Charge excess signature in the CODALEMA data. Interpretation with SELFAS2.

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Abstract: The systematic shift between the shower core estimation using the particle array data and the shower core estimation using the radio array data of the CODALEMA experiment is discussed. Using the simulation code SELFAS2 we show that the consideration of the charge excess contribution in the total radio emission of air showers generates a shift of the apparent ground radio core along the east-west axis. This radio core shift is then characterized for the CODALEMA statistic and compared with the experimental data. The good agreement between data and simulation suggests that this behavior can be considered as an experimental signature of the charge excess contribution.

Keywords: CODALEMA, SELFAS, radio detection, charge excess

1 Introduction

In 1965, Jelley *et al.* [1] experimentally demonstrated that air showers initiated by high-energy cosmic rays produce strong radio pulses that can be detected between 0 and 300 MHz. Different mechanisms were proposed to interpret this phenomena. In 1966, Kahn and Lerche [2] suggest two different main processes responsible for air shower radio emission : the radiation from the net charge excess of electrons in the shower (initially predicted by Askaryan [3]) and a geomagnetically induced transverse current in the pancake. Askaryan also pointed out in his paper [3] that the extensive air shower (EAS) radio emission is favored by the coherence of the signal for wavelength larger than the characteristic dimensions of the emissive area. This coherent condition is verified below 100 MHz which correspond to wavelengths larger than few meters, typically the longitudinal dispersion of the pancake. With some toy shower model Kahn and Lerche predicted that the dominant mechanism is the transverse current flow due to the geomagnetic field.

These last years, important efforts made on EAS radio emission modeling permitted to converge toward a consensus about the expected EAS radio signal in the MHz range [4, 5]. As it was recently confirmed by the recent experimentations CODALEMA [6, 7] and LOPES [8, 9], the dominant mechanism is due to the geomagnetic field, implying a strong asymmetry in the counting rates as a function of the arrival direction. However, recent models predict also an additive contribution due to the EAS charge excess variation which should be detectable [4, 10, 11]. A first hint of this charge excess contribution in experimental data has been done recently in [12].

In this work, we use a new observable due to the contribution of the charge excess in the total EAS radio signal. In section 2, we present the behavior of this observable for 10^{17} eV vertical air showers simulated with SELFAS2 at the CODALEMA site. In a section 3, we characterize with SELFAS2 the new observable introduced in section 2 for CODALEMA, predicting its behavior for the global experimental statistics. Finally, we directly compare this result to experimental data giving for the first time the interpretation of the systematic shift between the positions of the ground particles shower core and the corresponding ground radio core observed in the CODALEMA data.

2 SELFAS2 : 10^{17} eV EAS at CODALEMA

SELFAS2 [4, 13] is a code which computes the radio emission of extensive air showers using a microscopic description. SELFAS2 shows [4] that the total radio emission is mainly due to two phenomena : the transverse current and the charge excess variation (see also [10, 11])

As a first example, we simulated a 10^{17} eV vertical air shower for the CODALEMA configuration site. The ground altitude is fixed to 140 m. The geomagnetic field characteristics at the Nancay site are $|\boldsymbol{B}| = 50\ \mu$T, $\theta_B = 27°$ and $\phi_B = 270°$ where θ_B and ϕ_B are the zenith angle and the azimuthal angle of the earth magnetic field ($\phi = 0° =$ east, $\phi = 90° =$ North). The magnetic field comes from the south and is oriented toward the ground. All EAS simulated with SELFAS2 used for this paper are performed with this site configuration.

