Measuring radio signals from extensive air showers

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Understanding the origin and mechanism of production of the most energetic cosmic rays is one of the challenging question of contemporary astroparticle physics. The extremely low flux of those particles does not permit direct measurements and observations are made via the cascade of secondary particles they iniate in the atmosphere, the so-called extensive air shower (EAS). Two techniques are used to perform such measurements : the array of ground particles detectors and fluorescence telescopes. The latter offers a calorimetric measurement of the EAS but suffers a critical uptime of the order of 10 %. The ground detector array is much more robust but Monte Carlo simulations are needed for energy calibration. The above considerations illustrate the pertinency of a new observation technique that could come in addition to the existing one to increase both statistics and EAS understanding in the field of ultra high energy cosmic rays (UHECR). The radio detection technique, which has known a renewal of interest in the last 5 years, might be an appropriate candidate. We will give a brief review of the historical concept, present the modern theoritical approaches and the current experiment based upon this principle of detection.

1. Concept and first developments of the radio technique

The idea of radio detecting EAS was first impulsed by the work of Askar'yan [1] in the 60's. He suggested that the electromagnetic cascade should present a fractional negative charge excess due to electron scattering processes and positron annihilation in flight. From this charge asymmetry, the Cerenkov radiation observed at sufficiently long wavelength (compared to the shower front dimensions) should be linearly scaled with the shower energy.

In 1965, Kahn and Lerche [2] suggested that the earth magnetic field would impact the emission process. Due to the effect of the Lorentz force, the continuously created electron-positron pairs in the shower should be systematically separated, yielding to the creation of a transverse current and a dipolar radiation. They evaluated the contribution of each mechanism and concluded that the transverse current should dominate the overall emission.

On the experimental point of view, Jelley and his collaborators [3] discovered the first evidence for radio emission from cosmic ray air showers in 1965 with an array of dipole antennas at a frequency of 44 MHz in coincidence with Geiger counters. This first result lead to the creation of numerous experiments that explored several frequency bands ranging from 3 MHz up to 520 Mhz. Unfortunately, difficulties of interpretation and reproducibility due to radio interferences and technical limitations yielded to the disuse of this technique by the 70's. Allan summarized the work done during that period in an extensive review [4] and proposed a semi-empirical formula to describe the electric field at 55 MHz :

$$E_\nu = 25 \left[\frac{E_P}{10^{17}\ \mathrm{eV}} \right] \sin\alpha \times \cos\theta \times \exp\left(\frac{-d}{d_0(\nu,\theta)} \right)\ [\mu\mathrm{V/m/MHz}] \qquad (1)$$

where E_ν is the received voltage, $\mathrm{E_P}$ is the energy of the primary particle, α the angle between the geomagnetic field vector and the shower axis, θ the shower zenithal angle, d the impact parameter and d_0 a characteristic decrease distance function of both θ and the frequency ν wich is about 110 m at 55 MHz.

2. Renewal of theoritical models

Recently, innovative approaches have been proposed for the theoritical understanding of the air shower radio emission. Those models present some descrepancies but the comparison between them is not a straigth forward question as underlying processes might be similar while treated differently. The ability to reproduce features of the electric field observed in experimental data should permit to identify the most relevant picture.

2.1. The geosynchrotron approach

In 2003, Falcke and Gorham [5] proposed the radio emission of an EAS to be interpreted as synchrotron radiation in the earth's magnetic field, what they call coherent geosynchrotron. In this approach, the emission mechanism does not require a consideration of charge separation. The difference of charge between electrons and positrons is roughly cancelled by the opposite sign of the Lorentz force. Therefore, both populations contribute in the same way and does not interfere destructively. This model has been intensively developped by Huege [6,7] using analytically parametrized air showers. Results of those simulations given in [8] established a number of relevant features of the radio emission such as polarization characteristics and a roughly linear scaling of the field strength with the energy of the shower.

This model has been recently coupled to a much more sophisticated air shower simulation code [9]. It seems that the more realistic distribution of particle momentum angles in the shower axis impacts significantly the field strength. In [10], an experimental approach based on this model is proposed to estimate both the energy and the mass of the primary particle. The energy could be estimated from the measured voltage at a distance of 175 m from the shower core, a region where the field appears to be less sensitive to shower to shower fluctuations. Then the $X_{\max}$ parameter of the shower could be estimated from the ratio of this voltage to the one measured at 700 m from the shower core where the signal is highly sensitive to the $X_{\max}$ parameter.

