PROCEEDINGS OF SCIENCE

The MIRACLE Experiment: a cosmic rays' laboratory on a balloon

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The MIRACLE experiment, led by a team of Master's students in Physics in collaboration with the University of Pisa and INFN laboratories, is a cosmic rays experiment designed to flight on a High Altitude Balloon. The scientific goal is the measurement of the vertical and horizontal flux of cosmic particles at different altitudes. The experiment was realized from scratch and had a successful 2.5 hour long flight to take data.

The various phases of construction of the MIRACLE experiment are described in this article up to the launch. We also present preliminary results of the offline analysis of the data collected.

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1. Introduction

Cosmic rays have been an active field of research in Particle Physics since their discovery in 1912 by Hess [1]. Nowadays, numerous experiments studying cosmic rays are conducted both in laboratories and on satellites in orbit or on balloons. Most of the experiments on cosmic rays are however carried out in Physics departments worldwide because this free and inexhaustible source of particles from the Universe is perfect to introduce students to the world of experimental Particle Physics.

The MIRACLE experiment lies at the intersection between academic research on cosmic rays and the realm of education. MIRACLE is an experiment designed to fly on a High Altitude Balloon for measuring the vertical and horizontal flux of cosmic particles at various altitudes. The measurement of the horizontal flux at different altitudes is of scientific interest since it is not present in literature (as far as we know).

The experiment was conceived and realized by Master's students in Particle Physics at the University of Pisa thanks to the support of researchers and engineers from the University of Pisa and INFN.

2. The balloon payload

The MIRACLE experiment has been designed to fly on a High Altitude Balloon of small dimensions with an expected duration of the flight of about 3 hours. This poses several stringent conditions on:

- total weight (< 3 kg) and dimensions ($\sim 30 \times 30 \times 30$ cm^3) of the final payload;
- energy and power consumption ($\gtrsim 3$ h of autonomy);
- resilient against ground-impact, in order to recover the stored data and the detector hardware (for future projects);
- thermal and mechanical isolation to avoid over-heating and external humidity.

The experimental design has been driven by these constraints, which shaped the initial project and guided us throughout the successful realization of the MIRACLE experiment.

2.1 The CosmoCube

The CosmoCube detector [2] is a user-friendly cosmic rays' telescope realized by INFN as part of the OCRA project [3] to introduce students to the world of Particle Physics. CosmoCube is the physics detector of the MIRACLE experiment.

CosmoCube is composed of two parts:

1. a set of plastic scintillator tiles of size $14.4 \times 14.4 \times 3.5$ cm^3 coupled with two SiPMs to detect the scintillation light released by the interaction with charged particles (Figure 1). The detected signal is pre-amplified by a circuit next to the SiPM before being sent to the acquisition board. Each scintillator tile was characterized in the INFN laboratories in Pisa. The efficiency of these modules is measured to be $90 \pm 5\%$;

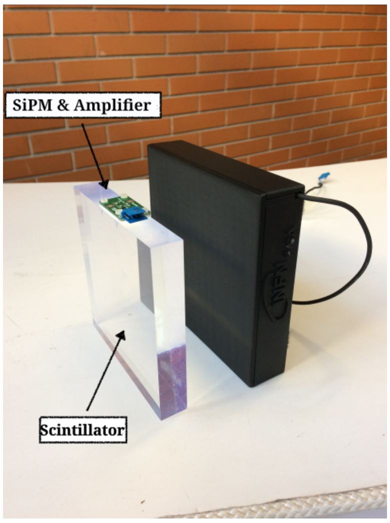

Figure 1: The CosmoCube detector with the elements of which it is made.

