

RADIO DETECTION OF HIGH ENERGY COSMIC RAY AIR SHOWERS

A short review

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Due to the very low flux, cosmic ray air shower studies at ultra high energy necessitate equipping very large areas with surface Cerenkov or scintillation detectors, to use fluorescence telescopes sensitive to a large volume, or to do both as in Auger. Another observable feature of an air shower, not accessed by previous methods, is the electric field created by the charged secondary particles of the shower. This field behaves as a very fast pulse propagating through the air and is detectable in the decametre radio wave range with dedicated antennas. Based on the renewal of this 1960's idea, since 2002 the researches initiated by the LOPES and CODALEMA collaborations have permitted to develop a new method of detecting air showers. This concept is now tested also at Auger. We will give a brief review of the concept, method and main results of the two main experiments currently running on this principle.

1 Brief historical and theoretical review

High-energy cosmic rays are detected indirectly by the observation of the giant shower of secondary particles they induce in the atmosphere, with particle detectors on the ground or fluorescence/Cerenkov light detectors. Their characterization requires the simultaneous measurement of several parameters and high statistics. Radio detection of associated electric field pulses, with or without the simultaneous use of other methods of detection, may provide a major and decisive contribution to this research. The potentialities of this detection technique are the possibility to determine the direction, energy and nature of the primary, with a high duty cycle and at relatively low cost. This idea has nearly 50 years, however it is still not completely mastered, neither from the experimental nor from the theoretical point of view. Though physical considerations describing the air shower induced electric field are based on well-known concepts, physicists struggle in precisely determining the main emission mechanisms. Two possible source

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processes have however been identified as dominating the emission. In 1962, Askaryan¹ pointed out that the number of electrons in a cosmic ray induced air shower should be in excess (typically of the order of 10 %) compared to the number of positrons. At the long radio wavelengths considered, the electrons in excess behave coherently: it leads to a Cerenkov emission proportional to the square of the number of charges N_p^2 . The second qualitative breakthrough arises in 1965, when Kahn and Lerche² pointed out that, regardless the negative charge excess considered by Askaryan, the negative and positive charge distribution should be asymmetric due to the Lorentz force exerted on the charges in motion in the Earth's magnetic field (so called *geomagnetic* field). This geomagnetic effect could be at the origin of a dipole continuously fed by a dipolar current along the shower path, thus leading to a radiative emission greater than the one predicted by Askaryan. Radio became a challenging method.

Such promising expectations naturally led to numerous experimental attempts to detect the predicted emission. The first convincing result is published by Jelley *et al.*³ in 1965, who measured for the first time the amplitude of the electric field pulse associated to an air shower. If technological limitations at that time prevented them to disentangle between the two theoretical predictions, the existence of a transient electric field was however demonstrated. A flurry of other experiments followed in the 60's, whose main results and remaining questions are well summarized in the (quite) exhaustive review of Allan⁴ in 1971. Confirming the predominance of a geomagnetic effect in the emission process, the latter even proposed an empirical, though still pertinent, expression of the electric field associated to an air shower:

$$E_\nu = 25. \left[\frac{E_p}{10^{17}} \right] \cdot \sin \alpha \cdot \cos \theta \cdot \exp \left(\frac{-d}{d_0(\nu, \theta)} \right) \mu\text{V/m/MHz} \quad (1)$$

where E_p is the primary energy, α the angle between the geomagnetic field direction 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 .

Radio detection method could have been considered as valuable at that time but, as shown by Allan, measurements of the various experiments in the 60's gave contradictory results, leading to a *statu quo* during nearly 30 years. Since 2002, two experiments on relatively small scales, LOPES in Germany⁵ and CODALEMA in France⁶, revisit this topic, accompanied by new theoretical developments. Among them, the most advanced approach, a microscopic model based on Monte-Carlo simulations, is by Huege *et al.*^{7,8}, but macroscopic models based on semi-analytical calculations are under construction^{9,10} and should also contribute to the global theoretical understanding of air shower radio emission.^b

The general properties of the radio detection technique can be summarized as follows: (a) it is a bolometric method (the atmosphere is used as a calorimeter); (b) it accesses the macroscopic properties of the shower (number of charges, *i.e.* energy, geometry, longitudinal development,...); (c) showers are potentially observable at large distances; (d) radio is sensitive to inclined or even horizontal showers¹¹, which makes the method a very challenging one for high energy neutrino detection; (e) it presents a potential 100 % duty cycle; (f) it is rather cheap. At last, radio is few technology dependent, which make it particularly robust: Fig. 1 shows numerous antennas that have all been successfully used on current experiments, illustrating that, once the trigger philosophy is established, one can change the antenna without changing drastically the results.

