Results from the PolarquEEEst missions

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Results from the PolarquEEEst missions

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Abstract. The PolarquEEEst scientific programme consists in a series of measurements of the cosmic ray flux up to the highest latitudes. It started in Summer 2018, when three telescopes made out of scintillators readout by SiPMs were built and installed in Italy, Norway and on

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a sailboat leaving from North Island, to circumnavigate the Svalbard archipelago and land in Tromsø. They collected data on a latitude range from 44°N up to 82°N, with a dense sampling of the Northernmost interval. The PolarquEEEst mission continued afterwards with a series of measurements in Italy, Southward reaching Lampedusa, and in Germany.

In May 2019 the PolarquEEEst collaboration accomplished another important result, installing a cosmic ray observatory for the detection of secondary cosmic muons at Ny Alesund, at 79°N, made of three independent identical detectors positioned a few hundred meters from each other, and synchronized in order to operate together as a network. The configuration used will allow high precision measurements never performed before at these latitudes on a long term, also interesting for their connection with environmental phenomena. The network will also complement the existing stations for the detection of cosmic neutrons at the Svalbard archipelago, enlarging by far the physics scope that is possible to pursue in this field at this peculiar location.

Here the various missions are presented, and some preliminary results from the measurements performed are shown.

1. Introduction

At the beginning of the last century it was believed that cosmic rays were high-energy neutral particles (i.e. gamma rays), and therefore no effects of the Earth's magnetic field on cosmic ray flux was expected.

Later on, the observation of the dependence of the cosmic ray flux on latitude led to the conclusion that cosmic rays are mainly constituted of charged particles. In fact, the geomagnetic field, roughly dipolar, swipes away low energy charged cosmic rays with an energy threshold depending on latitude, preventing them to reach the ground.

In 1933 A. H. Compton compiled a set of data collected by various groups at different locations, sometimes on the ground, sometimes on boats [1]. These data clearly showed an increase of the cosmic particles rates with latitude, roughly 20% in magnitude when passing from the Equator to about 50 degrees latitude. Above that value a flattening in the dependence of the cosmic rays intensity measured at sea level vs. latitude was observed. This behaviour had also been predicted with a model, by G.Lemaitre and M.S.Vallarta, published almost at the same time as Compton's paper [2].

The observed dependence of the cosmic rays intensity at sea level with latitude was verified multiple times in the second half of the twentieth century, using compilations of data from experiments located at various sites on the ground, or from smaller devices hosted on board of ships cruising the Oceans. Nevertheless, very scarce measurement are available above the Arctic Circle, even today, particularly concerning the charged components of the cosmic rays, and more data, possibly on a long time scale, are therefore needed.

The PolarquEEEst experiment was designed to fill in this gap. Its basic unit is a small, portable device, based on scintillators coupled to Silicon PhotoMultipliers (SiPMs), and equipped with custom trigger and read out electronics, able to measure the charged component of the cosmic rays impinging onto it. Four identical units were built, conventionally called POLA-01, POLA-02, POLA-03 and POLA-04, and used for multiple purposes in various occasions, in the framework of a scientific programme mainly devoted to the study of cosmic rays at extreme Northern latitudes.

This paper first describes the detector layout and characteristics. Then the various missions when the POLA detectors were used are discussed, and some preliminary results from the analysis currently undergoing are presented. Finally some considerations about the perspectives of the PolarquEEEst scientific programme are drawn.

2. The PolarquEEEst detector

Sensitive elements of the PolarquEEEst detectors are 1 cm thick planes of BC400 Saint-Gobain plastic scintillators, each made out of four tiles 20 $\times$30 cm^2 in dimensions, as shown in Figure 1. Each tile is read out by means of two AdvanSid ASD-NUV4S-P-40 Silicon PhotoMultipliers (SiPMs). Each POLA detector comprises two scintillator planes, separated by 11 cm, enclosed in a light-tight box.

The SiPMs are readout by Front End electronics (FE) custom cards, each able to independently process the analog signals from two SiPMs. Each card includes two input pre-amplifiers, and discriminators, whose thresholds can be remotely adjusted. Output from the FE card are low-voltage differential signals, fed to a custom Trigger and Read-out Board (TRB).

