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Measurement campaigns of the cosmic ray flux at different latitudes within the Extreme Energy Events Project

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Measurements of the cosmic ray flux at large latitudes, close to the Arctic Circle, were carried out in the last years by the Extreme Energy Events (EEE) Collaboration on board of a small boat, sailing from 66° to 82° N. A compact, scintillator-based, cosmic ray telescope was employed during such campaign. These measurements were later complemented at smaller latitudes, across Europe, from 35° to 52° N, by additional data taking campaigns. More recently, data were also obtained by installing the detector on board of the Italian training ship Amerigo Vespucci, during a three weeks-long travel around Italy, which covered the latitude range 38°- 46° N, partially overlapping with previous measurements. An ongoing initiative with the same detector is also in progress to exploit the latitude range from about 50° to 70° N by a car trip across North Europe. A survey of this activity and the main results achieved so far, together with its impact also on the overall outreach initiatives of the EEE Project, will be given in this contribution.

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1. Introduction

The Extreme Energy Events (EEE) project [1] is an international scientific and educational initiative aimed at studying cosmic rays and their secondary components through a network of detectors installed primarily in high schools and research centers across Italy, and in a few sites across Europe [2]. The core detector technology used in the project is based on Multigap Resistive Plate Chambers (MRPCs), which offer excellent spatial and time resolution. In addition to the MRPC-based telescopes, further measurements have been conducted using complementary detector technologies, such as the scintillator-based POLA-R units. These devices, developed to allow operation in mobile and remote environments, stand out for their portability, compactness, and versatility. These detectors, based on plastic scintillators coupled to Silicon Photomultipliers (SiPMs), have been successfully deployed in both mobile campaigns and fixed observatories, demonstrating their versatility in a broad range of experimental settings [3–6].

This contribution presents an extension of the measurements carried out with the POLA-R detectors, which have been employed in a first campaign to study the dependence of cosmic ray flux on geographic latitude and geomagnetic cutoff. In particular, it focuses on the data collected aboard the Italian training ship Amerigo Vespucci. These new measurements complement previous campaigns conducted in the Arctic and across Europe, further confirming the robustness of the detector design and enabling more detailed studies of cosmic ray flux variations as a function of latitude and geomagnetic conditions.

2. The EEE Project and the POLA-R detectors

The EEE project features a distributed network of cosmic ray telescopes installed mainly in high schools and research institutions across Italy and Europe [2]. Its scientific goals include the study of extensive air showers, long-distance correlations in cosmic ray flux, and the influence of solar and geomagnetic activity. The EEE telescopes are made of three Multigap Resistive Plate Chambers (MRPCs), which provide excellent spatial and time resolution and have proven highly effective for long-term measurements in school-based laboratories. Each chamber has an active area of about 80×160 cm^2, making the telescope well suited for tracking cosmic ray particles. The detectors, operated in a HV regime (18–20 kV), make use of a gas mixture (R134a + SF_6), which was recently revised (HFO1234ze + He) to reduce the environmental impact in line with updated green policies, while maintaining the required performance.

To complement these detectors and enable additional studies in mobile and remote environments, the POLA-R detectors were developed as a versatile and portable alternative. POLA-R units are compact and robust cosmic ray detectors made up of two detection planes, each consisting of four plastic scintillator tiles ($20 \times 30 \times 1$ cm^3). Each tile is equipped with a pair of silicon photomultipliers (SiPMs), positioned at opposite corners, providing a total of eight independent readout channels per plane. The signals are processed by a dedicated electronic board capable of handling coincident detections. The trigger condition used requires a coincidence between signals from both SiPMs on one scintillator tile in a plane and at least one SiPM on a tile in the other plane.

