Radio universality and template-based pulse synthesis
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Forward Model

- Large computation cost of full particle physics simulation
  ⇒ Accurate simulation-based reconstructions very expensive
- Poor control over indirect inputs ($X_{\text{max}}$)
- No analytical understanding
- Fully macroscopic models not accurate enough

- Build templates from CoREAS output
- Use macroscopic theory to modify templates
- For now: focus on $10^{17}\text{eV}$ vertical proton showers
Radio Emission – Shower Plane

\[ \vec{E} = E_G \cdot \hat{\nu} \times \hat{B} + E_A \cdot \hat{e}_r \]
Longitudinal – Slicing

- Radio emission sliced by atmospheric depth of origin
- Sum of all slices reproduces measurable signal
- Slices much larger than radio wavelengths, but smaller than longitudinal coherence length

\[ \vec{E}(t,r) = \sum_{X} \vec{E}(t,r,X) \]
Longitudinal – Parametrisation

- Key assumption: slice acts as discrete source
  - Point source amplitude scales as $1/l$
  - Radiation propagates in straight line with speed $c/n_{\text{eff}}$
  - Internal structure reducible to a few key parameters
Line-of-sight scaling

- Radio wavelengths >0.5m, slices >50m ⇒ expect near-field effects
- Scaling appears to be universal
- Convergence for \( l > 4 \text{km} \) corresponding to vertical \( X < 600 \text{g/cm}^2 \)

⇒ 10% systematic deviation for late stage of vertical showers
Pulse timing

- Peak position propagated by $\Delta t = n_{\text{eff}}(l) \cdot l / c$
- Shower front calculated with flat atmosphere
- CoREAS time precision $\delta t = 0.2$ns

$\Rightarrow$ Classical ray timing consistent within numerical limits
Longitudinal – Template Synthesis

Synthesis requires normalisation function $N(X)$.

Start with linear rescaling by electron+positron count (almost identical to standard longitudinal profile).

True universality if valid for individual slices, sum on ground sufficient for synthesis.

Alternatively consider and compensate geometry

$$\Delta X = X - X_{max}$$

and compensate geometry

$$\vec{E}_s = \sum_X \frac{N_r(X)}{N_t(X)} \vec{E}_t(X)$$
Best Case!

1. **N(X)**

2. **0-500MHz Geomag 51.0m**
   - real
   - synth
   - template

3. **0-500MHz Geomag 119.0m**
   - real
   - synth
   - template

4. **0-500MHz Geomag 255.0m**
   - real
   - synth
   - template
Longitudinal – Effective Dipole

\[ \vec{D}(X) = \sum_{\text{slice}} q \cdot (\vec{r}_{\text{end}} - \vec{r}_{\text{start}}) \sim n(X)/\rho(X) \]

- Refine particle count by considering distance traveled
- Quantity reflects an effective dipole moment across the slice
- Proportional to particle density and mean free path length in the slice
Longitudinal – Radio Emission

Equal transmission geometry ⇒ closest equivalent to particle profile

Not observable
Longitudinal – Summary

- No perfect match
- Radio emission has small-scale fluctuations
- Further study underway
Forward Model – Next Steps

- Find valid longitudinal description
- Quantify residuals and fluctuations
- Fill in lateral plane

- Generalise to other arrival geometries,
- Primary energies,
- Atmospheres etc.
Thank you!

Questions?
Backup
Radio emission

[Image with diagrams of radio emission, geomagnetic and Askaryan techniques]

Geomagnetic

Askaryan


Primary particle → air shower → radio pulse front
Radio analysis

Current radio analysis: MCMC simulation:

\[ \vec{E}(t) = \text{CoREAS}(E_0, X_{\text{max}}) \]

In following: vertical \(10^{17}\) eV proton
Radio Emission – Lateral Distribution

\[ \vec{E} = F(\vec{E}(s_1), \vec{E}(s_2)) \]

- Here: linear interpolation of Fourier amplitudes and phases

Graph: \( \vec{E} \times \vec{B} \) – polarisation Fourier interpolation

Lines:
- \( E(104m, t) \)
- \( E(112m, t) \)
- \( E(120m, t) \)
- \( F(E(104m), E(120m)) \)
Radio EAS Arrays

CODALEMA-3
(57)

CODALEMA-2
(24)

LOFAR
(384)

LOPES
(30)

Tunka-Rex
(25)

AERA
(153)

SKA-low
(~60000)

1 km