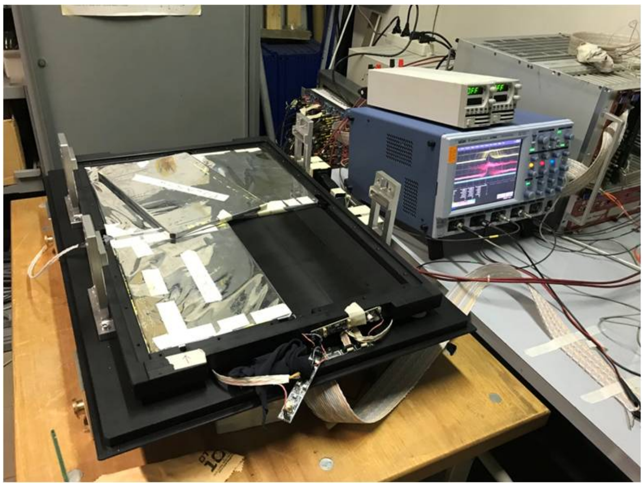

Figure 1. A photo of one of the POLA detectors, during construction. The tiles constituting one of the scintillator planes can be clearly seen.

The TRB is equipped with an Altera Cyclone 5 Field Programmable Gate Array (FPGA), a high performance Multi-Hit Time-to-Digital Converter (HPTDC), and an USB card with a FT232H chip. The trigger logic requires the coincidence in a 10 ns window of two signals coming from two SiPMs reading the same scintillator tile and an additional signal coming from a SiPM from a scintillator of the other plane, and is implemented in the FPGA.

The FPGA can be also used to measure the signal Time-Over-Threshold (TOT), namely the difference between the time when a signal from the SiPM overcomes the threshold, and the time it becomes lower again. The same measurement is also performed with the HPTDC. Counters implementd in the FPGA are used to count the number of triggers in a certain time window.

The electronics also includes a GPS (Global Positioning System) and a GLONASS (GLObal NAvigation Satellite System) boards used to provide the position of the device and a timestamp to each event recorded.

The DAQ is performed by a Raspberry Pi 3 B+ board (RPi3), controlling the TRB through a I2C connection and via a custom software, and receiving data from it and storing them on a SD device. The Raspberry Pi is also used for readout of several sensors, including three temperature, pressure and humidity sensors, an accelerometer, a 3 D gyroscope (both used to monitor the device orientation) and a magnetometer (see Figure 2).

3. The PolarquEEEst2018 mission

The first data taking campaign of the PolarquEEEst experiment took place in the framework of the Polarquest2018 expedition [3]. The Polarquest2018 expedition was conceived to celebrate the 90th anniversary of the unfortunate Airship "Italia" expedition, which in 1928 reached by air the North Pole, but wrecked during its way back due to adverse meteorological conditions.

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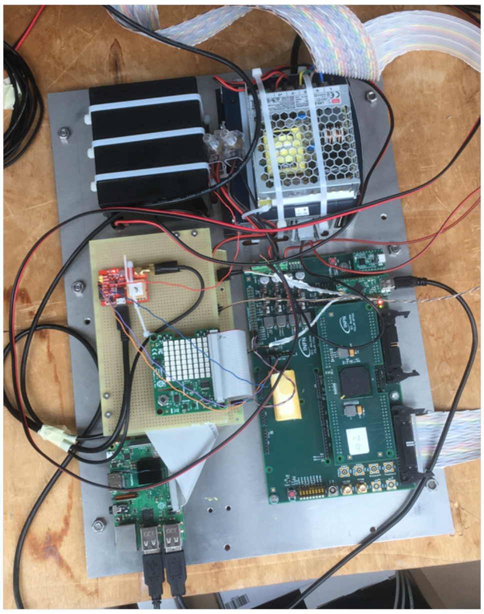

Figure 2. Photo of the electronics of one of the POLA detectors, before enclosing it in its aluminum box. Connections to the sensors used can be seen.

Polarquest2018 was a six weeks cruise of the eco-friendly 60 feet sailboat Nanuq which, on July 22, 2018, left Isafjörður (Iceland), reached and circumnavigated the Svalbard Archipelago, and ended its voyage on September 4, in Tromsø (Norway).

One of the POLA detectors, namely POLA-01, was installed on board, inside a fiberglass box specifically designed to host it, positioned on the deck of the sailboat, as shown in Figure 3. Its goal was to measure the rate of impinging cosmic particles during the whole cruise, covering in this way a latitude range between 66°05′ N and 82°07′ N, the last value corresponding to the Northernmost latitude reached during the trip. A nice story of this endeavour with, in evidence, the aspects related to the data taking with POLA-01 in such extreme conditions, is reported in [4].

