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EAS radio detection at large impact parameter: the inverse problem and the design of a giant array

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Abstract: Extensive air shower radio electric fields can be evaluated at large impact parameter with analytical expressions. Such a theoretical tool is most valuable in the present phase where the capabilities of the radio detection of extensive air shower are under investigations. It can help shaping strategies for the analysis of radio detection data. It can also be used to perform non trivial test of much more detailed numerical approaches which are currently under development. The approximation leading to such a formulation will be presented and two applications will be discussed: the ”inverse” problem of how to go from a sampling of the radio electric field on a few antennas to the main characteristics of the extensive air shower, and the question of the antenna spacing of a giant array for ultra high energy cosmic rays.

The model

A cosmic-ray air-shower is a charge and current system whose electromagnetic field carries genuine informations on some important aspects of the shower. Because the shower front moves at about the speed of light the electromagnetic signals emitted by the shower core at various stages of the shower history all travel with the particle front. Thus only at observation points located at sufficiently large impact parameters the sequence of emissions results in a sequence of receptions, and it is possible to collect a depiction of the shower evolution. The latter possibility stems from the fact that the time scale *at reception* associated with the shower development become much larger than those coming from the shower extension. The hierarchy of time scales relevant at large impact parameters is thoroughly studied in Ref.[1].

This hierarchy suggests a model where all time scales but that due to shower evolution are set to 0. Setting time scales associated with the shower extension to 0 corresponds to neglecting the shower extension hence taking the shower as a pointlike system. Of course, this is only meant as a model for the densest part of the shower core where most of the ultrarelativistic charges stand. As discussed

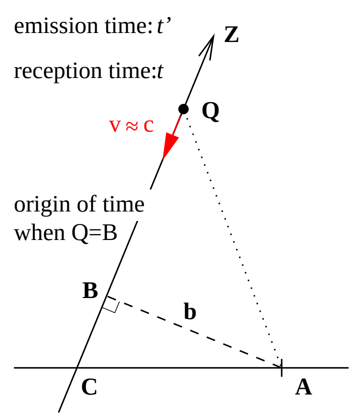

Figure 1: Geometry and notations.

in Ref. [2], this model makes sense for impact parameters in the km range and at not too large frequencies.

The explicit expression for the electric field depends on the origin of charge separation. For electron-positron acceleration in the Earth magnetic field, it is given in Ref. [2] where it is also explained that the electromagnetic pulse seen by an antenna comes from emission at small angle, but not too-small. Taking the geometry shown in

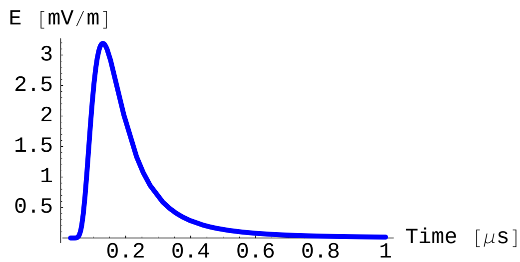

Figure 2: Electric field pulse.

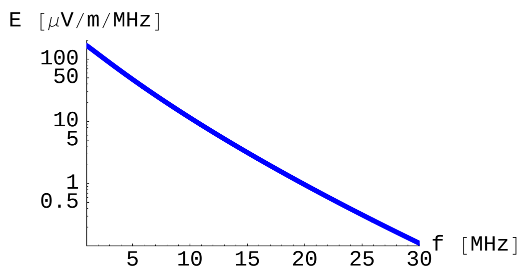

Figure 3: Electric field spectrum as a function of frequency in MHz.

Fig. 1, the relevant angle range translates into

$$-c\,t' \gg b/\sqrt{2} \gg c\,t,$$

where the relation between t, t' and b, reads

$$ct\,ct' \approx -b^2/2,$$

and the electric field amplitude has a very compact form

$$E(t,A) = \frac{e\,N_{ee}(t')\,a_T}{4\pi\epsilon c^2}\,\frac{b^2}{2\,(ct)^3}. \qquad (1)$$

The pulse is shown in Fig. 2 for a vertical shower of energy 10^{19} eV and $X_{\mathrm{max}} = 770$ g/cm^2 and an observer at $b = 0.7$ km.[1] The corresponding spectrum is shown in Fig. 3.

Eq. (1) shows the explicit relationship between the pulse shape and the time evolution of the shower charge number. Besides the t^{-3} factor, a Doppler-like effect, $t' \to t$, distorts the time dependence:

$$\frac{\delta t}{\delta t'} = \frac{1}{2}\left(\frac{b}{c\,t'}\right)^2.$$

Early times (corresponding to t' negative and large) getting more contracted than later times. This explains the sharp rise and slower decay of the pulse shown in Fig. 2. In the frequency domain, the shower growth is thus pushed at larger frequencies than the shower decay. Since large radio frequency interferences render radio observation difficult at frequencies below 20 MHz, radio detection is more sensitive to the first stage of shower evolution. For that matter it is different from, and complementary to, the fluorescence technique.

Designing a large array

Within the above model questions of efficiency and acceptance of a given antenna array are easy to investigate. A first look at this topic is given below. A more thorough study is underway [3].

Considering an hexagonal array with a given antenna spacing, and given a detection criterion it is straightforward to count the number of antennas that see a given cosmic ray shower event. Since radio frequency interferences show strong variations with frequency, a simple detection criterion is best formulated in the frequency domain. In a rather quiet radio environment, a detection threshold of 1 μV/m/MHz above 20 MHz in a 1μs time window is possible [4] and such a criterion will be used. Specifically, it will be considered that a cosmic ray is detected if the above threshold is reached for at least three antennas. A look at Fig. 3 indicates that an antenna located at 700 m receives an electric field magnitude close to this threshold for a vertical shower. For such vertical events and an antenna spacing $= 1$ km, Fig. 4 depicts the area spanned by impact parameters of 10^{19} eV events seen by 3 antennas. The proportion of detected events is simply given by the ratio of the area of one filled region to that of a basis triangle. For 10^{19} eV vertical shower and $d = 1$ km this is about 20 %. The behavior of this ratio as a function of antenna spacing is given in Fig. 5.