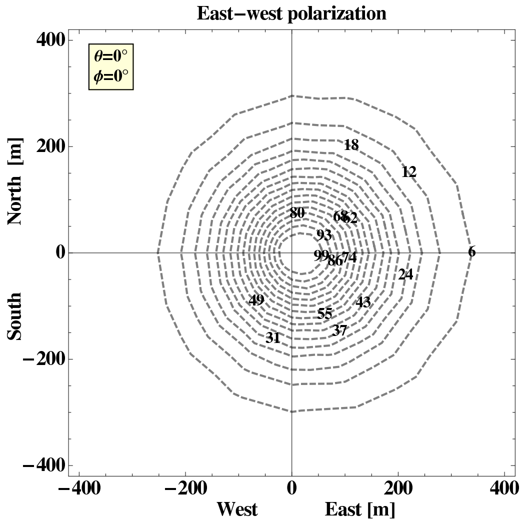

FIGURE 1 – Ground footprint of the signal deposited (absolute value) by a 10^{17} eV vertical EAS in the east-west polarization simulated with SELFAS2. The origin of the frame corresponds to the simulated ground particles shower core. The contour lines are in μV.m^{-1}, a 23-83 MHz numerical passband filter is applied on signal. The ground radio core is toward the east.

In Fig.1, we show the amplitude on the ground of the electric field in the east-west polarization. The simulated ground particles shower core is located in $(0, 0)$. As it is done experimentally, a 23-83 MHz numerical passband filter is applied on the signal of each of the 145 simulated antennas used to obtained this picture. The result reveals an east-west asymmetry of the observed signal, suggesting a shift of the apparent radio core (ground location where the signal is maximum) toward the east with respect to the simulated ground particles shower core. This behavior predicted by modern simulations (see [4, 10, 11]) is a direct consequence of the mixture of two different contributions in the total EAS radio signal : the charge excess mechanism and the geomagnetic mechanism. The combination of their different polarization patterns (see Fig.2) generates a loss of the cylindrical symmetry around the EAS axis. In this configuration, the signal amplitudes in the east-west polarization observed by antennas located on the east side of the plane containing the ground particles shower core and the geomagnetic field appear higher than the signal amplitudes of antennas located on the other side. This shifted radio core could be then considered as a signature of the charge excess contribution in the total radio signal emitted by EAS.

In Fig.3 we show different ground footprints for different EAS arrival directions in the plane containing the geomagnetic field and the south-north axis. With this picture, we see the evolution of the apparent radio core position as a function of the angular distance to the geomagnetic field (see the picture caption for more informations). The geomagnetic mechanism is arrival-direction dependent while the charge excess is not. This characteristics implies that the distance Δ_c between the reconstructed ground radio core and ground particles shower core, depends also on EAS arrival direction as it is qualitatively showed in Fig.3.

In the next section we suggest a method to predict the behavior of Δ_c for the global statistics observed in CODALEMA.

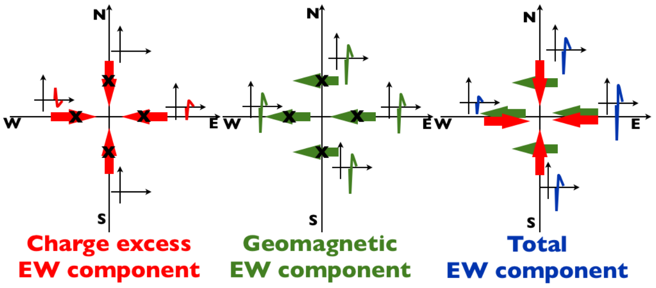

FIGURE 2 – Polarization vectors of the charge excess and transverse current contributions in the plane perpendicular to the shower axis. Due to the fact that the polarization vectors of these two contributions are not always oriented in the same direction, their combination can be constructive or destructive following the antenna position.

