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

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Abstract. Radiation in the microwave band has been measured in coincidence with the passage of a particle beam through a dedicated chamber. This radiation could provide a new technique for the study of ultra high energy cosmic rays, its main advantages being the possibility to instrument a large area with a detector sensitive to the mass compostion of cosmic rays, 100% duty cycle, virtually no atmospheric attenuation and the use of relatively cheap equipment. Cosmic ray detection in the GHz band is being actively pursued at the Pierre Auger Observatory with three different set-ups: MIDAS and AMBER are prototypes of an imaging radio-detector based on a parabolic dish reflector, while EASIER instruments the surface detector stations with a radio system of wide angular coverage. The status of microwave R&D activities at Auger, including the first event detected by EASIER, is reported.

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1. INTRODUCTION

The Pierre Auger Observatory is a 3000 km^2 hybrid detector focused on the study of Ultra High Energy Cosmic (UHECRs) ray showers [1]. The Auger Collaboration is pursuing several projects with the objective of enhancing the Observatory capabilities and serving as a testbed of the technologies for the next generation of UHECR detectors. In this context, radio-based techniques, relying on a signal proportional to the electromagnetic content of the shower benefit from the minimal radio attenuation in the atmosphere and the availability of instrumentation with very competitive costs. Both CODALEMA [2] and LOPES [3] have shown that it is possible to use radiation in the MHz frequency band to detect cosmic ray showers and have helped elucidate the precise emission mechanism responsible for this radio-signal. The current AERA setup in the Auger Observatory [4] is studying the feasibility of the MHz technique for the detection of UHECRs.

Interest in using the GHz band of the microwave spectrum has been triggered by recent results of a test beam experiment [5]. In this measurements, an electron beam at SLAC was used to create a weakly ionized plasma inside an anechoic chamber and to study the GHz radiation associated with it. The measured signal was stronger than expected in the most simplistic model and it scaled quadratically with the beam intensity. This signal has been interpreted [5] as molecular bremsstrahlung radiation (MBR) and is expected to be continuous within a wide frequency band, unpolarized and emitted isotropically with a time constant of several nanoseconds. These characteristics would make MBR in the GHz band a *golden channel* for the study of ultra high energy cosmic rays, since the isotropic emission would allow for the observation of the longitudinal shower profile and thus would provide good sensitivity for the primary mass, with 100% duty cycle and minimal atmospheric attenuation. In addition, instrumentation in several sub-bands of the GHz spectrum is readily available since it is routinely used for wireless telecommunication, satellite TV emission and other commercial endeavors.

The Pierre Auger collaboration is pursuing a set of R&D projects aimed at determining the feasibility of the GHz technique for the detection of UHECRs. Three different prototypes, AMBER, EASIER and MIDAS, are installed at the Observatory with the common objective of detecting microwave signals from showers in coincidence with the Surface Detector Array (SD) or the Fluorescence Detector (FD).

2. MICROWAVE DETECTORS AT THE PIERRE AUGER OBSERVATORY

AMBER and MIDAS are *radio-fluorescence* detectors, wide aperture radio telescopes that follow the idea of an optical FD, intending to exploit the isotropic nature of the MBR to measure the shower longitudinal profile. The main difference between the two is that while AMBER is triggered by the Auger SD, MIDAS has an internal trigger system modeled after the one in the Auger

FIGURE 1. The AMBER (Air-shower Microwave Bremsstrahlung Experimental Radiometer) telescope is installed alongside the High Elevation Auger Telescopes (HEAT). The 2.5 m parabolic dish (left) is instrumented with a 16 pixel camera (right).

FD [6]. EASIER, in the meantime, is designed as a radio-complement to the SD, instrumenting the detectors with an additional radio-receiver aimed at the observation of the GHz radiation from the forward region of showers which are significantly closer to the antenna than in AMBER or MIDAS.

All three experiments are designed to take advantage of the extended C-band region of the microwave spectrum (3.4–4.2 GHz) that, being reserved for the reception of direct broadcast television, is relatively free of interference and for which plenty of instrumentation at moderate costs is available. The AMBER receivers are feed-horn antennas coupled to a low noise block amplifier (LNB) while EASIER and MIDAS use LNBFs, where the feed (the active receiver element) and the LNB are integrated on a single unit. In both cases the amplifiers have a 65 dB gain figure and down-convert the output signal to a frequency in the 1–2 GHz range. A logarithmic power detector suitable for transient signals (time response of the order of 10 to 100 ns, depending on the configuration) is used to convert the RF signal to a DC level proportional to the power of the signal at its input. This fast DC signal is suited to digitization in a Flash-ADC.

