Applying template synthesis to the radio emission from air showers with different geometries

Mitja Desmet, Stijn Buitink, Tim Huege

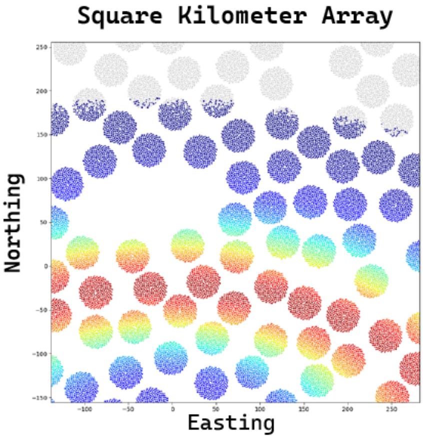
ARENA conference (11–14 Jun 2024)

MICROSCOPIC SIMULATIONS ARE ACCURATE, BUT COMPUTATIONALLY INEFFICIENT

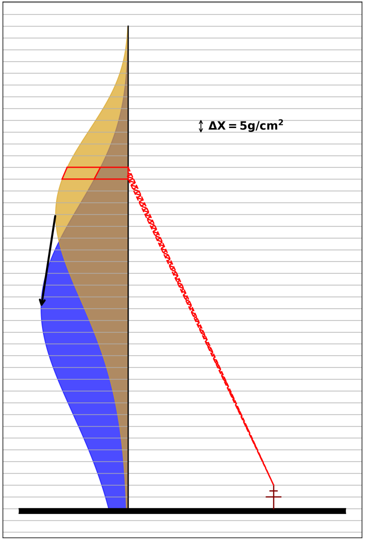
Traditionally we use Monte-Carlo based simulations in order to interpret our data.

- This becomes intractable for the next generation of cosmic ray experiments such as SKA.

To tackle this, we developed a hybrid approach: **template synthesis**



ATMOPSHERIC SLICES IN TEMPLATE SYNTHESIS ARE POINT SOURCES OF RADIO EMISSION



In the template synthesis approach, we divide the atmosphere into **slices** of constant atmospheric depth.

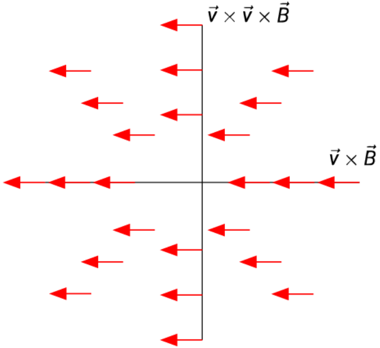
- Each slice is labelled by the atmospheric depth at the bottom of the slice.

The emission coming from each slice is **treated separately**.

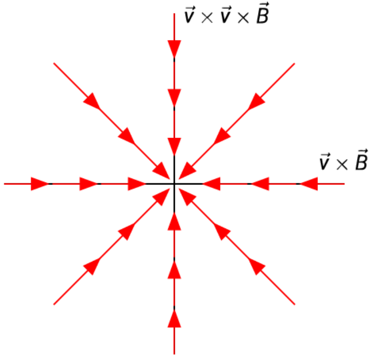
- The amplitude is rescaled with the number of (emitting) particles in the slice.

TEMPLATE SYNTHESIS PARAMETRISES THE EMISSION TO REDUCE COMPUTATION TIME

Geomagnetic component



Charge-excess/Askaryan component



WE HAVE SHOWN THIS WORKS FOR A FIXED ZENITH ANGLE

PoS **ARENA2022** 052

Template synthesis approach for radio emission from extensive air showers

Mitja Desmet,[a,*] Stijn Buitink,[a] David Butler,[b] Tim Huege,[a,b] Ralph Engel[b] and Olaf Scholten[a,c]

Astropart. Phys. 175 (2024), 102923

ELSEVIER

Astroparticle Physics
Volume 157, May 2024, 102923

Proof of principle for template synthesis approach for the radio emission from vertical extensive air showers

Mitja Desmet [a], Stijn Buitink [a], Tim Huege [a b], David Butler [b], Ralph Engel [b], Olaf Scholten [a c]

PoS **ICRC2023** 216

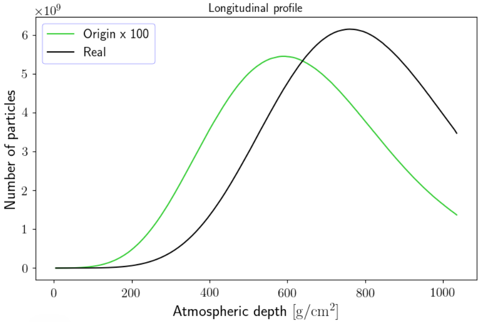
Generalising template synthesis of EAS radio emission to other geometries

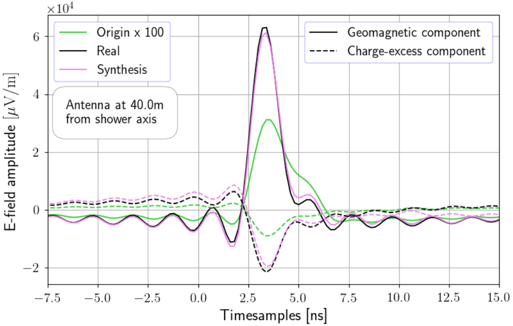
Mitja Desmet,[a,*] Stijn Buitink[a] and Tim Huege[a,b]

WE HAVE SHOWN THIS WORKS FOR A FIXED ZENITH ANGLE

We input an origin shower and use the parametrisations to synthesise a **target** longitudinal profile.

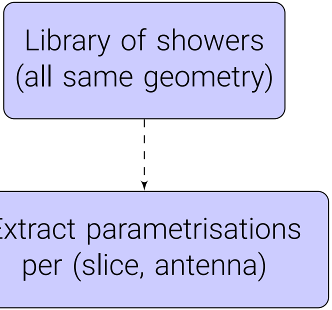
The synthesised pulse matches the one from **CoREAS** within 6% in amplitude.





