

# A reconfigurable scintillator-based small array facility for cosmic ray studies

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**Abstract.** The first operational tests of a low-cost, reconfigurable mini-array for cosmic rays are here reported. Such facility is intended mainly as an educational tool for master and PhD students, to carry out quantitative investigations in cosmic ray physics. Each detection module is based on a small scintillator tile, optically coupled to a Wavelength Shifter (WLS) bar and a Silicon photomultiplier for light collection and readout. An Arduino MEGA board is used for trigger, data acquisition and storage. GPS time stamping of the events is also provided. The tests carried out with a set of 30 detection modules, spread over an area of about 50 m<sup>2</sup>, are here reported. About 300k shower events were collected during a period of 13 days, with a trigger involving at least a three-fold coincidence between the modules. Individual rates of the modules, together with environmental data (pressure and temperature) were also measured along the acquisition period. Multiplicity distributions in stand-alone mode and in coincidence with an additional detector located some distance apart were extracted from the data. The dependence of the shower rate on the atmospheric pressure was also investigated.

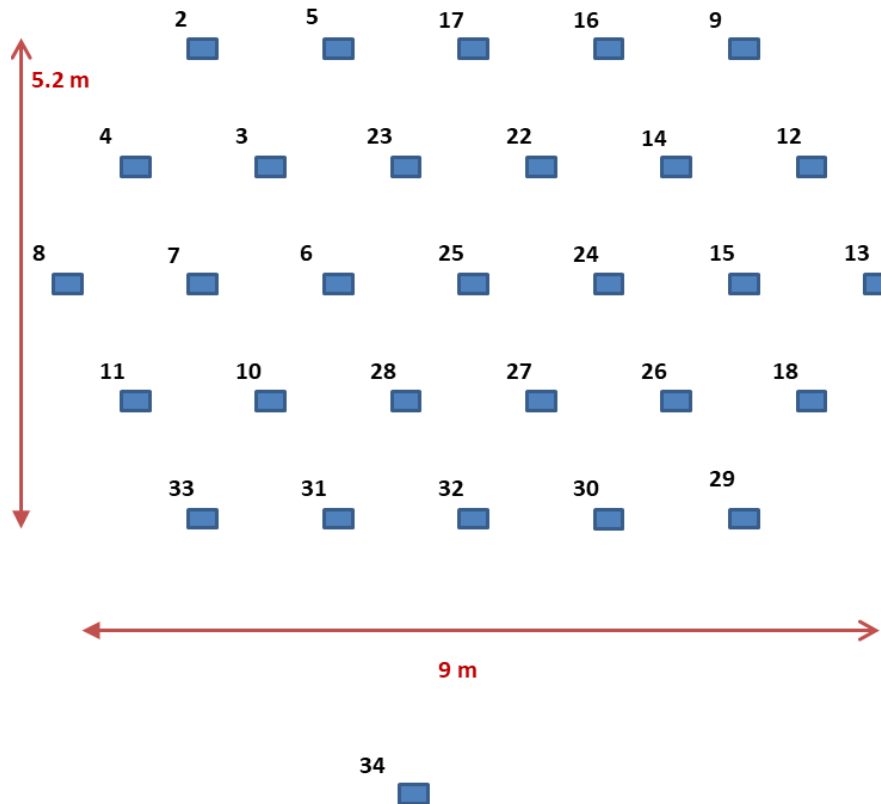
## 1. Introduction

Coincidence measurements between cosmic ray detectors placed some distance apart are the standard way to detect extensive air showers created in the Earth atmosphere by the interaction of a high energy primary particle [1]. A sparse array of detectors is able to detect showers with various average energies, depending on the relative distance between detectors. Various strategies have been employed over the years to build and operate small cosmic ray arrays, mainly for educational purposes [2]. Compact arrays would probe the low energy region of the energy spectrum of primary particles. In this Project we tried to exploit the potential of a detection configuration based on the use of small area individual detectors, which could be easily re-configured in different detection geometries and employed for various investigations. An important aspect of this Project is the educational activity which is being planned for undergraduate and graduate students in cosmic ray physics, together with the outreach and citizen science involvements.