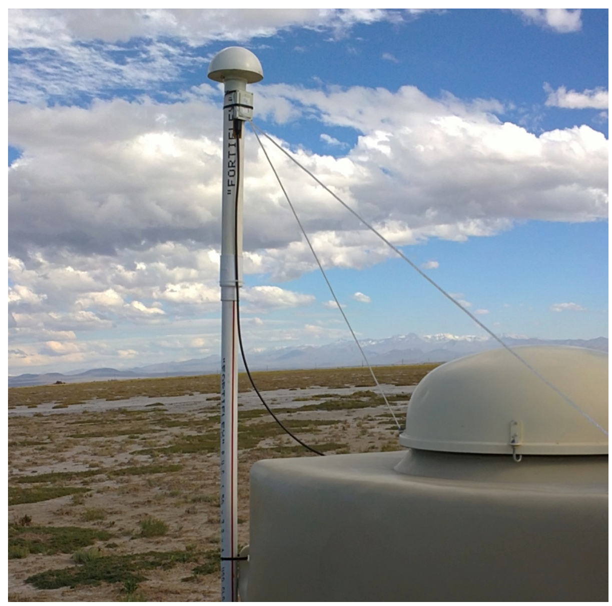

FIGURE 2. One of the EASIER (Extensive Air Shower Identification using Electron Radiometer) stations with the microwave receiver installed. The LNBF points upwards, protected by a radome weather cover, and is installed on top of a 3 m mast attached to the tank.

2.1. AMBER

An off-axis parabolic dish (2.5 m diameter) is the basis of the AMBER telescope. It is instrumented with a 16 pixel camera for a field of view in the sky of $7^\circ \times 7^\circ$ (Fig. 1). Alongside the dual polarized C-band feed horn, each one of the four central pixels is equipped with a Ku-band (10.9–14.5 GHz) feed. The 12 outer pixels are instrumented with single polarized C-band feeds. Signal processing takes place on a Compact-PCI electronics card that integrates the logarithmic power detector and a Flash-ADC with 100 MHz sampling rate.

The most salient characteristic of the digital electronics is its large circular memory buffer, capable of storing up to 5 s of data for each channel. The buffer is designed to accommodate the 3 s latency of the SD data process-

FIGURE 3. MIDAS (Microwave Detection of Air Showers) uses a 5 m parabolic dish (left) instrumented with a 53 channel camera (right) and is installed at one of the FD sites.

ing chain that acts as external trigger of the AMBER telescope. When the SD trigger is received at AMBER, the time of the shower crossing through the field of view of the telescope is calculated from a preliminary analysis of the SD data and 100 μs of data are read out from the buffer and stored to disk. The online event reconstruction has an uncertainty of 10° in the pointing angle of the shower and 500 m on the core position, that translates to an uncertainty in the expected arrival time of the microwave signal at the telescope that is properly accommodated in the length of the track being read out.

AMBER was installed and commissioned at the Auger Observatory in 2011 and data taking and analysis are underway to search for coincidences with the SD. The overall noise temperature in the the C-band pixels was determined to be in the range between 45 K (for the outer feeds) to 65 K (for the central feeds) as determined by an absolute calibration of the feeds using a liquid nitrogen bath plus a direct measurement of the dish contribution. This calibration was subsequently cross-checked during commissioning using transits of several known astronomical microwave emitters such as the Sun and the Crab nebula.

2.2. EASIER

EASIER instruments a set of SD detectors with a microwave receiver of about 60° field of view and $30 \cdot 10^{-3}$ m^2 effective area. This small area is compensated by closer distances to the shower and by the compression (up to a factor 10 increase) of the arrival times of the signal when the shower is observed in a direction close to the axis.

An LNBF unit pointing upwards is mounted on top of a 3 m mast attached to the SD station (Fig. 2). The LNBF signal is fed to a power detector and the output is then digitized in the Flash-ADC of the station using an available channel in the SD electronics board. With this arrangement EASIER acts as an additional data source for the station that is triggered and readout when the station is, and has its data integrated in the data stream of the SD.

The first seven EASIER detectors were instrumented in April 2011, followed by 54 additional detectors in April 2012, for a total of 61 instrumented detectors. Data analysis and search for coincidences are underway, and the first instrumented hexagon already yielded the first evidence of GHz emission in air showers (Sec. 3).

