

Detection of cosmic rays using microwave radiation at the Pierre Auger Observatory

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Abstract: The discovery of microwave radiation from the passage of charged particles has opened a new window for the detection of ultra high energy cosmic rays. The main potential advantages of this technique are the possibility to instrument a large area with a duty cycle of detection close to 100% and no atmospheric attenuation, all this using relatively cheap equipment. Cosmic ray detection in the GHz band is being pursued at the Pierre Auger Observatory with three different set-ups: MIDAS and AMBER are prototypes of an imaging parabolic dish detector, while EASIER instruments the surface detector units with a radio receiver of wide angular coverage. The status of microwave R&D activities at the Auger Observatory, including the first detections of cosmic ray air showers by EASIER, will be reported.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, extensive air showers, microwave detection

1 Introduction

The Pierre Auger Observatory [1] detects Ultra High Energy Cosmic Rays (UHECR) using a hybrid detector. The surface detector array (SD) is composed of 1660 water Cherenkov detectors that sample the air shower at the ground. The fluorescence detector (FD) consists of 27 telescopes installed at five sites and measures the shower development in the atmosphere by observing the fluorescence light. Recently the Auger Collaboration has undertaken the development of new detection techniques to enhance the current detection capability of the Observatory and serve as a test-bed for next generation experiments. Among these, radio detection techniques play a crucial role. The VHF band, between 30 and 80 MHz is extensively studied with the AERA [2] setup. Radio detection in microwave band is another alternative. It was triggered by the observation of a signal in the 1.5-6 GHz band upon the passage of an electron beam in an anechoic chamber [3]. The emission mechanism, interpreted as Molecular Bremsstrahlung Radiation (MBR), is expected to produce an unpolarized and isotropic signal. Moreover, the power emitted in microwaves was measured to scale quadratically with the beam energy. The expected emission from air showers together with the transparency of the atmosphere at these frequencies would allow the measurement of the shower longitudinal development with an almost 100% duty cycle. Three projects, AMBER, EASIER and MIDAS are being developed to measure this emission and prototypes are now operated at the Pierre Auger Observatory. We will describe the status of these developments and then report on the first detection of radio signals in microwave band in coincidence with air shower detected by the regular SD array and discuss their possible origin.

2 Microwave detection at the Pierre Auger Observatory

AMBER and MIDAS are imaging telescopes like an FD, instrumenting an array of feed horn antennas at the focus of

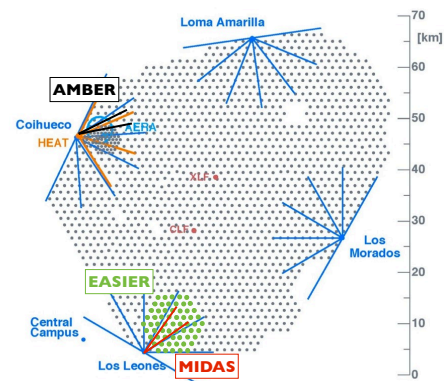


Fig. 1: Locations of the three microwave detection prototypes at the Pierre Auger Observatory. The field of view of AMBER and MIDAS are respectively delimited by the black and red lines. The EASIER array is represented by the green dots.

a parabolic dish. EASIER is an alternative design to a radio telescope: it is embedded in the SD, observing the shower from the ground with a wide angle antenna pointing to the zenith. The locations of the three prototypes at the Pierre Auger Observatory are depicted in Fig. 1. All three take advantage of the available commercial equipment for TV satellite reception. They all use horn antennas as receivers, in C-band (3.4-4.2 GHz) and Ku-band (10.95-14.5 GHz) for AMBER, and only C-band for MIDAS and EASIER. A Low-Noise Block down-converter (LNB) is used to shift the central frequency below 2 GHz and amplify the signal. The RF signal is then transformed using a power detector whose output is a DC voltage proportional to the logarithm of the input power. The signal thus integrated can be acquired with sampling rates below 100 MHz. The three prototypes benefit from the commissioning at the Pierre Auger Observatory because of the radio quiet environment and the possible coincident detection with the SD or the FD. We present



Fig. 2: AMBER detector at the Coihueco FD site.

here separately each prototype. More technical details can be found in a previous contribution [4].

2.1 AMBER

AMBER (Air shower Microwave Bremsstrahlung Experimental Radiometer) is a radio telescope instrumented with a 2.4 m off-axis parabolic dish imaging a section of $14^\circ \times 14^\circ$ of the sky at 30° elevation angle with 16 pixels. The dish and the receivers are shown in Fig. 2. The four central pixels are dual polarized and dual band (C-band and Ku-band) and the 12 outer pixels are single polarized in C-band. The power detector output of each channel is sampled at 100 MHz with FADCs. The dish and the feeds were calibrated separately using the Y-factor method. The combined noise temperature was measured to be 45 to 65 K for the C-band pixels and around 100 K in the Ku-band.