2 The two current and major experiments: LOPES and CODALEMA

2.1 CODALEMA at Nançay

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

^bA more detailed theoretical study is presented by H. Falcke in the same volume of these proceedings.



Figure 1: Some of the various antennas used on the current cosmic ray air shower radio detection experiments. From left to right: antenna from LOPES, Log Periodic Dipole Antenna (LPDA) used on LOPES^{STAR}, Nançay Decametre Array (DAM), CODALEMA active dipole and a LPDA used at Auger.

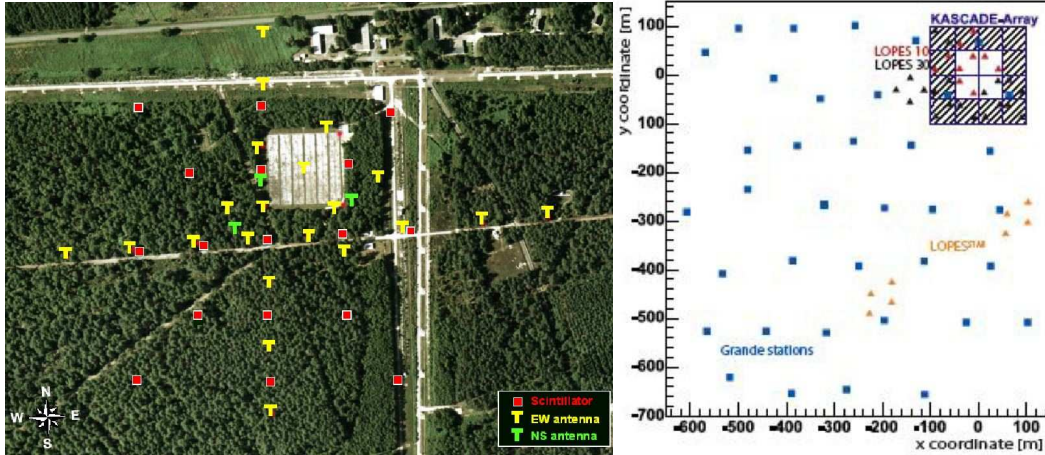


Figure 2: (left) Schematic view of the CODALEMA experimental setup on January, 2008. Plastic scintillators are red squares. Yellow and green “T” represent the dipole antennas oriented respectively in the EW and NS directions; (right) schematic view of the LOPES experimental setup within KASCADE and Grande. Red triangles are the antennas of LOPES10, black ones depict LOPES30 and orange ones are the LPDA of LOPES^{STAR}.

a cross of 600 m \times 500 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 m \times 350 m (Fig. 2, left). Since last array enhancement in late 2005¹², emphasis on simplicity, size, cost and performance was used as guidelines to develop a new broadband (100 kHz - 220 MHz) antenna based on a short fat active dipole concept¹³. Each particle detector station includes a thick plastic scintillator seen by two photo-multiplier tubes. 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 GS/s over 2.5 μ s. Besides acting as the trigger, the particle detector gives information on shower’s energy, direction, core position and number of electrons at ground above a threshold of some 10^{15} eV.

2.2 LOPES at Karlsruhe

Installed in the KASCADE particle detector¹⁴ of the Forschungszentrum Karlsruhe (FZK, Germany), LOPES¹⁵ is made of 30 wire-dipole antennas, of which 10 are in a dual polarization mode (Fig. 2). Radio signals are digitized also on 12-bits, at 80 MS/s, an analog filter restricting the observable frequency band to 40-80 MHz. The particle detector (here KASCADE or KASCADE Grande) also acts as a trigger for radio. 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 around 10^{17} eV and up to 10^{18} eV. Recently, new LPDA have

been installed throughout KASCADE Grande, with a dedicated electronics aiming to self-trigger on the radio signal only. This new setup, namely LOPES^{STAR}, is foreseen to work in any radio sky conditions, prefiguring what could be the solution for deploying antennas over a large array. Indeed, conversely to Nançay which is a quite well radio-protected area, the FZK exhibits strong man-made radio background noise, which constrains the way the data are analyzed.

