^2\theta$ dependence upon the zenithal angle [26], and a generation vertex uniformly distributed along the active surface area of 1.58×0.82 m² of the middle chamber of the EEE telescope, whose center was assumed as the origin. Tracks intersecting the top and bottom chambers of the EEE telescope, located at $z = 0.8$ m and $z = -0.8$ m respectively, were considered to further evaluate their intersection with the sensitive area of the POLA-01 detector (size 40×60 cm²), for various (X_P, Y_P, Z_P) position of its center. For each location, the geometrical acceptance, defined as the ratio between the number of generated tracks and the number of tracks passing through both detectors, was extracted. Typical examples are shown in figure 8, 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.

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 different layers of concrete to go from the third floor, where the

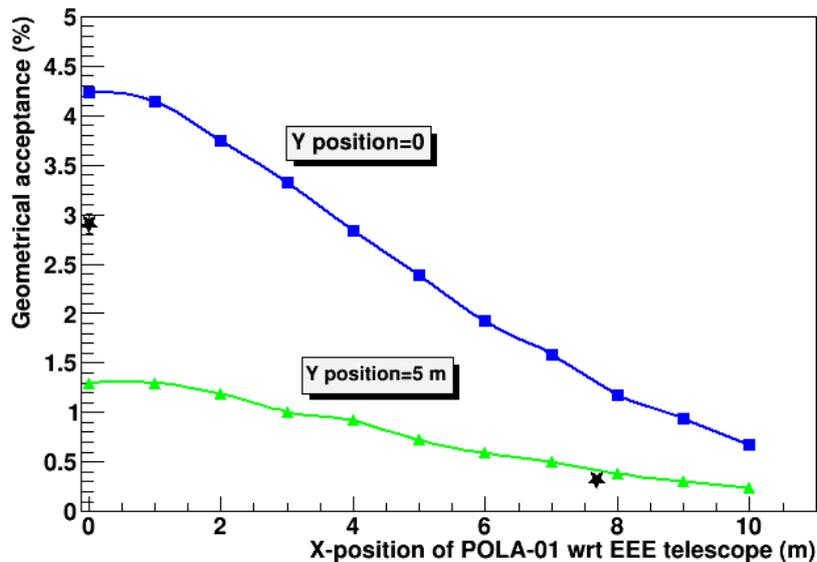


Figure 8. Detection acceptance as a function of the position of POLA-01 (along the X-direction) with respect to the EEE tracking telescope, for two different Y positions ($Y = 0$ and $Y = 5$ m). A vertical distance of 15.6 m was assumed in the simulation. The black stars show the two positions exploited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

scintillator was located, down to the underground floor which hosts the EEE telescope. The effect of the thin walls separating the various environments inside the building was considered less critical in this respect. Multiple scattering effects were evaluated by GEANT simulations, assuming a realistic composition of the material, for several muon momenta (from 1 to 4 GeV/c), as a function of the traversed thickness. Results are shown in figure 9. Even though the overall thickness of a layer separating two floors in a building is of the order of 30 cm, the concrete-equivalent solid thickness is much lower than this, and it can be estimated that 60 cm correspond to traversing four layers. For an average momentum of 3–4 GeV/c, as for cosmic muons at sea level, this correspond to about 0.1° – 0.2° , which is comparable to the uncertainty observed in our measurements.

5 Conclusions

Coincidence measurements between a muon tracking detector located in the underground basement and a scintillator-based detector placed in various positions at the last floor of the building, at about 15 m vertical distance from the muon tracker, were carried out for a period of several weeks, with the purpose of investigating the experimental conditions to monitor long term stability of civil structures. The work was carried out under realistic limitations of such technique, which has to take into account the difficulties of placing detectors in specific locations inside a building which is primarily employed for other purposes and the presence of large amount of solid material between the detectors (concrete layers, walls, . . .). Preliminary results point out that even with such limitations, it is possible to observe small shifts of the movable detector with respect to the tracking device, of the order of a few mm, in a reasonable data taking period (several weeks), especially if some optimization may be achieved concerning the location of the two detectors. EEE MRPC