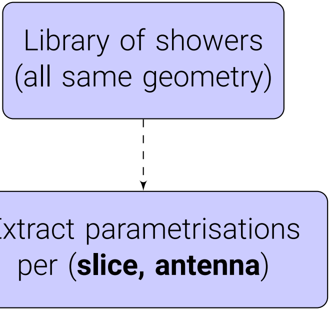
IN ORDER TO MAKE TEMPLATE SYNTHESIS VIABLE, WE NEED TO GENERALISE IT ACROSS GEOMETRIES

The current formulation of **template synthesis** does not allow for translating across air shower geometries (i.e. zenith and azimuth angle).



IN ORDER TO MAKE TEMPLATE SYNTHESIS VIABLE, WE NEED TO GENERALISE IT ACROSS GEOMETRIES

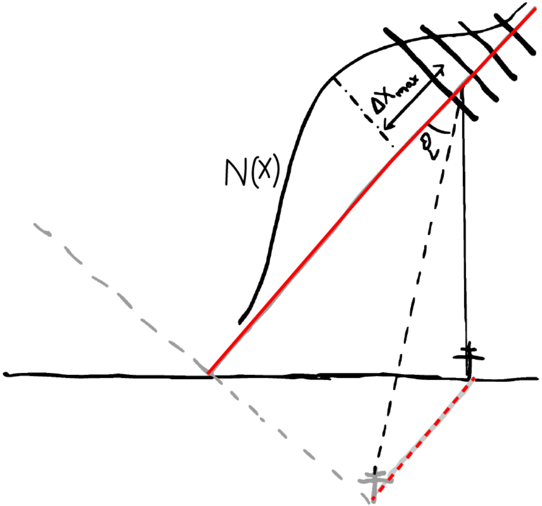
The current formulation of **template synthesis** does not allow for translating across air shower geometries (i.e. zenith and azimuth angle).



Combining slice and antenna in one quantity

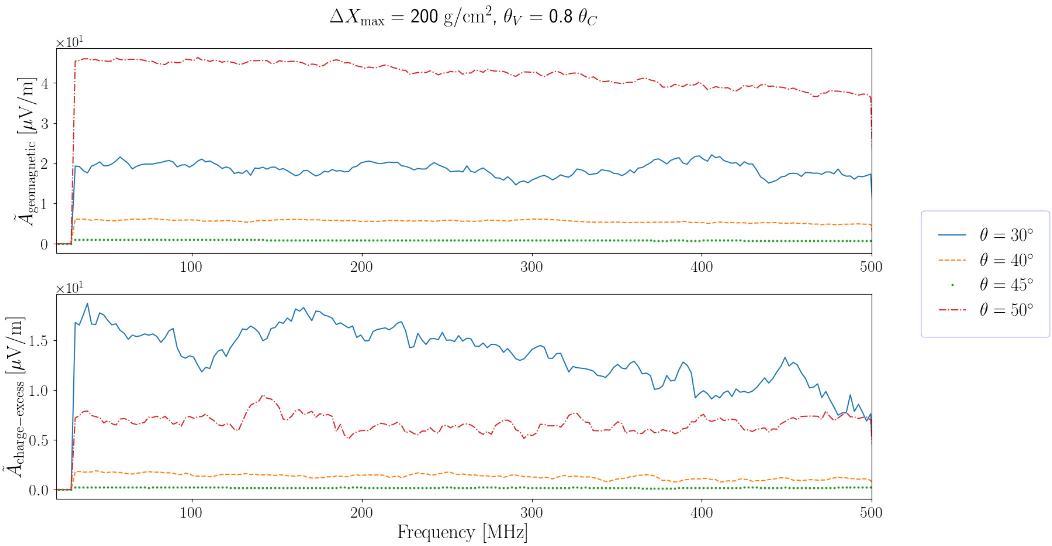
Viewing angle

THE VIEWING ANGLE AS FRACTION OF CHERENKOV ANGLE IS A COMPARABLE QUANTITY

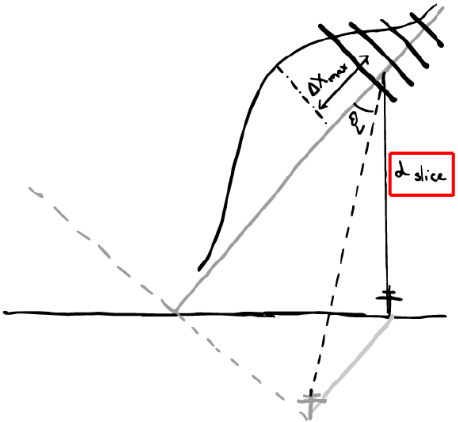


- Shower axis
- $N(X)$: longitudinal profile
- ΔX_{max} : distance from X_{max} to slice, in g/cm^2
- θ_V : viewing angle, as a fraction of θ_C
- Shower plane
- Antenna projection

