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A prototype station of the IceCube-Gen2 Surface Array at the Pierre Auger Observatory

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The detection of extensive air showers using radio antennas has evolved into a mature technique, complementing particle detector arrays by providing sensitivity to the longitudinal development of the showers and enabling an independent determination of the cosmic-ray energy. Both the Pierre Auger Observatory in Argentina and the IceCube Neutrino Observatory at the South Pole have been undergoing upgrades, including the integration of radio antennas. The next-generation neutrino detector IceCube-Gen2 will also feature a surface array for PeV-EeV cosmic-ray detection, consisting of scintillation detectors and radio antennas. Prototype stations for this upgrade have been in operation for several years at both, the South Pole and the Auger Observatory, enabling cross-checks and potentially a cross-calibration of the energy scales between the two experiments. In this contribution, we present an analysis of air showers observed with the radio antennas of the IceCube-Gen2 prototype station, coinciding with detections by the water-Cherenkov detectors of the densest part of the Pierre Auger Observatory's surface array, featuring a 433 m spacing.

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1. Introduction

The IceCube Neutrino Observatory [1], located at the South Pole, includes a surface array (IceTop), consisting of ice-Cherenkov detectors which enable air-shower detection in the PeV to EeV range. The planned extension of the observatory, IceCube-Gen2 [2], is also designed to include a surface array [3]. The design consists of scintillator detectors rather than Cherenkov detectors for the detection of shower particles. The scintillators will be complemented by antennas for the detection of radio emission produced by the air shower. A prototype detector station comprising eight scintillators and three antennas has been running for several years at the South Pole [4, 5], and two more stations have been deployed in the 2024/2025 Pole season [6].

In addition, a prototype station was deployed at the Pierre Auger Observatory [7] in Argentina. The Pierre Auger Observatory is the world's largest cosmic-ray detector, consisting of a surface detector array (SD) of 1660 stations with a spacing of 1500 m overlooked by fluorescence telescopes. The SD also includes two areas of denser instrumentation with 750 m and 433 m spacing. The water-Cherenkov detectors of the SD have recently been upgraded with the addition of a scintillator detector and radio antenna each, as part of the AugerPrime upgrade [8]. The IceCube-Gen2 prototype station is located within the SD-433 area (Fig. 1). It provides an R&D location that is more accessible than the South Pole and allows exploration of possible synergies between the observatories.

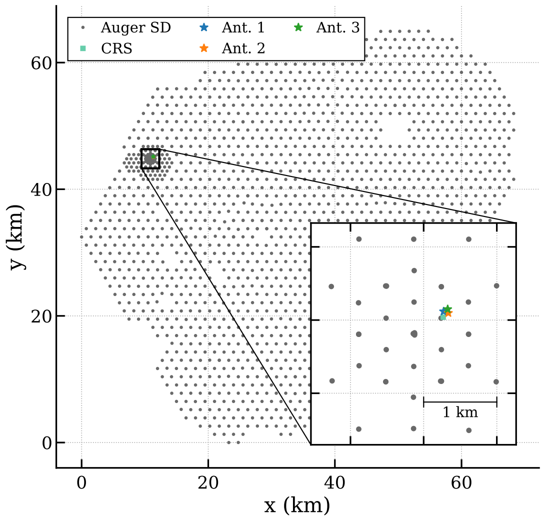

Figure 1: Positions of the SD stations of the Pierre Auger Observatory. The inset shows a zoom of the SD-433 area where the IceCube-Gen2 prototype station is located.

The inclusion of radio antennas in these observatories allows for the detection of the radio emission produced by the charged particles in the shower as a result of the geomagnetic and Askaryan effects. They allow for an independent measurement of the shower energy as well as of the depth of shower maximum with the option of a 100% duty cycle, and are therefore valuable for calibration purposes, mass composition measurements, and tests of hadronic interaction models.

In this work, we describe the IceCube-Gen2 station deployed at the Pierre Auger Observatory, and demonstrate the successful observation of radio signals from air showers.