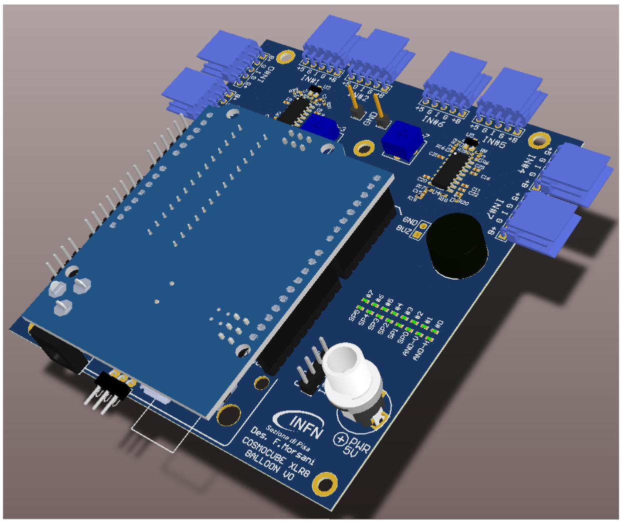

Figure 2: Custom INFN PCB board for data acquisition of the scintillating tiles.

2. a custom-made board responsible for discriminating the analog signals from the tiles, triggering on them and outputting the rate of coincidence. Up to eight inputs can be read simultaneously on the PCB board (Figure 2), where two independent trimmers, each coupled to 4 channels, are used to set the trigger thresholds. The PCB board is also used as a power supply for the detector modules. The other fundamental element of the board is an FPGA board (XLR8 by Alorium [4]) used to realize the trigger logic and real-time counters.

Each CosmoCube detector weights $\sim$ 500 g, therefore we could use just three of them on our payload.

2.2 The cosmic rays' telescope

The three scintillating tiles of the CosmoCube are arranged in a "hut" shape to be able to measure both the horizontal and vertical flux of cosmic rays. The supporting structure to which the tiles are attached is shown in Figure 3. It is designed to provide mechanical stability to the CosmoCube detector, to be reliable at different temperature conditions (from $\sim -20°$ C to $\sim 50°$ C) and to be light-weighted. The PETG material satisfies the above conditions, allowing also for an optimized design of the supporting structure through the employment of 3D printing.

The XRL8 allows us to create a custom trigger logic: we use it to record events of coincidence between the signals of more than one tile (*coincidence-mode*). To measure the horizontal flux we request a coincidence between all the scintillating tiles. The rate of each single tile is also recorded (*single-mode*), as well as the coincidence of the tile placed horizontally with one of the vertical tiles. Once the single counter rates are corrected for the different acceptances they can be used to evaluate the efficiency in real-time of the detector, while the coincidence between two tiles can be used to measure the vertical flux of cosmic rays.

Preliminary estimates of the acceptance of vertical and horizontal particles have been realized using a GEANT4 simulation (Figure 5).

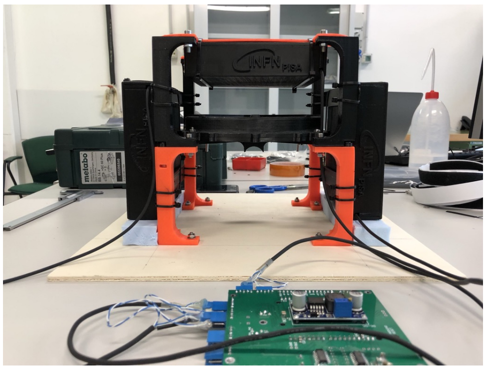

Figure 3: The 3D-printed plastic structure supporting both the CosmoCube detectors and the DAQ electronics.

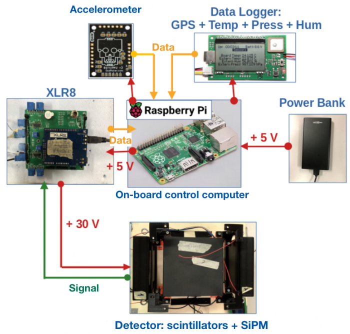

Figure 4: DAQ scheme. A central RaspberryPi communicates to all the other subsystems and controls the DAQ.

2.3 Data Acquisition and on-board control

The cosmic rays counters are read out using a RaspberryPi (Model 3B), which act as on-board control computer. The RaspberryPi is equipped with a custom software responsible of reading the signals from the XLR8 board with a frequency of 1 Hz. The received data are archived into an SSD card. The software has been designed to restart autonomously the data-acquisition in case of accidental reboot.

