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The cross-calibration array: a technique to cross-calibrate the energy scales of cosmic-ray experiments using a portable radio array

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The sources of the highest energy cosmic-rays are still a mystery. One way to try to understand these sources is to measure the energies and composition of cosmic rays and build models that describe their energy spectrum. However, at the highest energies, energy scales between experiments are inconsistent. Directly comparing the energy scales of different experiments is difficult because uncertainties on energy measurements depend on the location, technique, and equipment used. Here, we present a radio-based technique which can be used to cross-calibrate the energy scales of different experiments. The technique relies on a portable array of broadband antennas which measures radiation energy from air showers. This quantity scales quadratically with the electromagnetic energy in the shower, yielding a complete, calorimetric energy reconstruction which can be directly compared at different locations. The array can be deployed at different "host" experiments, measuring radiation energy independently, while the host experiment operates normally. The energy measured by each experiment can then be directly compared using the radiation energy measurements as a standard candle. Using radiation energy to compare the energies measured by different experiments eliminates uncertainties due to different measurement techniques and locations. Using the same detection system at each location eliminates the uncertainties associated with equipment and calibration. In this way, the energy scales of different experiments can be cross-calibrated with minimal uncertainty. Here we present the technique, prospects for event reconstruction, and plans for implementation.

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1. Introduction

In order to determine the origin of the highest energy cosmic rays it is necessary to understand the energy spectrum [1, 2]. The energy spectrum has a changing spectral index at the highest energies, indicating a transition of sources from Galactic to extra-galactic, and eventually a suppression of cosmic-ray flux. Experiments operating in this energy range have inconsistent energy scales, and so it is necessary to shift the energy scales with respect to one another in order to align them to produce a consistent spectrum [3, 4]. Comparing energy scales directly is challenging due to the fact that experiments use different detection, calibration, and reconstruction techniques, all of which affect the overall scale and associated uncertainties.

High-energy cosmic rays are detected indirectly, using the air showers generated when the primary interacts in the atmosphere. Detectors measure particles from the air shower which can be used to estimate the total energy [5, 6]. However, this method only samples a snapshot of the shower, and relies heavily on hadronic interaction models for the interpretation of data, introducing systematic uncertainties at high energies [7]. The energy deposition from the electromagnetic part of the air shower can also be measured by using fluorescence light. This approach provides a calorimetric energy measurement, but can only be done during dark nights and requires good knowledge of atmospheric conditions [8–11].

The radio emission that is generated as air showers develop has proven to be an effective detection technique [12–16]. This emission is primarily due to the geomagnetically induced, time-varying transverse current that develops as the shower propagates [17, 18]. The strength of the emission scales with the strength of the local geomagnetic field and the sine of the angle between the shower propagation and the geomagnetic field. Radio emission is produced primarily by the electromagnetic components of the shower, avoiding many uncertainties associated with hadronic interaction models [19]. Additionally, the measured radio signals are integrated over the whole air shower, and so measurements can be used to perform complete calorimetric energy reconstructions [20, 21]. In this contribution we introduce a concept that uses radio measurements of air showers to cross-calibrate the energy scales of different experiments.

2. Concept

The total energy radiated by the air shower in the form of radio emission is called radiation energy. It is a universal quantity that can be directly compared between experiments, once adjusted for the strength of the local magnetic field and second order effects. When found in conjunction with the air shower energy as determined using an independent method, it can be used to compare the energy of cosmic rays detected at different locations, allowing for the direct comparison of energy scales between experiments [22].

