Near-field radio emission induced by extensive air showers

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Take-home message

• **Low frequency** (< 10 MHz) radio emission of EAS needs a new treatment including *near-field* effects (d~λ)

• We expect the existence of a new signal called the *sudden death pulse* (SDP)

• We present a *formula suitable for* the calculation of the *low-frequency* electric field
Radio detection of cosmic rays (or neutrinos)

- A primary particle creates an EAS
- Charged particles in the EAS create electric field
- Electric field is measured (usually > 20 MHz)
Why low frequency?

• Several experiments (EASTOP, Akeno) have measured a large low-frequency emission (Castagnoli et al., 22nd ICRC, 363. // K. Nishi, K. Suga. Proc. 20th ICRC (1987) 125)

• Simulations and measurements (see A. Escudie, [CRI102]) indicate an emission at low frequency with a larger detection range

• We expect a new kind of signal, the sudden death pulse

450 - 500 kHz

2.3 - 2.9 MHz

3.1 - 4.1 MHz

EASRADIO (EASTOP)
Vertical polarisation

Castagnoli et al., 22nd ICRC, 363
Sudden Death Pulse

- Shower particles are **decelerated** upon arrival to the ground
- Large shower footprint, but **coherence** at low frequencies (1 MHz ~ 300 m)
- Pulse at $t = d/c$ after shower core arrival
- Low-frequency pulse

![Vertical component](Image)

ArXiV:1211.3305
The EXTASIS experiment

- New experiment at the Nançay radio observatory
- Detect the low-freq (1.7 - 3.7 MHz) counterpart to the known EAS field
- Detect the SDP
- See A. Escudie’s talk [CRI102]
Electric field for a track

- Codes such as SELFAS, ZHAireS or CoREAS use the far-field approximation ($kR \gg 1$)

- At 1 MHz, and $R = 100$ m: $kR \sim 2$. Near field!

- Formula for the field of a particle track at all frequencies:

$$E(x, t) = \frac{1}{4\pi \epsilon} \int d^3x' \left\{ \frac{\rho(x', t_{ret})r}{R^2(1 - n\beta \cdot r)} \right\}_{ret} + \frac{n}{c} \frac{\partial}{\partial t} \left[ \frac{\rho(x', t_{ret})r}{R(1 - n\beta \cdot r)} \right]_{ret} - \frac{n^2}{c^2} \frac{\partial}{\partial t} \left[ \frac{J(x', t_{ret})}{R(1 - n\beta \cdot r)} \right]_{ret} \right\}$$

- Caveat: Charge MUST be conserved!
Comparison with far-field: ZHS

- If charge is not conserved, pulses from the beginning and end of the track are not well reproduced.
Implementation in SELFAS

- **SELFAS** (open source) is a MC code that calculates the field of an EAS. It has been upgraded with a state-of-the-art treatment of the atmosphere (see B. Revenu [CRI109])

- We have implemented our formula assuming:
  - No static field after shower extinction
  - Particles are suddenly stopped at ground level
  - No reflection (can be taken into account with antenna pattern) or surface wave
  - No transmission (attenuation in soil)
Sudden Death Pulse amplitude

- **SDP amplitude** calculated as a function of energy and distance (vertical proton shower)

- The amplitude is proportional to the energy (number of particles arriving to the ground)

- At Nançay, we expect detectability between 1 and 10 µV/m
Low frequency emission at high altitude

- The amplitude is proportional to the energy (number of particles arriving to the ground)
- Altitude closer to the shower maximum means larger SDP signal
- More total signal below 10 MHz! See spectrum.
Conclusions

• We have presented an equation for the electric field of a particle track valid for all frequencies (includes near-field effects).

• Correctly taking into account near-field effects is crucial for low frequency measurements (below 10 MHz). That is the case for the EXTASIS experiment.

• We have implemented this formula in the SELFAS Monte Carlo code and checked its consistency with far-field (ZHS) calculations.

• An analysis of the surface wave and the effects of the interface on the field is underway.

• Caveat: we have talked about electric field, not voltage. The response of the antennas in the near field could be complicated; only far-field properties are usually well known.
Thank you
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Low frequency emission at high altitude

- The amplitude is proportional to the energy (number of particles arriving to the ground)
- Higher altitude means larger SDP signal
- More total signal below 10 MHz! See spectrum.

Figure: 30 degrees 5 EeV proton shower Ground at 2650 m of altitude
Comparison with exact formula (frequency)

Our formula (above, in frequency domain) yields the same result as the exact formula in frequency domain in Phys. Rev D 87 (2013) 023003.

Therefore, the formula in time domain reproduces the complete electric field

Figure: Cherenkov angle
1.2 m long track in ice, n = 1.78