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Abstract. The Pierre Auger Observatory is the largest ground-based experiment for the detection of ultra-high energy cosmic rays. In a hybrid approach, many detectors – including radio antennas – observe the extensive air showers induced by cosmic rays. As part of the AugerPrime upgrade, new antennas will be installed on each of the surface-detector stations covering a total area of around 3000 km^2. This will allow us to study the mass composition of cosmic rays arriving with large inclination angles.

The radio emission of air showers is heavily influenced in the presence of strong atmospheric electric fields during thunderstorm conditions. In that case measured data are difficult to interpret and therefore the atmospheric electric field over the array has to be monitored. We present the design and status of a new network of electric field mills (EFM) that will be used to take on this task. We show how we plan to perform the measurements with an absolute calibration. In addition, the electric-field data will be useful for other studies related to atmospheric electricity.

1. Introduction

Radio emission of extensive air showers initiated by cosmic rays is well-understood [1]. The mechanisms that lead to the emission of radio signals from showers can be described as a superposition of the geomagnetic [2] and the charge-excess [3] contributions. Similarly to how electrons and positrons get deflected in the Earth's magnetic field, causing them to emit radiation, they are influenced by the presence of a strong atmospheric electric field. Under fair weather conditions this electric field is of the order of 100 V/m and its contribution to the radio emission from extensive air showers is negligible. However, during thunderstorms electric field strengths in the atmosphere can rise to levels of the order of 10 kV/m. This can amplify the radio signals by large factors and make the measurement very difficult to interpret [4, 5, 6].

Therefore, the atmospheric electric field has to be monitored permanently in the vicinity of a radio-based cosmic-ray experiment. We show how this monitoring is done so far at the Pierre Auger Observatory near Malargüe, Argentina, and present the plan for an extended network of EFMs, where we also aim for an absolute calibration of the electric-field measurement. Furthermore, we show studies of the correlation between different EFMs and of diurnal variations of the electric field. The latter are a known phenomenon, described as the so-called

"Carnegie curve", which is explained by a periodic electrification of the Earth's atmosphere with thunderstorms and electrified clouds acting as atmospheric batteries [7, 8]. The Carnegie curve has been observed to appear globally at the same time and we present measurements, which are in accordance with this description.

Apart from the identification of thunderstorm conditions, calibrated data can also be useful for cosmo-geophysics-related analyses, such as those about Transient Luminous Events (TLEs) or the physics of lightning and thunderstorms itself.

2. Atmospheric Electric-Field Monitoring at the Pierre Auger Observatory

Currently two EFMs[1] are installed at the Pierre Auger Observatory within the Auger Engineering Radio Array (AERA), where they monitor the atmospheric electric field at AERA, an array of radio antennas extending over an area of $\sim 17\,\mathrm{km}^2$. The position of AERA is indicated in Fig. 3 as a light blue circle. The EFMs are installed at the Central Radio Station (CRS) on top of a shipping container and at the AERA Weather Station (AERAWS) in the field. The stations have a distance of $\sim 1.5\,\mathrm{km}$. A picture of the sensors at the AERAWS is shown in Fig. 1. The EFMs have an internal data logger and both sample the electric field at a rate of 1 Hz. At this rate a rotational vane periodically shields a sensor plate from the electric field with full exposure in between, such that a measurable voltage is built up, which is converted to a value of the electric field. The EFM at the CRS has been taking data since mid-2010 while the one at the AERAWS does so since mid-2014.

From the monitoring data, periods with thunderstorm conditions are identified, when the electric field exceeds a certain threshold or its fluctuation is exceptionally large [6]. These periods are used to cut affected events from analyses of AERA data. Depending on the inclination of an incoming air shower, its radio emission may be affected outside the footprint of the antenna array. Therefore, the direction and typical cloud heights and speeds are taken into account to also look for thunderstorm conditions before or after the actual event, that could have affected the radio signal. The signals from both EFMs can be combined to optimize the accuracy for thunderstorm flagging. For AERA the fraction of measurement exposure during thunderstorm conditions is around 4 % [6].