Radio measurements have previously been used to compare energy scales between experiments. The energy scales of KASCADE-Grande [23] and Tunka-133 [24] were compared using their radio extensions [25], although not using radiation energy, which is a limiting factor on the comparison. The fact that the same antennas were used at each location reduced the systematic uncertainties on the comparison. The energy scales of the particle detector installation at LOFAR [26] and [27]

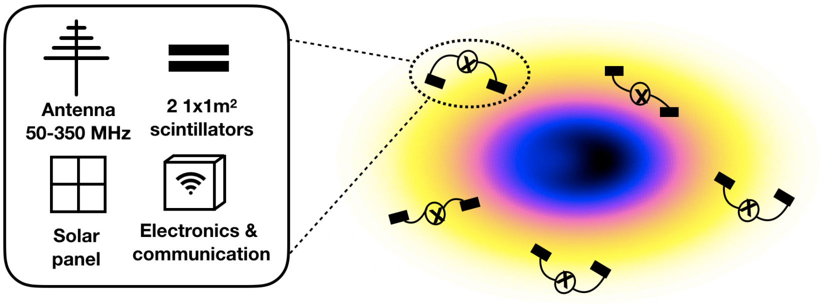

Figure 1: Energy cross-calibration array design. The array consists of 5 stations, each with an antenna, two scintillators, a solar panel, readout electronics and data storage.

were compared using radiation energy, however, the antennas used at each site differed, adding substantial uncertainty to the comparison [22].

Antennas are typically calibrated using the diffuse emission from the Galaxy as a reference source. The uncertainty on this galactic emission propagates to be the primary uncertainty in the reconstructed energy. Therefore, if the same galactic model, antennas, and hardware are used at both experiments, the predominant uncertainty is removed from the comparison. In this way, a meaningful, quantitative statement can be made about the energy scales of each experiment relative to one another. This concept is the basis for a project that aims to build a universal energy scale using a portable array of antennas.

3. Method

A cross-calibration array has two main requirements: it must be able to measure air shower radiation energy and it must use the same detection system in multiple locations to minimize the systematic uncertainty on the comparison. A portable array of antennas, which can physically be moved to multiple locations, satisfies these criteria. For every event detected by the cross-calibration array, the same event will also been seen by the host experiment and reconstructed using its methods, so that there is a radiation energy measurement linked to every traditional energy measurement. In this section we will present the array design and radiation energy reconstruction techniques.

3.1 Array design

The physics requirement of this array is to be able to make radio measurements that lead to an accurate reconstruction of the radiation energy of a given event. Logistically, there are other things to consider. First, the array has to be fully portable. This limits the number of array stations to five, striking a reasonable balance between portability and reconstruction ability. The array stations should also be fully autonomous so it can be used at different sites, independent of their infrastructure. Stations can be powered using solar panels, and data will be stored locally. Each station will operate independently and events will be correlated using timestamps offline. Stations will also include scintillator panels for triggering, as triggering on only the radio signal is very challenging. Two panels at each station will trigger on coincident events. The spacing of the scintillator panels dictates the trigger rate, and can be adjusted accordingly. At a spacing of 20 m,

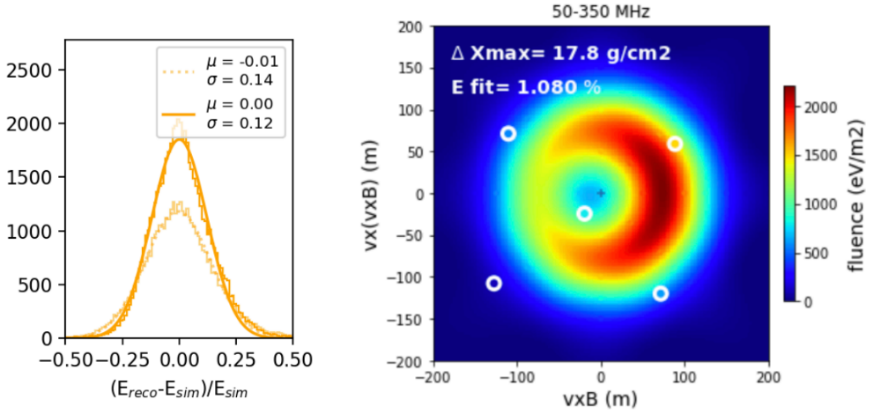

Figure 2: Right: the radio footprint and antenna positions of a simulated event, where X_{max} was reconstructed to within 18 g/cm^2 and energy to within 8%. Left: A histogram of reconstructed energy for many events, with the dashed line indicating 30 – 80 MHz and the solid line 50 – 350 MHz.

the trigger rate for a single station is on the order of 0.1 Hz which mitigates concerns about dead time and makes long term storage manageable. The array design is shown in Figure 1. Since the stations are all independent, their relative spacing can be adjusted to optimize detection in the energy range of interest.