Due to the requirement of a low cost project, technical solutions which do not make use of expensive detectors or commercial electronics were adopted. A description of the individual detection module, with various tests carried out with different Silicon Photomultipliers and under different conditions has been already reported [3]. GEANT4 simulations of the transport of photons inside the scintillators and the WLS fibers have been carried out [4] with the aim to optimize the working conditions of the detector and compare different light collection strategies.



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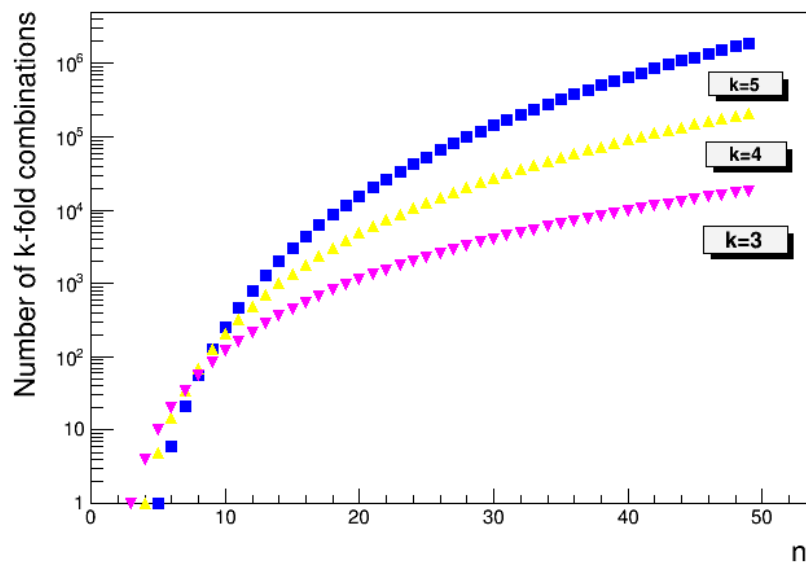
**Figure 1.** Geometry of the array employed during the commissioning measurements of this facility: modules were distributed over an approximate area of  $50 \text{ m}^2$  according to a hexagonal pattern with a distance of 1.5 m between close detectors. The labels report the ID number of each module, corresponding to the Arduino digital inputs. The array was installed in a big lecture hall of our Department, taking data for about two weeks.

In this paper we will concentrate on the organization of the array as a whole and on the first commissioning measurements.

## 2. Detection geometry

The geometrical configuration of an array of detectors, i.e. their number and relative locations, is a key factor to evaluate the performance of the setup for studies of extensive air showers [1]. Regular geometrical patterns (such as for instance hexagonal or squared lattices) have been widely used. The distance between close detectors determines the granularity, the overall size of the array and the average energy of the showers being detected. The relative distance between close detectors may vary from a few meters for small arrays to more than 1 km for large and extended arrays.

The number of possible coincidence configurations of  $k$  modules is shown in Figure 1 as a function of the number  $n$  of modules. Figure 1 shows how such number increases very fast with the number of modules. For instance, while for  $n=10$  the number of possible four-fold coincidences is 210, for  $n=30$  such number exceeds  $10^4$ . This is the basis to explain why even if the probability to measure a  $k$ -fold coincidence between  $k$  given detectors is very small, the



**Figure 2.** Number of  $k$ -fold possible combinations ( $k=3, 4, 5$ ) between  $n$  modules, as a function of  $n$ . More than  $10^4$  4-fold combinations are obtained with  $n=30$ .

overall effect of many detector combinations allows to measure a reasonable number of events.

With the present number of detectors in this Project (30), a high number of three-fold, four-fold and higher-order combinations is then accessible, thus allowing to detect a reasonable number of events even with small size individual detectors, distributed within an overall coverage area of hundreds square meters.

The present measurements were done by the use of 30 modules arranged in a hexagonal geometry over an approximate area of  $50 \text{ m}^2$ . To keep a correspondence with the digital inputs employed in the Arduino-based acquisition system, modules were labelled from 2 to 18 and from 22 to 34, whereas inputs 0, 1 and 19-21 were reserved for other purposes (see next Section). For all modules, except module 34, the distance between close detectors was 1.5 m.