2. Prototype detector station

The layout of the detector station deployed at Auger closely follows the reference design of the IceCube-Gen2 station; in-situ pictures are shown in Fig. 2. It consists of a central pair of scintillator detectors from which three arms extend, with another pair of scintillator detectors at the end of each arm. In the middle of each arm, a radio antenna of the SKALAv2 design is located [9]. By

Figure 2: Left: Drone picture of the prototype station at the Pierre Auger Observatory. The container in the top left is the CRS (see text for details). Right: A pair of scintillator detectors (top) and a radio antenna (bottom) of the station.

the central scintillator pair, a box houses the data-acquisition (DAQ) system, known as TAXI. The station is located in the SD-433 area of the Observatory, near the *Central Radio Station* (CRS) of the *Auger Engineering Radio Array* (AERA) [10]. Power to the station is provided by solar panels and batteries located at the CRS, where also a WhiteRabbit switch is located, which enables communication and provides precision timing information for TAXI.

The nominal frequency band of the radio system is 70 MHz to 350 MHz. The radio signals are recorded by DRS4 chips on the TAXI. Data have been recorded with sampling rates of 1000 Msps and 800 Msps, always in 1024 bin waveforms. The readout of the radio data is triggered in two ways: a scintillator trigger, which is formed when six out of eight panels see a signal over threshold within 1 µs, and a fixed-rate forced trigger. The former is used to look for air showers, while the latter is used to study the radio background. In this work, the scintillators are only used as a trigger for the radio readout; for more details about their design and operation, see Ref. [11].

3. Search for radio signals from air showers

To demonstrate the detection of radio signals from air showers, a simple analysis is performed, matching scintillator-triggered events with high-amplitude radio signals to events reconstructed by the Auger SD-433 array [12]. We use data recorded between January 2023 and February 2024. During this time, different modes of operation were tested. Importantly, the sampling rate for the radio data was changed from 1000 Msps to 800 Msps on October 20, 2023. The analysis is performed separately for the two periods, and results are compared for the obtained air-shower samples below. Other changes include the amount of time per day the collection of radio data is running (versus when only scintillator calibration data is collected), the SiPM bias voltage for the scintillators, and the individual scintillator trigger thresholds. This leads to the fractional runtime changing significantly throughout time, and to varying rates of the scintillator-triggered readout of the radio data, spanning a range between about 0.01 Hz and 0.12 Hz throughout the data period. However, in all cases, the energy threshold for the scintillator trigger is expected to be below the energies at which radio emission becomes significant. The fixed-rate trigger, on the other hand, operated at a continuous 0.1 Hz throughout the data period.

In the following, we describe how the event search is performed, after which we discuss the final sample of air showers with identified radio signals.

3.1 Method

The identification of radio signals from air showers is performed in two main steps: 1. the selection of events triggered by the scintillator detectors of the station which also have a large amplitude signal in all three antennas and 2. looking for a corresponding event with a matching trigger time and directional reconstruction in the Auger SD-433 dataset.

The ambient radio spectrum as recorded by the antennas is shown in Fig. 3. The analysis is performed in the frequency band of 110 MHz to 185 MHz due to the large background at lower and higher frequencies, mainly from FM radio around 100 MHz and from a TV station around 200 MHz. The differences between the spectra recorded at 1000 Msps and 800 Msps likely reflect a time-dependence in the anthropogenic background.

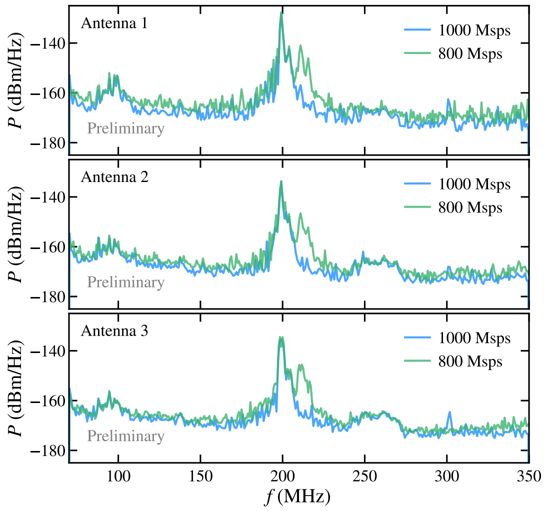

Figure 3: Frequency spectrum of the radio background recorded by the three antennas of the station at the Pierre Auger Observatory. In blue (green), the spectrum obtained in early (late) October 2023 with a sampling rate of 1000 Msps (800 Msps).