2.3 Different sites, different methods

On both LOPES and CODALEMA, when an air shower hits the particle detector, a trigger is sent to the ADC to record the radio waveform (40-80 MHz and 1-220 MHz respectively). In both cases, an offline analysis must be performed to find out if the antennas have seen the event but, due to the radio frequency interference (RFI) content, this analysis is very different. On CODALEMA, digital filtering is made in the band 40-70 MHz where no emitter is found in Nançay, without affecting the transient nature of the radio pulse. An amplitude threshold can be adjusted regarding the remaining noise on the signal¹⁶: if the transient signal is above the threshold, the antenna is flagged “on”^c. Once this tagging procedure is performed and the pulses are detected, an absolute time corrected from cable and electronics delays is associated. With the time information coming from a minimum of 3 antennas, the arrival direction of the shower plane can be computed by triangulation, independently from the particle detector. This “transient method” derives from those employed in particle physics: it deals with the time waveform $V(t)$. The main advantage is that it allows an event by event and antenna by antenna data processing, thus *to sample* the individual shower. Conversely, 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 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 directions¹⁷. It is a “stationary method”, whose 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 radio array not independent. This will not be the case with the LOPES^{STAR} instrument, for antennas will be self triggered and the signals recorded and analyzed on an antenna by antenna basis.

3 Main results on extensive air shower radio properties

Even through different analysis, UHECR radio detection technique appears robust enough to deliver significative information on air showers. We give here a comparative view on the results obtained by the two experiments in five selected points that should be questioned when dealing with UHECR radio detection.

3.1 EAS Energy threshold and detection efficiency

As shown on Fig. 3, LOPES¹⁸ and CODALEMA (plot updated from¹⁹) present the same energy detection threshold (around 4 to 6.10¹⁶ eV) and very similar detection efficiencies (ratio between the number of particle detector triggers and radio identified events). Note that both experiments work in EW polarization: it is likely that the absence of NS polarization is responsible for the

^cA more sophisticated method, based on linear prediction, is indeed currently used to flag the antennas, but the principle is still the same.

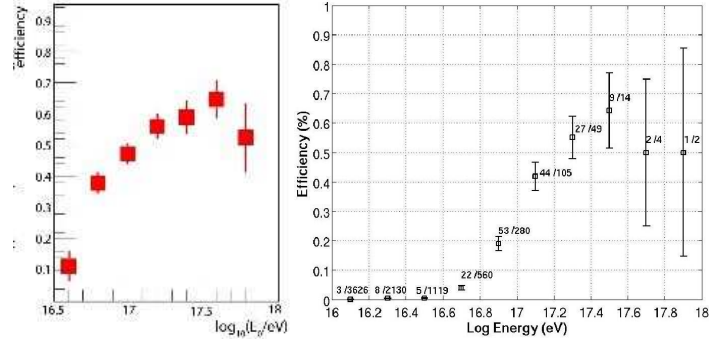


Figure 3: Efficiency plot for LOPES (left) and CODALEMA (right) in EW polarization. Energy threshold and detection efficiency are similar and may represent an intrinsic property of radio detection.