### 3. Description of the array

The proposed setup is organized as an easily reconfigurable mini-array of detectors made by small size individual detection modules. In the present stage of the project a simple digital readout of the hit modules has been employed, which allows for a reconstruction of the geometrical pattern of each detected event with its occurrence probability, complemented by a time tagging of the event obtained by the GPS time information. For this task, low cost solutions were exploited both for the detectors and front-end electronics, as well as for the trigger, time-stamping of the events and data acquisition and storage. For each detection module, these basic components were installed in a light-tight black box (approximate size  $40 \times 30 \times 13.5 \text{ cm}^3$ ): the scintillator tile and the WLS bar wrapped with aluminized tape, the Silicon Photomultiplier, a discriminator/shaper board and a power supply board providing the 5V to the amplifier and discriminator boards.

#### 3.1. Detectors and photosensors

Each detection module makes use of a small size ( $20 \times 20 \times 1 \text{ cm}^3$ ) scintillator tile coupled to a Wavelength Shifter (WLS) bar ( $20 \times 1 \times 1 \text{ cm}^3$ ) through one of its lateral sides. Extruded scintillators and WLS bars were used. The scintillator and the WLS bar were wrapped either

with an aluminized Mylar foil, or with *Al* adhesive tape. A single Silicon Photomultiplier (SiPM) was optically coupled to the WLS bar, to collect the light. A detailed description of the properties of these materials has been reported in a previous paper [4], where fully GEANT4 simulations were carried out with the aim of evaluating the light collection efficiency under various detection configurations and study the influence of different key factors on the average number of collected photons per event. Detection modules were fully characterized under different conditions, and the individual efficiency of each module was measured with respect to a three-fold coincidence trigger given by other detectors of the same size assembled in a telescope configuration [3]. Apart from the first prototypes, which were equipped with smaller size SiPM, for most of the modules the detection efficiency was found to be larger than 90%.

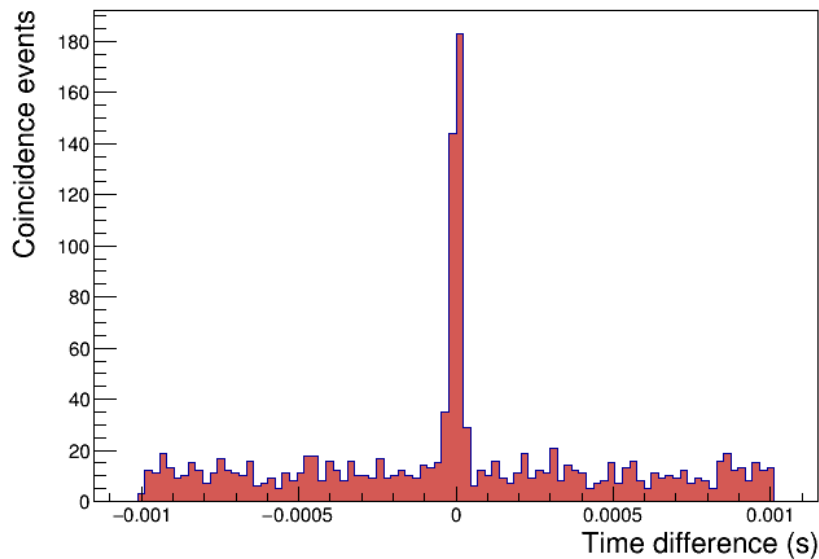
### 3.2. Electronics and data acquisition

The signal from each SiPM is sent to a trans-impedance fast amplifier. After amplification, the signal is sent to a discriminator/shaper to produce a TTL shaped logic pulse, whose width was adjusted to about 100 microseconds. This rather long duration of the output signal has been chosen to match the time required for the sequential readout of a large number of channels by the Arduino board (of the order of 1 microsecond/channel), in order not to lose true coincidence events from different detectors even when a long series of digital readouts must be carried out. Shaped TTL signals from each detection module were sent to the digital inputs of Arduino through a concentration box, which may handle up to 50 inputs by BNC panel connectors. Since the board has 54 digital inputs, able to accept TTL (+5V) signals, this is a low cost solution, able to combine the signals from several detection units and set an easily customizable software trigger, collecting a pattern of digital values which identify the topology of the coincidences being detected.