Details of the analysis steps have been described before in Ref. [13]; we summarize them below. For details of the SD-433 event reconstruction, we refer to Refs. [14] and [12].

Selection of candidate radio events

- A basic processing is applied to the radio data, including corrections for artifacts in the waveforms, bandpass filtering to the 110 MHz to 185 MHz range, and the application of a frequency weighting scheme to further reduce the influence of narrow-band background [15].
- The forced-trigger data is used to obtain distributions of the signal-to-noise ratio (SNR) in radio background waveforms. The 95th percentile of the SNR values is calculated for the next step in the analysis. This is done for each polarization of each antenna separately.
- To select candidates for air-shower events with observed radio emission, the scintillator-triggered events are considered. All events which do not have at least one polarization per antenna with an SNR value higher than 95% of the background SNR values are rejected.
- For each passing event, a simple directional reconstruction is applied by fitting a plane shower front to the signal peak times in each antenna.

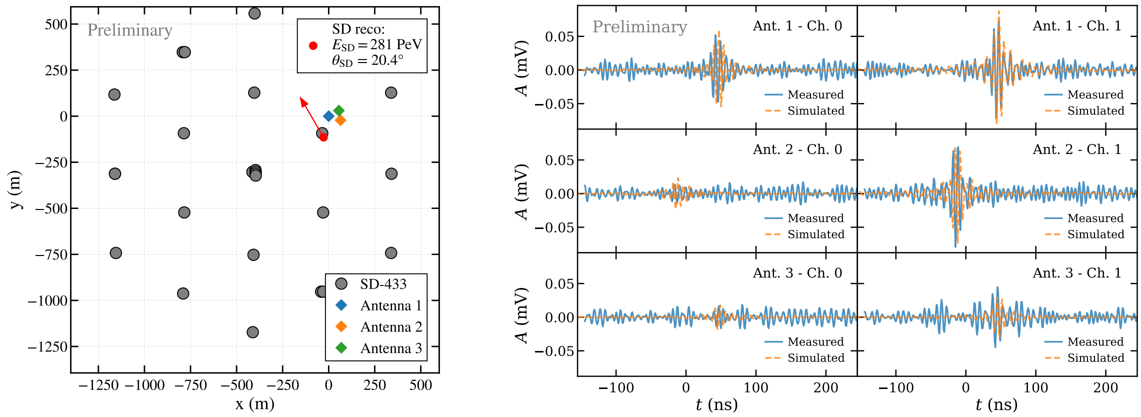

Figure 4: Example of an identified air-shower event. Left: The core position and direction from the SD-433 reconstructions compared to the antenna positions. Right: Comparison of the measured waveforms and waveforms from an air shower simulated based on the SD-433 reconstruction.

Matching with Auger SD-433 events

- The time offset between the IceCube-Gen2 prototype station and Auger SD is determined statistically by comparing a large number of scintillator-triggered events of the station to air-shower events recorded by SD. This is repeated every 12 hours due to a drift between the absolute times of the systems, which is taken into account in further analysis.

- For each radio event candidate, SD-433 events in a window of ±50 ms are considered after correcting for the time difference between the systems. (Due to the time drift between the systems and the imperfect corrections, this window is rather large. However, as the trigger rate of the SD-433 dataset is only around 0.01 Hz, chance coincidences are rare.)

- For each event found in the time window around the station trigger, the reconstructed directions from the radio signals and the SD-433 reconstruction are compared. To further ensure that the two events belong to the same air shower, the opening angle is required to be less than 5 degrees. (The event matching based on time and opening angle is visualized in Fig. 5, which is discussed more in the following section.)

- For each selected event, air-shower simulations are performed with CORSIKA [16], using the shower core position, direction, and energy from the SD-433 reconstruction as input parameters, assuming different primaries. The radio emission is simulated with CoREAS [17], and the response of the antennas and electronics chain is simulated. The simulated and measured waveforms are then compared for validation. A template matching is performed to find the best alignment between the two, after which a visual inspection is performed.

