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Studies of the microwave emission of extensive air showers with EASIER and MIDAS at the Pierre Auger Observatory

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1. Introduction

The measurement of the composition of the Ultra High Energy Cosmic Rays (UHECR) is crucial to constrain their origin. The two main techniques to characterize the Extensive Air Shower (EAS) induced by the UHECR, is either a particle detector array at ground or a fluorescence telescope. Unfortunately, in their actual form, the particle detector at ground are limited in their sensitivity on the mass composition measurement and the fluorescence technique is sensitive to it only with a limited duty cycle of 15% thus limiting the statistics at the highest energies. The development of an additional particle detector complementing the existing one is the focus of the upgrade effort undertaken at the Pierre Auger Observatory[1].
However, new detection channels have also been considered. The observation of the EAS through the radio waves emitted along its development in the atmosphere is one of them. Radio technique have been investigated since the 1960's and is now an experienced technique in the VHF band, a region of frequency where a strong signal is emitted in the forward direction within a Cherenkov cone of around 1 degree opening in air. This technique is now implemented in several observatories including the Pierre Auger Observatory[3]. However the lateral extension of the radio signal doesn't allow one to instrument large area required to compensate for the very low flux at the highest energies.
A promising technique was proposed in 2008 [2] after the observation of a signal in the microwave frequencies upon the passage of a particle shower in an anechoic chamber. This signal interpreted as originated from the acceleration of ionisation electrons in the molecular field, the molecular Bremsstrahlung radiation (MBR), has triggered a lot of interest. The MBR is emitted isotropically and it would allow one to measure the longitudinal profile of the EAS, as with the fluorescence but with a 100% duty cycle. Since the first beam test results, many efforts have been undertaken, new beam test have been carried out [4, 5] but were not able to reproduce the initial results. Estimation of the expected signal have been improved and yielded less optimistic results[7]. Finally, in situ experiments have tried to observe the MBR emission using existing CR observatory to probe this signal[6, **?**]. If clear signal were observed, their origin can be attributed to a coherent emission.
In the present contribution we present the development and the results of two radio experiments, EASIER and MIDAS, installed within the Pierre Auger Observatory and able to probe the MBR emission from the UHECR.

2. The Pierre Auger Observatory

The Pierre Auger Observatory is an hybrid detector. It comprises an array of 1660 particle detectors at ground, the surface detector (SD), and a fluorescence detector (FD) measuring the fluorescence light from 5 sites surrounding the SD.

The two radio detectors we present here aim at the measurement of the same emission but are implemented in a different way. EASIER is embedded in a local SD station and intends to measure the radio waves from the ground, whereas MIDAS is inspired of the FD, and tries to measure the radiation of EAS from the side. The footprint of EASIER is depicted in the Figure 1 and together with the Auger SD array and the limits of MIDAS's the field of view of MIDAS. Both experiments take advantage of the infrastructure but also use the reconstructed SD data from Auger to search for coincident event.

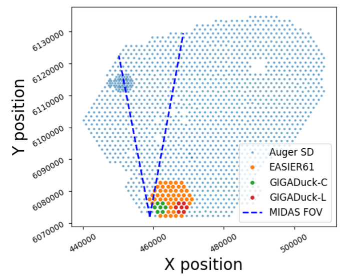

Figure 1: The EASIER arrays and MIDAS field of view overlaid with the surface detector of the Pierre Auger Observatory.

3. EASIER

3.1 Detectors

Concept EASIER (Extensive Air Shower Identification with Electron Radiometer) is designed to observe the radio emission from EAS with an antenna looking up in the sly, and located at ground. It is operated in slave mode with an Auger SD local station and thus takes advantage of the trigger of the particle detector. The detector is composed of an antenna followed by an amplification and a filtering stage. The radio frequency (RF) signal is then transformed into its power envelope with a logarithmic amplifier. The output of the logarithmic amplifier is in turn scaled to fit into Auger SD front end input where the EASIER signal replaces a low gain channel of one of the three PMTs. The scheme of EASIER detector is shown in the figure **??**. This concept has been implemented is three different versions, two in the C-band EASIER61 and GIGADuck-C and

