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GRAND@Auger: status and first results

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The Giant Radio Array for Neutrino Detection (GRAND) is an envisioned next-generation observatory designed to detect ultra-high-energy (UHE) neutrinos, cosmic rays, and gamma rays with energies exceeding 100 PeV. GRAND will consist of multiple large-scale ground arrays of self-triggered radio antennas, aiming to detect the radio emission from extensive air showers initiated by these UHE particles. These arrays will be distributed around the globe at different sites, allowing for a rich science case. GRAND is being built and validated in stages, ensuring thorough testing of the detection principle and the required technology. As of 2024, three prototype arrays are in operation: GRANDProto300 in China, GRAND@Nançay in France, and GRAND@Auger in Argentina. The latter came to be as an agreement between the GRAND and Pierre Auger Collaborations, in which ten AERA (Auger Engineering Radio Array) stations were repurposed into GRAND detection units. This configuration is advantageous for the detection of air showers by both GRAND@Auger and the Pierre Auger detectors in coincidence. Through event-by-event comparisons, the detection principle and the reconstruction performance of GRAND can be evaluated. In this contribution, a summary of GRAND@Auger's commissioning and first results are presented.

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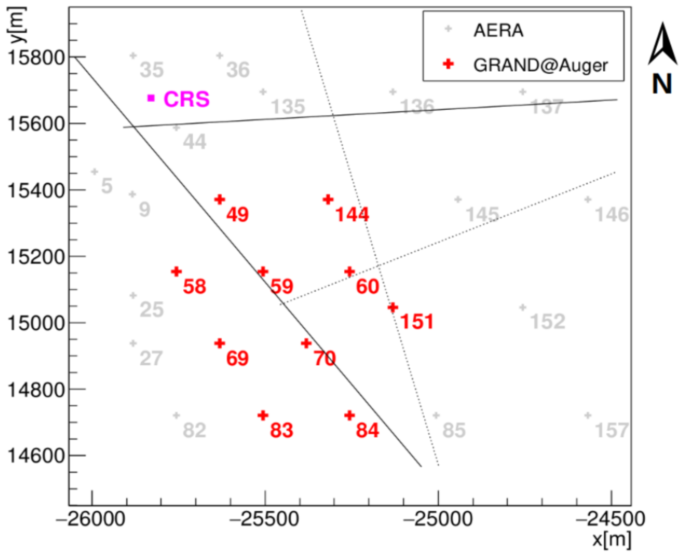

Figure 1: The G@A prototype layout in red and the nearby AERA stations in grey. The lines correspond to nearby roads. In magenta is the Central Radio Station, where the central data acquisition computer is housed. The map uses the coordinate frame used by the Pierre Auger Collaboration.

1. Introduction

The Giant Radio Array for Neutrino Detection (GRAND) [1] is a proposed sparse antenna array for the detection of ultra-high-energy (UHE) cosmic rays and neutrinos through the radio emission of their air showers. The planned detector will consist of several sub-arrays spread across the globe with a total area of 200, 000 km^2, which will be built in a staged approach. It is expected to have a sub-degree angular resolution, a wide instantaneous field of view, and excellent sensitivity to neutrino fluxes. Identifying air showers through their radio signal is a technique that has been maturing since the early 2000s. However, there is still much to be learned and improved. Thus, in order to validate a self-standing radio array for the detection of very inclined air showers with radio self-trigger, the GRAND Collaboration deployed three prototype arrays: GRAND@Nançay in France, GRANDProto300 in China and GRAND@Auger (G@A) in Argentina.

2. GRAND@Auger

A joint interest between the Pierre Auger [2] and the GRAND Collaborations led to the deployment of a GRAND prototype array at the site of the Pierre Auger Observatory in Malargüe, Argentina. Ten butterfly antenna stations from the Auger Engineering Radio Array (AERA) [3] were made available to be repurposed into GRAND detector units. These are located within the Auger 750 m array, near the Coihueco Fluorescence Telescope. The antenna arms, the nut, the GPS, the electronics box, the battery and the charge controller of the original AERA station were replaced by GRAND instrumentation. A 3.5-meter pole was added to support the antenna, while the external infrastructure, the communication antenna, and the solar panel were re-used. The comparison between the original AERA station and the final GRAND detector unit is shown in Figure 2. The

Figure 2: Stages of deployment of the GRAND detector unit. On the left, the original AERA butterfly station. In the middle, the dismantled AERA station ready to receive the GRAND instrumentation. On the right, the final GRAND detector unit.

deployment was done by GRAND teams with the help of the Pierre Auger Observatory staff in two trips to Argentina in March and August 2023.