Figure 3. Photo of the POLA-01 detector enclosed in its fiberglass yellow hutch on the deck of the Nanuq sailboat. (Photo by O. Pinazza).

At the same time, POLA-02 was installed at Nesodden, close to Oslo in Norway, at 59.84° N, 10.68° E, and POLA-03 at Bra, in Piedmont (Italy), at 44.69° N, 7.864° E, to be used as cross-reference detectors.

The rate of impinging particles as a function of the time (henceforth called "raw rate") measured by the three detectors of the PolarquEEEst experiment during the full period of official data taking is shown in Figure 4. POLA-03 measured a rate systematically lower than the other

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POLA detectors because it was positioned in a room covered with a roof mainly made of full bricks, while there was much less material above the other detectors. Moreover, while the rate measured by POLA-03 stays stably around its 28 Hz average value, significant fluctuations can be observed in the rate measured by POLA-01 and POLA-02.

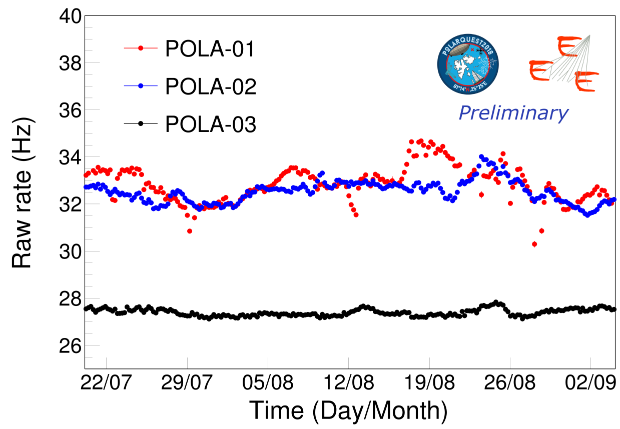

Figure 4. Raw rate of cosmic particles measured by POLA-01, POLA-02 and POLA-03 during the PolarquEEEst2018 mission.

However, in order to draw reliable conclusions about a possible dependence of the observed rate of cosmic particle on the latitude, all local effects which can affect such measurement have to be taken into consideration. One important factor to be taken into account for POLA-01 is its variable inclination with respect to the vertical direction, due to the fact that it was mounted on a sailing boat which stayed inclined for long periods of time because of the sea conditions or the sailing pace.

Also a correction to the measured raw rates of all three POLA detectors, associated to the instantaneous atmospheric pressure, has to be applied. An increase in pressure, in fact, causes a reduction of the observed rate because cosmic secondary particles have to traverse more material from their production high up in the atmosphere before reaching the ground.

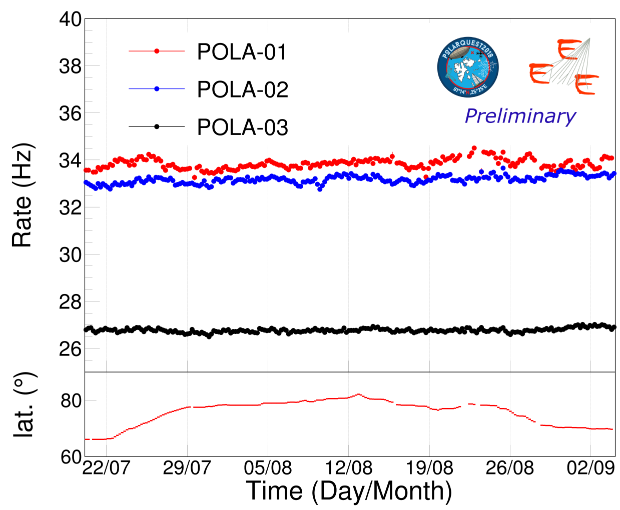

Figure 5. (Top): Rate of cosmic particles measured by POLA-01, POLA-02 and POLA-03 during the PolarquEEEst2018 mission, computed taking into account corrections for the effects due to inclination and pressure mentioned in the text. (Bottom): POLA-01 latitude as a function of time.

