MGMR3D, a semi-analytic code for the obtaining the radio footprint from the shower currents

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Motivation:
Use radio emission as tool to learn about shower-currents

Need: Fast and non-MonteCarlo code for radio footprint (Intensity & polarization).

MGMR3D: Complete pattern for arbitrary current profile in 10 seconds on windows laptop

Approach: Semi-analytic & conveniently parametrized shower structure

This talk:
- Implemented shower parametrization, inspired by CORSIKA
- Compare results with COREAS
We parametrize the charge-current densities in the shower depending on:
- height in the atmosphere = \( z = -c t_s \)
- lateral distance to the shower axis = \( r_s = \sqrt{x_s^2 + y_s^2} \)
- distance behind the shower front = \( h \)

The radiation fields are calculated from the vector potential, including retardation (Cherenkov) effects.

\[
A^\mu (t_o, \vec{x}_o) = \int \! d^3 \vec{x'} \frac{j^\mu(t_r, \vec{x'})}{D} \quad D = \frac{1}{nR} \left| \frac{dt_o}{dt_r} \right| = nR \left( 1 - n \vec{\beta} \cdot \hat{n} \right)_{\text{ret}} \quad n_{GD} = 1 + n_\rho \rho(z)
\]
Charge excess & drift velocity

Net charge $= J^0(z) = a(z) N(z)$

Net transverse current $= J^i(z) = v_d^i(z) N(z)$
Charge excess & transverse current Pulses

MGMR3D (full lines)
CoREAS (dashed lines),
Vertical shower,
\(X_{\text{max}} = 540 \text{ g/cm}^2\)
Stokes

Stokes parameters: 
I, Q, U, V

Linear polarization angle: 
2 \phi = \text{atan}(U/Q)

Circular polarization = V/I

\[ I = \frac{1}{n} \sum_{0}^{n-1} \left( |\mathcal{E}|_{i,v \times B}^2 + |\mathcal{E}|_{i,v \times (v \times B)}^2 \right) \]

\[ Q = \frac{1}{n} \sum_{0}^{n-1} \left( |\mathcal{E}|_{i,v \times B}^2 - |\mathcal{E}|_{i,v \times (v \times B)}^2 \right) \]

\[ U + iV = \frac{2}{n} \sum_{0}^{n-1} \left( \mathcal{E}_{i,v \times B} \mathcal{E}^*_{i,v \times (v \times B)} \right) \]
Fair weather,
Vertical, $X_{\text{max}} = 540 \text{ g/cm}^2$

Stokes parameters (30 -- 80 MHz)

Transverse currents

I
Q/I
U/I
V/I

Linear polarization
Circular polarization
Fair weather, 30 deg, $X_{\text{max}} = 693 \text{ g/cm}^2$

Stokes parameters (30 -- 80 MHz)
Shower parameters depend on atmospheric electric field.

Important for analysis of thunderstorm events:
- Pancake distribution
- Peak radio power (30-80 MHz)

Graphs showing:
- 50-percentile distance [m] vs. E [kV/m]
- Amplitude vs. Force [keV/m]

Legend:
- CoREAS
- MGMR3D

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ARENA-2018 E-Field
2-layered electric field, Vertical, $X_{\text{max}} = 510 \text{ g/cm}^2$

Stokes parameters (30 -- 80 MHz)

- $I$
- $Q/I$
- $U/I$
- $V/I$

$Q = -1 \rightarrow$ polarization along $vx(vxB)$

Peak at finite distance, **NOT** due to Cherenkov
Interference of emission from different heights

Electric fields in different layers are in opposite directions

Destructive interference depends on relative arrival times, or distance to shower axis.
Intensity pattern will have a ring-like structure.

Signal is linearly polarized along direction of atmospheric electric field
Triple layered field, Vertical, $X_{\text{max}} = 660 \text{ g/cm}^2$

Stokes parameters (30 -- 80 MHz)

Transverse currents

U=1: polarized at 45 deg

Large circular polarization near axis
Circular polarization in thunderstorm events

Electric fields in different layers are at an angle

The pulses from the upper layer arrive with a delay with respect to the pulses from the lower layer resulting in a change of the polarization angle over the duration of the pulse, seen as circular polarization.

Measured signal has strong circular polarization (Stokes V/I ≠ 0)

See: Trinh et. al. (2016) *Physical Rev. D* 95, 083004
Fair weather, Vertical, $X_{\text{max}} = 540 \text{ g/cm}^2$

Stokes parameters (100 -- 200 MHz)
Summary & Conclusions:

MGMR3D Gives a realistic physics-based estimate of the radio footprint
- intensity
- polarization
- time structure & frequency content
- handles complicated current profile

Code is fast and can be used in chi-square search

Ref: PRD97(2017)0230005; code available upon request
Fair weather vs thunderstorm

Observations; intensity footprint

S. Buitink et al., PRD 90, 082003 (2014)
P. Schellart et al., PRL 114, 165001 (2015)
A reconstructed thunderstorm event

P. Schellart et al. (Summitted PRL, 2015)