An example event identified following these steps is shown in Fig. 4. Note that deviations between the simulated and measured waveforms are expected due to uncertainties in the reconstructed core position, direction, and energy, in addition to the unknown depth of shower maximum.

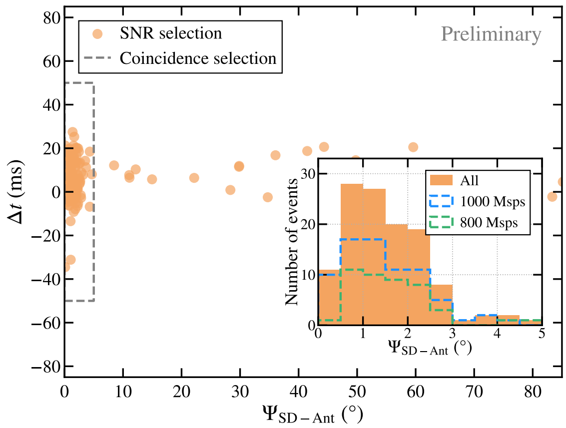

Figure 5: Time difference and opening angle between radio candidate events and SD-433 events. The box defines the selection of coincident events. The inset shows the opening angle distribution of selected events for the total sample, as well as the 1000 Msps and 800 Msps subsamples.

3.2 Identified air showers

We analyzed data recorded between January 1, 2023 and February 12, 2024. The radio data acquisition typically ran for 18 hours per day, with the other hours used to collect scintillator calibration data. Later in 2023, the radio data recording was increased to periods of 21-23 hours per day. Taking this into account, and removing periods of downtime due to hardware and software issues, a total runtime of 241.2 days was available for analysis. Following the method described above, a total of 135 events with radio emission matching an event reconstructed in SD-433 was found. Of these, 17 did not have a successful energy reconstruction from SD-433 and are excluded for the following discussion. After this, the average rate is 0.49 ± 0.05 events per day of runtime.

The sampling rate of the radio DAQ was changed from 1000 Msps to 800 Msps on October 20, 2023. The 1000 Msps data corresponds to a runtime of 143.3 days in which 74 events were found. The 800 Msps data corresponds to 97.9 days of runtime with 44 identified events. There is no significant difference in the event rates between the two periods.

The identification of the events based on the time and direction observed in both the prototype station and SD-433 is visualized in Fig. 5 for the full data period included in this analysis. SD-433 events with small time differences compared to the prototype station typically also cluster at small opening angles, indicating that these are real hybrid events. The opening angle distribution of the identified events, shown in the inset of the figure, peaks near 1°, indicating that even with three radio antennas, a good angular resolution is possible. Note that there is a tail of events at small time differences which have large opening angles; these are likely misreconstructed events which may be recoverable in future work.

The core positions for the identified events, as reconstructed by SD-433, are shown in Fig. 6 (left). All events cluster near the location of the antennas, mostly within a radius of ~ 250 m around the station center. In Fig. 6 (right), the reconstructed arrival directions are shown. We observe a tendency for events to appear more frequently at larger angles to the geomagnetic field direction, which is expected due to the radio emission produced by the geomagnetic effect. The area around the zenith is currently excluded from the event selection, as some DAQ artifacts not caught by our