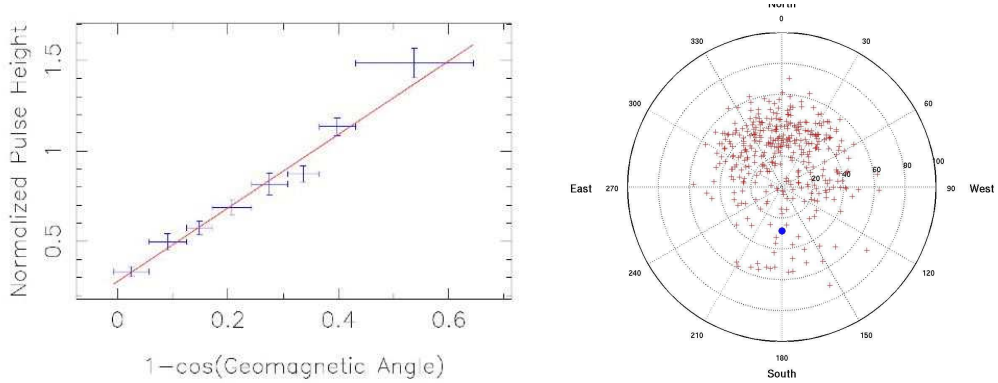


Figure 4: (left) Normalized amplitude of pulses observed by LOPES as function of $1-\cos \alpha$; (right) skymap of radio events observed by CODALEMA, showing a strong azimuthal dependence and a depletion in event count in the direction of the geomagnetic field at Nançay (blue dot).

50 % lack of efficiency, showing that the electric field may be strongly linearly polarized. The two collaborations have recently added or changed antennas to study the NS component.

3.2 Geomagnetic field dependence

Another important behaviour, connected to the previous observation on polarization, is the dependence of detection regarding the so-called “geomagnetic angle” α (angle within the shower axis and the geomagnetic field direction). As geomagnetic effects are thought to be dominant in the electric field production process, one can expect a lack of radio detected events in the local direction of the Earth’s magnetic field, simply because of the vector cross-product $\mathbf{V} \times \mathbf{B}$ where \mathbf{V} is the vector along shower’s axis and \mathbf{B} the magnetic field vector. Such a dependence is observed by LOPES²⁰ (Fig. 4, left) but as a function of $(1-\cos \alpha)$ rather than $\sin \alpha$ as one could expect at first sight from the vector cross-product. Nevertheless, regarding CODALEMA results (Fig. 4, right), a clear depletion is observed in the direction of \mathbf{B} in the skymap of radio detected CR event arrival directions (plot updated from¹⁹). This strongly confirms a geomagnetically dependent origin of the shower’s electric field, but at that time it is not possible to conclude on the nature (dipolar current, geosynchrotron⁷ emission?) of the main process.

3.3 EAS electric field profile

As proposed by Allan⁴ and described by eq. 1, the expected electric field profile should follow a decreasing exponential function of the distance to the shower axis. Particle detectors giving a good estimate of the shower direction and core position, this assertion is easy to verify by

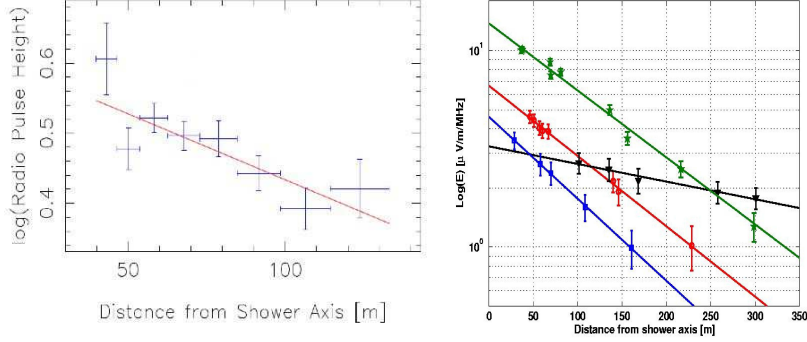


Figure 5: (*left*) Distribution of the normalized amplitude of radio pulses observed by LOPES as function of a mean distance of the antenna array to the shower axis; (*right*) an example of 4 event profiles observed by CODALEMA. Each color is related to a single event and each mark (circle, square, triangle, star) represents the distance of an individual antenna to the shower axis projected in the shower coordinate system.

plotting the pulse strength (even uncalibrated) as a function of the distance to the shower axis. For CODALEMA, this is possible on an event by event basis^{21,22}, while LOPES needs to build the distribution of the measured electric field for several events²⁰. Results shown on Fig. 5 undoubtedly confirm an exponential dependence with the distance.

