Modelling the Radio Emission of Inclined Cosmic-Ray Air Showers in the 50-200 MHz Frequency Band for GRAND

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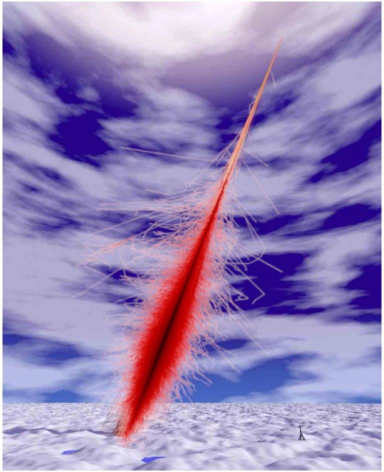
Karlsruher Institut für Technologie

Measuring Air Showers with GRAND

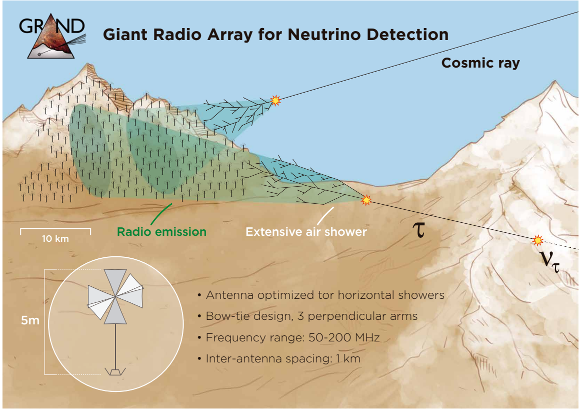
- **Ultra-high energy** (UHE) cosmic rays induce so-called **air showers** when entering the atmosphere
- Secondary electrons and positrons emit **radio waves**
- Detection with **ground-based radio antennas**



Adapted from Alameddine et al. (2021, arXiv:2112.11761) and CORSIKA Shower Images

Detection Principle

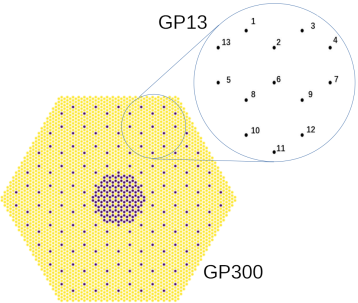
- $200\,000\,\mathrm{km}^2$ of planned **antenna coverage**
- Split into **several sub-arrays**
- Sensitive between $10^{17} - 10^{21}\,\mathrm{eV}$
- **No secondary trigger**



GRAND Collaboration (2018), arXiv:1810.09994

Prototype Arrays

- **GRAND@Nançay**
  4 antennas to **test hardware and trigger systems**
- **GRANDAuger**
  10 antennas for **cross-calibration**
- **GRANDProto 13**
  13 antennas in China for **noise and signal tests**
- **GRANDProto 300** (in construction)
  Test array for autonomous **cosmic ray detection**

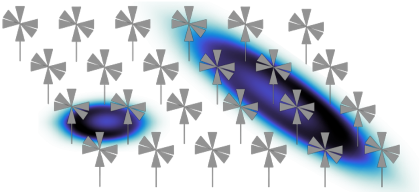


Preliminary antenna layouts for GP13 and GP300

My Contribution

Signal Model:

- Model the **signal pattern at ground level**
- **Generalise** for more frequency bands and sites
- Reconstruct cosmic ray **radiation energy**



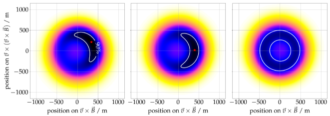
Goal:

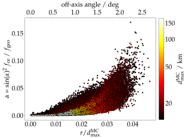
- Provide **precise event reconstruction** for GP300 and GRAND

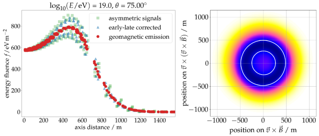
Original Model

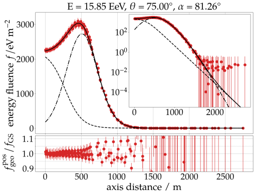
Signal model and event reconstruction for the radio detection of inclined air showers