The 10-antenna array covers an area of approximately 0.5 km^2 with a 250-meter unit spacing. The G@A layout is shown in Figure 1, that also includes the nearby AERA stations. A simulation study showed that about 30 air shower events per day, with energies ranging from $10^{16.5}$ to $10^{18.5}$ eV, are expected to land in this area. The prototype goal is to validate the GRAND detection concept through cross-calibration with Auger. The search for air shower events in time coincidence with those detected with the Surface Detector (SD) of Auger would not only demonstrate the GRAND setup capability to detect air showers with only self-triggered radio antennas but also allow for the validation of the reconstruction performance of GRAND by comparison with the one from Auger.

2.1 Setup specifications

The GRAND detector unit consists of the butterfly-type Horizon Antenna, measuring in three polarization directions: North-South, East-West, and Vertical. The nut holds the arms and houses the Low Noise Amplifier (LNA) board, all held at the top of the 3.5-meter pole. Midway through the pole, the GPS and communication antennas are mounted. The latter is used for wireless data transfer between the detector unit and the data acquisition computer. At the base, an aluminum box supports the solar panel and houses the battery, the charge controller, and the front-end electronics board. The last two are kept within well-sealed Faraday cages so as not to produce an electromagnetic background that could interfere with the measurements.

The Front-End Board (FEB) contains a 500 MSPS (mega samples per second) ADC chip for digitization, while a Xilinx-SoC is used for flexible filtering and triggering. The wireless data transfer uses the Ubiquity bullet-rocket system. The signal from the antenna arms is amplified on

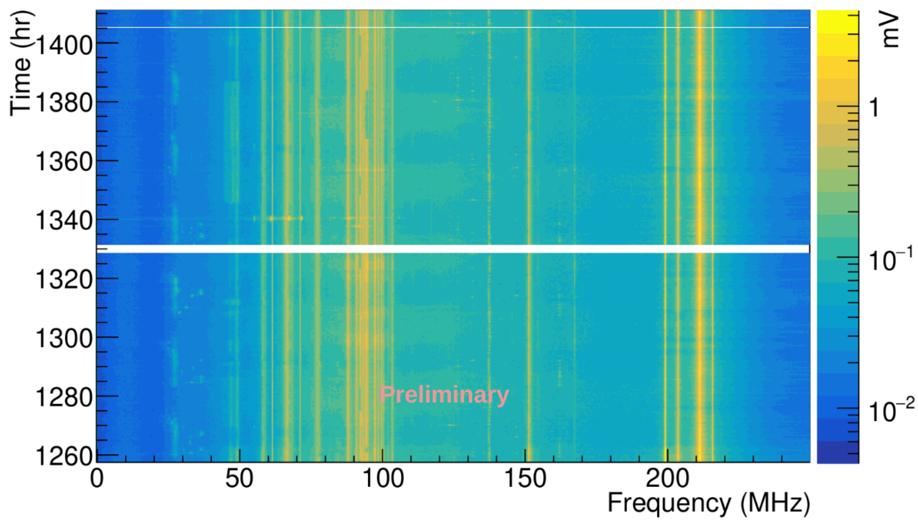

Figure 3: Periodogram of five days of data from the detector unit 59. Constant radio background lines can be seen in the vertical yellow lines, as well as regions free of noise. The white horizontal lines correspond to hibernation periods, where the detector unit shut down the acquisition and returned autonomously when the conditions were appropriate.

the LNA board and taken by cables inside the pole to the input on the FEB. A 30-200 MHz filtering is applied, and the FPGA chip creates the trigger type: a periodic or a threshold-based trigger. The measured traces are processed by the local data acquisition software in the processor chip, which creates the event and sends it to the central data acquisition software over wireless communication. The central computer, located at the Central Radio Station (CRS), processes the events and stores them into the event files. The data are transferred daily by 4g connection to the CCIN2P3 data center in Lyon, where they are made available for analysis.

3. First results and analyses

The progress in the prototypes deployed by the GRAND Collaboration led to the first experimental data to be analyzed. A focused Collaboration effort developed and/or adapted reconstruction methods for radio-only air shower events, establishing GRANDlib [4] as the Collaboration's analysis tool. A realistic Monte Carlo simulation library was produced to help with the validation of these methods, some of which were already applied in preliminary analyses of GRAND data from both the GRANDProto300 and G@A prototypes. A more detailed description of the applied methods and the results from the GRANDProto300 prototype is given in [5].