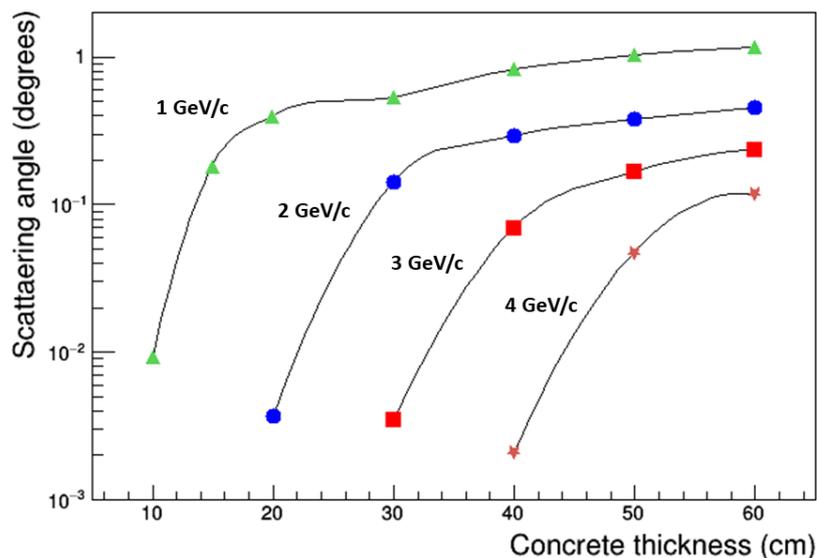


Figure 9. Scattering angle of cosmic muons after traversing a given thickness of concrete, as due to the different layers separating the floors in the building.

telescopes turn out to be a realistic choice as muon tracking devices, due to their good tracking performance, high detection efficiency and close to 100% duty cycle. A scintillator with a sensitive area ($40 \times 60 \text{ cm}^2$) such as that employed in the present investigation was also seen to be adequate to carry out such investigation over long data taking periods, due to the high efficiency and operational conditions. The measurements also demonstrated that an off-line coincidence may be achieved by tagging the events independently collected by the two detectors, by means of GPS synchronization. This is another interesting aspect, since at least one of the detectors (or maybe both) could be employed as stand-alone devices or for other physical investigations. This is the case for instance of the EEE telescopes, which take data all the year, where off-line coincidences with additional detectors do not disturb in any way the usual data taking process. Since most of the EEE telescopes are presently located inside school buildings, the addition of one or several small scintillators with good capabilities in the same building could offer in principle a further contribution to the EEE activities in the school.

Several improvement of this technique may be discussed, depending on the possibility to build and install a larger number of secondary detectors or to employ secondary detectors with tracking capabilities in itself, or even to place more than one detector along the same acceptance cone, thus intersecting muon tracks passing through three or more detectors. Detecting smaller movements of the building structure would imply either longer time measurements or even better tracking capabilities, which are in any case limited by the possible amount of multiple scattering along the muon path. Although all the MRPC chambers presently in operation within the EEE project have the same geometrical structure and strip granularity, one could also consider in the future to develop new chambers especially devoted to such applications, with a better granularity — hence a larger number of readout channels — so as to achieve an even better angular resolution.

Due to the small values of the expected angular shifts in normal operating conditions, a large effort must be undertaken to keep under control all the working parameters of the detectors,

especially those which could produce an apparent shift of the overall angular distributions of muon tracks. Seasonal effects, as well as small variations of the Earth magnetic field could influence in principle the average track direction defined in a certain data taking period. Most of these effects however may hopefully be investigated by inclusive measurements taken with the tracking device operating in stand-alone mode, thus evaluating and correcting for variations due to these external causes.