THE ΔX_{MAX} DETERMINES THE EQUIVALENT SLICE IN A DIFFERENT GEOMETRY

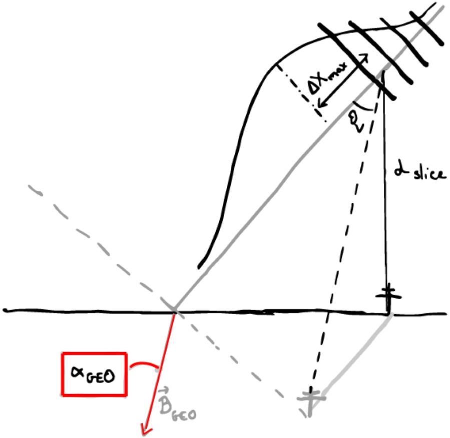


THE EQUIVALENT SLICE STILL HAS DIFFERENT PROPERTIES THAT AFFECT THE AMPLITUDE



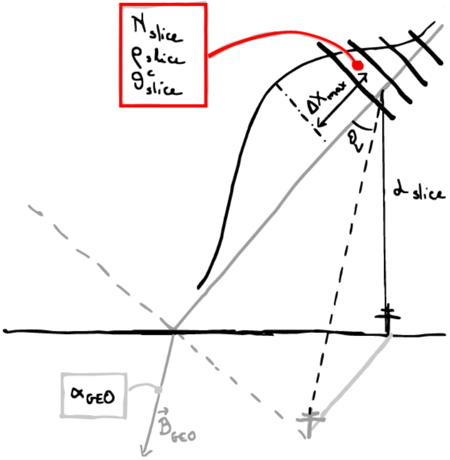
- d_{slice} : distance slice - antenna

THE EQUIVALENT SLICE STILL HAS DIFFERENT PROPERTIES THAT AFFECT THE AMPLITUDE



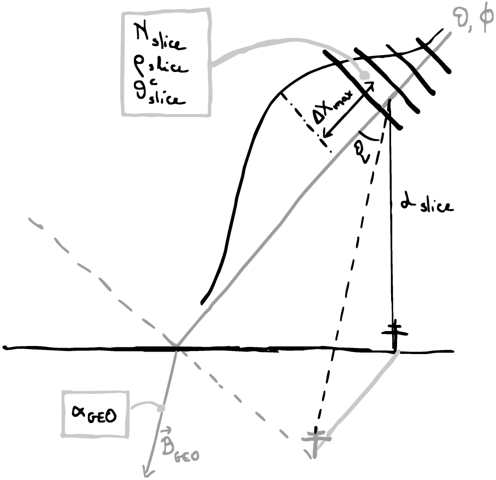
- d_{slice} : distance slice - antenna
- α_{GEO} : geomagnetic angle

THE EQUIVALENT SLICE STILL HAS DIFFERENT PROPERTIES THAT AFFECT THE AMPLITUDE



- d_{slice} : distance slice - antenna
- α_{GEO} : geomagnetic angle
- N_{slice} : # of emitters in slice
- ρ_{slice} : density in slice
- θ^{C}_{slice} : Cherenkov angle at slice

THE EQUIVALENT SLICE STILL HAS DIFFERENT PROPERTIES THAT AFFECT THE AMPLITUDE



- d_{slice} : distance slice - antenna
- α_{GEO} : geomagnetic angle
- N_{slice} : # of emitters in slice
- ρ_{slice} : density in slice
- θ^C_{slice} : Cherenkov angle at slice
- θ, ϕ : zenith/azimuth of shower

WE RELATE THE SPECTRUM TO THE PROPERTIES OF THE SLICE

The **geomagnetic** amplitude frequency spectrum an antenna observes coming from a given atmospheric slice, scales with

- the **geomagnetic angle** (for the geomagnetic component), $\propto \sin(\alpha_{\text{GEO}})$
- the **air density**[1], $\propto 1/\rho_{\text{slice}}$

For the **charge-excess** emission we have a scaling with

- The **Cherenkov angle**[1] (related to the refractive index), $\propto \sin(\theta^{C}_{\text{slice}})$

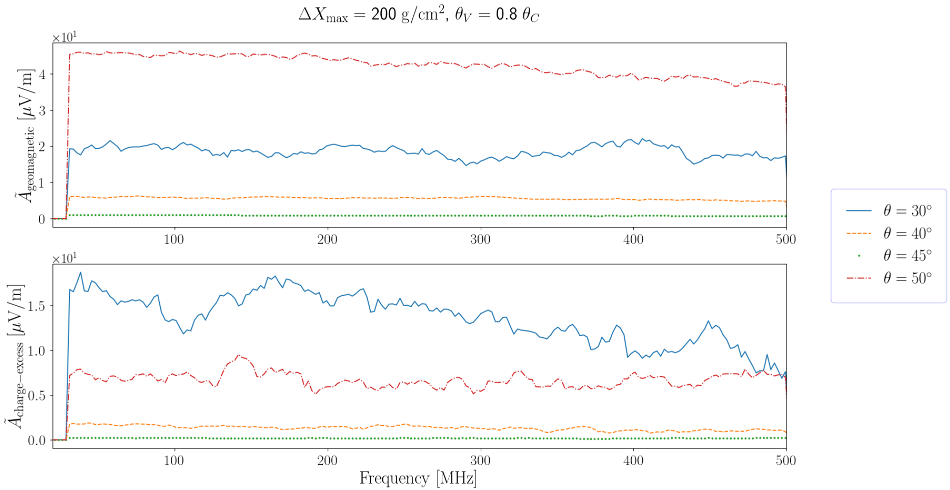
Both components also scale with

- the **distance** to the slice, $\propto 1/d_{\text{slice}}$
- the number of **particles** in the slice, as $\propto N_{\text{slice}}$

[1] Juan Ammerman-Yebra *et al* JCAP08(2023)015

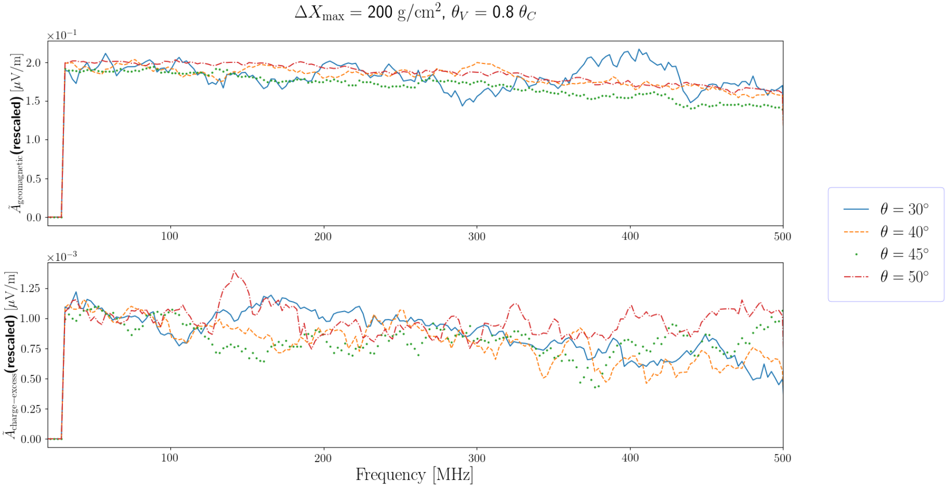
APPLYING THESE SCALING RELATIONS, ALIGNS THE SPECTRA FROM THE EQUIVALENT SLICES

Before:

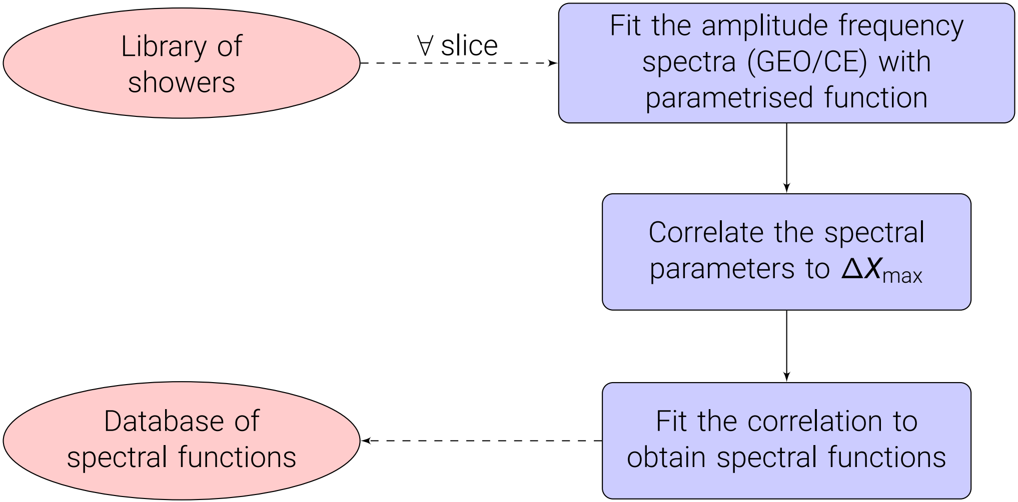


APPLYING THESE SCALING RELATIONS, ALIGNS THE SPECTRA FROM THE EQUIVALENT SLICES

After:

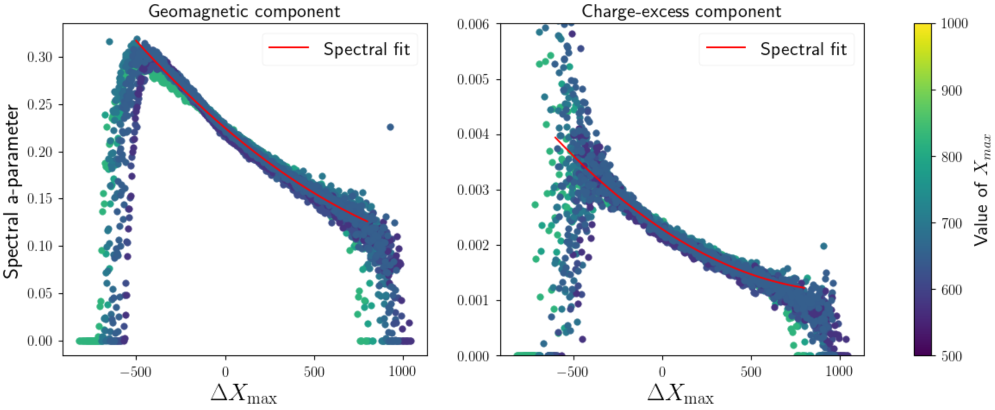


NOW WE CAN APPLY THE STANDARD TEMPLATE SYNTHESIS MACHINERY

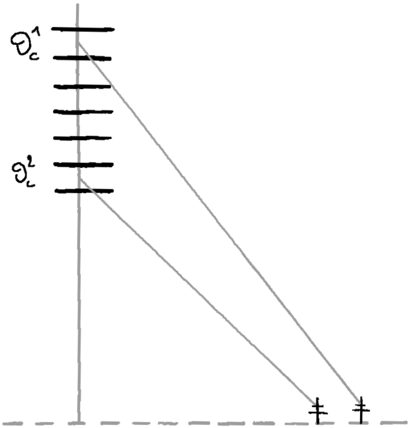


WE FIND SPECTRAL FUNCTIONS PER VIEWING ANGLE

If we correlate the values of the parameters from the parametrised function to the ΔX_{max} of the slice they were extracted from, they all fall onto a parabola.



TO SYNTHESISE THE EMISSION IN AN ANTENNA, WE USE INTERPOLATION IN EVERY SLICE



We can now **synthesise** the emission **per slice** for the viewing angles we have the spectral functions for.

For every slice, a viewing angle will result in a different distance in the shower plane.

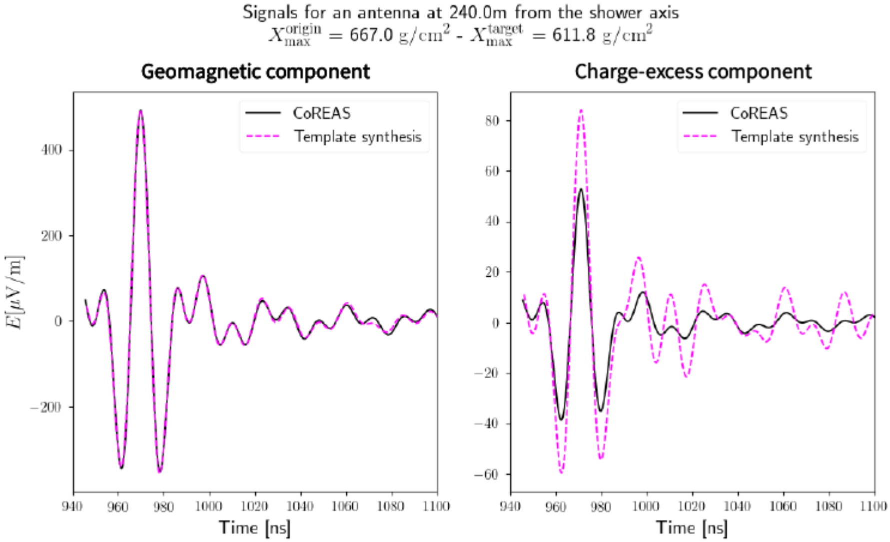
- Viewing angles are function of Cherenkov angle, which varies per slice.
- Distance to the showerplane also changes.