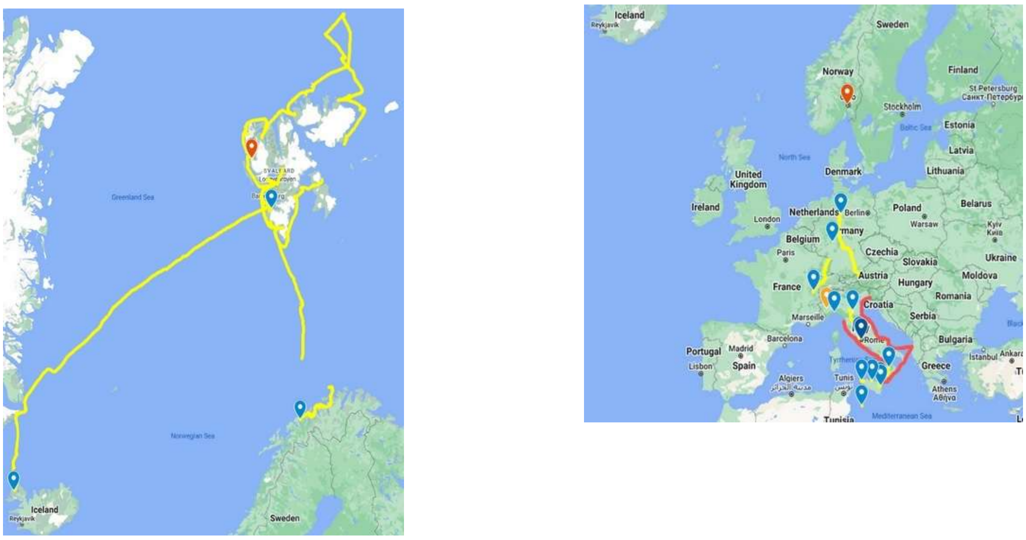
The simplicity of the design and the use of low-voltage, low-power SiPMs make POLA-R detectors ideal for deployment in field conditions. They are enclosed in compact, light-tight boxes and can operate on battery or external power, with data stored locally or transmitted via network. POLA-R detectors have been successfully used in campaigns on land, sea, and Arctic regions, demonstrating excellent time stability and resistance to environmental variations.

3. Campaigns of measurements

A total of four POLA-R units have been built so far, designated POLA-01 through POLA-04. POLA-01 was first used in the PolarquEEEst campaign in 2018, collecting data during a sailing expedition aboard the Nanuq vessel that traveled from Iceland to the Arctic regions near the North Pole. Afterward, it was driven across Europe in a long-range overland campaign and eventually installed in Ny-Ålesund (Svalbard Islands), where it remains active as part of the EEE network [3–6]. During the same campaign, two additional units — POLA-02 and POLA-03 — were installed permanently in high schools: one in Nesodden near Oslo, Norway, and the other in Bra, Piedmont, Italy. POLA-03 was later relocated to Ny-Ålesund, where it joined POLA-01 and the newly added POLA-04 to form a small array for cosmic ray shower detection. POLA-02, after its initial school deployment, was transferred to Bologna for upgrades and subsequently used in 2022 aboard the Amerigo Vespucci, in the framework of a joint collaboration between the University of Bari and the Italian Navy, marking a new phase in the use of POLA-R detectors in maritime environments. Figure 1 shows the POLA-R detectors in the campaigns discussed in this work: on the left, the POLA-01 detector is shown installed aboard the sailboat Nanuq, the central panel shows the same detector mounted inside a car during the overland campaign across Europe, on the right a picture of the POLA-02 detector aboard the Italian Navy training ship Amerigo Vespucci is shown.

Figure 1: Pictures of the POLA-R detector campaigns. Left: POLA-01 on board the sailboat Nanuq during the Arctic mission. Center: POLA-01 installed in a vehicle for the European land campaign. Right: POLA-02 aboard the training ship Amerigo Vespucci during the 2022 cruise.

The first POLA-R campaign in 2018–2019 provided data on the cosmic ray flux across a wide range of latitudes, from 35°N to 82°N. The subsequent campaign aboard the Amerigo Vespucci followed a coastal route around Italy, starting from Trieste and proceeding southward along the Adriatic Sea, around the southern tip of the peninsula, and then northward through the Tyrrhenian Sea to Livorno. During this journey, POLA-02 recorded data over a latitude range from approximately 38°N to 46°N. Although this interval is narrower than that explored during the Arctic campaign with POLA-01, the Vespucci measurements offer two key advantages. First, they were conducted using a different POLA-R detector, providing an important cross-check of the reproducibility and consistency of the results obtained with this technology. Second, the ship's steady progression along the coast allowed for fine-resolution sampling of the cosmic ray flux as a function of latitude, detecting small variations with fine, regular steps. Figure 2 summarizes the routes followed by the POLA-R detectors during the measurement campaigns. The left panel shows the trajectory of POLA-01 around the Svalbard islands during the 2018 Arctic expedition, while the right panel presents the combined paths of all detectors from 2018 to 2022, including sea, land, and stationary deployments. These routes illustrate the geographic coverage and versatility of the POLA-R units across multiple environments and latitudes.



(a) Travel of POLA-01 (yellow lines) around the Svalbard islands in 2018.