In the sequence of Arduino digital channels, some of them are dedicated to specialized operations (for instance the communication to the PC, the handling of the 1 PPS GPS signal and the connection to pressure and temperature sensor making use of the I2C protocol), so they were skipped in the readout sequence, by a proper labeling of the input channels. After the fast readout of all channels, a time stamp of the event is obtained through the information provided to Arduino by an external GPS engine (see next subsection for details), and the channel multiplicity  $m$  (i.e. the number of channels which presented a low-to-high transition in each event) is built. A software trigger may then be defined, which allows to validate and store the event on the basis of the channel multiplicity (for instance triggering on events with  $m > 2$ , i.e. at least three-fold coincidences) or selecting specific patterns of detection configurations. A binary pattern of the hit modules in each triggered event is then written on file, together with its time stamp (date, seconds and nanoseconds during the day).

### 3.3. GPS time stamping of events

For the purpose of identifying the arrival time of the events of interest and correlate them to those measured from other detectors, we also provided a GPS time stamping to each detected event. A GPS module providing the UTC time in NMEA format and the 1 PPS (Pulse Per Second) signal was used, with an external antenna which was attached to one of the external walls of the building. The 1 PPS signal was sent to one of the Arduino digital inputs using the interrupt procedure available on the Arduino board, in order to synchronize the internal clock every second with the satellite information. Within the second, the event time was estimated by the internal 16 MHz Arduino clock. Since the frequency of the Arduino clock, which is based on a ceramic resonator, may drift by large amounts over long time intervals, also due to temperature variations, the actual value of the frequency is continuously checked against the 1 PPS signals from GPS satellites over the previous second and taken into account to estimate the duration of the time clock on a second-by-second basis. A check of the overall time resolution was done



**Figure 3.** Time difference spectrum between the events tagged by the (Arduino+GPS) board and those detected from an additional detector placed about 20 m apart, taking data with its own GPS.

during these commissioning tests by an offline time correlation between the events collected with our setup and cosmic events detected by an additional detector with its own precision GPS unit, able to tag the events with a resolution of about 40 ns, and placed at about 20 m distance. Fig.3 shows the time difference spectrum between the two detectors, showing a peak at  $t=0$ , superimposed to the background originating from random coincidences. An acquisition time of about 145 ks was used for this coincidence measurement, during which about 400 events were observed, once the background due to spurious coincidences was subtracted. The RMS of the peak has a value of about 15 microseconds. This gives a typical performance which can be achieved when looking to coincidences with other detectors.

#### 3.4. Acquisition and analysis software

Event-by-event data are written on a text file. Each event line includes the multiplicity, the binary pattern of the 30 modules, the date (in DDMMYY format) and the time (in HHMMSS.NNNNNNN format, with 7 decimal digits corresponding to 100 ns resolution). Info data lines, which are written every 30 minutes include a status flag from GPS, the number of satellites seen, the date and time, the temperature, atmospheric pressure and the individual count rates of all detection modules, averaged over an interval of 60 seconds. For subsequent analysis, a ROOT macro was used to produce a file including two trees, one with the event-by-event data (event time, multiplicity, detection pattern, and the first channel which was fired in each event), and the other containing the temperature, atmospheric pressure, number of GPS satellites seen and the 30 individual counting rates, measured in steps of 30 minutes.

#### 4. Preliminary measurements with the mini-array

Several commissioning measurements were carried out, with different geometrical configurations of the array and various electronics settings, so as to check the overall working conditions of the setup. In the present paper we mainly discuss some of the results obtained with an overall

number of 30 modules, arranged in a hexagonal configuration, as described in Sect.2 (Fig.1).

#### *4.1. Running conditions*

The measurements were carried out for a total of about 13 days. Out of the 30 modules, 21 modules were equipped with  $6 \times 6 \text{ mm}^2$  low dark current SiPMs, resulting in detection efficiencies close to 100%, whereas 9 modules were still working with the old  $4 \times 4 \text{ mm}^2$  devices, with a somewhat smaller efficiency. Temperature and atmospheric pressure were also measured in time steps of 30 minutes along all the 13 days period, in order to investigate the dependence of individual and coincidence rates on these parameters.