Solution: interpolate[a] to the required viewing angle per slice

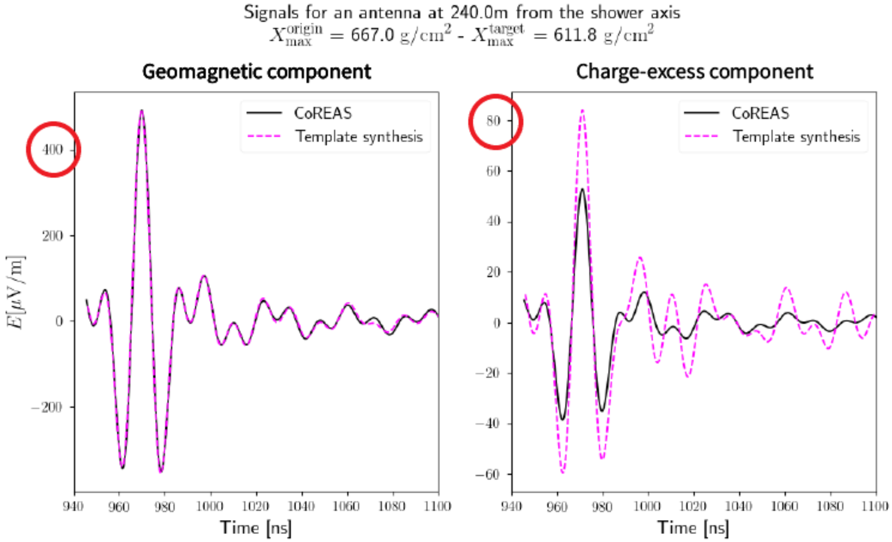
---

[a] A. Corstanje et al 2023 JINST 18 P09005

GEOMAGNETIC SIGNAL SYNTHESISES WELL, CHARGE-EXCESS COMPONENT NEEDS ADJUSTMENTS



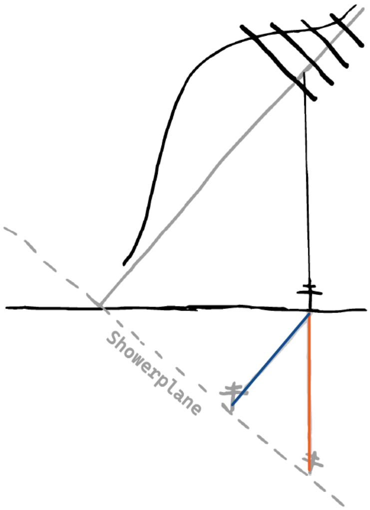
GEOMAGNETIC SIGNAL SYNTHESISES WELL, CHARGE-EXCESS COMPONENT NEEDS ADJUSTMENTS



OPEN QUESTION: SHOWERPLANE PROJECTION

How should one project to the showerplane?

- Along the shower axis?
- Or rather along line of sight?



TAKE-HOME MESSAGE

We found a set of **scaling relations** which relate the amplitude frequency spectra from slices of showers with a different zenith angle.

- Key components are the viewing angle, $\boldsymbol{\theta_V}$, and the distance of the slice to the shower maximum, $\boldsymbol{\Delta X}_{\text{max}}$.

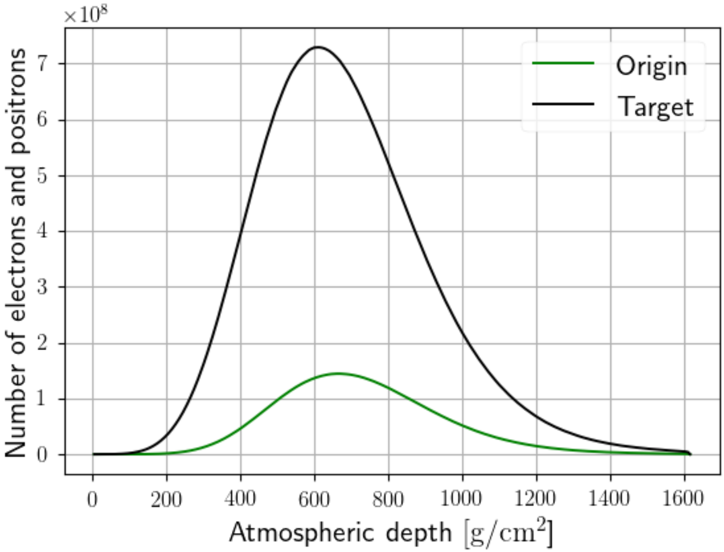
Combining these with a geometry based on viewing angle, we can

a) remove the dependency on the slice,
b) reduce the number of parameters to store and
c) generalise the spectral functions for all geometries.

$\Rightarrow$ **We are ready to apply template synthesis to cosmic ray air showers** from any arrival direction, which will allow us **to simulate the radio emission at macroscopic simulation speeds**, complementary to Radio Morphing.

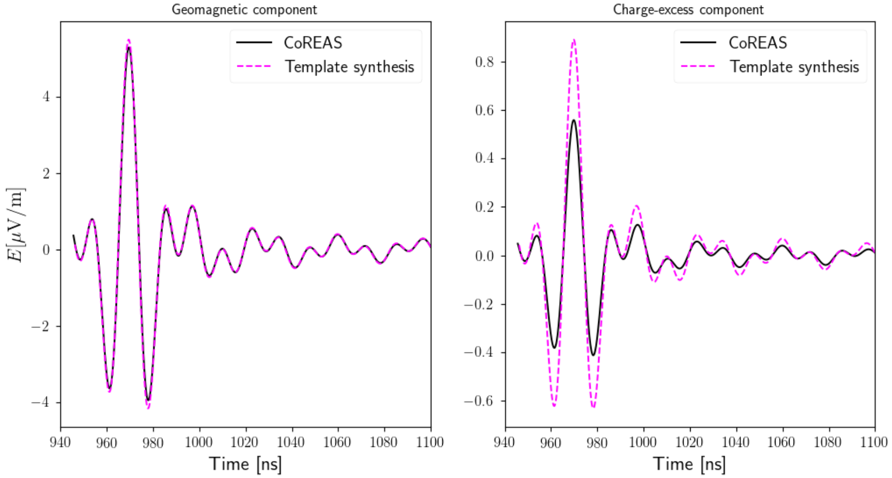
Thank you!