3.1 Data acquisition through 2023 and 2024

The deployment of G@A was completed in August 2023. Throughout the remainder of 2023 and 2024, the Collaboration commissioned and debugged the hardware and software deployed on-site. This was a joint effort with GRAND teams working on the two GRAND prototypes, and demonstrated the importance of setup adaptability to the site environment. By March 2024, the ten G@A detector units were operational. The data taking was stable, and hibernation settings due to

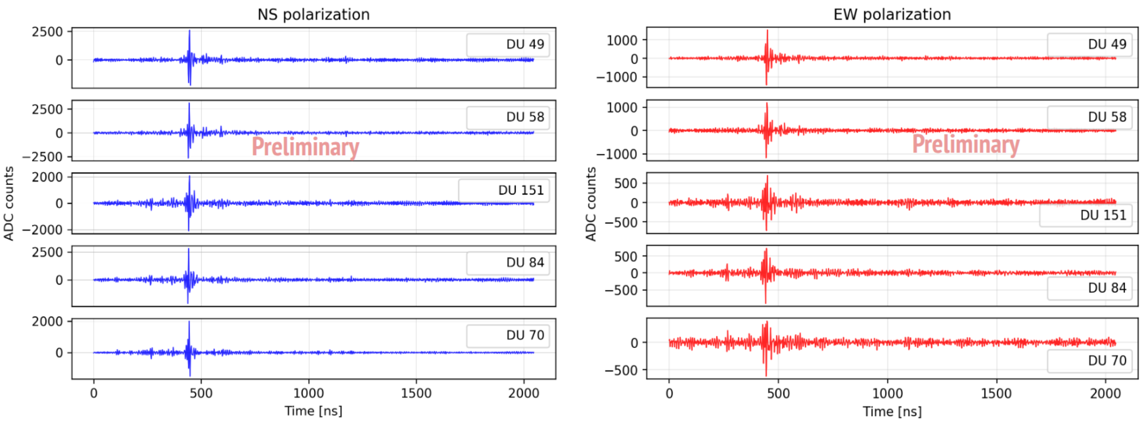

Figure 4: Self triggered online coincidence between five G@A detector units, observed at both NS, on the left, and EW, on the right, polarizations.

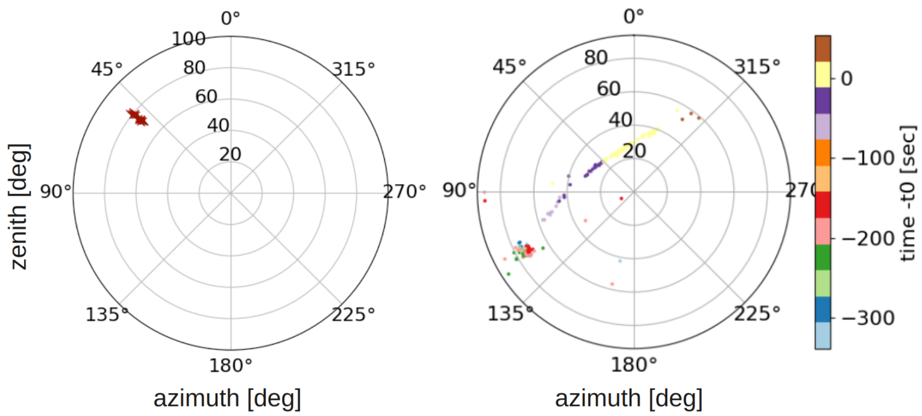

Figure 5: Direction reconstruction results for the self-triggered online coincidences from G@A. On the left, 14 events were reconstructed, pointing towards the nearby village of El Sosneado. On the right is a set of events with directional reconstruction consistent with a plane track. The event timestamps match flight TAM8133 from Santiago to São Paulo.

either high temperature and/or low battery levels were functional. An example periodogram from one detector unit containing almost 200 hours of continuous periodically triggered data is shown in Figure 3.

The online self-trigger algorithm was tested and optimized. Parameters of the threshold-based trigger were adapted to the local electromagnetic background such that the unit trigger rate was about 100 Hz. It was verified that the central data acquisition software was capable of processing real-time online coincidences between more than one detector unit. A five-unit event in shown in Figure 4, where an air shower-like pulse was triggered at both NS and EW polarizations. These self-triggered coincident events are reconstructed and have their timestamps compared to those of Auger independently triggered air shower event timestamps.

