A new LDF parameterization for the air shower radio footprint applied to LOFAR data
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Radio emission

On the vxB = 0 axis, the geomagnetic and charge excess component can be separated completely!

A new LDF function

\[
f_{geo} = \begin{cases} 
\frac{1}{N_{R-}} E_{geo} \exp\left(-\left(\frac{r-R_{geo}}{\sqrt{2}\sigma_{geo}}\right)^2\right) & R_{geo} < 0 \\
\frac{1}{N_{R+}} E_{geo} \left[\exp\left(-\left(\frac{r-R_{geo}}{\sqrt{2}\sigma_{geo}}\right)^2\right) + \exp\left(-\left(\frac{r+R_{geo}}{\sqrt{2}\sigma_{geo}}\right)^2\right)\right] & R_{geo} \geq 0
\end{cases}
\]

\[
f_{ce} = \frac{1}{N_{ce}} E_{ce} r^k \exp\left(-\frac{r^2(k+1)}{2\sigma_{ce}^2}\right)
\]

\[R_{ce} = \frac{\sqrt{k}}{\sqrt{k+1}}\]

[2]

**Geomagnetic on \(vxB = 0\) arm**

**Charge excess on \(vxB = 0\) arm**

\[
f_{v\times B}(r) = \sqrt{f_{geo}(r) + \cos\phi \sqrt{f_{ce}(r)}}^2
\]

\[
f_{v\times(v\times B)}(r) = \sin^2\phi f_{ce}(r)
\]

\[f = f_{v\times B} + f_{v\times(v\times B)}\]

[2]
CoREAS simulations

Footprint of radio emission on the ground

$$f(E_{geo}, E_{ce}, R_{geo}, R_{ce}, \sigma_{geo}, \sigma_{ce}, x, y)$$

$$f(E(E_{geo}, E_{ce}), D_{x\text{max}}(R_{geo}, R_{ce}, \sigma_{geo}, \sigma_{ce}), x, y)$$

- CoREAS simulations are used to parametrize the function
- New function has only 4 parameters
- Just dependent on shower properties
CoREAS simulations

Shower plane event 118956923

Energy fluence event 118956923
CoREAS simulations

**Parametrizations**

- $R_{geo} = p_0 + p_1 \cdot D + p_2 \cdot D^2 + p_3 \cdot D^3 + p_4 + D^4$
- $\sigma_{geo} = p_0 + p_1 \cdot D + p_2 \cdot D^2 + p_3 \cdot D^3 + p_4 + D^4$
- $k = p_0 - \frac{p_1 - p_0}{1 + \exp(1 - p_2 \cdot D)}$
- $\sigma_{ce} = p_0 + p_1 \cdot D + p_2 \cdot D^2 + p_3 \cdot D^3$
- $\log\left(\frac{E_{geo}}{\sin(\alpha) T^2}\right) = p_0 + p_1 \cdot \log(E)$
- $\log\left(\frac{E_{ce}}{\sin(\alpha) T^2}\right) = p_0 + p_1 \cdot \log(E)$
CoREAS simulations

- 250 showers based on real LOFAR events are used for analysis
- Simulations with realistic atmospheric model
CoREAS simulations

Reconstructed versus true energy

Reconstructed versus true distance to $X_{\text{max}}$

$\mu = -0.05 \quad \sigma = 0.05$

$\mu = 3.8 \quad \sigma = 21.6$
CoREAS simulations

Difference reconstructed and true x-coordinate of shower axis

\[
\mu = -1.70 \\
\sigma = 4.85
\]

Number of events

\[ x_{sim} - x_{fit} \ [m] \]

Difference reconstructed and true y-coordinate of shower axis

\[
\mu = -0.88 \\
\sigma = 0.52
\]

Number of events

\[ y_{sim} - y_{fit} \ [m] \]
LOFAR data

Shower plane event 118956923

Superterp

Energy fluence event 118956923

Energy fluence [eV/m^2]

Position in vxvxB [m]

Position in vxvxB [m]

Position in vxvxB [m]
LOFAR data

- 60 showers with at least 3 stations triggered are used for analysis

Parameters of measured showers
LOFAR data

Example fit of data for event 48361669

![Diagram showing energy fluence and position in vxB and vxvxB for event 48361669]
LOFAR data

Fit result examples

Event #1

Event #2

Shower plane

Distance to shower axis [m]

Distance to shower axis [m]

Distance to shower axis [m]

Distance to shower axis [m]

Position in vxB [m]

Position in vxvxB [m]

Position in vxvxB [m]

48361669

Energy fluence [eV/m²]

Energy fluence [eV/m²]

Distance to shower axis [m]

Distance to shower axis [m]

Distance to shower axis [m]

Distance to shower axis [m]
LOFAR data

- $E_{fit}$ values are compared with $E$ from particles detector or with $E$ from old LDF
- $D_{X_{max}}$ values are compared with $D_{X_{max}}$ from computational intensive method, which uses old LDF as starting values
LOFAR data

**Compare $x_{fit}$ with $x$**

![Graph showing comparison between $x_{fit}$ and $x$ with mean $\mu = -1.64$ and standard deviation $\sigma = 7.58$.]

**Compare $y_{fit}$ with $y$**

![Graph showing comparison between $y_{fit}$ and $y$ with mean $\mu = 0.84$ and standard deviation $\sigma = 7.71$.]
Conclusions

- New analytic function to describe radio footprint on the ground
- Successfully applied to LOFAR data
- Function used to reconstruct properties of simulated shower with $\sigma_E = 5\%$, $\sigma_{Dx_{max}} = 29.51 \text{ g/cm}^2$, $\sigma_x = 4.85 \text{ m}$, $\sigma_y = 0.52 \text{ m}$
- Function used to reconstruct properties of measured events with $\sigma_E = 30\%$, $\sigma_{Dx_{max}} = 33.9 \text{ g/cm}^2$, $\sigma_x = 7.58 \text{ m}$, $\sigma_y = 7.71 \text{ m}$