EFMs measure the electric field above them between the ground and cloud and therefore see thunderclouds moving directly overhead. However, lightning strikes can cause sudden changes in the atmospheric electric field. Previous studies have shown that the lightning detection range of the EFMs via these changes of the electric field is in the order of 20 km, while the detection efficiency decreases with distance [10].

3. Motivation and Station Design for a New Network of Electric-Field Mills

With the radio detector of AugerPrime aiming at observing very inclined showers, the effective area over which thunderstorms can influence the radio emission of extensive air showers becomes very large compared to the case of AERA. One goal will be to track thunderclouds moving over the array and to allow for smart thunderstorm flags that only veto events actually affected by strong electric fields. Therefore, the electric field has to be monitored at multiple points spaced in such a way to cover the whole array of the new radio detector, which will have a total area of $\sim 3000\,\mathrm{km}^2$. The currently operational EFMs are not sufficient to meet these needs and call for a new network of EFMs.

This new network will consist of five almost identical EFM stations with only small differences between them in the DAQ hardware. The station design was developed in a way to meet the requirements for a measurement of the electric field with an absolute calibration, which were taken from Ref. [11]. Apart from the requirement to avoid nearby buildings or other tall

[1] Campbell Scientific CS110 Electric Field Meter

Figure 1. The EFM and other weather sensors at AERAWS. The rotating vane shielding the sensor plate is visible.

Figure 2. The test setup of the new EFM stations at Karlsruhe Institute of Technology. The tripod holds the EFM at the top and the WiFi antenna below. On the ground the electronics box and the solar panel are placed.

structures and to clear the installation site from larger vegetation, any installation setup has its unique site correction factor. This factor has to be determined and multiplied to the output of the EFM. The manufacturer of the EFM provides site correction factors for a few pre-designed setups.

The design of the stations presented here was adapted from one of these setups with a site correction factor $C_{\mathrm{site}} = 0.105$. In this setup the EFM is mounted on a steel tripod with the sensor at a height of 2 m above ground and facing downward. The space between the EFM and ground is kept free of any objects. A 5 GHz directional antenna is mounted on the tripod below the EFM and on the opposite side of the mast as not to shield the field sensor from the atmospheric electric field. The whole setup is connected to a copper grounding rod to prevent damage due to lightning strikes. A rainwater- and dust-proof aluminium box is placed next to the tripod and contains all electronics of the setup. These are an analog-to-Ethernet converter, a power-over-Ethernet adapter, a radio[2], a battery and a charge controller.

The data stored in the logger of the EFM will be passed through the analog-to-Ethernet converter and sent to the radio. This radio will transmit the signal via 5 GHz WiFi over the directional antenna and it will be picked up by a sector antenna connected to a base station[3] at the Fluorescence Detector (FD) buildings of the Pierre Auger Observatory (indicated in Fig. 3 in dark blue). A similar WiFi link in use at AERA was tested to work for ranges up to at least 10 km [12]. A PC in the network of the Observatory will read out the data and process

[2] Ubiquiti Bullet AC
[3] Ubiquiti Rocket AC

it for access via internet. Power for the EFM station will be provided by a 100 W solar panel connected to the charge controller.

A test setup was operated at Karlsruhe Institute of Technology for the duration of one week. A photo of it is shown in Fig. 2. The requirements for an absolute calibration were not fully met in this test, but the functionality of all items and the signal chain were successfully validated. Unfortunately, no strong-field conditions were recorded and there was no time for a longer test operation before the shipment of the stations to Argentina.