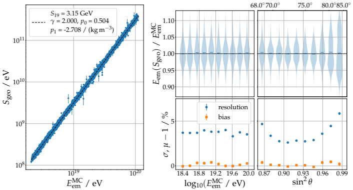
F. Schlüter[a,b,1] and T. Huege[a,c]





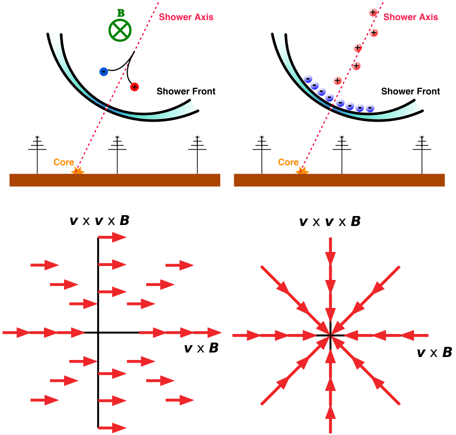






Emission Mechanisms

- **Geomagnetic emission**
  Charge separation in geomagnetic field
- **Charge excess emission**
  Accumulation of negative charges at shower front
- For very inclined showers, **geosynchroton emission** becomes relevant



Huege (2016), arXiv:1601.07426

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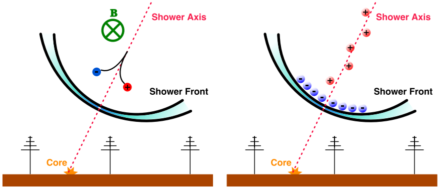
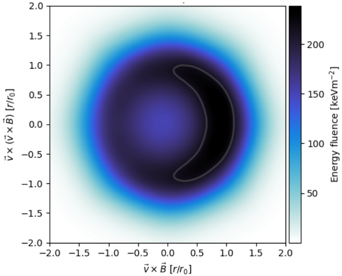
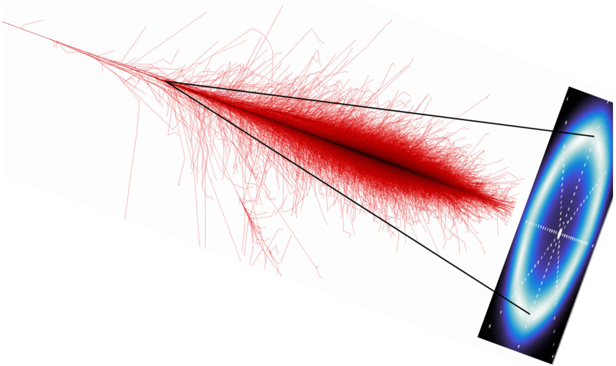




Cherenkov Ring

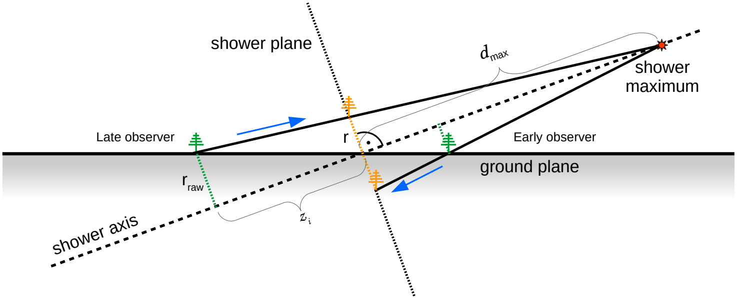
- **Cherenkov-like** emission in atmosphere
- Air density **changes emission angle**
- Time compression causes **high-intensity ring** in emission pattern



Early-late Correction

- Antennas projected into **shower plane**
- Apply **correction to energy fluence**
- Eliminates **signal differences** from shower geometry

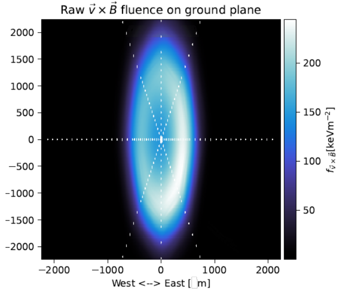
Early-late correction for simulating inclined showers



Schlüter (2022), arXiv:2203.04364

Step-by-Step Symmetrisation

Air shower simulation in $\underline{30 - 80\,\mathrm{MHz}}$ with zenith angle $\underline{\theta = 75^\circ}$