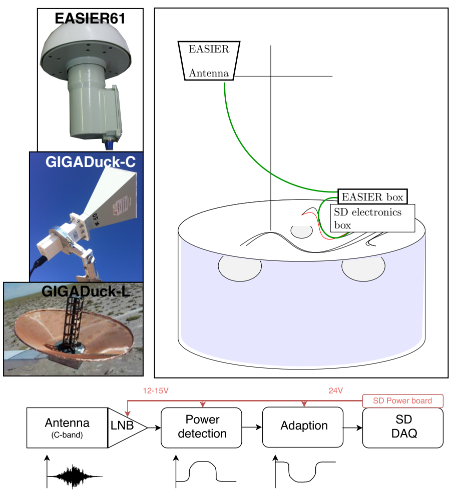

Figure 2: Scheme of EASIER concept. The sensor placed on the tank is one the three antenna shown in the left side. The signal chain common for all the setup is represented on the bottom part.

one the L band, GIGADuck-L (see Figure **??** for the picture of the three types of antenna).

EASIER61 The EASIER61 is the first array installed in the Pampa. A test bed of 7 antennas was installed in April 2011 and the completion to 61 detectors took place a year later. Each detector is composed of a C-band cylindrical horn antenna with a half power beam width (HPBW) of 90°. The antenna points toward the zenith. EASIER61 has measured clear events in coincidence with the particle detector (see section 3.3). However, because of the short distance to the shower axis, or inclined events, the origin of this signal can be attributed to coherent processes and cannot be an evidence for the MBR.

GIGADuck-C GIGADuck is an improvement of the EASIER61 detector. It is an array of seven detectors instrumented with a larger gain antenna to increase the sensitivity, and an optimized geometry to enhance the coincidence probability between radio detectors.Such a coincidence would favour the MBR origin of a signal against a coherent process. In this modified geometry, each antenna points in a different direction, the central one looks at the zenith while the other six are tilted by 20° and have their azimuth oriented in the direction of the central detector. This design was implemented in the C-band and the L-band. In the C-band, the antenna is a pyramidal horn with 15dB gain and a HPBW of 60°, followed by an LNB (Norsat 8115F).

GIGADuck-L The GIGADuck design has been implemented in the L-band as well. The antenna is a helix antenna with a maximum gain at 1.4GHz and a HPBW of 60°. Contrary to the two other setups, we developed the amplification board with two commercial LNA chip (Broadcom Limited MGA633P8 and MGA13116) in series. We integrated a band pass filter and an Electric Surge protection at the input before any amplification. The gain and noise temperature of this board were characterized before the installation. The gain in the bandwidth is around 50dB and the noise temperature from 60 to 80K among the 9 boards tested.

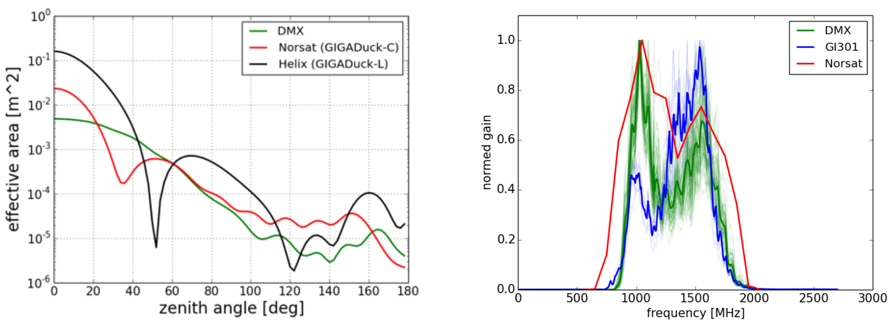

Figure 3: Scheme of EASIER concept. The sensor placed on the tank is one the three antenna shown in the left side. The signal chain common for all the setup is represented on the bottom part.

3.2 Detector calibration

The sensitivity of a radio power detector like EASIER can be estimated with the figure of merit that defines approximately the minimum flux one can detect:

$$F_{min} = \frac{k_B T_{sys}}{A_{eff}\sqrt{\Delta\nu \Delta t}} \tag{3.1}$$

where the T_{sys} is the system temperature, A_{eff} the effective area, $\Delta\nu$ and Δt the bandwidth and the time over which the signal can be integrated.

Figure 4 (left) shows the measured bandwidths for the 2 C-band detectors. The GIGADuck-C bandwidth (Norsat) is larger which also increase the sensitivity. The comparison of the simulated effective area of the three C-band detectors in the figure 4 (right) shows the direct increase in sensitivity from this parameters.