4. Deployment and Prospects

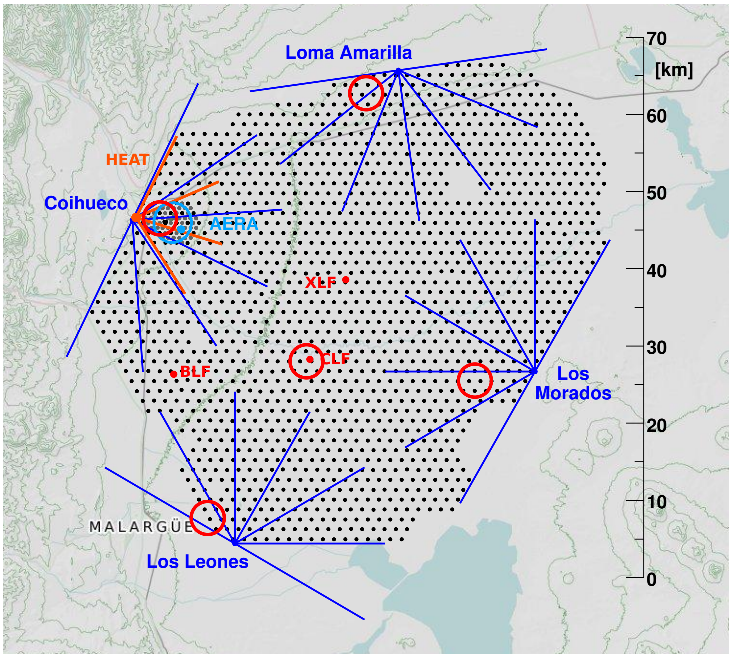

Figure 3. A map of the Pierre Auger Observatory with the four FD sites illustrated in dark blue. Each black dot marks a station of the surface detector array. The red circles indicate the planned positions of the new EFM stations. AERA is marked in light blue.

The station positions of the new EFMs need to be spread out adequately to cover the whole array of the Pierre Auger Observatory and also need to meet site requirements for an absolute calibration of the EFMs. The chosen locations are indicated by red circles in Fig. 3 with four stations close to each of the FD sites and one station at the Central Laser Facility (CLF). The WiFi bridge allows the system to be placed far away from any building or object that would distort the local atmospheric electric field.
Exact locations were chosen from visits in the field and by considering a good accessibility, permission by the landowner, and vegetation as low as possible. Large bushes could namely reduce the effective height of the EFM and growing vegetation might introduce a time variability of the effective gain. The station at the CLF is different to the effect, that the EFM will be connected via fiber cable to the local network inside the CLF container. A long range microwave link connects the CLF to the Coihueco FD site, which is planned to be upgraded for a larger bandwidth. All stations will be fenced in with an area of 15 m × 15 m to shield them from animals.

To prepare for the task of trying to track thunderclouds moving over the array, the measurements from both EFMs at AERA have been examined for correlations. Fig. 4 shows a thunderstorm event with strong electric fields recorded by both EFMs. While most of the large spikes are not overlapping, the overall behaviour of the electric field is very similar and time shifts between the curves could be used to deduce the movement of the thundercloud over the array.

Furthermore, analyses of the correlation between the atmospheric electric field and other weather observables are being performed. In data from the EFMs at AERA a diurnal variation of the atmospheric electric field is seen, shown in Fig. 5 together with the variation of the air temperature. The data are from January 2022 and averaged in 10 min bins. The electric field has a minimum between 11:00 and 12:00 UTC-3. The location of this minimum varies to later hours for other months, up to 18:00 UTC-3. This behaviour is consistent with global atmospheric electric-field variations described by the Carnegie curve [7, 8].

In the context of cosmo-geophysics, one idea is to correlate data from the EFMs with signals seen by the surface detectors, that are candidates for downward-going terrestrial gamma-ray flashes (TGFs) [9, 13]. In another idea, the amplification of cosmic-ray radio signals taken during thunderstorm conditions can be correlated to the strength of the atmospheric electric field to try to find out more about the details of how thunderstorms affect extensive air showers.