#### *4.2. Detection of extensive air showers*

The coincidence between different modules in the array allows to detect the arrival of an extensive air shower. The acquisition trigger during this run was set to measure at least a three-fold coincidence between all modules. Taking into account the number of possible threefold combinations (4060) out of 30 detection modules, an overall spurious rate of 0.06 Hz is estimated, to be compared with an overall experimental trigger rate of 0.30 Hz, mainly originating from triple coincidences, which have a trigger rate of 0.25 Hz. Coincidences with multiplicity  $m > 3$  are virtually free from spurious contribution.

#### *4.3. Multiplicity distributions*

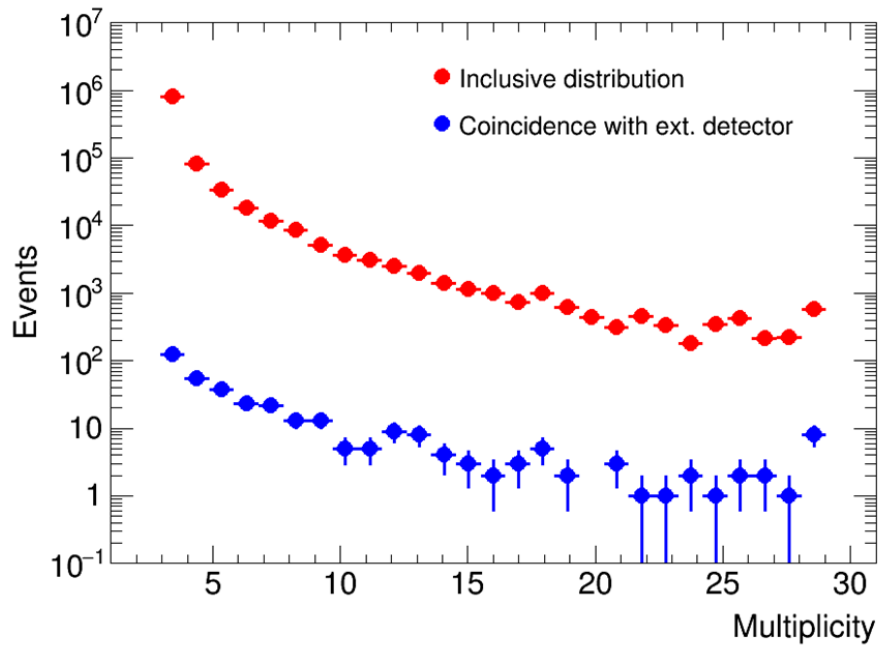
The raw multiplicity distribution of the collected events in this run is shown in Fig.4. Coincidences involving even a large number of modules, up to the maximum allowed multiplicity, were observed. Approximately a factor 200 in the abundance of events with  $m=4$  with respect to the highest multiplicity events was observed. The raw multiplicity is related to the average shower particle density over the detection area. Taking into account the integrated sensitive area of all detection modules ( $1.2 \text{ m}^2$ ) and the area where such modules were deployed (about  $50 \text{ m}^2$ ), average particle densities between  $2.5/\text{m}^2$  and  $25/\text{m}^2$  may be roughly estimated.

The inclusive raw multiplicity distribution measured by the array, as reported in Fig.4, was also compared to that obtained from a coincidence measurement with an additional detector placed at about 20 m distance, selecting a time window around the coincidence peak shown in Fig.3. The average detected multiplicity increased from a value of 3.6 (inclusive distribution) to 6.5 (coincidence distribution), reflecting the detection of showers with a higher local particle density.