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References

- [1] P. La Rocca, D. Lo Presti and F. Riggi, *Cosmic ray muons as penetrating probes to explore the world around us*, in *Cosmic Rays*, Z. Szadkowski ed., InTechOpen (2018).
- [2] I. Bodini et al. *Cosmic ray detection based measurement systems*, *Meas. Sci. Technol.* **18** (2007) 3537.
- [3] A. Donzella et al., *Historical building stability monitoring by means of a cosmic ray tracking system*, *Nuovo Cim.* **C37** (2014) 223.
- [4] A. Zenoni, *Historical building stability monitoring by means of a cosmic ray tracking system*, in the proceedings of the *Advancements in Nuclear Instrumentation Measurement Methods and their Application (ANIMMA2015) conference*, April 20–24, Lisbon, Portugal (2015).
- [5] G. Bonomi, *Muons: civil applications*, *PoS(Bormio2015)039*.
- [6] G. Bonomi, *Monitoraggio della stabilità degli edifici storici*, talk given at the *Giornate di Studio sulla Radiografia Muonica (GSRM 2018)*, October 29–30, Florence, Italy (2018).
- [7] www.centrofermi.it
- [8] EEE collaboration, *Observation of the February 2011 Forbush decrease by the EEE telescopes*, *Eur. Phys. J. Plus* **126** (2011) 61.
- [9] EEE collaboration, *Results from the observation of Forbush decreases by the Extreme Energy Events experiment*, *PoS(ICRC2015)097*.
- [10] EEE collaboration, *First detection of extensive air showers with the EEE experiment* *Nuovo Cim.* **125 B** (2010) 243.
- [11] EEE collaboration, *Time correlation measurements from extensive air showers detected by the EEE telescopes*, *Eur. Phys. J. Plus* **128** (2013) 148.
- [12] EEE collaboration, *Looking at the sub-TeV sky with cosmic muons detected in the EEE MRPC telescopes*, *Eur. Phys. J. Plus* **130** (2015) 187.
- [13] EEE collaboration, *A study of upward-going particles with the EEE telescopes*, *Nucl. Instrum. Meth.* **A 816** (2016) 142.
- [14] EEE collaboration, *Time and orientation long distance correlations between extensive air showers detected by the MRPC telescopes of the EEE project*, *Nuovo Cim.* **C40** (2017) 196.

- [15] EEE collaboration, *Search for long distance correlations between extensive air showers detected by the EEE telescopes*, *Eur. Phys. J. Plus* **133** (2018) 34.
- [16] EEE collaboration, *Extreme Energy Events project: construction of the detectors and installation in Italian high schools*, *Nucl. Instrum. Meth. A* **588** (2008) 211.
- [17] EEE collaboration, *The EEE project: cosmic rays, multigap resistive plate chambers and high school students*, *2012 JINST* **7** P11011.
- [18] EEE collaboration, *A multigap resistive plate chamber array for the EEE project*, *2014 JINST* **9** C10024.
- [19] EEE collaboration, *Recent results and performance of the multigap resistive plate chambers network for the EEE Project*, *2016 JINST* **11** C11005.
- [20] EEE collaboration, *The EEE Project: a sparse array of telescopes for the measurement of cosmic muons*, *2016 JINST* **11** C12056.
- [21] EEE collaboration, *Operation and performance of the EEE network array for the detection of cosmic rays*, *Nucl. Instrum. Meth. A* **45** (2017) 383.
- [22] EEE collaboration, *The Extreme Energy Events experiment: an overview of detector performance*, *2018 JINST* **13** P08026.
- [23] <http://www.polarquest2018.org/>
- [24] <https://www.raspberrypi.org/>
- [25] R. Nania and O. Pinazza, *Measuring cosmic ray showers near the North Pole with the Extreme Energy Events Project*, *Nuovo Sagg.* **34** (2018) 27.
- [26] P.K.F. Grieder, *Cosmic rays at Earth*, Elsevier, Amsterdam The Netherlands (2001).