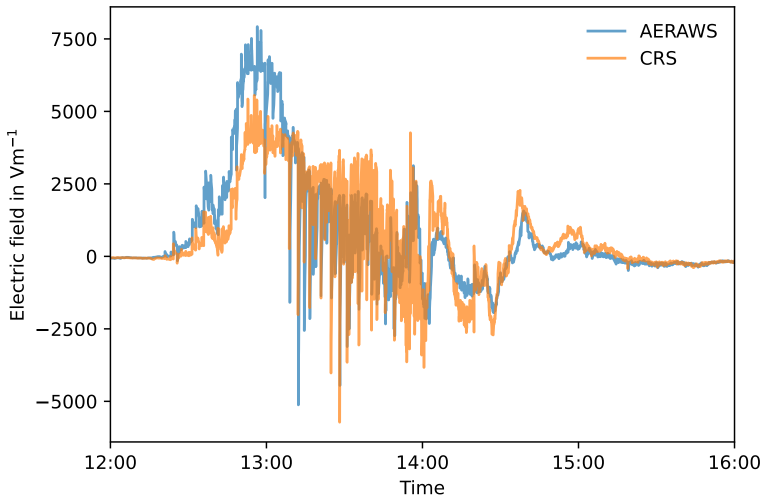

Figure 4. The atmospheric electric field measured by the EFMs at the CRS (orange) and AERAWS (blue) during a thunderstorm event on 26th January 2022. Strong electric fields are seen from around 12:30 to 15:30 local time. Large fluctuations on short timescales are due to lightning strikes.

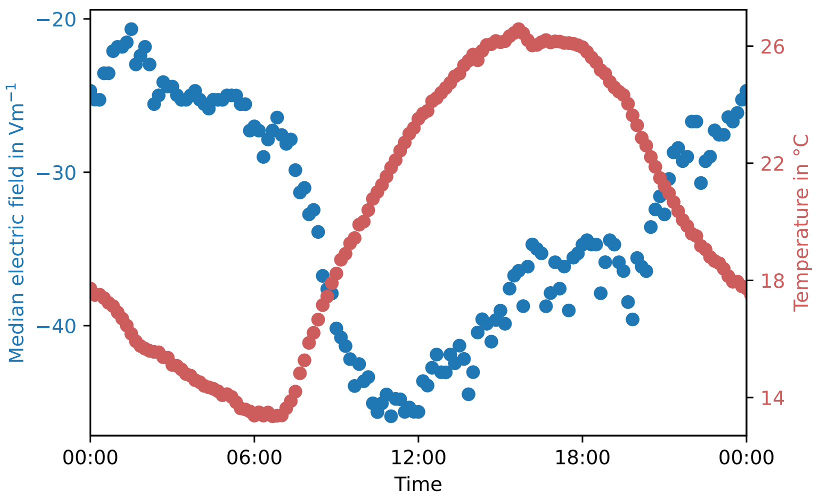

Figure 5. The median atmospheric electric field (blue) and air temperature (red) at the CRS from January 2022 as a function of the local time of day. The data are binned into 10 min intervals.

5. Conclusion

Monitoring the atmospheric electric field at cosmic-ray observatories is crucial for operating radio detectors. At the Pierre Auger Observatory a new network of five EFM stations will extend the monitoring carried out so far with two EFMs for AERA. The stations are designed to measure the electric field with an absolute calibration and to operate autonomously. Readout of the EFMs will be performed remotely from the network of the FD detectors over WiFi links. The installation sites were chosen to reasonably cover the array of the Observatory with the goal to use the data to track thunderstorms and provide veto flags for the radio detector. We find correlated measurements of the same thunderstorm in both EFMs at AERA, showing the potential to track thunderstorms also on a larger scale with the new EFM network. Additionally, analyses related to cosmo-geophysics will profit from the electric-field data and the new network of EFMs can possibly help to better understand atmospheric electricity. In a study of data from the EFMs at AERA we see a behaviour that agrees with previous findings of a global variation of the electric field.

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