The antennas used will be of the SKALA design [28]. These are well characterized and used by a number of experiments [29, 30]. The scintillators have been recycled from the KASCADE experiment [23], and the digitizing electronics for the radio readout have been provided by the CODALEMA experiment [16].

3.2 Radiation energy reconstruction

The reconstruction of radiation energy is critical to this project. We build on the reconstruction techniques used by AERA [31] and proposed by ARIANNA [32]. The AERA group demonstrated that it was possible to reconstruct radiation energy with only three 30 – 80 MHz antennas using a technique that compares the measured fluence to a two dimensional lateral distribution function that describes the radio footprint [20], achieving a resolution of 22% for the whole data set, and 17% for events with 5 illuminated antennas. The cross-calibration array will make use of an increased bandwidth, which retains the higher fluence regime at the lower frequencies, while also including the higher frequencies that sharpen the features of the fluence footprint. This will help constrain the event geometry. The reconstruction of a simulated event is shown in Figure 2. The right panel shows the radio footprint and antenna positions, where X_{max} was reconstructed to within 18 g/cm^2 and energy to within 8%. The left panel shows a histogram of reconstructed energy for many events, with the dashed line indicating 30 – 80 MHz and the solid line 50 – 350 MHz.

The ARIANNA experiment has shown through a simulation study that it is also possible to reconstruct radiation energy using just one broadband antenna [33]. Using a set of realistic Monte Carlo events and an 80 – 300 MHz bandwidth, they have reconstructed radiation energy with a resolution of better than 15%. This is possible because the frequency content of the signal is different at different radii from the core in the radio footprint, allowing for the determination of the

Figure 3: Right: Prototype array station located on the roof of the Vrije Universiteit Brussel. The antenna is highlighted in the center, with scintillators housed in black boxes on either side. The roof prototype uses CODALEMA butterfly antennas, while the field setup will use SKALA antennas. Left: Power spectra for a sample event. The average background is showen as the shaded colored background. The region of a FM bandpass filter is shown in gray.

antenna's position in the footprint. With more than one antenna in the illuminated area, and with potential knowledge of the shower core, we expect to able to achieve at least 15% resolution in radiation energy.

3.3 Implementation

A prototype energy cross-calibration array consisting of three stations was built at the Vrije Universiteit Brussel in 2020. This installation was valuable for developing the prototype and characterizing backgrounds. An image of the prototype is shown on the right side of Figure 3. The power spectra of a sample cosmic-ray event is shown on the left. To demonstrate the technique, the first cross calibration will involve LOFAR and Auger, chosen for logistical reasons. LOFAR is local to the involved collaborations, and so provides an excellent first site. Data will be collected for approximately 6 months, resulting in a few hundred reconstructable events. Then, data will be collected in the densely instrumented area of the Auger observatory for 6 months to a year. The radiation energy for each event be determined, and a relation drawn between the radiation energy and reconstructed cosmic ray energy for each experiment (in the same was as was done in [22]). With this information, the difference between the LOFAR and Auger energy scales will be quantitatively determined with minimal uncertainties. After demonstrating the effectiveness of this technique, the cross-calibration array will be moved to other experiment sites.

The design of this cross-calibration array was also used in the Radar Echo Telescope for Cosmic Rays (RET-CR) project [34]. The antenna station is a complementary surface component to an in-ice radar detection system. The surface array provides a trigger for radar readout and also an independent event reconstruction method. More information can be found in [34, 35].

4. Summary

The energy cross-calibration array will allow for the direct comparison of the energy scales of different experiments using the universal measurement of radiation energy. Because the same detection system will be used in each location, the comparison will have very small systematic uncertainties. The quantitative understanding of the different energy scales between experiments is critical input to model building, leading to answers about the origin of the highest energy cosmic rays.

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