2.2. The macroscopic decription of geomagnetic radiation

In [11], Scholten, Werner and Rusydi draw up a macroscopic description of geomagnetic radiation. The emission mechanism considered here is again the effect of the Lorentz force that pulls in opposite directions the electrons and positrons of the shower. An electric current is thus induced in the direction perpendicular to the geomagnetic field and the shower axis. This approach is closer to the one proposed by Kahn and Lerche [2] than to the coherent geosynchrotron one. While the latter reffers to the acceleration of particles as the emitting process, the macroscopic picture suggests that this acceleration, once averaged over all electrons, transforms into a drift velocity due to the multiple collisions with the air molecules.

Following this model, an analytical expression of the electric field is obtained in [11] that gives the relation between the pulse shape and the shower profile. The radio signal waveform should present a clear bipolar structure with a zero crossing time related to the maximum in the shower profile and a maximum of the radio signal corresponding to the earlier development of the shower.

In [12], the effect of a more realistic refractive index of the air on the emission process is also investigated and it appears that the geomagnetic contribution should be the dominant one except for direction of arrival of the shower close to the direction of the geomagnetic vector. In this particular case, the charge excess contribution should not be neglected.

2.3. Boosted Coulomb and Cerenkov field

Another approach, proposed by Meyer-Vernet, Lecacheux and Ardouin[13] suggests that the air refractive index, which is commonly approximated to unity in other models, but is slightly different in reality, should be considered more precisely as it might significantly affect the emission mechanisms : a Cerenkov field should be radiated by supraluminal charges of the shower while subluminal charges should emit a boosted Coulomb field which is estimated using an equivalent Lorentz factor in vacuum.

In the scope of this model, it is found in [13] that the boosted Coulomb should be the dominant process, the Cerenkov field being emitted by the high energy part of shower particles where the net charge and separation mechanism are smaller. The calculated field strengths from boosted Coulomb is compared to the published values of the geosynchrotron model and experimental data published on LOPES and CODALEMA experiments and it shows a good agreement in both case. There is also a good agreement in terms of spectral shape, control by observer distance and geomagnetic field direction effect

3. Modern experiments

Besides the theoritical developments mentionned above, the radio technique has also known a major evolution on the experimental point of view. Two experiments using this technique are currently taking data on a regular basis : the CODALEMA and LOPES experiments.

3.1. The CODALEMA experiment

The CODALEMA experiment is installed since 2002 at the Nançay radio astronomy observatory (France). It is made of two independent detector arrays : one of 24 radio antennas arranged in a cross of $600\,\text{m} \times 500\,\text{m}$ (21 antennas oriented in the East-West and 3 in the North-South polarization), and a 17 plastic scintillator array disposed on a square of $350\,\text{m} \times 350\,\text{m}$ (fig. 1).

Since last array enhancement in late 2005 [14], emphasis on simplicity, size, cost and performance was used as guidelines to develop a new broadband ($100\,\text{kHz} - 220\,\text{MHz}$) antenna based on a short fat active dipole concept [15]. Each particle detector station includes a thick plastic scintillator seen by two photo-multiplier tubes.

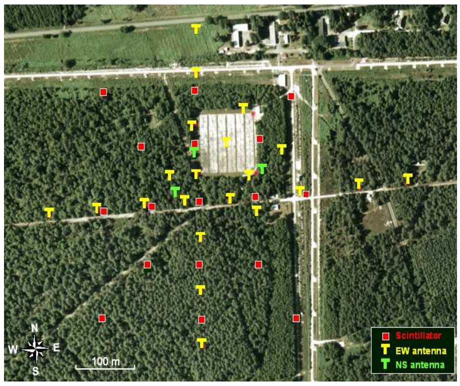

Figure 1. The experimental setup of CODALEMA at Nançay.

All the detectors and antennas are wired to a central shelter. In the standard acquisition mode, the particle detection system acts as a master EAS trigger while the antennas are configured in a slave mode. Signals are digitized over the full frequency band on 12 bits at 1 MS/s over $2.5\,\mu$s. Besides acting as the trigger, the particle detector gives information on the shower energy, direction and core position for events falling inside the particle detectors array above a threshold of some 10^{15} eV.