Measured rates corrected taking into account all these effects are shown in Figure 5. The variations of the measured rates around their average values are clearly reduced with respect to the ones noticed in the previous Figure 4, in particular for POLA-01 and POLA-02, where they were more evident. The fluctuations of the rate measured by POLA-01 around its 33 Hz average value amount to about ± 0.26 Hz, namely less than 1 %. In the same Figure 5 also the geographical latitude where the POLA-01 detector was located is shown.

A map of the cruise performed by the sailboat Nanuq with on-board the POLA-01 detector, is shown in Figure 6, with, superimposed, the cosmic particle rate measured, expressed in colour code. From the Figure, no clear evidence of an increase of the rate measured when the boat was Northbound moving can be seen.

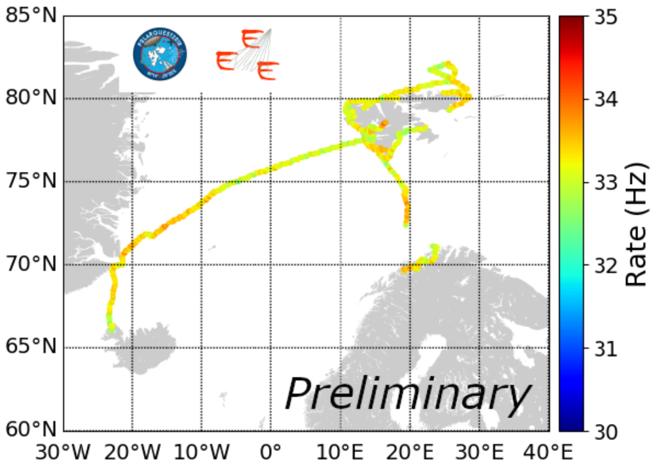

Figure 6. Rate of cosmic particles measured by POLA-01 during the PolarquEEEst2018 mission, expressed in code of colours, superimposed to a map showing the sailboat Nanuq trip.

The rate of cosmic particles measured by POLA-01 as a function of the geographic latitude, divide by it average value, is shown in Figure 7. The same rate, but plotted as a function of the geomagnetic latitude, which, in these regions, can significantly differ from the geographic one, is shown in Figure 8. In both cases, the rates stay more or less constant around their average values, with fluctuations generally contained in the ± 1 % range already cited, and no clear trend can be seen which could suggest a possible dependency of the cosmic particle rate on the latitude where it was measured.

All these considerations strongly support the hypothesis of a basically flat behaviour of the flux of cosmic rays at sea level in the range of latitudes explored, in agreement with the measurements and the model previously cited.

4. The PolarquEEEst journey in Italy and Germany

In Fall 2018, after the dismounting of the POLA-01 detector from its location on-board the sailboat Nanuq, a new campaign of measurements with the PolarquEEEst experiment was started. Goal of this campaign was to explore a range of latitudes where the cosmic ray flux at sea level is expected to have an important dependence on latitude and to evaluate the amount of such a dependence. For this purpose, the POLA-01 detector was mounted onto a car, and transported across Italy and Germany, taking data on programmed stops during the trip. The detector did not receive any modification with respect to the configuration adopted for the previous data taking campaign, except that its power system was modified in order to be powered up with a standard 220V AC current.

POLA-01 collected data on multiple occasions, in a variety of conditions. Locations, periods of data taking and the corresponding geographic latitudes are listed in Table 1. Usually the periods of data taking ranged from several hours to a couple of days: in October 2018 in Genova;

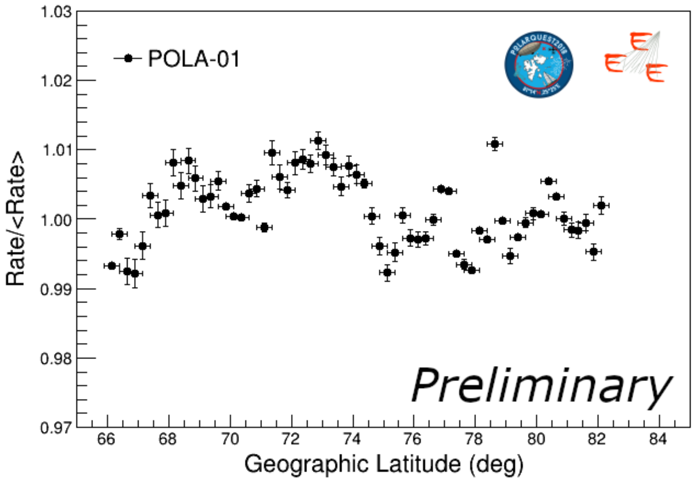

Figure 7. Rate of cosmic particles measured by POLA-01 during the PolarquEEEst2018 mission, divided by its average value, as a function of the geographic latitude.