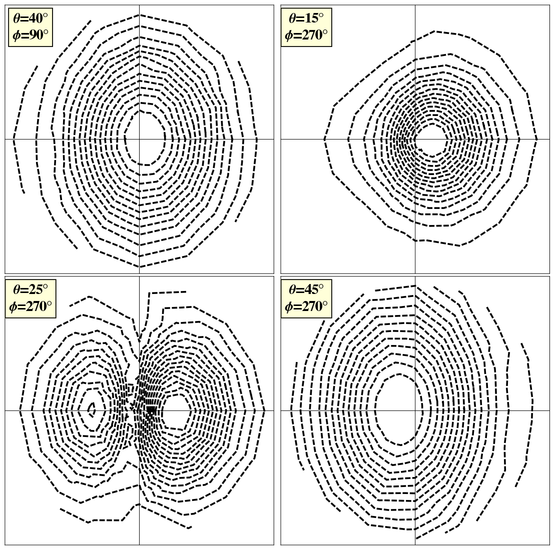

FIGURE 3 – Evolution of the ground footprint for different EAS arrival directions in the plane containing the geomagnetic field and the south-north axis. The axis scales are the same as in Fig.1 and the origin of the frame corresponds to the particles ground shower core. Top left : the event is coming from the north. In this configuration the geomagnetic mechanism is large in comparison to the charge excess component, the shift of the radio core appears less evident as in Fig.1. For an event coming from the south (top right), the radio core is strongly shifted due to the fact that the relative intensity of the geomagnetic mechanism decreases. In the case of an EAS parallel to the geomagnetic field (bottom left), only the charge excess contributes to the radio emission. For air showers coming from the south with zenith angle larger than the geomagnetic field in CODALEMA (bottom right), the radio core is shifted toward the west.

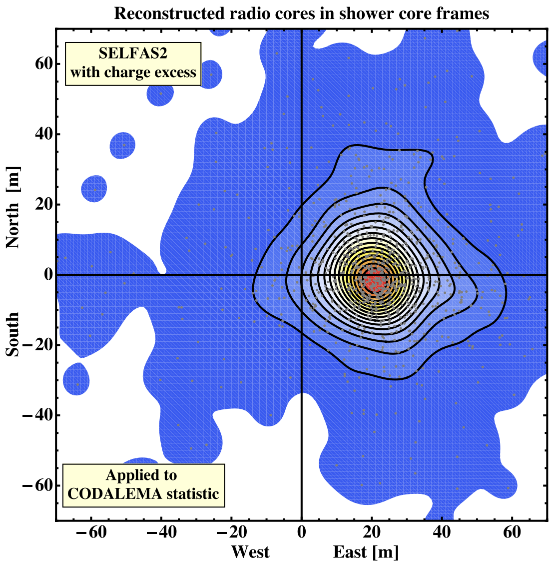

FIGURE 4 – Reconstructed radio cores (gray dots) of one thousand events simulated with SELFAS2 respecting CODALEMA statistic, using the reference frame centered on the ground particles shower core of each event. The black lines represent contour levels of a 10 m smoothed map. A global shift toward the east is clearly visible.

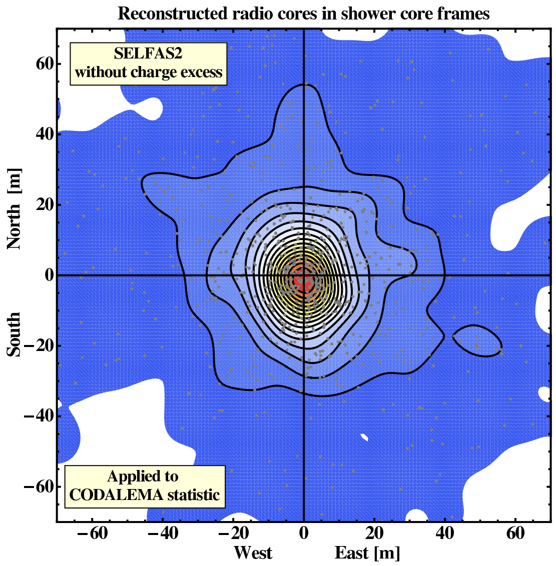

FIGURE 5 – Same legend as in Fig.4 except that charge excess was off in SELFAS2. This time, the global density of ground radio core localization is centered on the origin, corresponding to the ground shower core.

3 Predicted radio core density map for CODALEMA

Following the arrival direction density probability distribution observed experimentally in CODALEMA [7], we simulated with SELFAS2 one thousand air showers with an energy of 10^{17} eV (corresponding to the energy range of CODALEMA). Using the same setup than the CODALEMA array, we draw the position of the ground particles shower cores in the CODALEMA frame, following the density probability distribution of the experimental ground particles shower cores observed in the CODALEMA data.