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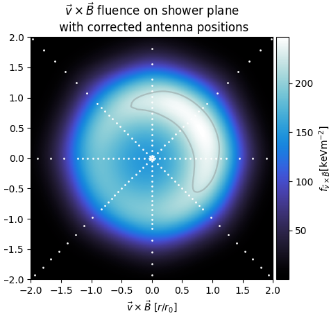

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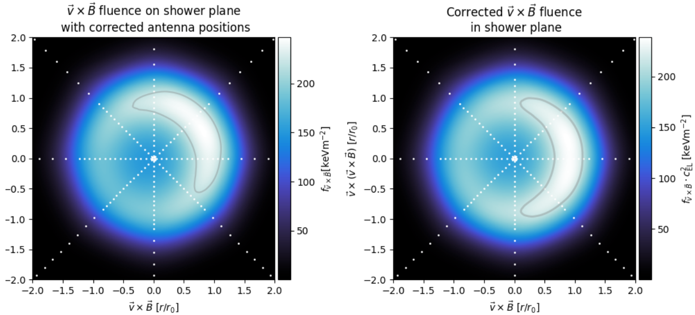

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Lukas Gülzow - lukas.guelzow@kit.edu

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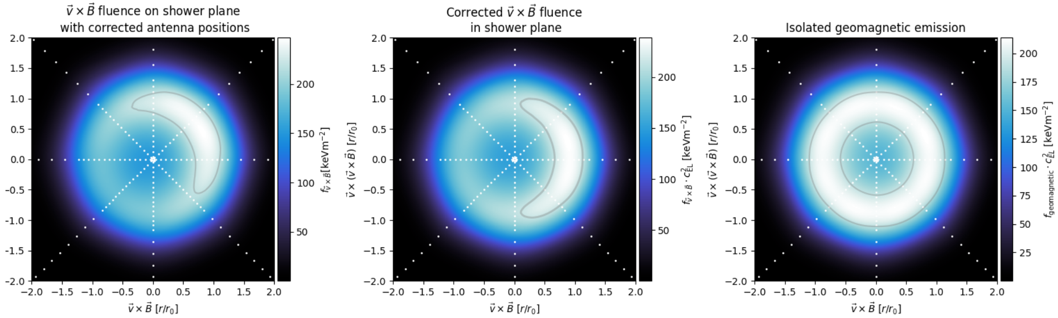
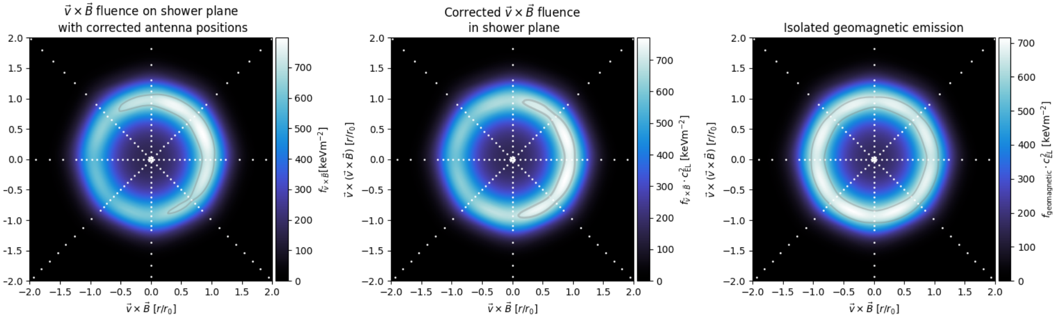