SYNTHESISED SLICES

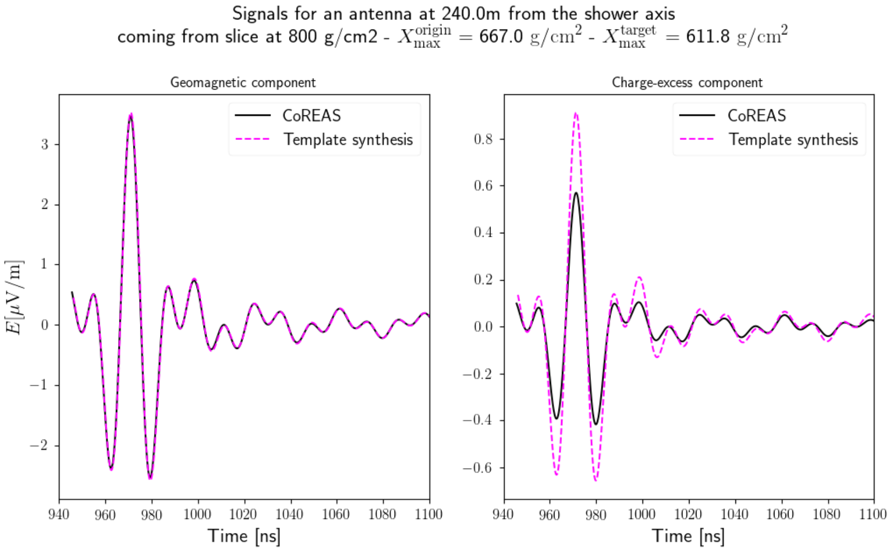


SYNTHESISED SLICES

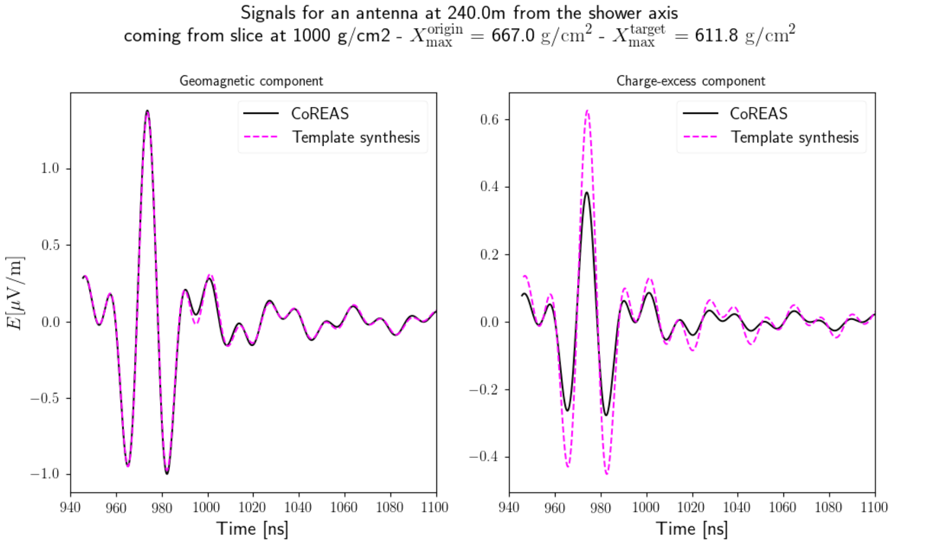
Signals for an antenna at 240.0m from the shower axis
coming from slice at 600 g/cm^2 - $X_{max}^{origin} = 667.0$ g/cm^2 - $X_{max}^{target} = 611.8$ g/cm^2



