Karlsruher Institut für Technologie

REAS3: A revised implementation of the geosynchrotron model for radio emission from air showers

ARENA 2010

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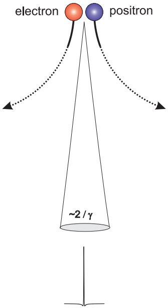
01.07.2010

Motivation

- Two different geomagnetic models made conflicting predictions for radio emission ($\longrightarrow$ Talk 34, T.Huege et al)
- REAS describes radio emission by geosynchrotron effect
- Radiation due to the variation of the number of charged particles in EAS was not considered
- All time-domain models miss this radiation contribution so far

$\Longrightarrow$ The implementation of the geosynchrotron model had to be revised



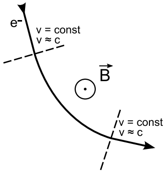
General structure of REAS

- Simulate EAS with CORSIKA $\rightarrow$ save information in histograms
- Generate shower particles according to the desired distributions
- Follow each particle analytically on its track in the geomagnetic field (long trajectories are described by several short tracks)
- Superpose the radiation received from the shower particles at a given observing position

Technical implementation in REAS

REAS2

- Continuous radiation processes along the tracks, not at the end or the beginning of track
- e^-/e^+ with $v \approx c$ before and after being tracked analytically in the B-field



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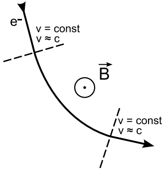
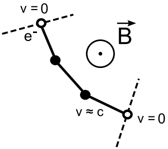
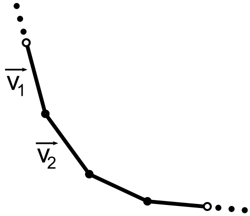


REAS3

- Straight track fragments joined by "kinks"
- Variation of $\vec{v}$ in kink: discrete radiation process
- e^-/e^+ with $\vec{v}=0$ before and after being tracked analytically ⇒ radiation due to creation/annihilation is considered



Discrete calculations



- Look at the time averaged process (change of velocity is instantaneously)
- Integrated field strength from radiation formula
- $\vec{v}(t_1) = \vec{v}_1 = \vec{\beta}_1 c\,;\ \vec{v}(t_2) = \vec{v}_2 = \vec{\beta}_2 c$
- Radiation contribution in kink

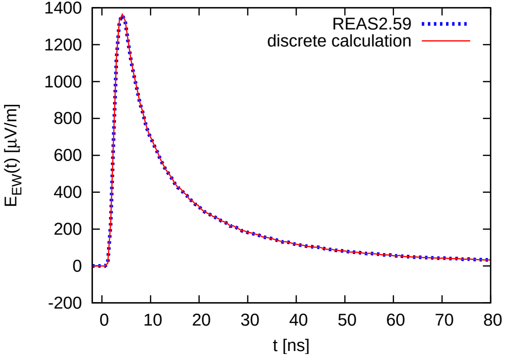
$$\int \vec{E}(\vec{x},t)dt = \int_{t_1}^{t_2} \frac{e}{c} \left| \frac{\vec{n} \times [(\vec{n}-\vec{\beta}) \times \dot{\vec{\beta}}]}{(1-\vec{\beta}\cdot\vec{n})^3 R} \right|_{ret} dt = \vec{F}(t_2) - \vec{F}(t_1)$$

$$= \frac{e}{cR}\left(\frac{\vec{n}\times(\vec{n}\times\vec{\beta}_2)}{(1-\vec{\beta}_2\vec{n})}\right) - \frac{e}{cR}\left(\frac{\vec{n}\times(\vec{n}\times\vec{\beta}_1)}{(1-\vec{\beta}_1\vec{n})}\right)$$

- Refractive index set to unity
- With discrete endpoint description several radiation processes can be described

Continuous vs. discrete calculation

- Radio emission for track without endpoints (to verify the implementation in REAS)

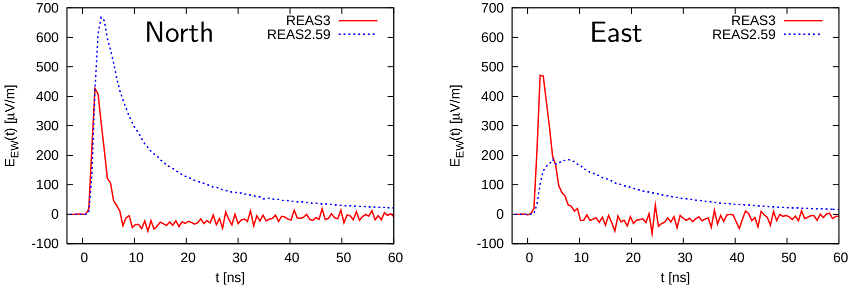


- Results are identical
- Discrete description is equivalent with continuous description
- In discrete picture endpoints are kinks with $\vec{v}_i = 0 \neq \vec{v}_j$