Figs. 6 and 7 show the sensitivity of the ratio to threshold conditions for vertical events and an array with antenna spacing $= 0.86$ km.

1. The observation is considered at sea-level and the horizontal component of the magnetic field is 20 μT.

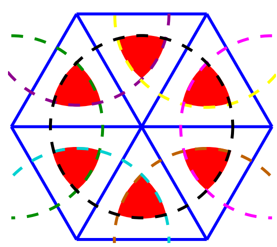

Figure 4: Array and region of detected events.

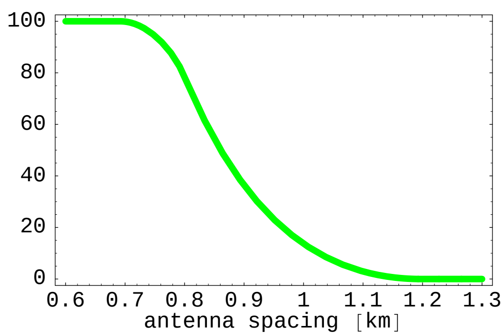

Figure 5: Rate of detected events vs antenna spacing.

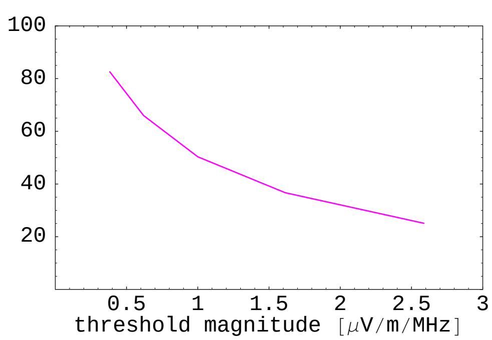

Figure 6: Rate of detected events vs threshold magnitude. (Threshold condition applied at 20 MHz.)

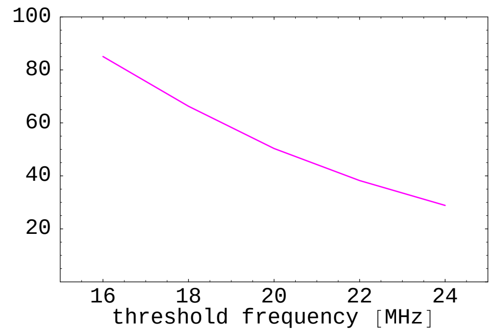

Figure 7: Rate of detected events vs frequency at which the detection threshold of 1 μV/m/MHz is applied.

The inverse problem

From Sect. 1, the electric field magnitude observed at the location of antenna i, A_i, reads

$$E(t, A_i) \approx K N_{ee}(t') \frac{d_i^2}{(ct)^3}, \quad t' = \frac{-d_i^2}{2c^2 t},$$

where K is independent on the observation point of the event and is thus irrelevant, and set to 1, for the reasoning.

Such a simple expression for E makes it possible to illustrate what knowledge can be gained from radio measurements. First, imagine the full geometry of the shower is known, i.e., both the shower incidence and the impact point location, either by some joint particle detector array or by the analysis proposed below, then it is possible to obtain the full time evolution of N_{ee} by looking at

$$(ct)^3 \times E(t, A_1) = f(-d_1^2/(2ct)).$$

In principle, one single antenna is enough, but several antennas may be used to enhance the signal over background ratio. In addition, the signal can only be extracted in practice in a limited frequency-range and thus tools of signal analysis are necessary in order to unfold the electric field pulse from the recorded signal. It is clear that a thorough investigation of these aspects is necessary to actually assess the actual possibility of radio in the extraction of the N_{ee} evolution.

As alluded to above, it is also possible to devise a method for extracting the shower geometry and some important physical parameters from the variation of the electric field on a set of antennas. The starting point is to integrate the electric field pulse over time. Making a change $t \rightarrow t'$ leads to

$$I_i = \int dt\, E(t, A_i) = \frac{4}{d_i^2} \int dt' \,(-ct') N_{ee}(t').$$

A second change, $t' \rightarrow Z(t') = Z_i - ct'$, is useful. Z is a coordinate along the shower axis, pointing upward, with $Z = 0$ at the impact point on the ground (C on Fig. 1). Z_i is the coordinate of the orthogonal projection of A_i on this axis. This change leads to

$$I_i = \frac{4}{cd_i^2} \int dZ\, (Z - Z_i) N_{ee}(Z).$$

Two quantities that depend on the shower physical properties show up

$$\mathcal{N} = \int dZ\, N_{ee}(Z), \quad \bar{Z} = \frac{1}{\mathcal{N}} \int dZ\, N_{ee}(Z) Z,$$

that can be used to rewrite the integrated pulses

$$\frac{c}{4} I_i = \frac{\mathcal{N}}{d_i^2} (\bar{Z} - \underbrace{\vec{e}_Z(\theta, \varphi) \cdot \overrightarrow{CA_i}}_{Z_i}).$$

From a minimal set of 6 integrated pulses, I_i, it is possible to extract

- θ and φ ($\vec{e}_Z(\theta, \varphi)$ is the unit vector along Z),
- (x_C, y_C), the coordinates for the impact point on ground,
- $\mathcal{N}$ and $\bar{Z}$.

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