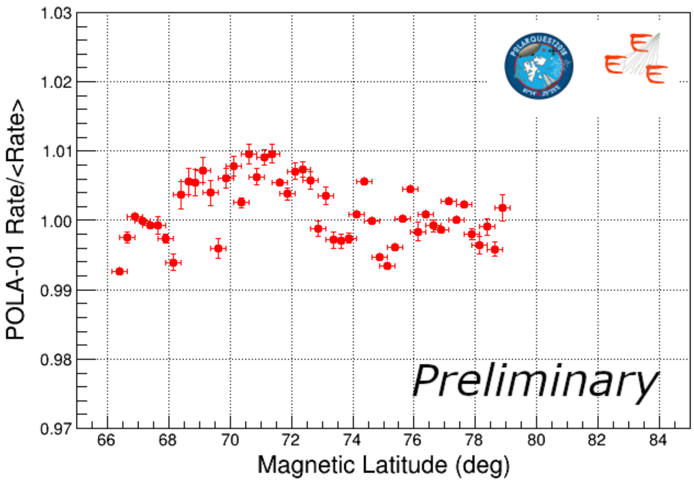

Figure 8. Rate of cosmic particles measured by POLA-01 during the PolarquEEEst2018 mission, divided by its average value, as a function of the geomagnetic latitude.

in November 2018 at the Italian military aviation base located at Vigna di Valle (Rome); in December 3, 2018 at a high school in Cosenza; from December 5th to 12th 2018 during a trip by car from Cosenza heading to Erice (Trapani), collecting data during the trip thanks to an inverter that was powering up the detector when attached to the car lighter; from December 6th to 8th, 2018 in Erice, about 900 m above sea level; from December 12th 2018 to February 15th 2019 POLA-01 measured the cosmic-rays rate in Catania, at the sea level, and thereafter on the Etna volcano up to 2000 m above sea level; from March 6th to 15th at a high school in Lampedusa, an Italian island between Sicily and the African coasts, which corresponds to the lowest latitude reached by the POLA-01 detector.

To explore even more of the region of interest, also another short data taking campaign was performed in April 2019, again transporting the POLA-01 detector by car and leaving from Bologna, Northbound to Munich, Hannover, Frankfurt am Main, to finish the trip at CERN, where the detector collected data for another twenty days. The latitudes corresponding to the location where POLA-01 took data during this campaign are reported in Figure 9 on the original plot made by Compton in his already cited paper [1], and indeed show that an important part of the latitude range, where a significant variation of the cosmic rays intensity is expected, has been explored. In the same Figure, also the latitude range explored during the PolarquEEEst2018

Table 1. The various stops of the POLA-01 detector during its trip in Italy and Germany at the end of 2018 and first months of 2019.

Location	Date	Latitude North
Genova	October 25, 2018	44°24'
Vigna di Valle (Rome)	November 27, 2018	42°04'
Cosenza	December 3, 2018	39°18'
Messina	December 5, 2018	38°11'
Cefalú (Palermo)	December 6, 2018	38°02'
Erice (≈ 900 m a.s.l., Trapani)	December 6-8, 2018	38°02'
Catania-Etna (≈ 2000 m a.s.l.)	December 12, 2018 - February 15, 2019	37°30'
Lampedusa	March 6-15, 2019	35°30'
Bologna	April 3-4, 2019	44°29'
Munich	April 10, 2019	48°08'
Hannover	April 10-11, 2019	52°22'
Frankfurt am Main	April 11-12, 2019	50°06'
CERN	April 12 - May 2, 2019	46°12'