For the offline analysis, a digital filter is applied in the $40 - 70\,\text{MHz}$ frequency band where no emitter is found in Nanąy, without affecting the transient nature of the radio pulse. An amplitude threshold can be adjusted regarding the remaining noise on the signal [16] : if the transient signal is above the threshold, the antenna is flagged "on". With the time information coming from a minimum of 3 antennas, the arrival direction of the shower plane can be computed by triangulation, independentely from the particle detector. The main advantage is that it allows an event by event and antenna by antenna data processing, thus to sample the individual shower. The radio detected showers are finally identified by making a comparison between the arrival time and direction estimated separately with the particles detectors array and the antennas array.

3.2. The LOPES experiment

Installed in the KASCADE particle detector [17] of the Forschungszentrum Karlsruhe (FZK, Germany), LOPES [18] is made of 30 wire-dipole antennas, of which 10 are in a dual polarization mode (fig. 2).

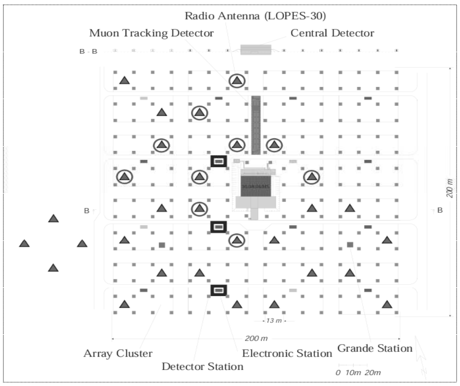

Figure 2. The setup of the LOPES experiment at Karlsruhe.

Radio signals are digitized also on 12 bits, at 80 MS/s, an analog filter restricting the observable frequency band to $40 - 80\,\mathrm{MHz}$. The particle detector (here KASCADE or KASCADE Grande) also acts as a trigger for the radio array. LOPES antennas are spread out over the KASCADE array (a 200 m side square), but KASCADE Grande can also trigger the acquisition and allows to see more distant events from the antennas. KASCADE and Grande offer a detailed and complete information on the EAS from 10^{17} eV up to 10^{18} eV.

The poor quality of the sky over the FZK implies first to clean the recorded radio signal by using a RFI suppression algorithm. Time scaling between all the antennas is then performed by applying a variable delay on the signals, determined thanks to the particle detector information on the shower's arrival direction. Signals are then summed up to produce a synthetic signal representative of the total electric field strength over the whole LOPES array. This method, called "beam forming", is frequently used in radio astronomy interferometry and allows to produce an image of the radio source by phasing antenna signals in all sky directions [19]. The main advantage of this method is a gain in terms of signal to noise ratio. However, a drawback lies in the fact that the transient radio event can not be sampled over the ground and that a precise information on the shower (direction, core position) is required from the particle detector, making the radio array dependent.

3.3. Results on the radio technique

The recent results on the radio technique allow us to draw up a more comprehensive picture of the radio signal associated with air showers.

The event by event approach used on the CODALEMA experiment makes possible the observation of the electric field distribution on the ground [20]. The electric field topology associated to EAS exhibits a large dynamic and follows a bell-shape. Once back projected onto the shower frame, the electric field can be described by a decreasing exponential function as first suggested by Allan [4] :

$$E(d) = E_0 \exp\left(\frac{-d}{d_0}\right) \qquad (2)$$

with d the distance of the considered antenna to the shower axis, E_0 and d_0 respectively the amplitude and slope parameter.

This particular behavior differs from the topology associated with radio frequency interferences and could thus constitute a creterion to discriminate radio events independently from particle detectors.

Another feature observed in the CODALEMA data concerns the arrival direction of the radio detected events. Indeed, as shown fig. 3 a strong North/South asymmetry was observed with a lack of events in the direction of the geomagnetic vector [21]. This is a clear signature of a dominant geomagnetic contribution and it confirms what was all ready seen in other experiments [4,19].