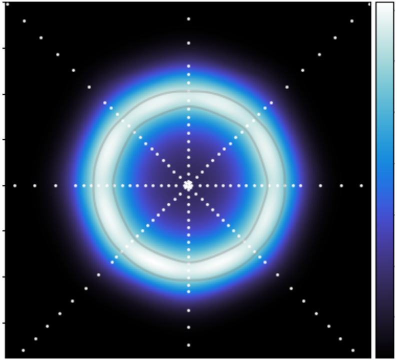
Step-by-Step Symmetrisation

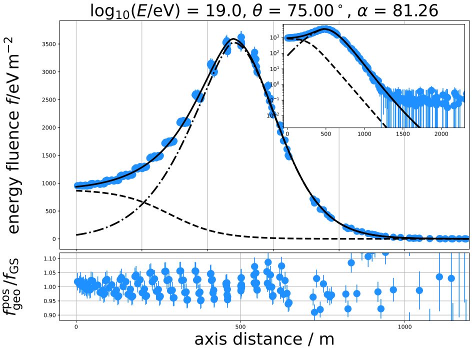
Air shower simulation in $\underline{50 - 200\,\mathrm{MHz}}$ with zenith angle $\underline{\theta = 75°}$



Lateral Distribution Function of Energy Fluence

Radially symmetric fluence → Lateral fluence distribution





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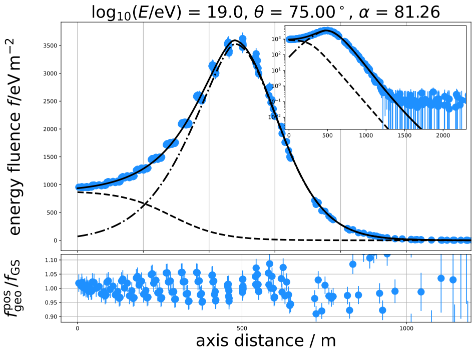
Lateral Distribution Function of Energy Fluence

Fit geomagnetic LDF ⇒ Integrate to find shower radiation energy



normalization — Gaussian — Sigmoid*

$$f_{\mathrm{GS}}(r) = f_0 \left[\exp\left(- \left(\frac{r - r_0}{\sigma} \right)^{p(r)} \right) + \frac{a_{\mathrm{rel}}}{1 + \exp\left(s \cdot \left(\frac{r}{r_0} - r_{02} \right) \right)} \right]$$

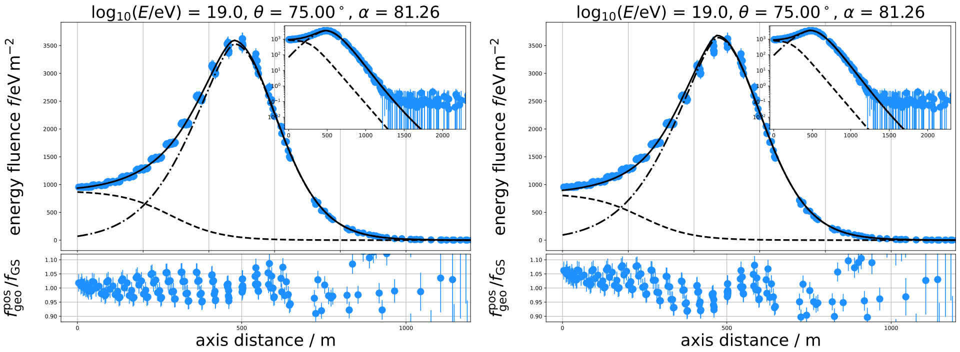
- $p(r)$: ~2
- σ: width of Gaussian
- r_0: position of Gaussian
- a_{rel}: relative amplitude of Sigmoid vs. Gauss
- s, r_{02}: shape parameters

Parameterize all 6 “shape” parameter with d_{max}

Fit function slightly modified from *Schlüter (2022), arXiv:2203.04364*

Fit Performance

Fit with free parameters as well as parametrisations work well for 50-200 MHz simulations at Auger site!



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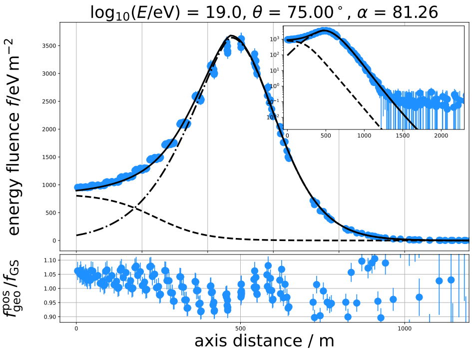
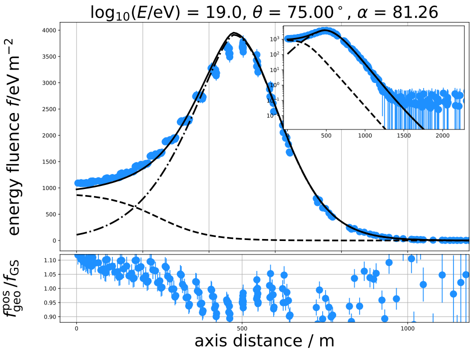
Fit Performance