Keeping tracks of the payload conditions during the flight is crucial for reconstructing the flight conditions and to correct *a-posteriori* the acquired data accounting for inclination of the payload and environmental conditions. For this purpose we integrated in the DAQ other electronics components:

- Data Logger: STRATO3 board [5], equipped wiht a GPS (measuring the altitude, speed over ground and geographical coordinates) and temperature, pressure and humidity sensors.
- Inertial Measurement Unit: BerryIMUv3 [6] board equipped with accelerometer, gyroscope and magnetomer sensors.

These components are both read out by the RaspberryPi through the daemon software, as in the case of the XLR8 board. The RaspberryPi is responsible for powering through its 5 V output pins all the electronic sensors composing the experiment, included the XLR8. The RaspberryPi is powered by a commercial Power Bank with 35 Wh energy.

The DAQ and powering scheme is shown in Figure 4.

2.4 Final assembly

Much attention has been put into designing the payload to protect the telescope both from electronic-induced overheating and external environment. The SiPM gain and noise level are in general strongly dependent on temperature. To avoid the electronics-induced heat, the CosmoCube telescope is placed in the middle of the payload, surrounded by thermally-isolating polystyrene. The electronic components are installed on the outer sides of the inner polystyrene cube. In addition, we surrounded the electronics with an outer layer of polystyrene to protect the boards from external humidity which may cause shortages (see Figure 6). The base of the payload is a 5 mm-thick wood

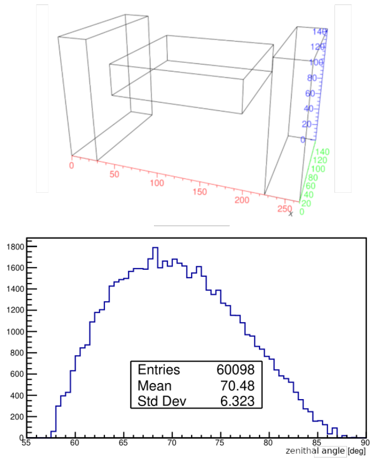

Figure 5: Top: Geometrical disposition of the CosmoCube detectors. **Bottom**: Geometrical simulation of the angular acceptance for the horizontal flux. The cosmic-rays angular distribution used in the simulation is $\propto \cos^2\theta$, where θ is the zenith angle, known to be valid at sea-level.

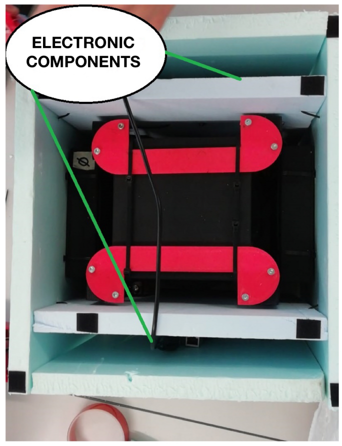

Figure 6: The cosmic rays' telescope surrounded by thick thermally-isolating polystyrene layers. Electronics is placed in the outer cavities.

board, which is light but ensures good mechanical stability and protection from the ground-impact. The final weight budget is

$$\begin{aligned}
\text{Final weight} &= \text{Wood board} + \text{polystirene} + \text{electronics (cables, power bank, boards etc...)} \\
&\quad + \text{3D-printed structure} + 3 \times \text{scintillator tiles} = \\
&= (210 + 240 + 480 + 370 + 3 \times 510)\ \text{g} = 2.93\ \text{kg} < 3\text{kg}
\end{aligned}$$

The most energy-consuming components are the Raspberry Pi, the XLR8 and the datalogger (estimated power usage ~ 3 W). Therefore a power bank with ~ 35 Wh energy was enough to carry out the experiment.

3. The flight

The flight took place on July 1st 2022 near Livorno (Italy) and lasted 2.5 h. The balloon is filled with a predetermined amount of helium to reach the desired altitude before explosion.