AMBER was originally operated at the University of Hawaii with a self-triggered system. During this period, the validation of the optical performance of the telescope was performed by measuring the Sun transit. A search for signals induced by air shower was also performed, however the environment was found to be too noisy and no unambiguous event was found.

AMBER was shipped to Argentina and is now installed at the Coihueco FD site pointing in direction of the SD infill array [5] (cf. Fig. 1). AMBER uses a modified version of the SD trigger at the three-level trigger [6] that performs a fast geometrical reconstruction of the SD events and retrieves the time at which the shower crossed its field of view. Uncertainties in this reconstruction are compensated for by pulling an appropriately long trace (currently 150 μ s), from a large circular buffer of 5 s for each channel. This fast reconstruction is found to be valid within 10° in the shower direction and 500 m in the core position, uncertainties that are accounted for in the length of the trace being read out.

The triggering system requires a precise synchronization between the timing of Auger and AMBER detectors. It was tested twice on separate occasions by instrumenting first one, and then three surface detectors with C-band antennas and power detectors. A strong RF pulse was used to create a trigger in the antenna-equipped detectors and at the same time recorded in AMBER. An agreement in the order of 1 μ s was found in the single tank test.

A calibration method based on the microwave signal emitted by the galactic plane is also in development to complement the Sun transit calibration. The baseline of the

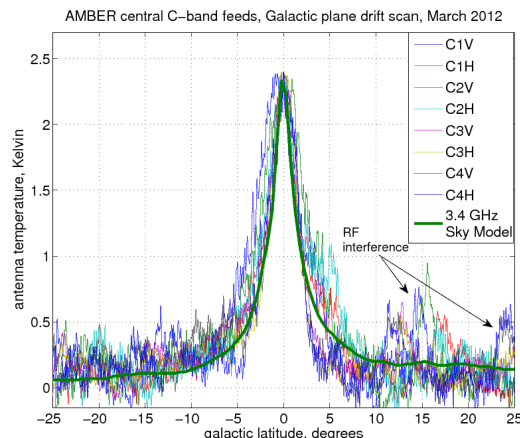


Fig. 3: Temperature elevation during the crossing of the Galactic Plane in the AMBER field of view.

central C-band pixels averaged over 20 minutes is shown in Fig. 3 as a function of the galactic latitude. AMBER has acquired more than 18 months of data, and the data analysis is underway. An upgrade of the camera is under development to improve the sensitivity by 40% by lowering the noise temperature of the electronics and by increasing the efficiency of the focal surface. The field of view is also planned to be extended to 17° .

2.2 EASIER

EASIER (Extensive Air Shower Identification with Electron Radiometer) is a radio detector array integrated with the Auger SD as illustrated in Fig. 4. Each detector is composed of a C-band horn antenna oriented towards the zenith covering a large field of view, 3 m above the ground. The output is sampled at 40 MHz by one of the six FADC channels initially used for the anode signal of one of the three PMTs. In this way, whenever an air shower triggers the SD, the radio trace is automatically recorded through the same stream as the SD data.

In April 2011, seven tanks were instrumented with an EASIER prototype and the first clear UHECR radio detection in this band was performed by one of those prototypes in June 2011. An extension of 54 units was carried out in April 2012. EASIER is now an array of 61 detectors with 33 antennas oriented with a North-South polarization and the other 28 ones with East-West polarization.

Calibration of the EASIER antennas is still underway. The simulation of the antenna pattern shows a half power beam width of around 100° and a maximum gain of 5 dBi.

The EASIER antennas collect the air shower signal from the ground. In such conditions the signal emitted along the air shower is compressed in time. The exact signal enhancement due to this compression depends on the arrival direction and distance to the shower axis. The smaller effective area with respect to a telescope is thus compensated by this compression effect.

EASIER has been taking data in a very stable way for two years for the first set up and one year for the second and up to now, it has recorded a total of three unambiguous radio signals in coincidence with an air shower detected by the SD array. The data selection, the radio signals and their possible origin are discussed in Section 3.

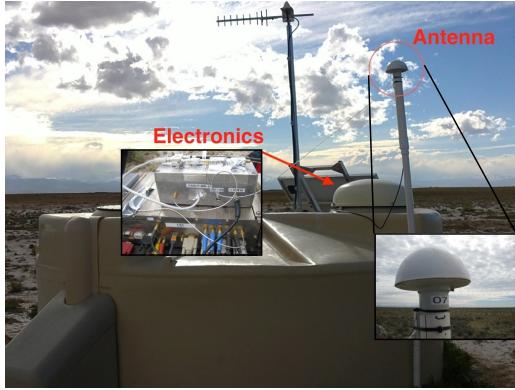


Fig. 4: EASIER detector installed at a surface detector.