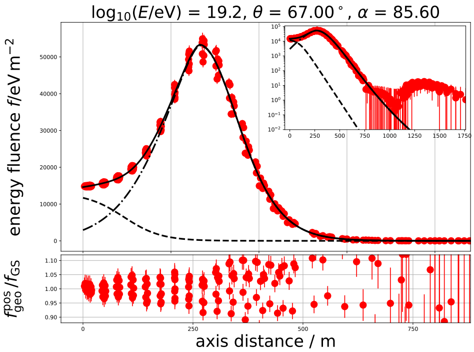
Fit with free parameters as well as parametrisations work well for 50-200 MHz simulations at Auger site! But there's an Xmax dependency.

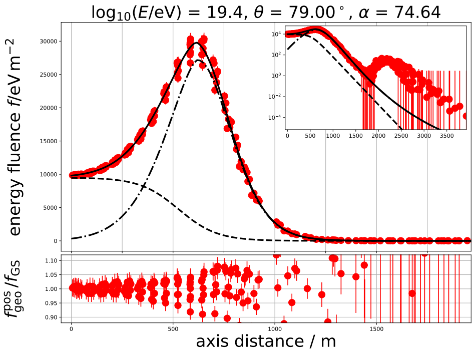




Fit Performance

Free LDF fit applied to GRAND simulations!
Generally performs well, but a few problems remain.





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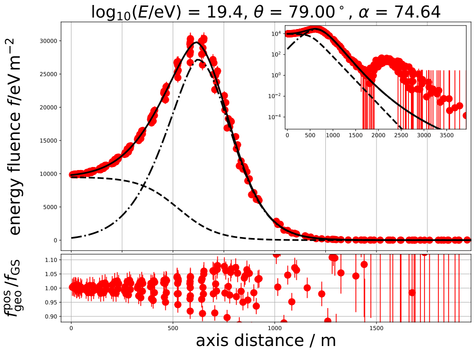
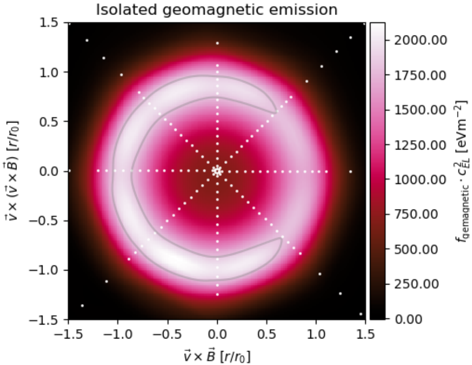
GRAND

New Features

Problems: bump at high axis distance, signal incoherence, geosynchrotron effect?



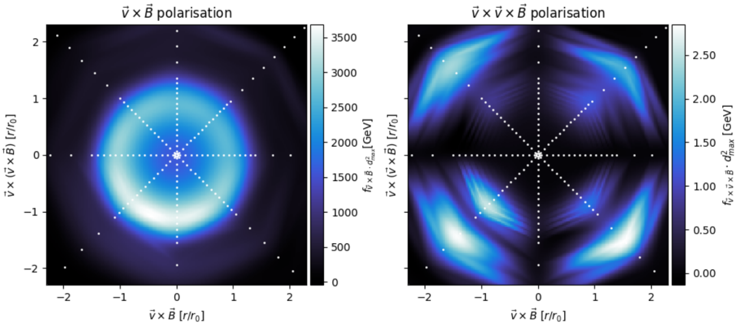


New Features

Effect of a stronger geomagnetic field:

New signal features appear for strongly inclined showers and high frequencies!

