Symmetrizing the signal distribution of radio emission from inclined air showers

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The radio signal distribution of inclined showers

- inclined air showers illuminate elliptical area on the ground
- strong asymmetries in the distribution: geometrical, charge excess

CoREAS simulation, 30-80 MHz

$\theta = 75^\circ$
Symmetrizing the signal distribution

- goal: take out asymmetries, then apply simple 1d model LDF

1: raw shower plane
Symmetrizing the signal distribution

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1: raw shower plane  
2: early-late-corrected
Correcting for early-late asymmetries

- correcting axis distances and energy fluences

\[ f = f_{\text{raw}} \cdot \left( \frac{R}{R_0} \right)^2 \]

\[ r = r_{\text{raw}} \cdot \frac{R_0}{R} \]

\[ R \equiv R_0 + x \]
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Performance of early-late correction

- compare early-late corrected simulations with direct shower-plane sim.
- correction generally accurate to within 2%
- deviations possibly related to refractive index asymmetries?
  (see talk M. Gottowik)

$E_{CR} = 15.85$ EeV, $\theta = 80.00^\circ$, $\alpha = 84.15^\circ$
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1: raw shower plane
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3: CE subtracted
The charge-excess fraction in the energy fluence

\[ \frac{\langle p_{0} \cdot e(p_{1} \cdot (p - \rho_{avg})) \rangle}{10^{18.4}-10^{20.2} \text{ eV}} \]

\[ 60-80^\circ \]

charge-excess fraction

\[ a \equiv \sin^2(\alpha) \cdot \frac{f_{ce}}{f_{geo}} \]

depends on off-axis angle, lateral distance and density at Xmax
Parameterisation of charge-excess fraction

- analytic parameterization optimized for universal applicability

\[ a(r, d_{\text{max}}, \rho_{\text{max}}) = 0.373 \cdot \frac{r}{d_{\text{max}}} \cdot \exp \left( \frac{r}{762.6 \, \text{m}} \right) \cdot \left[ \exp \left( \frac{\rho_{\text{max}} - \langle \rho_{\text{max}} \rangle}{0.149 \, \text{kg/m}^3} \right) - 0.189 \right] \]

off-axis angle \hspace{1cm} axis distance \hspace{1cm} atmospheric density correction

- with this, we can calculate geomagnetic energy fluence at any location by subtraction of charge-excess fluence from \( \mathbf{v} \times \mathbf{B} \) measurement

\[ f_{\text{geo}}^{\text{par}} = \frac{f_{\mathbf{v} \times \mathbf{B}}}{\left( 1 + \frac{\cos(\phi)}{|\sin(\alpha)|} \cdot \sqrt{a(r, d_{\text{max}}, \rho_{\text{max}})} \right)^2} \]

Performance of charge-excess correction

\[ E_{CR} = 15.85 \text{ EeV}, \theta = 70.00^\circ, \alpha = 78.42^\circ \]

- application of early-late correction and charge-excess correction results in a mostly symmetric LDF
- some scatter remains, arising from deviations from circular symmetry of charge-excess fraction
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Overall performance of symmetrization

- average bias for all showers is below 1%, spread below 2.5%
- deviations from true geomagnetic energy fluence only at small values (not relevant for the radiation energy integration)
Fitting a rotationally symmetric LDF

$E_{CR} = 15.85$ EeV, $\theta = 70.00^\circ$, $\alpha = 78.42^\circ$

- canonical exponential of a cubic polynomial works well

$$f_{ABCD}(r) = A \cdot \exp \left[-B \cdot r - C \cdot r^2 - D \cdot r^3\right]$$

- some deviations at large lateral distances, but minor influence on radiation energy integration
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- canonical exponential of a cubic polynomial works well

$$f_{ABCD}(r) = A \cdot \exp \left[ -B \cdot r - C \cdot r^2 - D \cdot r^3 \right]$$

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Radiation energy integration via fitted LDF

- Density-corrected geomagnetic radiation energy correlates well with energy in the electromagnetic cascade, spread smaller than 3%

\[
S_{\text{rad,geo}}^\rho = \frac{E_{\text{geo}}}{\sin^2(\alpha)} \cdot \frac{1}{1 - p_0 + p_0 \cdot \exp[p_1 \cdot (\rho - \langle \rho \rangle)]}
\]
Conclusion

- radio signal distribution of inclined air showers is highly asymmetric
- have developed analytic model to symmetrize the distribution
- symmetrized distribution can be fit with simple 1d LDF
- integration over 1d LDF yields *geomagnetic radiation energy*
- 3% intrinsic energy resolution in 30-80 MHz band and for $\theta = 60-80^\circ$
- will develop event reconstruction on this basis
Backup
Performance of early-late correction

- most significant deviations are at large lateral distances and small energy fluences
Determining charge-excess fraction directly

\[ f_{\text{geo}}^{\text{pos}} = \left( \sqrt{f_{v \times B}} - \frac{\cos(\phi)}{|\sin(\phi)|} \cdot \sqrt{f_{v \times v \times B}} \right)^2 \]

\[ f_{\text{ce}}^{\text{pos}} = \frac{1}{\sin^2(\phi)} \cdot f_{v \times v \times B}. \]

For a given observation position, the charge-excess fraction can be determined directly via the known polarisation characteristics of the geomagnetic and charge-excess contributions, cf. Glaser et al., Astroparticle Physics 104 (2019) 64-77.
Total CE fraction and density at Xmax

\[ A(\rho_{\text{max}}) = p_0 \exp(p_1 \cdot (\rho_{\text{max}} - \langle \rho_{\text{max}} \rangle)) + p_2 \]

- total charge-excess fraction correlates with density at Xmax, see Glaser, Erdmann, Hörandel, Huege, Schulz, JCAP 09 (2016) 024