During ascent and descent, the balloon is transported by the wind. The presence of strong winds in altitude tends to carry it far away; but in certain moments of the year, this effect is compensated by the presence of wind currents in opposite directions, which prevent the balloon from flying too far from the launch point. Before launching, online software with real-time information on the weather conditions is used to predict the likely trajectory during the flight, to ensure that the balloon may be recovered.

Overall, the High Altitude Balloon set-up is the same as described in [7]: the payload is attached with a nylon rope to a commercial High Altitude Balloon made of latex and filled with helium to fly up in the sky. A small parachute is set between the payload and the balloon. Two additional

Figure 7: The balloon during the take-off.

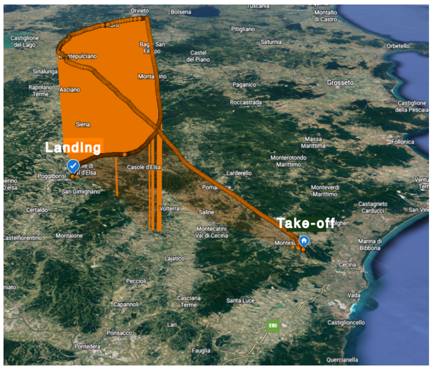

Figure 8: The trajectory of the balloon during its flight, from take-off to landing, registered with a GPS onboard and visualized with Google Earth.

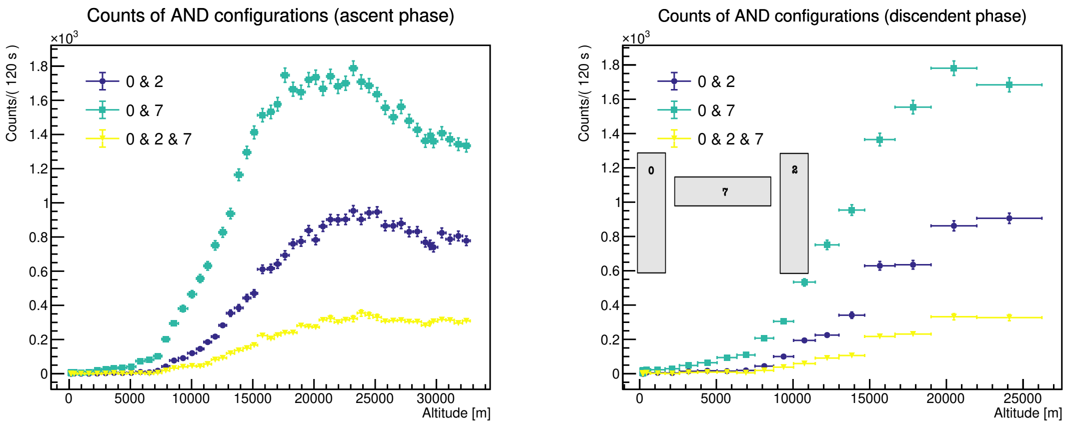

Figure 9: Rate of coincidences of the tiles during the ascent and the descent of the balloon. The legend indicates the number of the tile in coincidence. A schema of the tile numbering is placed for reference inside the right plot.

GPS' are placed outside the payload. They send regular information about the balloon's position, on a smartphone application, which is essential to track the balloon and recover the payload.

After the MIRACLE experiment has been properly closed in its walls of polystyrene and secured to the balloon, the balloon is filled with helium until it leaves the ground and starts flying (Figure 7).

The trajectory followed by the balloon during its flight of 2.5 h is shown in Figure 8). The payload was successfully recovered thanks to the communication with the additional GPS devices. Except for the exploded latex balloon, everything else was intact: we recovered every single component of the MIRACLE experiment without a scratch. The experiment took data continuously during the flight. The payload reached the maximum altitude of 33 km after ∼ 1.5 h, then the balloon burst and the payload free falled until the opening of the parachute at ∼ 7 km of altitude.