(b) Travel of POLA-01 (yellow lines) on the road across Europe in 2018-2019 and travel of POLA-02 (red line) sailing around Italy aboard the Vespucci in 2022.

Figure 2: Travel of POLA-R detectors during all the campaigns of measurements in 2018-2022.

4. Recent results with the POLA-R detectors

The data acquired with POLA-01 during the PolarquEEEst campaign have been fully analyzed and published [3–5], providing a detailed mapping of cosmic ray flux over a broad latitude range, from 35°N to over 80°N. In contrast, the data collected with POLA-02 during its deployment aboard the Amerigo Vespucci in 2022 are currently under analysis. Preliminary results from this campaign are presented here. These new measurements will be integrated with those obtained from POLA-01, contributing to a more complete understanding of latitude-dependent cosmic ray flux variations and enabling cross-validation of results between different detector units and campaigns.

During its trip aboard the Vespucci ship, POLA-02 detector operated continuously for over 95% of the time, recording cosmic ray events under varying geographic and environmental conditions. In order to directly compare with the results obtained from POLA-01, the same analysis procedure was applied to the Vespucci data, including identical quality cuts and a consistent evaluation of systematic uncertainties.

After the application of basic quality cuts, the first correction applied was related to the barometric effect, which refers to the well-known anti-correlation between the measured cosmic ray rate and the atmospheric pressure. This effect was quantified by analyzing the event rate as a function of pressure, which is shown in Figure 3. The data were fitted with a decreasing exponential function, from which a barometric coefficient of –0.23%/mbar was extracted, with a reference atmospheric pressure equal to 1026.03 mbar. This correction was essential to remove atmospheric influences and ensure a reliable comparison with previous campaigns.

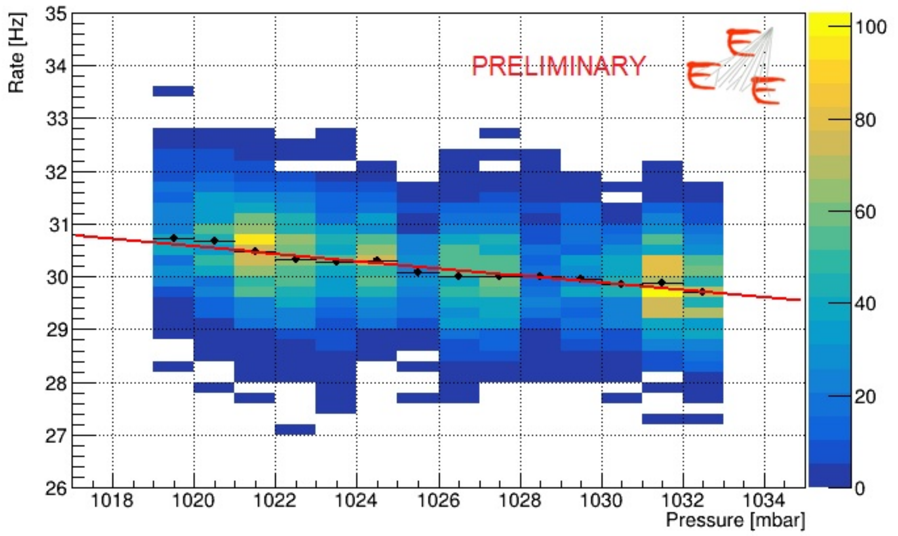


Figure 3: Cosmic ray rate measured by POLA-02 as a function of atmospheric pressure during the Amerigo Vespucci campaign. The plot shows a clear anti-correlation, fitted with a decreasing exponential function.

Furthermore, the average pressure during the POLA-02 measurements was different from that recorded during the POLA-01 data on the Nanuq (1011.88 mbar) [5]. This pressure difference was corrected using the barometric coefficient, resulting in a +3.2% adjustment to the POLA-02 data.

Data collected on board the POLA-02 vessel, given the ship's stability throughout the entire voyage, were considered sufficiently stable to neglect any correction for boat inclination.

Assuming that the POLA-R detectors are identical, the same 96% efficiency correction applied in the previous analysis [5] was applied to the POLA-02 data.

Measurements with POLA-02 were conducted inside the ship, so a minimal shielding effect is expected. For this reason, at the beginning of the voyage, before leaving the port of Trieste, a measurement was performed on the external deck lasting approximately 1.5 hours. This allowed us to estimate an absorption effect of +2.3%, which was used to correct the data.