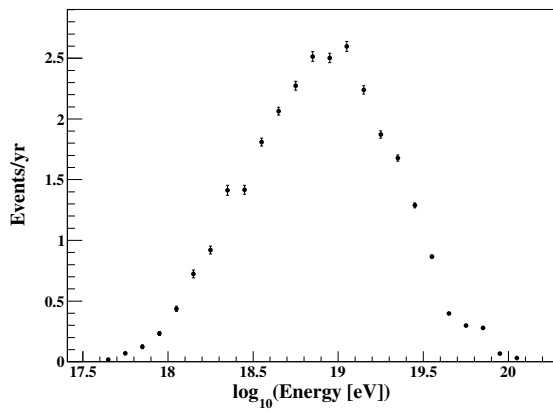


Fig. 5: Simulated event rate computed for the MIDAS detector [7] accounting for a linear scaling with energy of the observed signal in [3].

2.3 MIDAS

MIDAS (MICrowave Detection of Air Showers) is a radio telescope instrumented with a 5 m² parabolic dish and a 53 pixels camera at its focal plane. Each pixel is a C-band LNBF covering approximately 1.3°x1.3° of the sky, for a total field of view of approximately 20°x10°. Each channel is digitized by a 14 bit FADC at 20 MHz sampling rate. MIDAS incorporates its own triggering logic. A First Level Trigger (FLT) at the pixel level is issued if the running sum of 20 data samples exceeds a predefined threshold. The FLT remains active for 10 μs and the value of the threshold is adjusted to keep a FLT rate of 100 Hz. The Second Level Trigger (SLT) searches for four-fold patterns corresponding to the expected topology of a cosmic ray air shower in the overlapping FLT pixels. There are 767 expected patterns compatible with a cosmic ray air shower track giving an accidental SLT rate of 3×10^{-4} Hz [7].

The telescope efficiency was calculated by performing a complete electromagnetic simulation of the MIDAS detector. The effective area at the central pixel was found to be 9.1 m² and falls to 20% of this value at the borders of the camera.

The MIDAS detector was originally installed at the University of Chicago. During this period of commissioning, the Sun was used as a calibrated source. Firstly the electromagnetic simulations were validated measuring the Sun transit over the camera. Secondly, as the

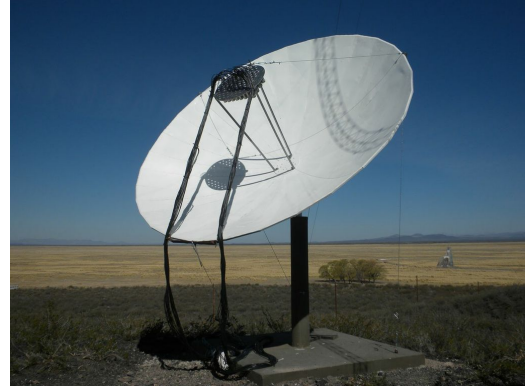


Fig. 6: MIDAS detector installed at the Pierre Auger Observatory next to the Los Leones FD building.

flux of the Sun is monitored by several radio observatories, it was used to compute an absolute calibration. The system temperature of the central pixel was found to be 65 ± 3 K and similar values were obtained for the other pixels.

The data taking at the University of Chicago validated the principle of MIDAS and showed a stable behavior regardless of the weather conditions. No clear event candidate was found, thus excluding a quadratic scaling with the air shower energy [8] of the microwave signal measured in the beam experiment mentioned in the introduction. In the hypothesis of a linear scaling, a realistic simulation of the MIDAS detector yields a total of ≈ 30 events per year. The expected energy spectrum is shown in Fig. 5.

MIDAS is now installed at the Pierre Auger Observatory, next to the FD building Los Leones (cf. Fig. 6) and has been taking data since the beginning of 2013.

3 First detections of air showers in microwave band

The first detection of an air shower in microwave was performed in June 2011 by one of the EASIER detectors. It was in coincidence with an air shower registered by the SD that had an energy of 13.2 EeV and a zenith angle of 29.7°. The recorded GHz signal of this event is shown in Fig. 7 together with the PMT traces. The maximum of the signal was found to be more than 11 times larger than the noise fluctuations and occurred just one time bin (25 ns) before the signal in the water Cherenkov detector.