The system temperature is more difficult to measure. For the three setups it was indeed measured with different methods. For EASIER61 detectors it was estimated with a dedicated measurement, we simply measured the power output when the antenna pointed to the sky and when oriented towards the ground. From the power difference between these two measurements, an intrinsic system temperature of 120 K was measured (the so called Y-factor method).

For the GIGADuck-C band, we have developped a method using the sun as a calibration source. The GIGADuck-C antenna are sufficiently sensitive to measure the solar flux, and an example of the sun contribution during a day is shown in the Figure **??** (top). After applying a selection on the daily monitoring baselines based on quality of the radio data and quality of the fit of the sun bump, we combine the measurements of each days and compute the system noise temperature. Indeed, the sun bump height measures the ratio of power with and without sun which reads:

$$\frac{P_{on}}{P_{off}} = \frac{k_B T_{sys} + F_{sun} A_{eff}}{k_B T_{sys}} \tag{3.2}$$

where F_{sun} is the expected contribution from the sun based on observations at the Nobeyama Radio Observatory (NRO) [**?**] at 3.75 GHz and A_{eff} is the simulated effective area of the antenna. One can also compare the timing of the sun in the simulation and the data, some difference were found indicating a shift in the antenna orientation. We combined these information in a global fit of the system noise temperature and the antenna orientation. The noise temperature value and time of maximum of one antenna on the set of selected days is shown in the Figure **??** (bottom) for the optimal antenna orientation. We found system noise temperature ranging from 50 to 70K antenna pointing shifts up to 12 degree.

The baseline of the GIGADuck-L detectors exhibit also a clear bump attributed to the sun. However other contributions can be noticed along the day. These modulations are likely to be signal from positioning satellite which all emit in the L-band and prevent us to isolate the sun signal. We thus deduced the system temperature directly from the baseline level measured in monitoring data and the calibration information recorded prior the installation. Noise temperatures ranging from 95 to 145 K were found for the seven installed detector.

	antenna	geometry	FOV / A_{eff} max	system temperature
EASIER61	C-band cylindrical horn	(0,0)	$90 / 5 \times 10^{-3}$	120 K
GIGADuck-C	C-band pyramidal horn	6 tilted 1 vertical	$60 / 2 \times 10^{-2}$	70 K
GIGADuck-L	L-band helix	6 tilted 1 vertical	$60 / 2 \times 10^{-1}$	145 K

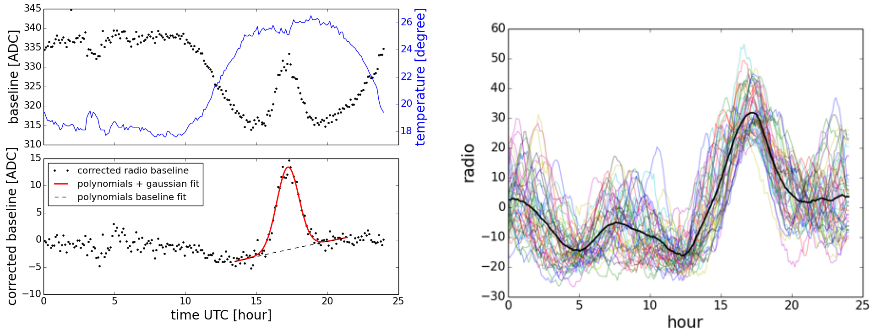

Figure 4:

3.3 Event search

The operation of the various EASIER arrays have been overlapping. The first installed array is made of 7 detectors of EASIER61 in April 2011 and have been operating since 2011. Indeed, the fir acquiring data together with the Auger normal stream since more than 6 years for the EASIER61 array to 6 month for GIGADuck-L array, the last installed.

We show in this section a search for radio event in coincidence with EAS recorded by the Auger SD.
We build a data set from the Auger data, and we proceed to a first selection on the cosmic ray event quality i.e. regular cuts on the reconstruction and the removal of events tagged as lightning. A second set of cuts is applied on the radio trace caracteristics, we remove traces with large RMS or with more than 10 bins saturated (out of 768).

Event search The data set is split in a *backgroundset* composed of the station with a distance larger than 3km from the shower axis and a *signalset* which select among the EAS event of energy larger than 5 EeV and zenith angle smaller than 60° the station closer than 2km from the shower axis. The distribution of the radio maximum as a function of the time of this maximum is shown in the figure **??** for the 4 setups. One can see a clear accumulation of event with large radio signal at the time bin 240 which is only 100ns before the SD trigger. To extract the radio events, we determine a threshold from the background sample which impose 99.7% of the events to have a lower radio maximum than this threshold. A time condition is also set so that the time of maximum is inside 500ns around the particle trigger. Events are found only in the EASIER61 setup where event with radio signal up to 63 sigma are recorded. The parameters of these events are listed in the Table **??**. A striking caracteristic is the short distance of all the detected events.