- Radiation contributions due to the variation of the number of charged particles can be included canonical in the discrete calculation

Comparison of REAS2 and REAS3

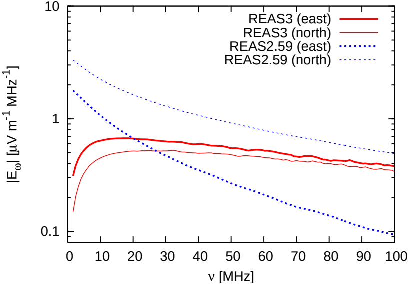
- Calculations were done for a vertical shower with $E_p = 10^{17}$eV in a horizontal magnetic field of 0.23 Gauss
- Raw pulses for observers 100 m north and east of the shower core at sea level

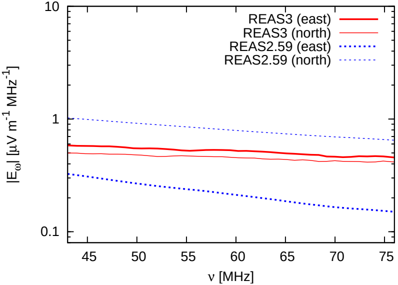


- Pulse shape with REAS3 bipolar
- REAS3 emission pattern nearly azimuthal symmetric
- Height of amplitudes changed

Frequency spectra

- Frequency spectra for observers 100 m north and east of the shower core
- Right plot: ∼ frequency range of experiments (43-76 MHz)

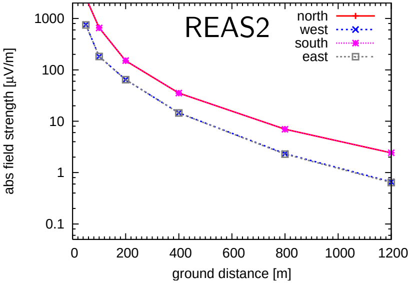


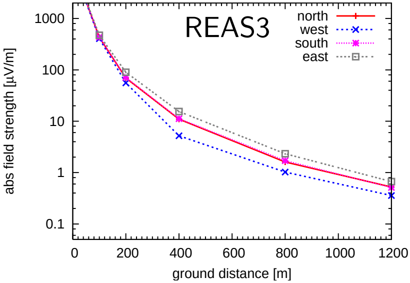


- Spectral field strengths drop to 0 for frequency 0
- In general the spectra became flatter
- REAS3 more symmetric than REAS2

Lateral distribution

- Lateral dependence of REAS2 and REAS3 with full bandwidth amplitudes

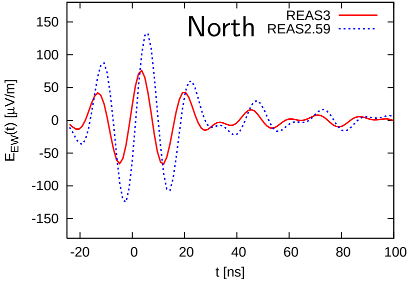


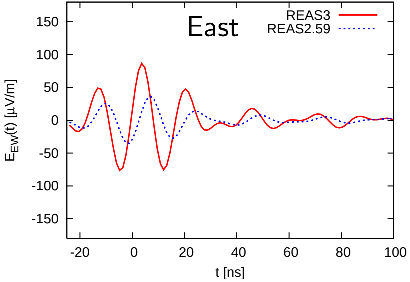


- In REAS3: east-west asymmetry
- REAS3: for larger distances smaller field strengths
- Azimuthal symmetry in REAS3 as expected

Filtered pulses

- For comparison with experimental data: filter simulations to a finite observing bandwidth
- Simulations were processed with a frequency filter from 43 MHz to 76 MHz (with REASPlot)
- Pulses for observers 100 m north and east of shower core at sea level