2.3. MIDAS

MIDAS instruments a 5 m parabolic reflector with 53 C-band feeds for a field of view of 20° × 10° (Fig. 3). It was installed and commissioned in September 2012 close to one of the FD telescopes. The prototype was previously installed and operated on a 4.5 m dish at the University of Chicago campus [7].

The MIDAS LNBFs are connected to a logarithmic power detector with 100 ns time resolution. The output of the power detector is digitized by a custom 14-bit Flash ADC operating at 20 MHz sampling rate. The MIDAS digital electronics implements a multi-level trigger system capable of identifying fast transient events against the radio frequency background [7].

The absolute calibration of the setup at Chicago was performed using the Sun as a known emitter and yielded a value for the system temperature of 65 K for the central pixel. This value was cross-checked with other known

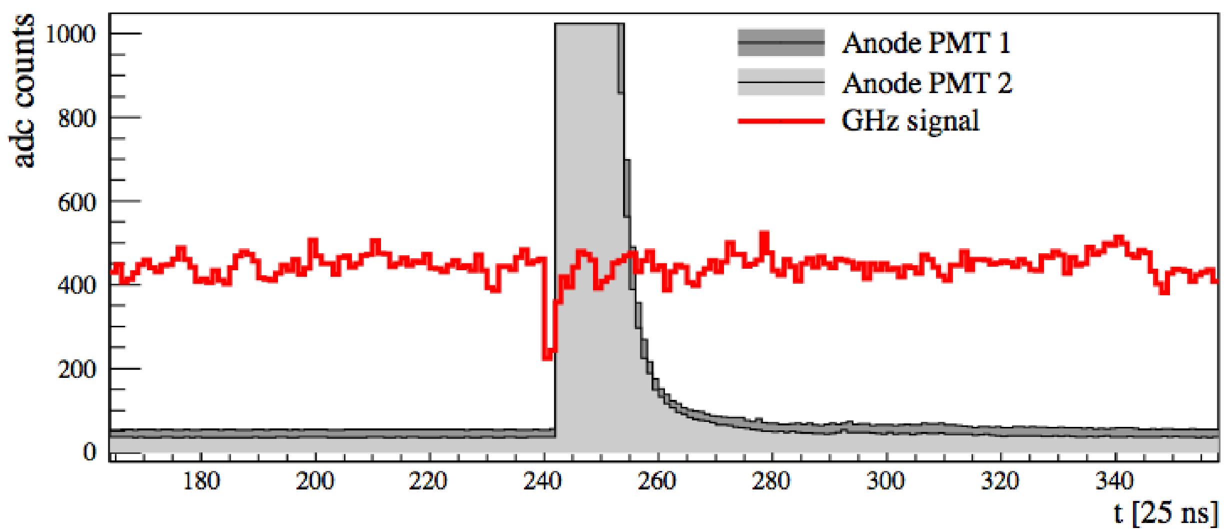

FIGURE 4. Signal in the EASIER antenna (red, thicker line) recorded in coincidence with the signal in two of the photomultipliers in the surface detector (thin, shadowed histogram) for a 13.2 EeV event in June 2011. The power output is inverted, so a decrease in the signal like here implies an increase in the power at its input. Both of the photomultipliers are saturated, as expected for a shower landing so close (140 m) to a detector.