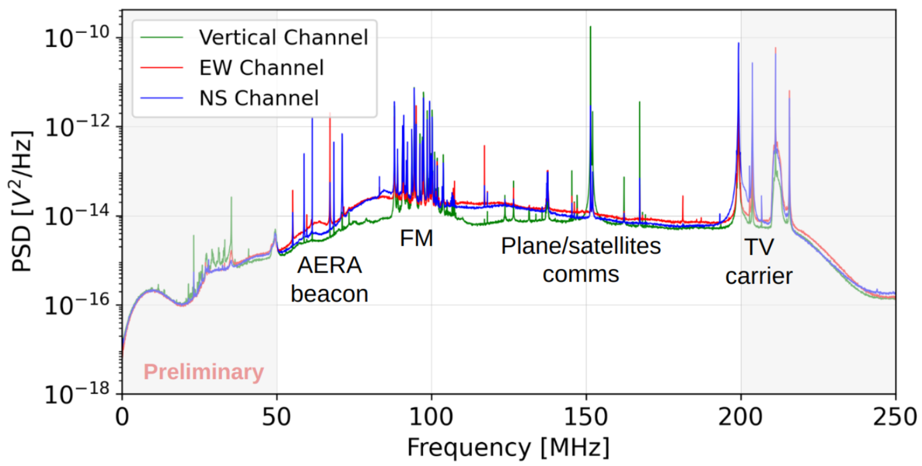

Figure 6: Power Spectrum Density averaged over 8 hours of data with a frequency resolution of approximately 0.6 MHz. The filtered out regions are shaded in grey. Some peaks in the spectrum can be identified. At around 70 MHz, the four AERA beacon lines are seen in the NS polarization. The FM radio band is seen at all three polarizations around 100 MHz. The peaks nearby 150 MHz correspond to planes and satellite communications. The high power peaks at 200 MHz are known local television channels.

3.2 Directional reconstructions

Online coincidence self-triggered events for G@A, containing enough stations, was selected for the reconstruction of the arrival direction. A preliminary set of 14 events with five detector units in coincidence were reconstructed using three independent analyses: an analytic Plane Wave Fit (PWF) [6], a Minuit minimized PWF and Spherical Wave Fit (SWF), and the SWF used in the TREND experiment [7]. The reconstructed direction using all methods, as seen in Figure 5, is pointed towards the village of El Sosneado, located close to the G@A array and an expected source of human-made Radio Frequency Interference (RFI). Also, within the reconstructed online coincidence events, several plane tracks were identified, see an example in Figure 5. The event timestamps were checked to correspond to actual flight times, a strong indication of plane detection. Further analyses on transient detection rates and timing precision are currently ongoing. Within this project, an antenna calibration using the available AERA beacon will also be performed.

3.3 Background studies

Besides the online coincidence data, the abundance of periodically triggered data was used to characterize the local environmental background. Self-triggered radio arrays require a precise understanding of the local electromagnetic background to adjust the trigger settings and discriminate air shower-like pulses from real air shower events. A preliminary study of the local background in Malargüe measured by the G@A antennas is shown in Figure 6. Narrowband transient noise sources were identified through arrival direction reconstructions and by knowledge of known local noise sources.

The radio emission from the galaxy center is a known background. Its measurement is important due to the antenna calibration potential, which is achieved by comparing the expected power (from simulation) versus the measured one. The first step towards the calibration is to have an adequate

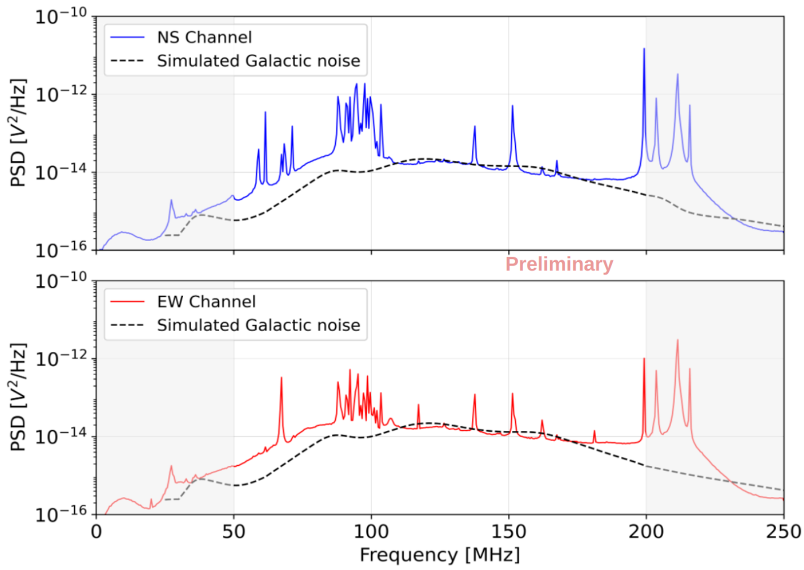

Figure 7: Measured PSD averaged over 24 hours of data for both the NS, top, and EW, bottom. The polarizations are compared to the simulated Galactic Background noise folded into the GRAND RF chain, in the black dashed line. The match in power level from 100 to 200 MHz indicate that the detector should be able to measure the Galactic Background in the periodic data.