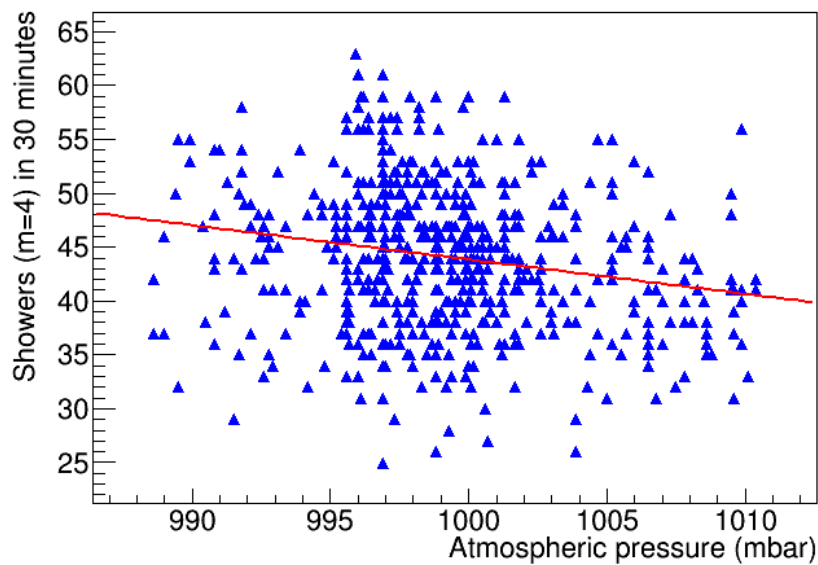
#### *4.4. Dependence of the shower rate on the atmospheric pressure*

The effect of the atmospheric pressure on the detection of single particles from an extensive air shower is often expressed by means of the barometric coefficient, which is a measure of the flux variation per mbar. This coefficient is different for the various components in the shower or at different altitudes. For single muons of average momenta such coefficient is of the order of 0.2%/mbar at the sea level. The effect on the detection of air showers, which implies the correlation between several particles from the same shower, leads to a higher value of the barometric coefficient. As a first approximation, values close to 1%/mbar were obtained by different authors. However, detailed investigation of this effect is still of interest for any specific setup and geographical location.

For our small setup we correlated the shower rate measured by the array with the trend of the atmospheric pressure measured every 30 minutes, integrating the number of events in the corresponding time interval, to investigate the effect of the particle absorption in the atmosphere. Fig.5 shows the scatter plot of the number of showers (with multiplicity equal to 4) measured in 30 minutes time intervals versus the atmospheric pressure. The solid line is a linear fit to



**Figure 4.** Multiplicity distributions measured by the array either in stand alone mode (inclusive distribution, upper points with red symbols) or in coincidence with an additional detector placed 20 m apart (lower points with blue symbols). An increase of the observed multiplicity from 3.6 to 6.5 was observed.



**Figure 5.** Variation of the shower rate of four-fold coincidence events versus the atmospheric pressure. The solid line is a linear fit to the data, resulting in a barometric coefficient of  $(0.72 \pm 0.14) \text{ \%}/\text{mbar}$ .

the data, which gives a slope of  $(-0.319 \pm 0.06)$ , resulting in a barometric coefficient of  $(0.72 \pm 0.14)$  %/mbar.

### 5. Educational impact and outlook

A small array of cosmic ray detectors has been built with a main emphasis on teaching activities in a cosmic ray laboratory course addressed to master and PhD students in Physics. Its use makes possible to introduce students to the main aspects of building a cosmic ray detector based on scintillators. While most students have the possibility to employ a single detector to measure cosmic rays in the lab, the possibility of detecting extensive air showers over a large area from correlated measurements involving the simultaneous use of several detectors may add something new in their curricula, opening new problems and solutions. Several of the problems encountered during this activity were actually proposed to bachelor, master or PhD students, who contributed with interest and in a creative way, sometimes suggesting new solutions.

The peculiarity of the array, namely its modularity and transportability, should also allow for new measurements in the future. Among these, the study of inclined showers, the investigation of specific detection topologies, the measurement of the decoherence curve at small relative distance between detectors, or the investigation of extensive air showers at different altitudes could constitute interesting topics to be addressed by this facility.

### 6. References

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- [3] La Rocca P et al 2019 Design and characterization of small detection modules based on scintillators and WLS bars with SiPM readout for a cosmic ray mini-array *JINST* **14** T01003
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