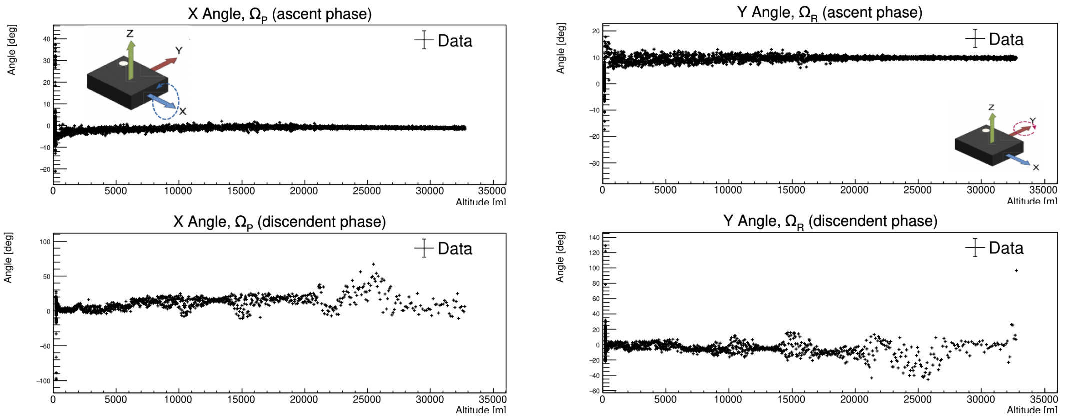

Figure 10: Horizontal plane angles as a function of the altitude. Axis z points towards the sky. The axis of rotation is indicated by the drawing inside each subplot.

4. Analysis of the first physics data

A first look at offline data shows that the maximum flux of cosmic rays is reached at the altitude of $\sim$ 22 km. The peak in the number of counts is clearly visible both in the ascent and the descent phases of the flight, and both in the *single-mode* and in the *coincidence-mode* (shown in Figure 9) counters. This rules out - at the first order - biases due to environmental conditions such as temperature and humidity variations.

To evaluate the vertical and horizontal flux of cosmic rays we need to know from Monte Carlo simulations the geometrical acceptance of the detector, which changes during the flight. We will use accelerometer data to keep track of the payload orientation during the flight. In Figure 10 we plot the measured inclinations of the payload during the ascent (top) and the descent (bottom). In the ascent phase, the payload was inclined of $\sim 10°$ with respect to the horizontal plane, probably due to non-perfectly balanced cable tension. This is an issue to be better handled in future missions, since this tilt changes the acceptance for the measurement of horizontal coincidence significantly.

5. Conclusions and future prospects

The MIRACLE experiment was successful in launching a small cosmic rays telescope on a High Altitude Balloon to measure the rate of charged particles as a function of the altitude. The data analysis has just started to try to measure the horizontal flux of cosmic rays as a function of the altitude: a proper Monte Carlo simulation of the expected rates, necessary to interpret the experimental results, is being developed.

This was MIRACLE's first flight. An upgraded version of the experiment will fly again in the near future, exploiting the experience gained by the present team and the energy that new students will bring to the project. In the future, new detectors may be integrated into the payload. We describe briefly those two detectors which already went through a bit of R&D to fly on the MIRACLE payload, although they couldn't make it to the flight because of time issues.

MicroMEGAS A team of INFN researchers lead by F. Pilo are working to develop a MicroMEGAS detector suitable for small space missions [8]. At the moment, such a technology has only been tested in laboratories, therefore a test on a balloon experiment would be of great importance to validate the status of this technology.

Neutron detector A light neutron detector (made of a LiI(Eu) scintillating crystal coupled with a SiPM, weight < 250 g) has already been acquired and tested in the laboratories of the University of Pisa, and will be integrated in the detector system for a future mission. The study of neutron rates as a function of altitude has a great scientific interest in many sectors: for example, the interaction of neutrons with nuclei in the atmosphere is responsible for the presence on Earth of many different isotopes.

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We thank the INFN section of Pisa which provided the CosmoCube detector and a laboratory where to build the experiment. The support of many INFN researchers has been essential for the success of the experiment.

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