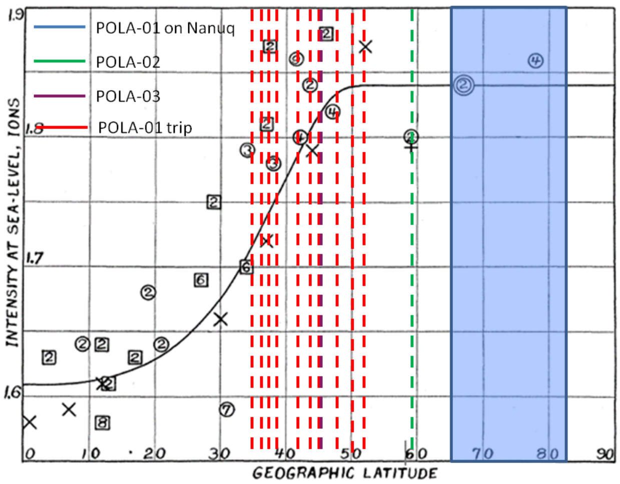

Figure 9. The original plot from Compton's paper [1] re-elaborated marking onto it the latitudes where POLA-01, POLA-02 and POLA-03 took data during the PolarquEEEst2018 mission and the POLA-01 trip in Italy and Germany.

mission is reported, and POLA-02 and POLA-03 latitudes.

During the trip of POLA-01 in Italy and afterwards in Germany, POLA-02 and POLA-03 kept on taking data, and were used for cross calibration and for the identification of possible seasonal variations in the cosmic rays flux common to all detectors and therefore to be subtracted when studying the dependence of the rate measured by POLA-01 as a function of latitude.

Analysis of the data taken by the three detectors to identify the expected dependence of the measured rate with latitude are ongoing, and will be published in a forthcoming paper. Some preliminary results, which demonstrate an increase of the cosmic particle rate with latitude, are reported in [5].

In May 2018, POLA-03 was dismounted from its location at Bra and brought to CERN. In the meanwhile another detector, identical to the others and labelled POLA-04, was manufactured and moved to CERN as well. POLA-01, POLA-03 and POLA-04 underwent careful tests and calibrations, and also a software upgrade, before being used for the following data taking campaign, described in detail in the next Section.

5. The PolarquEEEst2019 mission

The series of data taking campaigns of the PolarquEEEst experiment continued in May 2019 with the installation of three POLA detectors at the Ny-Ålesund international Research Station, located in the Svalbard Archipelago, in order to start a long term study of the high-energy cosmic ray flux with charged particles at sea level and at the northernmost latitudes.

For these studies, a configuration envisaging a mini-array of three POLA detectors, located at few hundred meters from each other, synchronized via the GPS signals and operating together as a network, was chosen. It this way the POLA detectors can provide a time stamp to each recorded event at a few nanosecond precision. This allows to search for correlations in time among the events recorded at the three stations, making it possible to identify very high energy Extensive Atmospheric Showers (EAS) with a front at the ground large enough to impinge at the same time in the whole region of interest. Also the low energy background component, unable to provide events in coincidence on two or three stations, would be rejected. Moreover, using a network of three detectors, makes it possible, by means of triangulation, to reconstruct the direction of arrival of the cosmic radiation, opening the possibility to search for any anisotropy in the cosmic radiation distribution, particularly interesting so close to the magnetic North Pole.

In addition to operating as a network, the three detectors can perform interesting measurements locally, i.e. at the level of the single detector, measuring just the muon flux and its variations in connection with transient astrophysical phenomena, among them the detection of Forbush decreases connected with Solar Flare followed by Coronal Mass Emissions, or providing alerts for Ground Level Enhancement of Solar cosmic rays.

The actual position of the three detectors was dictated by the available infrastructure, in particular the presence of buildings with heating, electric power and connection to the internet. At Ny-Ålesund three sites satisfying the requirements above, and available to host the three POLA detectors, were identified: a small wooden hut close to the Amundsen–Nobile Climate Change Tower where POLA-01 was decided to be located, the "Dirigibile Italia" station, managed by the Consiglio Nazionale delle Ricerche (CNR), that was to host POLA-03, and the Gruvebadet Laboratory for POLA-04. The locations chosen are shown in Figure 10, superimposed to a map of the Ny Alesund Research Station and surroundings.