Event characteristics

Discussion

4. MIDAS

4.1 Detectors

The MIDAS detector, first commissioned at the University of Chicago in 2010 [**?**] and cur-

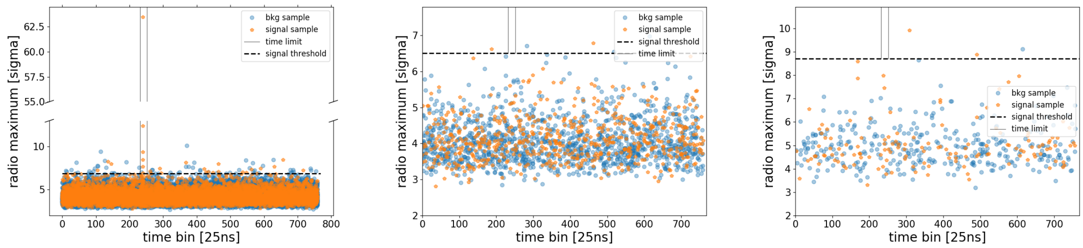

Figure 5: Scheme of EASIER concept. The sensor placed on the tank is one the three antenna shown in the left side. The signal chain common for all the setup is represented on the bottom part.

Figure 6: Scheme of EASIER concept. The sensor placed on the tank is one the three antenna shown in the left side. The signal chain common for all the setup is represented on the bottom part.

rently installed at the Pierre Auger Observatory as seen in ??. Equipped with a 5 m diameter parabolic antenna with a 53 pixel camera at its focus (3.2), the design of the MIDAS telescope is analogous to the design of one of the FDs at the Auger observatory as explained in Âğ 1.3.1. Collectively, the 53 pixel ensemble covers approximately a 20 ÃŮ 10 field of view, and works together to observe microwave emission in the extended C band (3.4 to 4.2 GHz). Individually, each pixel is a channel composed of a feed horn, a low noise amplifier, and a frequency down converter. Radio waves detected by a channel are transformed into a radio equivalent analog signal which then undergoes digitization by one of four analog-to-digital converter (ADC) boards at a sampling rate of 20 MHz. A detailed description of the instrument can be found in Alvarez-Muiz et al. (2013). The four ADC boards are designed to accommodate 16 channels each and store a total of 2048 samples in a circular buffer per channel. In addition, each ADC board allows for the first level trigger (FLT), a simple threshold trigger, for each channel through an on-board field programmable gate array (FPGA). A Master Trigger board, which is connected to each ADC board, is equipped with its own FPGA which can execute the second level trigger (SLT), a search for one of the 767 possible 4-pixels pattern possibly associated to an EAS. The master trigger board can also read the data from the ADC boards via a VME if the SLT conditions are fullfilled.

4.2 Event search

MIDAS has collected data from September 14 2012 to September 26 2014. We present in this section a search of radio event in coincidence with Auger SD events. Contrary to EASIER which is trigger by the SD local station, MIDAS has an independent system of triggering. Thus we first show the selection of event in MIDAS and Auger data and then their comparison to look for coincident events. The first data selection occurs on the radio data to exclude high noise period. The accidental SLT rate is expected to be less than 1mHz but could reach several kHz. To remove these periods, we impose the SLT rate to be less than 0.5Hz furthermore we also remove the period when the FLT rate exceeded 2.4kHz. The resulting observational time is about 359 days.
The selection of the EAS data set from Auger SD data imposes a threshold in energy of 1EeV, and conditions on the event topology (we select the 6T5 event which have the tank with the largest signal surrounded with 6 active tanks). We also select only the events possibly observed by MIDAS by imposing the core of the shower to be within $\pm$ 10° of the MIDAS opening angle and the event detection time to be in the MIDAS active operation time.
A coincidence time window of $\pm 300\mu s$ is chosen to account for the time delays induced by the RF wave propagation. In this window only one event has fullfilled the requirement and was accepted as a candidate event. Its configuration is represented in the Figure 8.
The number of coincident event expected only by chance was estimated analytically assuming the arrival event time of Auger and MIDAS are both independent and follow the Poisson distribution. With these assumption the chance coincidence rate $\mathrm{r_c}$ reads:

$$\mathrm{r_c} = \frac{\mathrm{P_c}}{\tau} = \frac{\mathrm{r_A r_M}\tau^2 \exp^{-\tau(\mathrm{r_A}+\mathrm{r_M})}}{\tau} \simeq \mathrm{r_A r_M}\tau \tag{4.1}$$