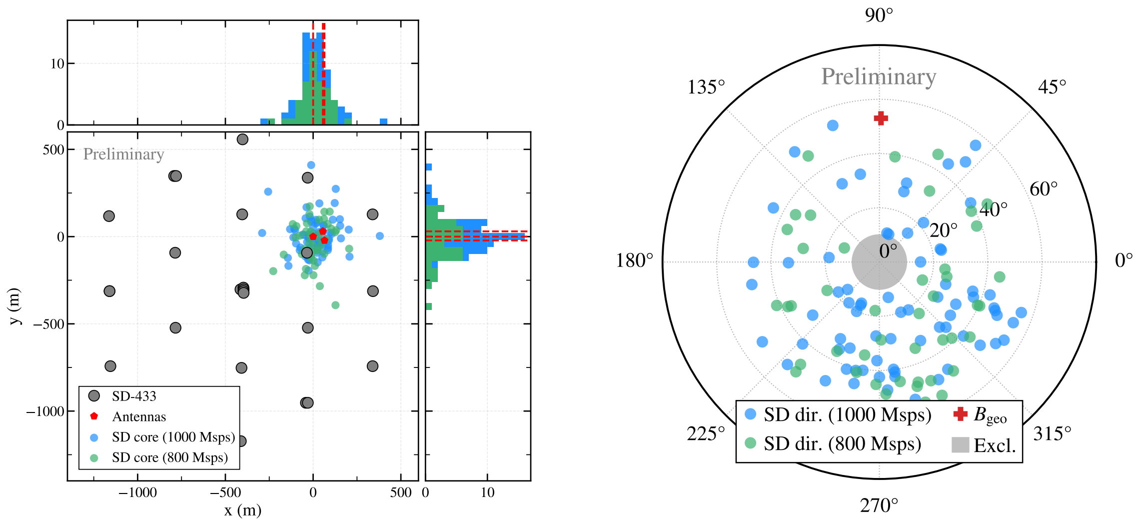

Figure 6: Shower geometry of the identified events as reconstructed with SD-433, for the 1000 Msps and 800 Msps subsamples. Left: Core positions compared to the position of the antennas. The dashed lines in the histograms represent the antenna positions. The coordinates have been centered on the position of Antenna 1. Right: Reconstructed arrival directions compared to the geomagnetic field direction. (The zenith is excluded due to occasional artifacts in the radio data.)

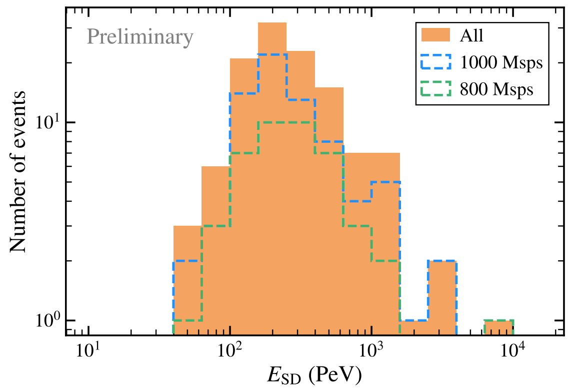

Figure 7: Distribution of the SD-433 reconstructed shower energies, for the total sample as well as the 1000 Msps and 800 Msps subsamples.

cleaning algorithms tend to mimic vertical air showers.

In Fig. 7, the distribution of energies reconstructed by SD-433 is shown. The lowest energy events are around several 10s of PeV and the distribution peaks around 200 PeV. SD-433 reaches full efficiency for showers below 40° around 63 PeV [12]. For the future, it would be of interest to study the efficiency for radio observation as a function of the SD-433 energy, given a certain shower geometry. A recently deployed array of 18 SKALA antennas is expected to reach full efficiency for the reconstruction based on radio signals around 300 PeV for showers with zenith angles below 30° [18].

4. Summary & Outlook

A prototype detector station for the surface component of the IceCube-Gen2 Observatory, consisting of scintillator panels and radio antennas, was deployed at the Pierre Auger Observatory and has been taking data for several years. First data from the station was used to successfully observe the radio emission from air showers trigger by the accompanying scintillators. By matching with showers reconstructed using the Auger SD-433 array, 118 events were identified in about 241 days of runtime, corresponding to a rate of 0.49 ± 0.05 events per day.

The selection of events with radio signals could be improved in the future, e.g. through more sophisticated SNR-based cuts, the use of neural networks for classifying and/or denoising [19], or by a more focused search for radio signals for events already reconstructed with SD-433. The successful radio detection of air showers with the station at this location suggests that future combined studies with the surface array of IceCube(-Gen2) and the Pierre Auger Observatory could be explored. Using the same antennas at both sites will reduce systematic uncertainties, e.g. in a comparison of the cosmic-ray energy scales in the overlapping energy range of the observatories [20].

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