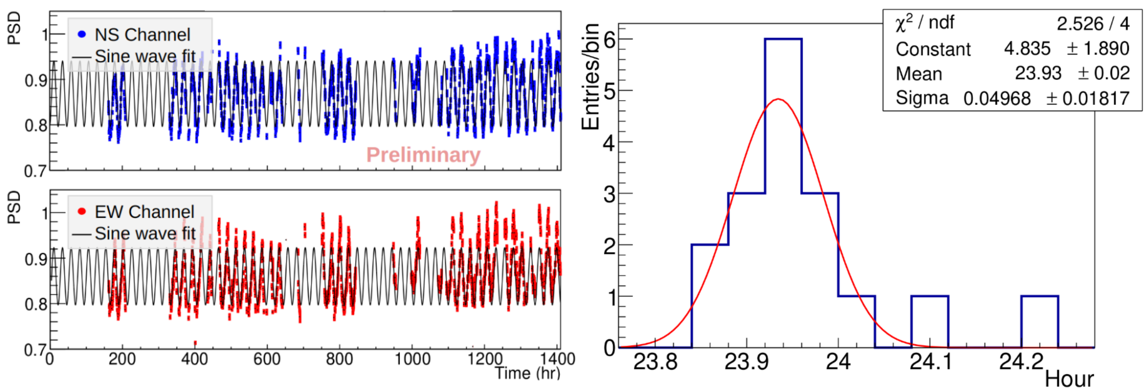

Figure 8: Preliminary searches for the Galactic Background periodicity in G@A data. Two months of data were filtered in the 120 to 200 MHz range and the FFT values were summed up. On the left, an example with data from one detector unit, with the NS polarization in blue and EW polarization in red. The amplitude oscillations were fitted with a sine wave, in black, for simple period extraction. This procedure was performed for all ten units and both polarizations. The values were combined using a Gaussian fit, on the right, with the resulting mean period of oscillation of 23.93 ± 0.02, in agreement for the expected period of the Galaxy.

Galactic Background (GB) simulation folded into the detector Radio Frequency chain (RF chain). Preliminary comparisons of the GB + RF chain simulations and the measured PSD from G@A indicate agreement, see Figure 7. This demonstrates that the noise level in the GRAND setup and the local environment is low enough that the GB should be visible in G@A data.

Indeed, preliminary searches using periodically triggered data from March and April 2024 indicated the presence of the GB. Due to the Earth's rotation, it is expected that the GB has a periodicity of 23 hours and 56 minutes, or 23.934 hours. When performing an offline filter of the G@A data between 120 and 200 MHz, a clear oscillation in amplitude can be seen, see Figure 8. A sine wave was fitted to these data as a straightforward way to obtain the period. This analysis was done for both NS and EW channels of all ten G@A detector units, which were stacked into a histogram and fitted by a Gaussian curve, see Figure 8. The mean period was found to be 23.93 ± 0.02 hours with a standard deviation of 0.05 ± 0.02 hours with a χ^2/ndf of 2.5/4, a strong indication that the galaxy is seen by the antennas. Further analyses are currently ongoing.

4. Summary and Perspectives

The ten antennas of the G@A prototype array were deployed in 2023 and commissioned in 2024. The goal of this setup is to cross-validate the GRAND detection concept and reconstruction through a comparison with independent data from the Pierre Auger Observatory. The first measurements are promising, with stable data taking, functional hibernation settings, and self-triggered radio traces. The central data acquisition can produce online coincidences between the detector units, which were analyzed with GRAND's developing analysis framework. Coincident events had their arrival direction reconstructed, pointing to expected RFI sources and indicating plane tracks. The local electromagnetic environment is being studied, from the identification of constant background lines in the frequency spectrum to ongoing analyses of the signal from the galactic background. Preliminary results indicate that the galaxy is detected by the antennas as there is an amplitude periodicity in the data with the same period as the galactic center moves through our field of view. The first results are already promising. Searches for coincident air showers between G@A and the Pierre Auger Observatory are starting.

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