As it is done experimentally, the lateral profile of each simulated event is reconstructed using an exponential function $E(d) = E_0 e^{-d/d_0}$ with four free parameters : E_0, the extrapolated field strength on the shower axis, d_0, the lateral slope and (x_c^r,y_c^r), the ground position of the radio core in the CODALEMA frame, contained in d which is the antenna distance to shower axis. The radio core position is then defined as the ground position where the field strength is maximum. In order to put them in the same figure, the reconstructed radio core positions with the lateral fitting procedure for all the simulated events are represented in their corresponding ground particles shower core frame in Fig.4. The reconstructed radio cores are represented by the gray dots and a 10 m gaussian smoothed map is superimposed where black lines represent contour levels. A global shift toward the east is clearly visible.

The same procedure is applied on simulated events performed with SELFAS2 without the charge excess contribution. It means that the same number of electrons and positrons were generated during the simulation. The density map of one thousand reconstructed radio core positions with respect to the corresponding simulated particles shower core frame is presented in Fig.5. We do not observe any shift as compared to Fig.4.

The charge excess contribution has therefore a clear signature on the core location. In the next section we compare the result derived from SELFAS2 to the data.

4 Experimental shifted radio cores in the CODALEMA data

The first setup of CODALEMA used in the following is completely described in [6, 7]. The radio detector array composed of 24 east-west polarized antennas is triggered by a particle detectors array covering 340x340 m^2. Thanks to these two different kinds of detection, an independent reconstruction using radio data and particles data can be directly compared. After some quality cuts applied to the data, 315 events exhibit a good χ^2 and fitted parameters within boundary conditions (see [7, 14]). The result for the 315 reconstructed EAS radio cores in their particle shower core frame is presented in Fig.6.

Possible experimental biases coming from trigger effect or from the array geometry have been tested but the east-west radio core shift is robust (see also [15]). The similarity of this general behavior with what we obtained in section 3, Fig.4, suggests that this radio core shift along east-west axis in the CODALEMA data is an experimental signature of the charge excess contribution in the total EAS radio emission.

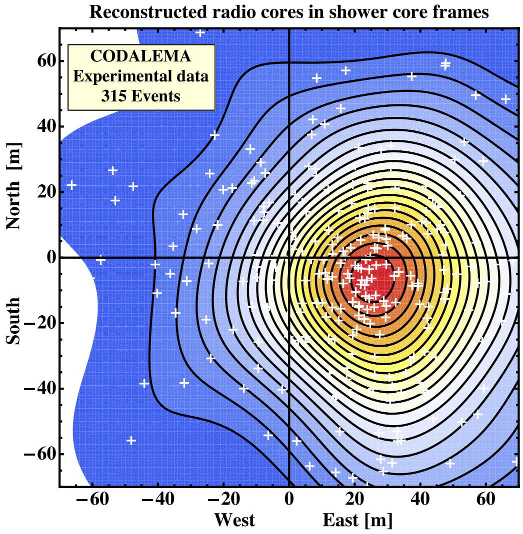

FIGURE 6 – Reconstructed radio cores (white crosses) of 315 events detected by the CODALEMA radio array, using the reference frame centered on the ground particles shower core of each event. The black lines represent contour levels of a 10 m gaussian smoothed map. The global density of ground radio core localization is shifted toward the east as observed in Fig.4 with SELFAS2.

A first hint of the arrival direction dependence is presented in Fig.7. In this figure the expected behavior of the east-west shift as a function of the $\boldsymbol{v} \times \boldsymbol{B}$ east-west component (where $\boldsymbol{v}$ and $\boldsymbol{B}$ are respectively the air shower and the geomagnetic field directions) is superimposed to experimental data (black line, gray dashed lines and blue empty circles). The lack of events coming with arrival directions close to $\boldsymbol{B}$ and from the south at the CODALEMA site, does not allow to state on a clear correlation for $|\boldsymbol{v} \times \boldsymbol{B}|_{EW} < 0.3$ ⇔ $(\boldsymbol{v},\boldsymbol{B})<16°$. To increase the statistics in this region, we add on Fig.7 events previously rejected by the fact that their ground particle shower core is not contained within the particle array but having their radio core contained within the radio array (red filled circles). The transition at $(\boldsymbol{v} \times \boldsymbol{B})_{EW} = 0$ is strongly perturbed, even for simulated data. The reason is contained in Fig.3 (bottom left) ; in this configuration, the geomagnetic mechanism vanishes and the radio signal is mainly due to the charge excess mechanism. In this case, the lateral density function cannot be simply described by an exponential function due to the fact that two local maxima coexist.