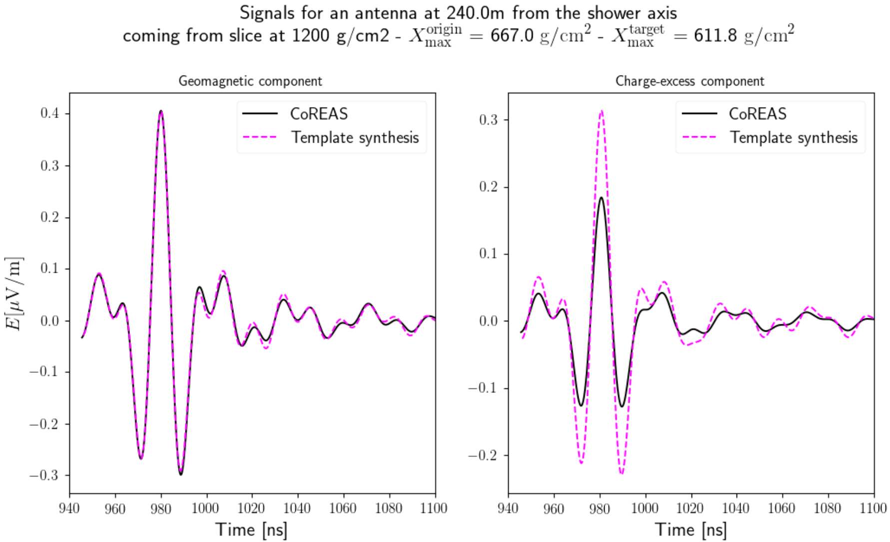
SYNTHESISED SLICES



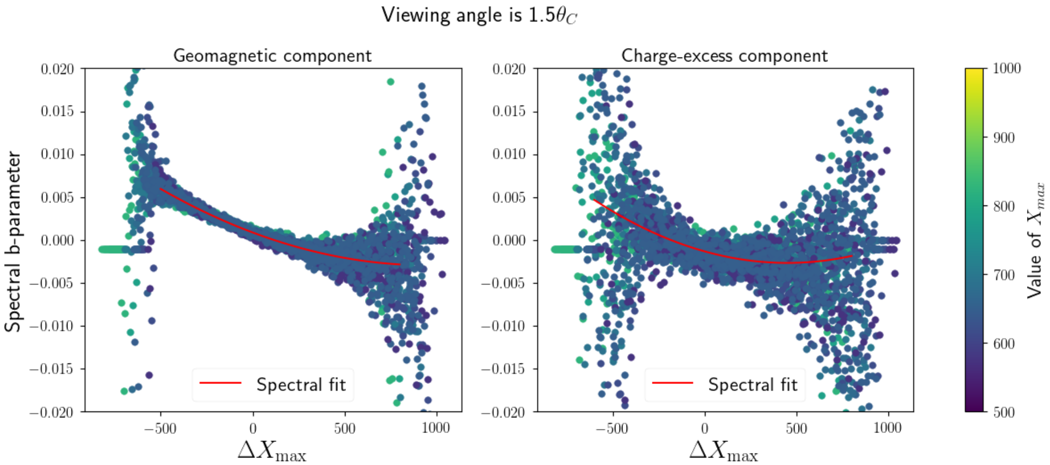
SYNTHESISED SLICES



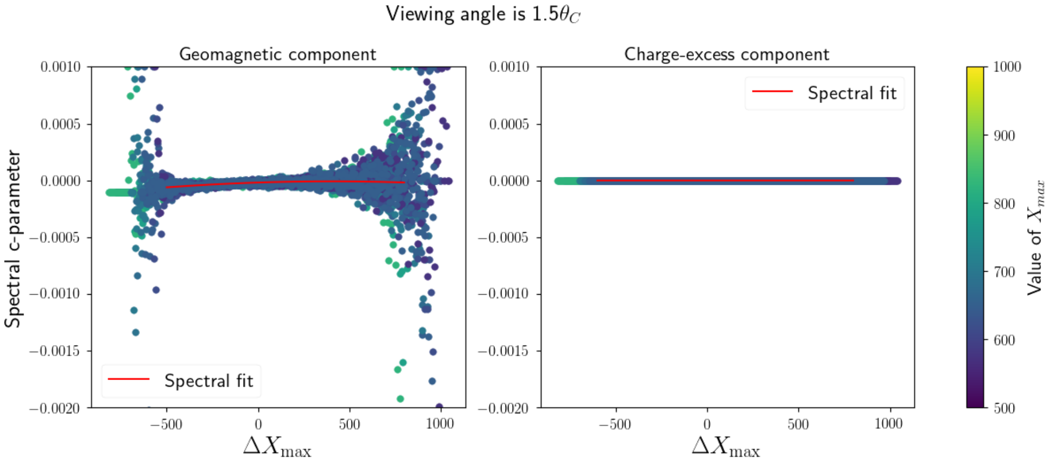
SYNTHESISED SLICES



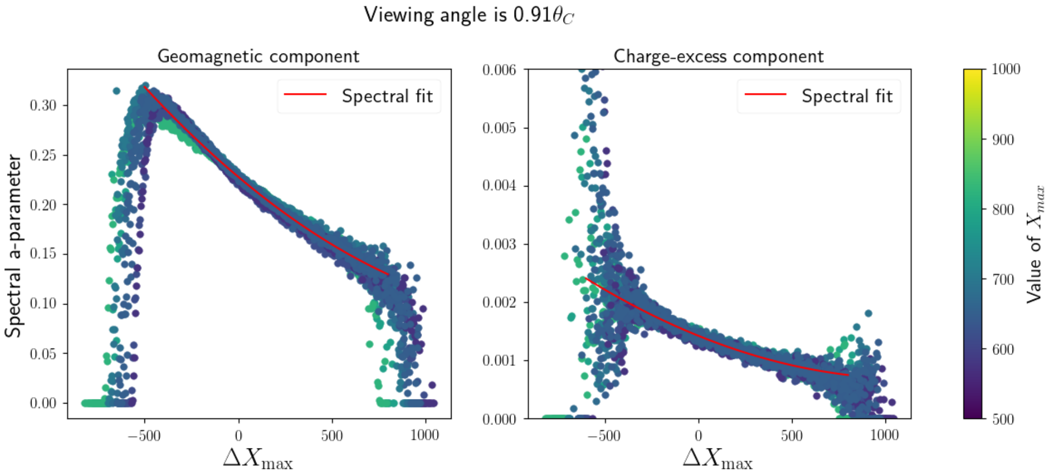
SPECTRAL FITS FOR OTHER PARAMETERS



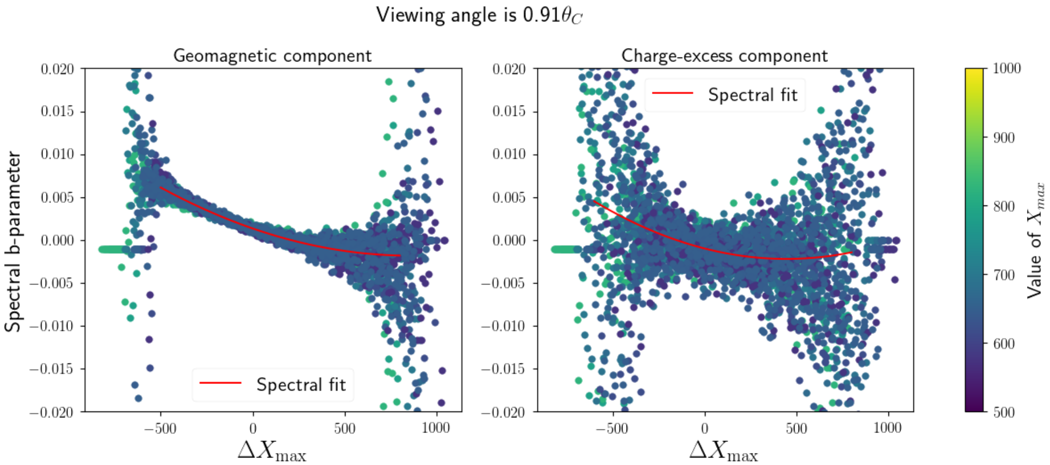
SPECTRAL FITS FOR OTHER PARAMETERS



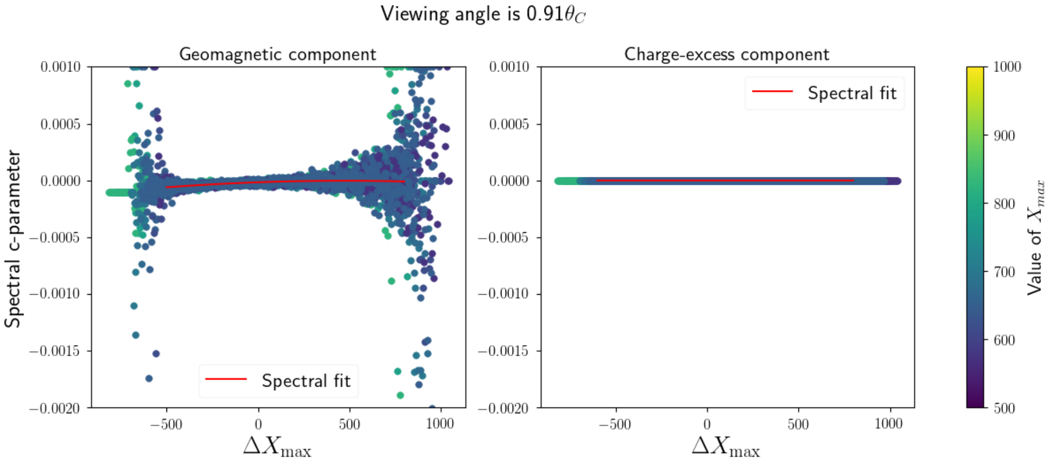
SPECTRAL FITS FOR OTHER VIEWING ANGLE



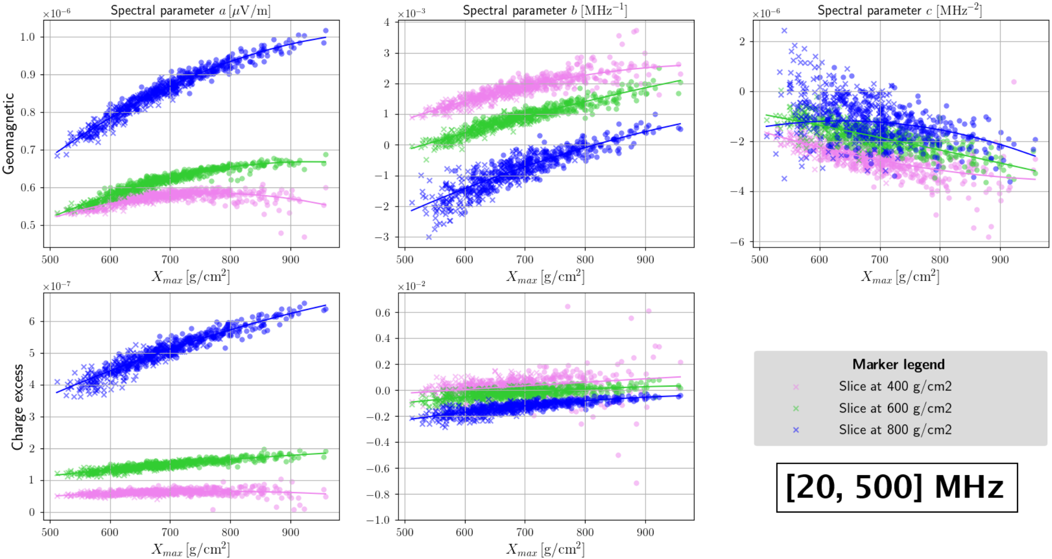
SPECTRAL FITS FOR OTHER VIEWING ANGLE



SPECTRAL FITS FOR OTHER VIEWING ANGLE

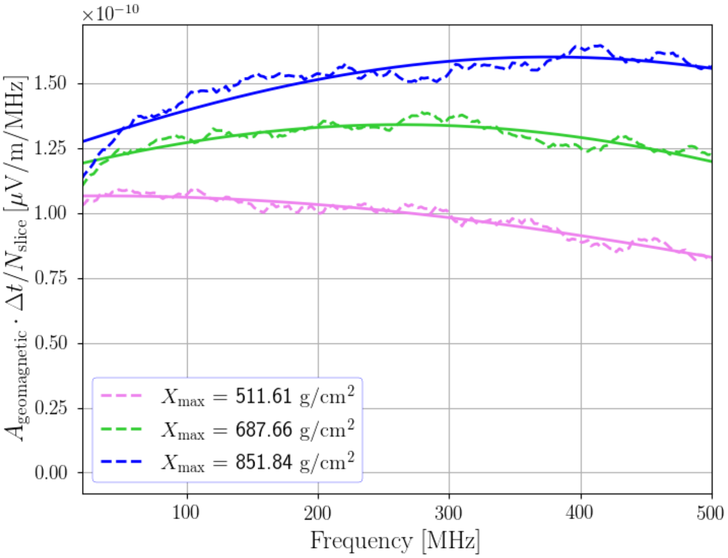


HIGHLIGHTS FROM THE PAPER



[20, 500] MHz

HIGHLIGHTS FROM THE PAPER



THE FINAL EQUATIONS FOR THE PARAMETRISED SPECTRA

$$\tilde{A}_{\mathrm{geo}}(f, \Delta X_{\mathrm{max}}) = \left(a_{\mathrm{geo}} \cdot \frac{N_{\mathrm{slice}} \cdot \sin(\alpha_{\mathrm{GEO}})}{d_{\mathrm{slice}} \cdot \rho_{\mathrm{slice}}} \right) \cdot \exp\left(b_{\mathrm{geo}} \cdot (f - f_0) + c_{\mathrm{geo}} \cdot (f - f_0)^2 \right)$$

$$\tilde{A}_{\mathrm{ce}}(f, \Delta X_{\mathrm{max}}) = \left(a_{\mathrm{ce}} \cdot \frac{N_{\mathrm{slice}} \cdot \sin(\theta_{\mathrm{Cherenkov}})}{d_{\mathrm{slice}}} \right) \cdot \exp\left(b_{\mathrm{ce}} \cdot (f - f_0) \right)$$