A search for signals of air showers has been performed in the data of the extended EASIER array analyzing the maximum of the trace within a window of 200 ns around the station trigger. The normalized distribution of the maximum in this time window is shown in Fig. 8 in red and in σ units (where $\sigma = (\text{maximum} - \text{mean}) / (\text{standard deviation})$). On the same figure the distribution shown in blue represents the trace maximum found outside the selection window (and thus expected to be uncorrelated with the shower). We present in Table 1 the characteristics of the three events that lay above the noise distribution, i.e. above 8σ .

All the air showers that gave rise to a radio pulse landed close to an EASIER antenna with an E-W polarization. The maximum distance from the antenna to shower axis is around 270 m for a rather inclined shower (55°). The

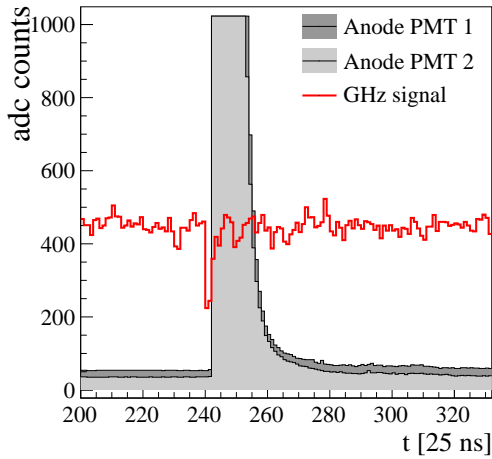


Fig. 7: Radio trace (in red) of the first event recorded by an EASIER detector with the signal of two low gain PMT channels (gray). The PMT signals are saturated as expected for a shower with the core at 136 m of the detector.

| Event ID | E [EeV] | θ [°] | ϕ [°] | d [m] | pol. |
|----------|---------|--------------|------------|-------|------|
| 12046376 | 13.2 | 29.7 | 344.6 | 136 | E-W |
| 20830870 | 17.1 | 55.3 | 33.8 | 269 | E-W |
| 21050180 | 2.6 | 47.4 | 290 | 193 | E-W |

Table 1: Main characteristics of the air showers detected in GHz range. Here E stands for energy; θ and ϕ for the zenith and azimuthal angle, d for the distance the shower axis and pol. for the polarization of the antenna)

detected radio pulses are not longer than 75 ns and their maximum occurs just before the start time of the PMT signal of the corresponding water Cherenkov detector. These characteristics make the interpretation of the signal difficult and are similar to the ones of the event candidates reported by another microwave experiment, CROME [9] at KASCADE site. On one side, at such close distance any emission from an air shower, even an isotropic one, is compressed in time and the signal is shortened and amplified, as seen in the EASIER data. On the other side, the viewing angle of the showers is close to the Cherenkov angle and the compression effect would also increase the observed frequency. One cannot discard an emission at lower frequencies shifted to the C-band. For instance, the radiation from the transverse current due to the geomagnetic deflections of the charged particles observed in the VHF [10] band could be the underlying emission process. An excess of detected events from the southern direction would point to a geomagnetic origin, but a larger data set is required to make relevant polarization comparisons.

Further studies will be focused on the search for a fainter but longer signal and from more distant air showers. The current development of simulations of the MBR and other processes and detectors simulation as well as future results from the test beam experiments AMY [11] and MAYBE [12] will enable a better understanding of the observed emissions. Furthermore, the recent installation of MIDAS, the ongoing

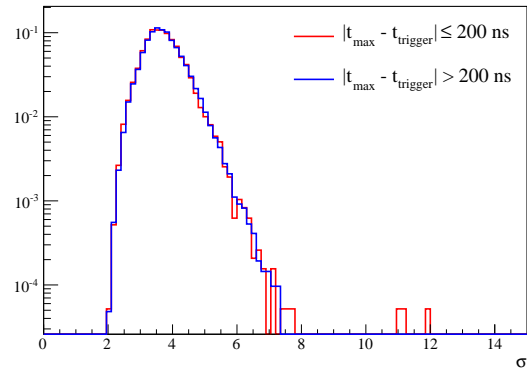


Fig. 8: Distribution of maxima found in a 200 ns time window around the trigger (in red) and outside this window (in blue).

analysis of the AMBER data and its future upgrade will help in disentangling the origin of the emission process.

4 Conclusions

The effort undertaken in microwave detection of air showers within the Pierre Auger Collaboration resulted in the installation of three prototypes at the Observatory site. All of them are now in the phase of stable data taking. The first three unequivocal radio signals detected in the GHz range by EASIER in coincidence with air showers detected by Auger SD were reported. However, because of their characteristics one cannot draw a conclusion on the emission mechanism. The viability of this technique remains an open question and the unique conditions offered by the Pierre Auger Observatory site should allow it to be addressed in the near future.

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