3.4 EAS electric field extent

A subsequent result deriving from the previous one is directly the electric field extent on ground, or the characteristic distance d_0 in the exponential profile function. Using the data of LOPES30 and KASCADE Grande (necessary to reach large shower distances), LOPES finds a value of $d_0 \sim 230$ m. On CODALEMA data, an exponential fit $E_0 \cdot \exp\left(\frac{-d}{d_0}\right)$ can be applied on each of the detected events, and the resulting distribution of the inferred d_0 can be plotted. The mean value of this distribution is... also ~ 230 m! Indeed, these concordant results only mean that the characteristic extent of the electric field for showers above $5 \cdot 10^{16}$ eV is of the order of 200 m, which constitutes an important information for any antenna array pitch determination.

3.5 Shower energy dependence

The last aspect, which is certainly one of the keys to the success of the technique, is related to the correlation with the energy. In CODALEMA, although this analysis is still regarded as preliminary, one can deduce a value E_0 for the shower core electric field after fitting the parameters for each event, as explained above. This should make possible to establish the correlation between the energy of the primary cosmic ray deduced from the particle analysis and the electric field amplitude using E_0 as a calorimetric estimator of the energy of the shower. First investigations indicates that $E_0 \sim \sin \alpha \cdot \cos \theta \cdot E_p^{1.4}$, where E_p is the primary particle energy estimation. However, in 2006 LOPES²⁰ published a similar parametrized correlation function, *but* with a $(1 - \cos \alpha) \cdot \cos \theta$ correction for the amplitude instead of $\sin \alpha \cdot \cos \theta$. Despite this difference, as can be seen on Fig. 6, both correlations seem relevant. The main explanation concerning those discrepancies may lie in the fact that both experiments work close to their energy threshold and with a poor energy dynamics, which can make the interpretation of results uncertain. However, it seems that the main tendencies are established and that a reliable energy calibration of the radio signal should soon be found.

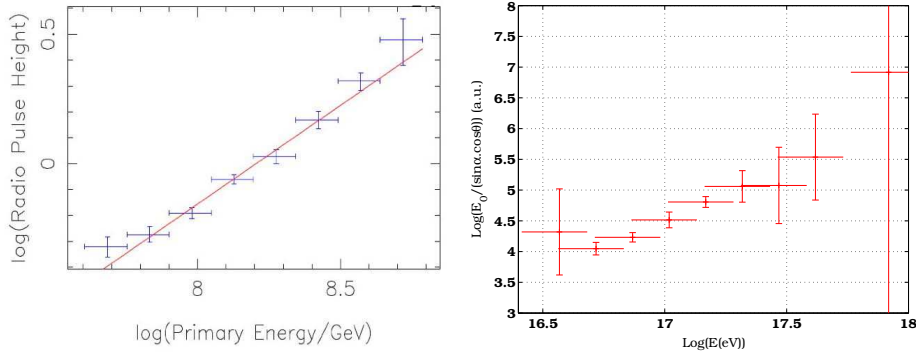


Figure 6: Correlation between the energy E_p of the shower, deduced from the particle detector, and the radio estimator of the energy: for LOPES (*left*) a normalized radio pulse height and for CODALEMA (*right*, preliminary result) the E_0 value fitted on each event. For the right plot, error bars in X are 30 % of E_p wide.

4 Radio@Auger

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 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. At last, the radio quality of the sky over Malargüe is excellent, which greatly helps in test phases. The Auger collaboration supports a reflection in this way, associating people from Netherlands, Germany, France and USA ²³.

4.1 Prospective schedule

For the R&D around radiodetection, it is very important to get a relatively high counting rate of cosmic rays in coincidence with Auger, which can not be achieved if the radio covered array is not big enough. In the coming months, additional tanks will be added to the surface detector (SD) of Auger, in order to lower the energy detection threshold of the SD (so-called “infill” array). A muon detector will also be installed at the same place. In parallel, the closest fluorescence telescope will be upgraded and its field of view will be enlarged. The radio@Auger collaboration thus proposed to install a radio engineering array at the same location as the infill, *i.e* over 20 km^2 . For such an area, it is mandatory to develop autonomous radio detection stations, which means a system able to self-trigger, acquire and transmit the data, with a local power supply. First attempts to test such autonomous stations were made since end of 2006, close to the Central Laser Facility (CLF) building of Auger ²⁴. The goal was to self-detect radio events and to find time coincidences with Auger events offline. In parallel, other systems (mainly various antenna designs and acquisition electronics) were tested near the Balloon Launching Station (BLS) ²⁵. The first results briefly presented hereafter were convincing and opened the way to the engineering array study for an installation in 2010.