With P_c is the chance coincidence probability, and $\mathrm{r_A} = 8.910^{-4}$Hz ,$\mathrm{r_M} = 1.810^{-2}$ Hz the Auger and MIDAS event rate median, and $\tau = 600\mu$s is the coincidence time window. The expected number of event is then given by $\mathrm{N_c} = \mathrm{r_c t_{obs}} = 0.3(+0.55/-0.3)$ with $\mathrm{t_{obs}} = 359$ days. This analytical result was cross checked by producing mock samples with the Auger detection time randomly shifted. The number of event detected in these mock sample agrees very well with the analitical prediction. Furthermore, the reconstructed event, a 2.5EeV shower at 52.94 km is not energetic enough and too far to produce a signal like the one observed.

4.3 MBR limits

Following [2], the MBR flux density from an EAS can be expressed as:

$$\mathrm{F(t)} = \mathrm{F_{ref}} \cdot \frac{\rho(\mathrm{t})}{\rho_0} \cdot \left(\frac{\mathrm{d}}{\mathrm{R(t)}}\right)^2 \cdot \left(\frac{\mathrm{N(t)}}{\mathrm{N_{ref}}}\right)^\alpha \tag{4.2}$$

where F_{ref} is the flux density for a shower of energy $E_{ref} = 3.37\ 10^{17}$ eV with a number of particles at it maximum developpement of N_{ref}, measured at the sea level density ρ_0, a distance d = 0.5m in [2]. This reference is scaled to a EAS developping in a time dependent density of $\rho(t)$ at a distance from the detector of R(t) and a particle number N(t). Note that the exponent α on the particle scaling is assumed to vary between 1 and 2 depending on coherence condition inside the shower plasma.
The expected flux density was computed with varying F_{ref} and α for the showers selected in section **??** and folded with the detector response. An example of simulated event is shown in the figure for illustration. The comparison of the expected number of event in simulation with the null result obtained in the data allows us to place limits in the (F_{ref}, α) plane, see Figure **??**. The interpretation of the observation reported in [2] are ruled out. A more recent modeling of the MBR emission yields estimation of a factor 200 lower and a linear dependence with energy (or the nuber of particles).

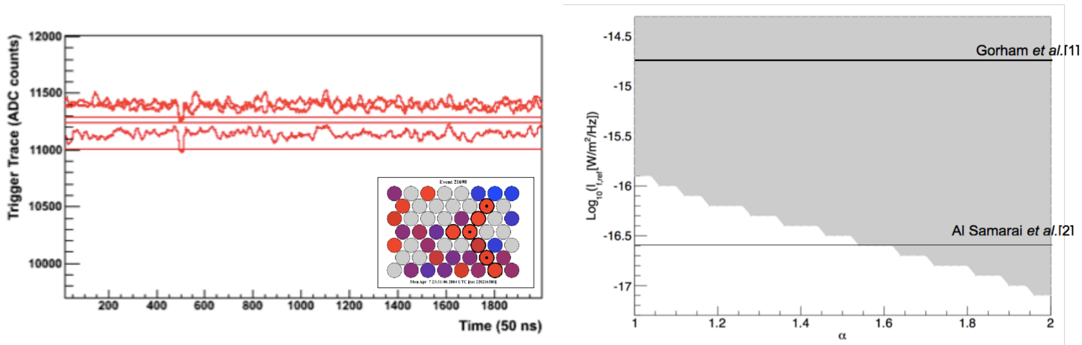

Figure 7: âĂć

5. Discussion and conclusions

Two setups, EASIER and MIDAS, aiming at the observation of the Molecular Bremsstrahlung Radiation in coincidence with event detected at the Pierre Auger Observatory were presented. We presented a search for Ultra High Energy (E > 1EeV) EAS events in these setups. While clear radio events were observed in the radio surface detector EASIER, no signal were found with MIDAS microwave telescope. These results are however compatible if one considers other emissions origin. Indeed, the radio signal observed with EASIER are all from closeby showers and might be attributed to coherent emissions known to be dominant at lower frequencies.

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