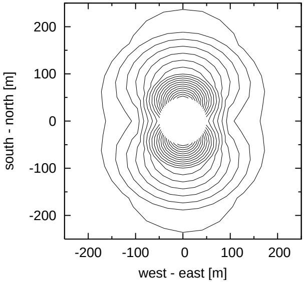




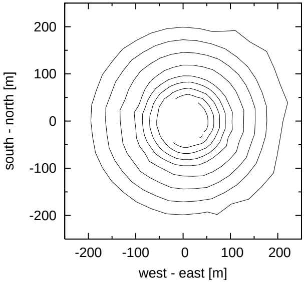
Contour plots

- Contour plots of the 60 MHz total field strength
- Contour levels are 0.1 μV/m/MHz
- In contour plots general symmetry visible as well as east-west asymmetry for REAS3

REAS2



REAS3

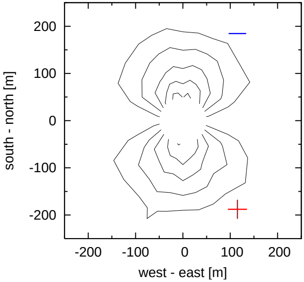


Contour plots for B=0 Gauss

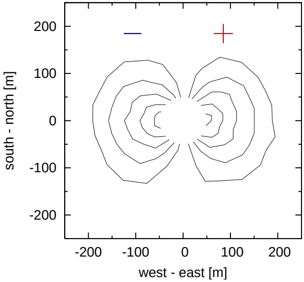
- Contour plots of the 60 MHz field strength (NS and EW polarisation)
- Contour levels are 0.03 μV/m/MHz
- Radiation pattern is radially polarised

$\Rightarrow$ Charge excess leads to non-geomagnetic contribution

NS



EW



Charge excess vs. pure geomagnetic

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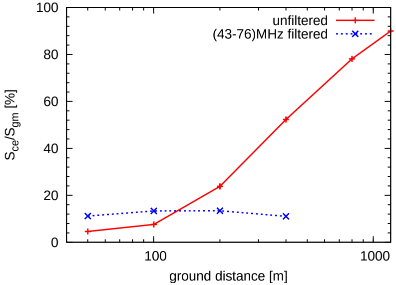
- Comparison of charge excess (CE) and pure geomagnetic (gm) contribution for EW polarisation



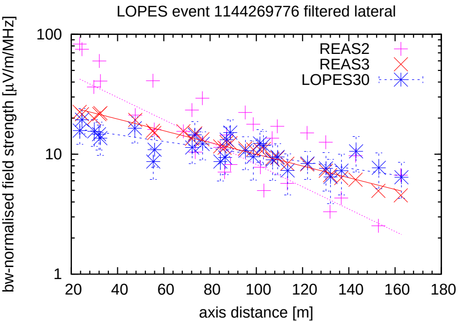
- For filtered pulses influence of CE around 10%
- For lateral distance larger than 400 m filtered signal is not distinguishable from noise

- Radio signal is dominated by geomagnetic contributions in the frequency range of experiments
- For raw radio pulses CE is getting more important with lateral distance