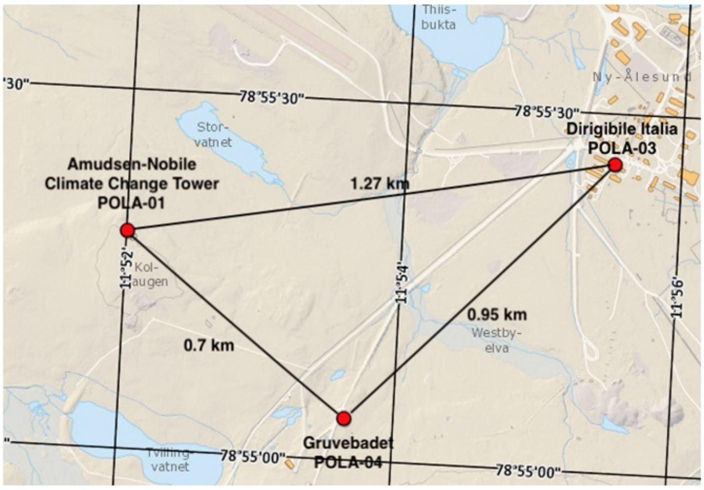

Figure 10. Installation sites of the three POLA detectors at Ny-Ålesund.

The three detectors were installed in May 2019, and since May 30, 2019, POLA-01, POLA-02 and POLA-04, are in operation. POLA-02 remained at Nesodden (Norway) as a reference station in controlled conditions.

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A first demonstration of the validity of the principle of concept for detecting EAS is reported in Figure 11, where a histogram filled with the time differences of events detected by POLA-01 and POLA-04 between June and September 2019 is shown. A peak of events characterized by a time difference close to zero, namely impinging almost at the same time onto the two detectors, can be clearly seen above the background of accidentals. As it can be seen from the map, POLA-01 and POLA-04 is the pair of closest stations of the network, selecting therefore EAS with a relatively low energy. The detection of coincidences among POLA-01 and POLA-03 or POLA-04 and POLA-03, or among the three POLA detector, would select EAS of progressively higher energy, giving the possibility to indirectly measuring the cosmic rays energy spectrum.

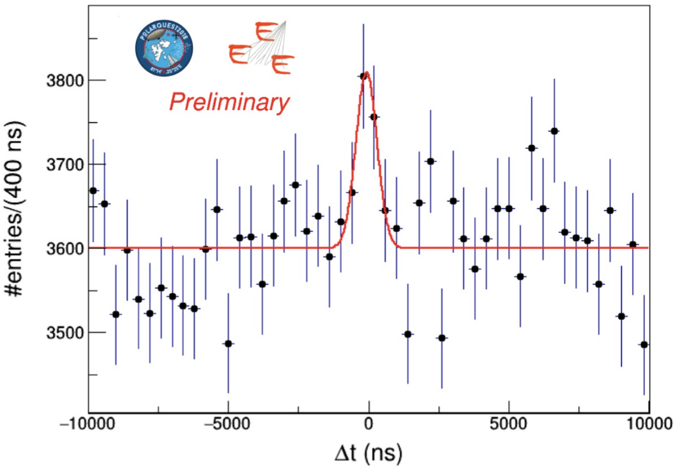

Figure 11. Preliminary analysis showing events recorded in coincidence by POLA-01 and POLA-04 between June and September 2019, at the Ny-Ålesund Research Center.

Note that the measurements performed by the POLA detectors complement the ones performed by the existing stations for the detection of cosmic neutrons at the Svalbard archipelago, enlarging by far the physics scope that is possible to pursue in this field at this peculiar location.

The proposed measurement would last longer than one year, ideally for many, in order to appreciate the cosmic rays seasonal variations and to monitor part of the eleven-year solar cycle, particularly interesting since we are now close to its final part and the beginning of the next. This kind of study, in addition to being an absolute firstling at latitudes around 80 N, would perfectly insert in the framework of measurements on cosmic rays which is currently being performed worldwide, filling a gap in the presently available observations.

6. Conclusions

The PolarquEEEst experiment has undergone three campaigns of data taking. The first, whose goal was to measure the cosmic particle flux at the Northernmost latitudes, where very few measurements are available, allowed to demonstrate that, in the range explored, no appreciable dependence on the geographical latitude has been found, in agreement with the theoretical expectations.

The second campaign was aimed at assessing such a dependence, performing measurements from 35°N and Northbound, where effects are expected to be appreciable by the PolarquEEEst instrumentation. Even if analysis is still ongoing, preliminary results show that such a measurement was successful.

The third campaign is continuing now, and will be for several years, and its goal is to perform accurate measurements at 79°N of both Extensive Air Showers and of the local cosmic particle flux, opening new interesting perspectives in this research field.

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