The POLA-02 data were collected several years after the measurements performed on the Nanuq and the car, thus requiring a correction to account for the solar cycle (which showed a minimum at the beginning of 2020) and seasonal effects. Data from the other POLA-R detectors operating in Svalbard over the past several years were used to model the long-term time trend of the cosmic ray rate, incorporating both the 11-year solar cycle and seasonal periodic variations. This analysis showed that the POLA-02 data need to be corrected by a factor of -0.8% to normalize

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them with respect to the POLA-01 data collected on the Nanuq in 2018. Finally, despite the applied corrections and quality cuts, a residual dependence of the POLA-02 rate on temperature was observed, especially above 35°C. This behavior is expected and related to the use of SiPMs, whose noise strongly depends on temperature. In the specific case of POLA-02, the detector's position exposed it—particularly during the early part of the journey—to direct sunlight. To avoid any such influence, only data acquired during nighttime hours, from 6 PM to 6 AM (UTC), were selected for the analysis.

The evaluation of systematic uncertainties is currently ongoing, and the same sources of uncertainty considered in the previous analysis are being assessed [5]. At this stage, the results presented account for the largest systematic uncertainty estimated during the POLA-01 campaign, namely 1.4%. However, this value is expected to be refined, as there is room for improving the uncertainty estimation.

Figure 4 shows the cosmic ray rate measured by the POLA-02 detector as a function of geographic latitude, after applying all the corrections described in Section 4. For comparison, previously published results from earlier campaigns [5] are also included. The error bars include statistical uncertainties, shown in black, and total uncertainties—combining both statistical and (provisionally assigned) systematic uncertainties in quadrature—shown in grey.

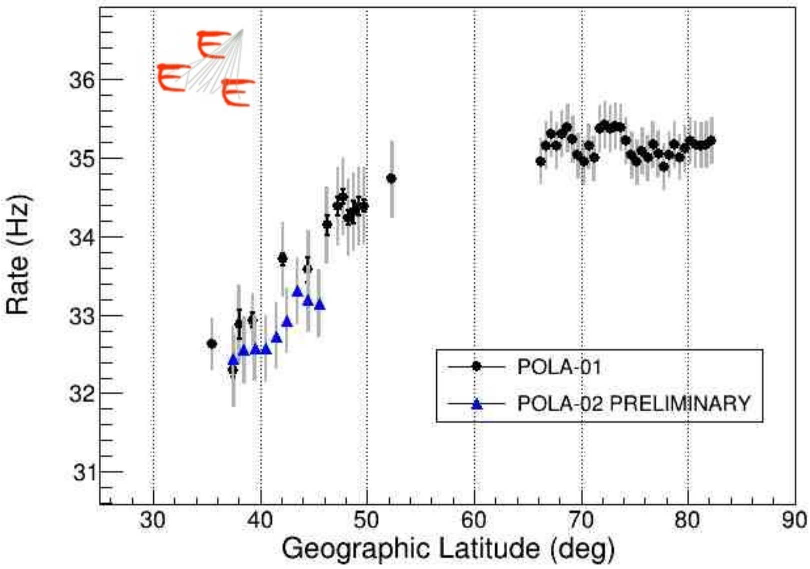

Figure 4: Cosmic particle rate measured by the POLA-01 (black circles) [5] and POLA-02 (blue triangles) detectors as a function of geographic latitude.

The event rate showed a consistent variation with latitude, aligning well with previous results from POLA-01. The corrected data demonstrate fair agreement between the two detectors, despite the different measurement periods and experimental setups. A slight discrepancy between the two measurement sets remains, with POLA-02 data tending to show somewhat lower rates. However, the results remain compatible with those of POLA-01 within the estimated uncertainties. Further investigation into the origin of this slight mismatch is ongoing, and it is most likely due to a small difference in the detection efficiency of the two detectors, which has so far been assumed to be identical, or to the longitudinal dependence, which has not yet been taken into account. These results confirm the high reproducibility and robustness of the POLA-R detector design. The successful data collection aboard the Vespucci ship paves the way for future measurement campaigns in unexplored regions and supports the long-term monitoring goals of the EEE project.

5. Conclusions and outlook

The POLA-R detectors have proven to be effective tools for mobile and stationary measurements of cosmic ray fluxes. The new data collected aboard the Amerigo Vespucci ship further validate the reliability of the POLA-02 unit and its compatibility with the results obtained by POLA-01.

These findings strengthen the case for deploying POLA-R detectors in diverse environments, including ships, remote research stations, and educational institutions. Future efforts will focus on covering latitude regions that have not yet been explored, through a road trip with the POLA-02 detector, starting from Bologna and heading to Oslo.

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