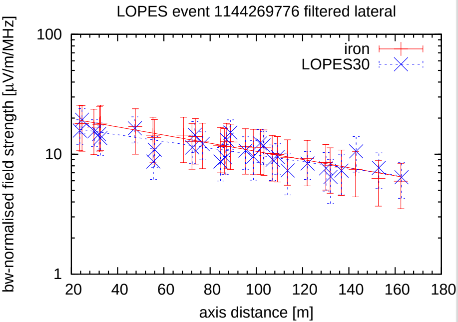
Comparison with LOPES data

- $E = 2.75 \cdot 10^{17}$ eV, 24° zenith angle

proton shower



iron shower

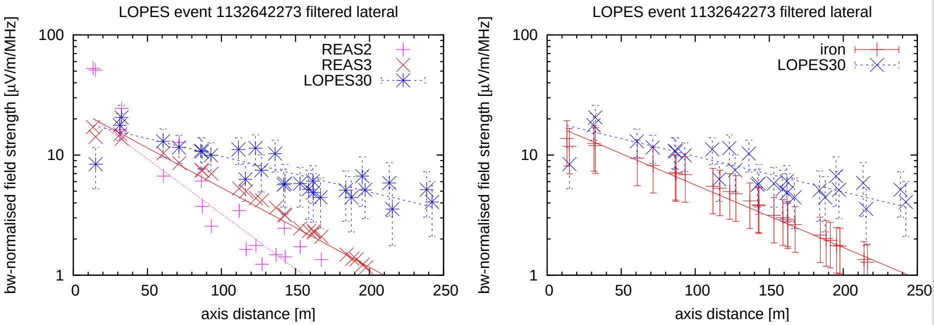


Apel, W.D. et al. - LOPES coll., Astropart. Ph. 32 (2010) 294-303

Comparison with LOPES data

- E = $3.13 \cdot 10^{17}$eV, 12° zenith angle

proton shower　　　　　　　　　　iron shower

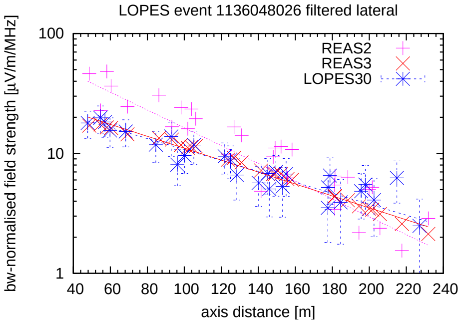


- Noise treatment maybe changes slope of this event (⇒ Poster of F. Schröder)

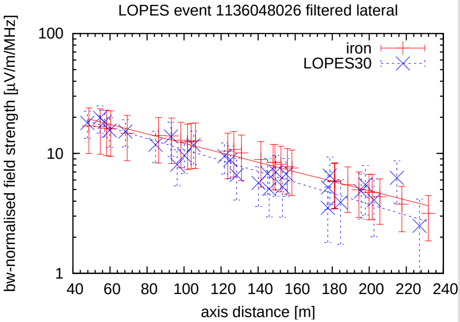
Comparison with LOPES data

- $E = 2.92 \cdot 10^{17}$eV, 31° zenith angle

proton shower



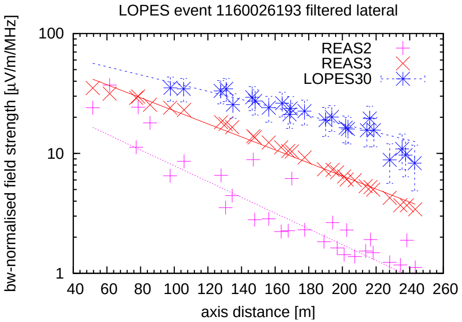
iron shower



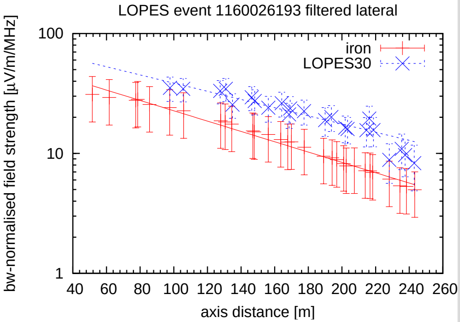
Comparison with LOPES data

- $E = 9.65 \cdot 10^{17}$eV, 29° zenith angle

proton shower



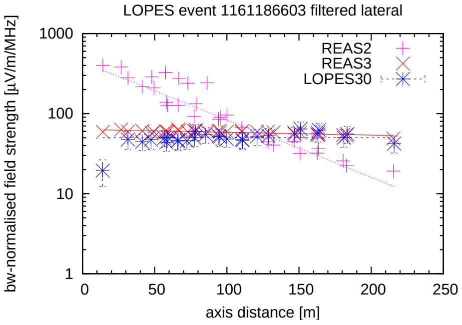
iron shower



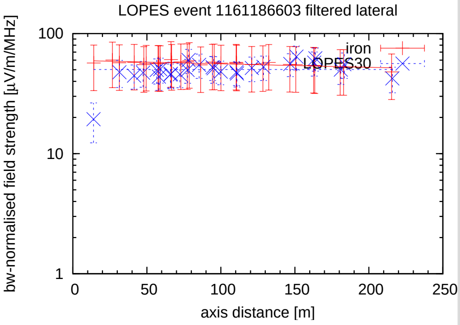
Comparison with LOPES data

- $E = 2.88 \cdot 10^{18}$eV, 58° zenith angle

proton shower



iron shower



Conclusion

- Emission contributions due to the variation of the number of charged particles in an EAS are included:
  - Pulse structure is bipolar
  - Azimuthal emission pattern nearly symmetric
  - Remaining asymmetry explainable by charge excess in EAS ⇒ radio emission not purely of geomagnetic origin
  - REAS3 in good agreement with LOPES data
- REAS3 is the first self-consistent time-domain model which takes the full complexity of EAS physics into account (provided by CORSIKA)
- REAS3 has no free paramters
- Detailed paper has been submitted to Astroparticle Physics

⇒ **Code will be freely available after publication**