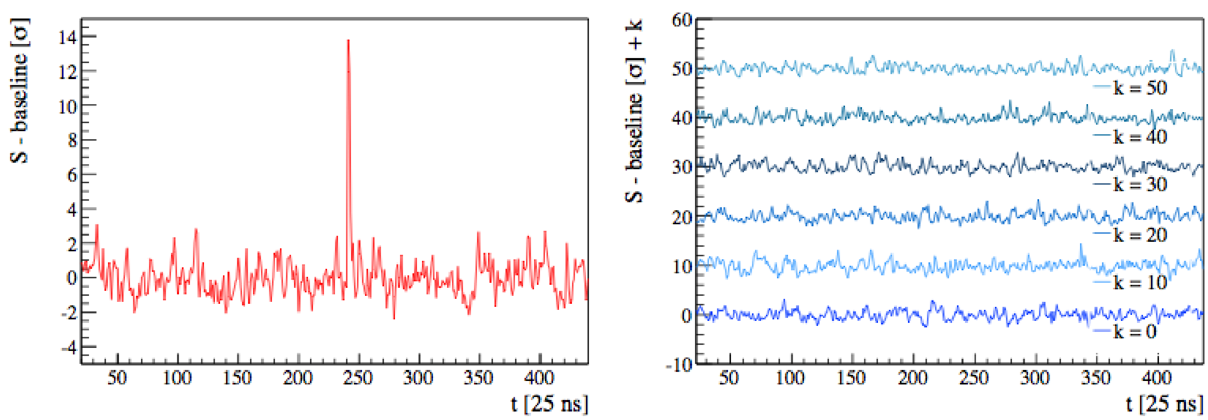

FIGURE 5. The signal of Fig. 4 has a 14σ significance (left panel, plotted as power above background, in units of the baseline fluctuations). None of the other 6 stations instrumented at the time registered a significant signal (right panel, a constant term k has been added to each trace for clarity).

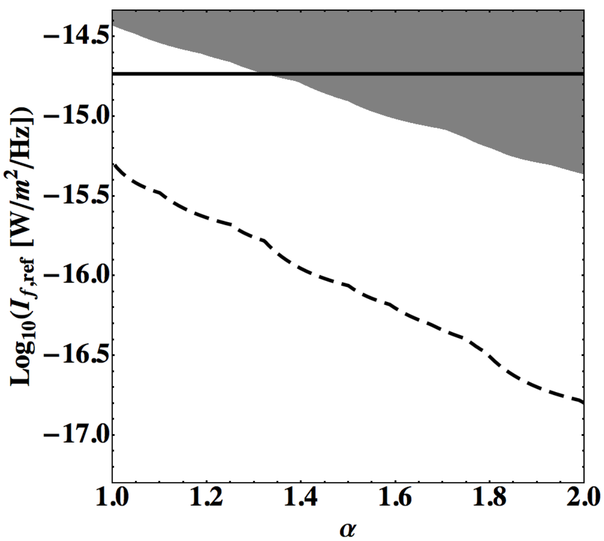

FIGURE 6. The MIDAS limit on the microwave emission of air showers. The shadowed region represents the excluded values (95% CL) of the intensity (vertical axis) and the scaling (horizontal axis) of the microwave emission for a reference shower of energy 3.36×10^{17} eV. The full horizontal line corresponds to the value measured in [5] while the dashed line is the projected limit using a year of data taken in coincidence with the Auger Observatory [8].

microwave emitters such as the Moon and the Crab nebula. The noise temperature of the rest of the pixels of the camera was found to be compatible with the value of the central one.

3. RESULTS

The EASIER set-up produced the first evidence of GHz emission by an air shower in June 2011, recording a signal in coincidence with an SD detector in the central station of the instrumented 7-detector hexagon (Fig. 4). The event, as measured by the SD had an energy of 13.2 EeV, 30° zenith angle and landed at a distance of 140 m of the closest station, the one that registered the GHz signal. The relative timing of the SD detector and the antenna signal (with the latter arriving slightly in advance of the former) excludes the possibility of a spurious radio trace induced by the photomultiplier. The significance of the measured signal is 14σ (Fig. 5).

The MIDAS prototype recorded some shower candidates during the run at Chicago, but the signals were not strong enough to unambiguously identify these as produced by a cosmic ray shower. The absence of clearly identified candidates that passed the several criteria established in a search program, compared to what was expected from detailed Monte-Carlo simulations allowed us to set a limit [8] to the air shower microwave emission strength and scaling with energy (Fig. 6).

4. CONCLUSIONS

The Pierre Auger Observatory is running a strong program dedicated to the feasibility of using the microwave technique for the detection of UHECRs. This program has already produced the first evidence of GHz emission by an air shower, a result that has been confirmed by the CROME experiment [9]. The signal recorded by EASIER is in principle compatible with what is expected if the signal in [5] is scaled linearly, but with a single event it can not be excluded that other processes may contribute partly or totally to the measured signal. Recent results by MIDAS [8] and by test beam experiments [10] suggest that in certain conditions the emission could be lower (or scale differently) than expected from the measurements in [5].

The objective of the program is now to establish the nature and the characteristics of the GHz emission. We expect that the information gathered at the different setups within the Observatory, together with the one coming from the new generation of test beam experiments (like MAYBE [10] and AMY [11]) will allow us to establish if GHz radiation can be a useful tool for the study of UHECRs.

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