4.2 First results

As cosmic ray air shower transients exhibit the same characteristics as most of man-made transient interferences, it is for the moment very difficult to recognize them by the only radio signal. With a large antenna array, this difficulty should be overcome, but our 3 autonomous station system at CLF extends only over a few hundred of m^2 and needs an independent confirmation for cosmic ray identification. Radio events are thus time-tagged by the same GPS system as

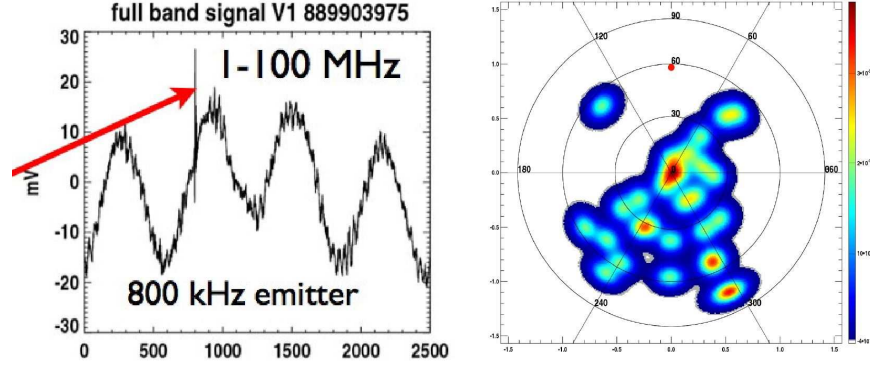


Figure 7: (*left*) An event observed in autonomous mode and identified as a cosmic ray signal by time coincidence comparison with Auger. The transient (red arrow) clearly appears in this wide band record (0.1-100 MHz), superimposed to the local 800 kHz radio broadcasting frequency (big sine) and other FM transmitters; (*right*) contour sky map of the radio self-detected events (direction of events is given by the Auger's SD). The event density depletion around the direction of the magnetic field (red dot) is clearly visible on the North.

in Auger, which allows recognizing real cosmic ray radio events from noise by searching time coincidences with particle events detected by Auger's SD²⁶. Fig. 7 (left) shows an example of such a coincident signal. In about 6 months of effective time, 25 coincident events have been detected between radio and Auger, above an energy threshold very similar to the one observed on LOPES and CODALEMA. Those events constitute the first ever detection of cosmic ray events by an independent, self triggered radio system, definitively demonstrating the ability of radio to be a very complementary technique for UHECR studies. Besides this technical breakthrough, and though low statistics has been reached, a very important result has also been found. In the northern hemisphere, a clear event density depletion has been observed in the distribution of radio detected cosmic ray events in the South direction, toward which the Earth magnetic field is oriented (see paragraph 3.2). In the southern hemisphere, the magnetic field is directed toward North and such depletion would thus be expected in the northern part of the sky. Indeed, such an asymmetry has clearly been observed by the autonomous system at CLF (Fig. 7 right), undoubtedly confirming a geomagnetic origin for the shower's electric field production process, at least at this energy level²⁷.

5 Conclusion and outlook

As a conclusion to this short review, and beyond the physics results obtained, the state of the art in radio detection of cosmic rays can be summarized: (*a*) radiodetection of cosmic rays works and is roughly independent of the antenna and electronics; (*b*) the signal is driven mainly by geomagnetic effects (but not necessarily geosynchrotron); (*c*) theoretical work is still needed despite strong advances and good predictions; (*d*) current results concern energies close to the threshold: analysis is difficult, interpretation may differ, but main tendencies are defined. There is thus a need to extend the energy range; (*e*) radio is very promising for detecting inclined air showers (neutrinos?), transient radio detection is also foreseen on other sites than LOPES, CODALEMA and Auger (LOFAR in Europe, 21CMA in China...): the method is spreading.

Besides the continuation of the R&D and data production on LOPES and CODALEMA, a super hybrid detector covering a large area on Auger should help making strong progress on all those scopes.

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