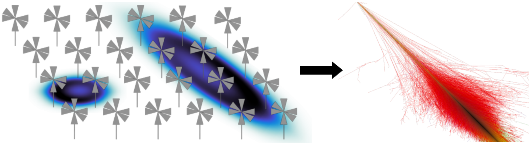
See *Huege, Falcke (2005, arXiv:astro-ph/0501580v2), Huege, James (2013, arXiv:1307.7566v1) & Chiche, Zhang, Kotera, Huege, de Vries, Tueros, Schlüter (2023, PoS(ICRC2023)394)*



Outlook

Final steps for the **Signal Model** and towards **Event Reconstruction:**

- **Optimise & parametrise** LDF fit
- Reconstruction of **em. energy** (and **shower maximum**)

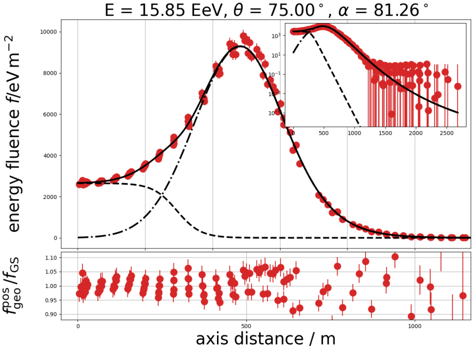


Overall Goal:

- Model and reconstruction **applicable to many frequencies and sites**
- Provide **input for GRAND trigger** algorithm

Backup: LDF Fit Function

Fit function used directly from *Schlüter (2022), arXiv:2203.04364*



normalization — Gaussian — Sigmoid*

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- $p(r)$: ~2
- width of Gaussian
- position of Gaussian
- relative amplitude of Sigmoid vs. Gauss
- shape parameters

Parameterize all 6 “shape” parameter with d_{max}

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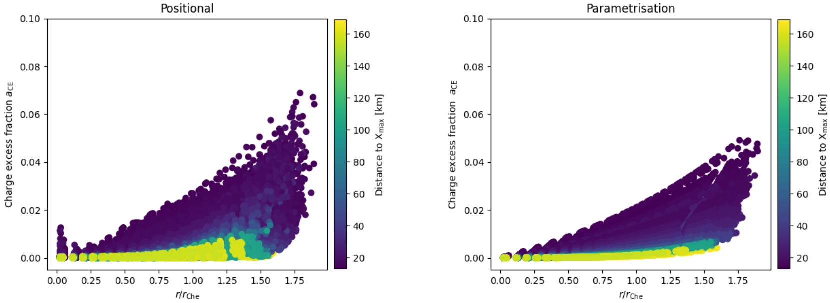
Backup: Charge Excess Fraction Fit

Compare positional and parametric charge excess fraction at $50 - 200\,\mathrm{MHz}$

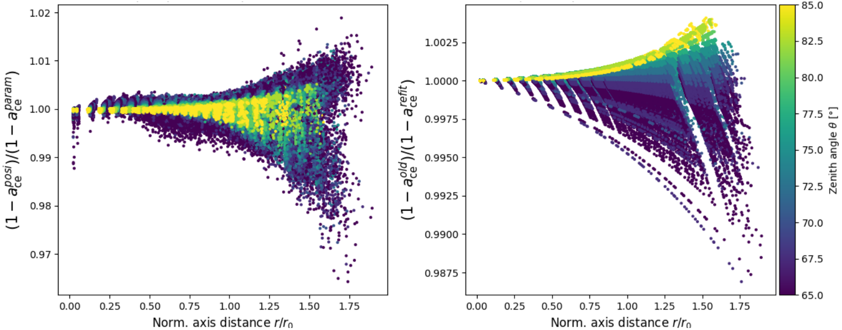


$$f_{\mathrm{geo}}^{\mathrm{par}} = \frac{f_{\vec{v}\times\vec{B}}}{\left(1 + \frac{\cos(\theta)}{|\sin(\alpha)|} \cdot \sqrt{a_{\mathrm{ce}}}\right)^2}$$

$$a_{\mathrm{ce}} = \left[0.348 - \frac{d_{\max}}{850\,\mathrm{km}}\right] \cdot \frac{r}{d_{\max}} \cdot \exp\left(\frac{r}{622.3\,\mathrm{m}}\right) \cdot \left[\left(\frac{\rho_{\max}}{0.428\,\mathrm{kg\,m^{-3}}}\right)^{3.32} - 0.0057\right]$$

Backup: Charge Excess Fraction Fit

Relative deviation of charge excess fraction fit at 50 – 200 MHz



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