5 Conclusion

After checking if experimental biases could be the cause of the interpretation, the east-west disagreement between radio core positions and ground particles shower core positions appears to be due to physical reasons. We show that a similar behavior with SELFAS2 is reproducible only if the charge excess is considered during the EAS development. This similarity between expected behavior with SELFAS2 and the experimental data gives a strong argument to interpret experimental east-west radio core shift as a signature of the charge excess contribution. The fraction of the charge excess contribution to the total EAS radio emission depends on the arrival direction and on the observation point. In the case of a vertical shower, it can contribute from few percents to almost 30% of the total EAS radio signal according to the observation point. If a clear correlation of the shifted radio core with the arrival direction is confirmed with the new generation of CODALEMA array presented in this issue [16], this signature will mark a new step in the understanding of the radio emission process.

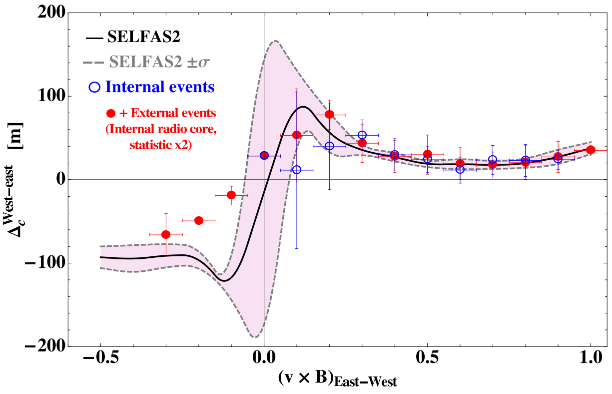

FIGURE 7 – East-west shift of the ground radio core from the particle shower core as a function of the $(\boldsymbol{v} \times \boldsymbol{B})$ east-west component ($\boldsymbol{v}$ = air shower direction) expected with SELFAS2 for the CODALEMA experiment (black line and gray dashed lines). Experimental data are superimposed (circles, see text for details). Monte-Carlo simulation were done on each event reconstruction to obtain error bar on Δ_c.

References

[1] J.V. Jelley *et al.* , Nature 205 (1965) 658

[2] F.D. Kahn, I. Lerche, Proc. Roy. Soc. A 289 (1966) 206

[3] G.A. Askaryan, J. Exp. Theor. Phy. 21 (1962) 658

[4] V. Marin, B. Revenu, sub. Astropart. Phys. May 2011

[5] T. Huege *et al.* Proc. of the ARENA conference 2010, Nantes, France, arXiv :1009.0346.

[6] D. Ardouin et al., Astropart. Phys. 26 (2006) 341.

[7] D. Ardouin, the CODALEMA Col, Astropart.Phys. 31 (2009) 192.

[8] H. Falcke et al., Nature 435 (2005) 313.

[9] W.D. Apel et al., Astropart. Phys. 26 (2006) 332.

[10] K.D. de Vries et al, Astropart. Phys. 2010, 34 : 267

[11] M. Ludwig, T. Huege, Astropart. Phys. doi : 10.1016/j.astropartphys.2010.10.012

[12] B. Revenu for the P. Auger Col. Proc of the 32nd ICRC, Beijing 2011.

[13] V. Marin, B. Revenu, ARENA 2010 doi :10.1016/j.nima.2010.10.123

[14] O.Ravel ARENA 2010 doi :10.1016/j.nima.2010.12.057

[15] A. Lecacheux Proc of the 31st ICRC, LODZ 2009

[16] A. Belletoile for the CODALEMA Col. This issue.