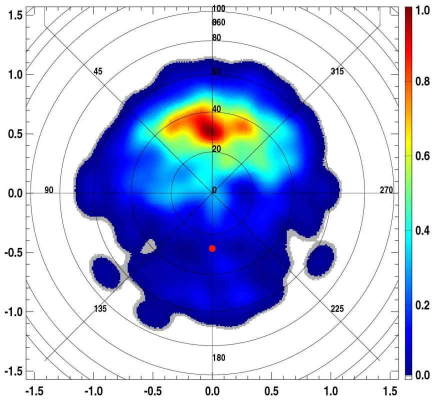

Figure 3. Extracted from [21] : 10 gaussian smoothed sky maps of observed radio events on CODALEMA. The zenith is at the center, the azimuth is: North (top, 0), West (left, 90), South (bottom, 180) and East (right, 270); the direction of the geomagnetic field at Nançay is indicated by the dot.

Moreover, this density map in fig. 3 can be reproduced by simply considering the vector cross product $\mathbf{v} \times \mathbf{B}$ of the Lorentz force, suggesting an electric field directed along the $\mathbf{v} \times \mathbf{B}$ direction and proportionnal to $\frac{|\mathbf{v}\times\mathbf{B}|}{(v.B)}$. It is then possible to correct the fitted amplitude parameter E_0 from eq. 2 by the $\frac{|\mathbf{v}\times\mathbf{B}|}{(v.B)}$ factor to estimate the energy of the shower.

In [22], this radio estimator is found to be roughly linearly scaled with the shower energy estimated with the particle detector. Moreover, the spread of the radio estimation is of the same order of magnitude than the one obtained from the particle estimation, around 30 %.

The LOPES analysis does not permit an event by event approach because the beam forming process provides only one estimation of the electric field strength per event. Nevertheless, by adjusting separately the measured EW component of the pulse amplitude to the geomagnetic angle, the distance to the shower axis and to primary energy, all of them supplied by the KASCADE-Grande detector, a global parametrization is obtained in [23] :

$$\epsilon_{EW} = (11 \pm 1.)((1.16 \pm 0.025) - \cos\alpha) \times \cos\theta \exp\left(\frac{-R_{SA}}{(236 \pm 81)\mathrm{m}}\right) \times \left(\frac{E_P}{10^{17}\,\mathrm{eV}}\right)^{(0.95\pm0.4)} [\mu\mathrm{V/m/MHz}] \quad (3)$$

where α is the geomagnetic angle, θ the zenith angle, R_{SA} the mean distance of the antennas to the shower axis and E_P the estimated primary energy.

This expression is quite similar to eq. 1 established by Allan [4] except for the $(1.16 - \cos\alpha)$ term of the geomagnetic dependency. The primary energy estimation from radio data using eq. 3 gives a combined statistical spread between LOPES and KASCADE-Grande that is 27 % for strong events [23], which is again similar to the fluctuation in the measurements with the particles detector alone.

4. Prospective at higher energy

The current sizes of LOPES and CODALEMA limit exploration to energies around some 10^{17} eV with a poor energy dynamics. To get a better knowledge of the radio signals at higher energies, a natural subsequent stage is to associate antennas to larger detector arrays such as the Pierre Auger Observatory, in Malargüe, Argentina. Moreover, as Auger houses surface and fluorescence detectors, adding a radio component and merging information from 3 independent detectors should be of great interest in global shower physics understanding.

A radio detection R&D program was initiated in 2006 in a collective effort by the Auger, CODALEMA and LOPES groups. During a first phase, various antenna designs and acquisition electronics triggered by particle detectors have been tested [24].

One major item of the R&D program lies in the trigger system. Indeed, on other radio experiments, like CODALEMA or LOPES, the antenna array is triggered by an associated particle detector array. This should not be feasible on a large array of antennas and a trigger based on the radio signal itself has to be achieved.

The RAuger experiment is a prototype of a fully autonomous and self-triggered cluster of 3 antennas developped by the CODALEMA collaboration in association with the Auger group installed on the Auger surface detector [25]. To identify radio detected showers, time coincidences are searched between Auger events and radio events triggered on the radio signal itself.

The RAuger experiment has already detected 28 self-triggered air showers in coincidences with the Auger surface detector with energies ranging from 0.2 to 8 EeV [26,27]. This first validation of an autonomous radio detection gives a proof of principle for the new generation of giant radio array.

5. Conclusion and outlook

Many progress have been made in the interpretation of the radio signals but this effort still demands inputs from the experiments and the theory. A new generation of larger antenna array is now needed to bring this detection method to maturity.

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