Producing realistic atmospheres for radio simulations of EAS using GDAS

AtmoHEAD2018

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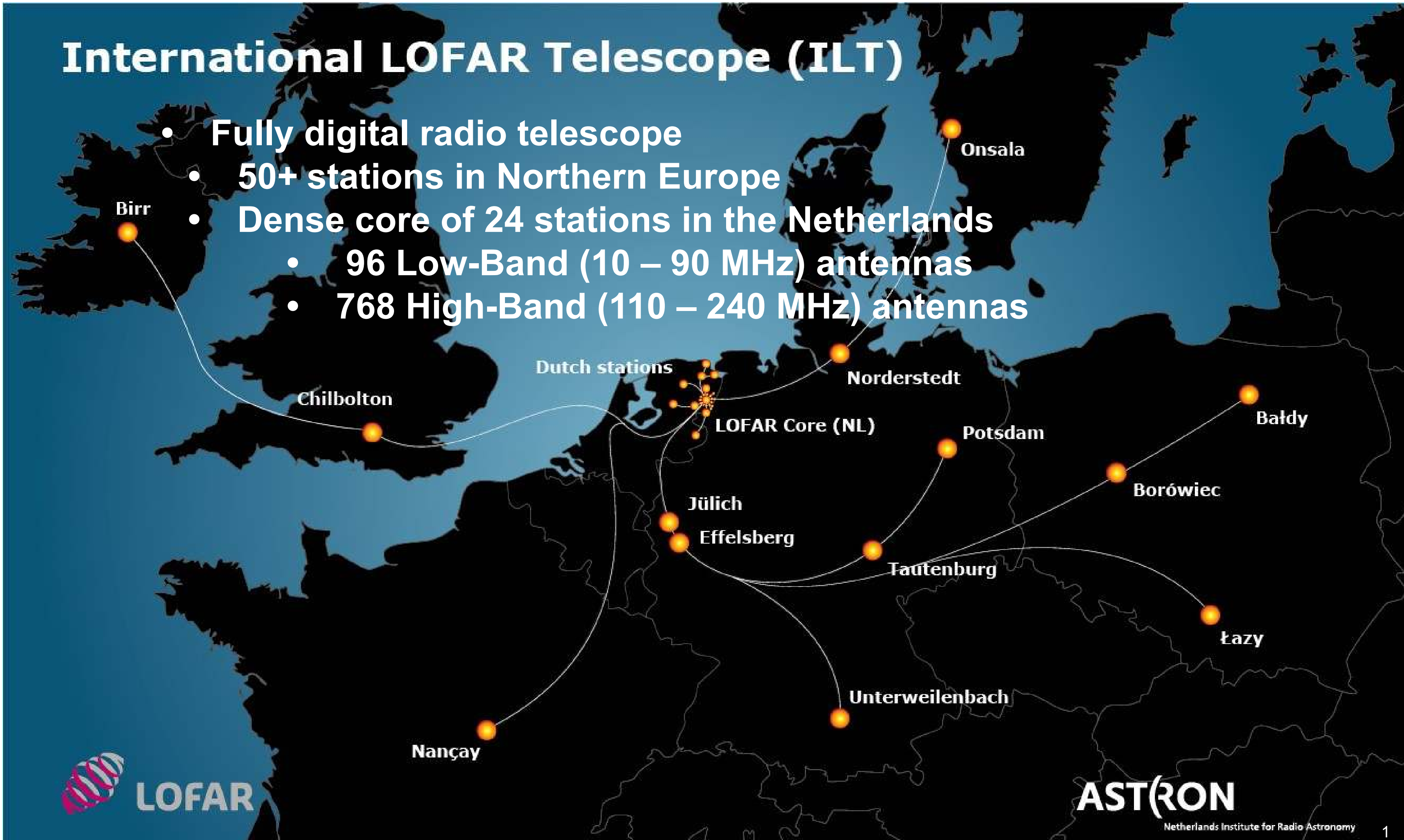
VUB

erc European Research Council

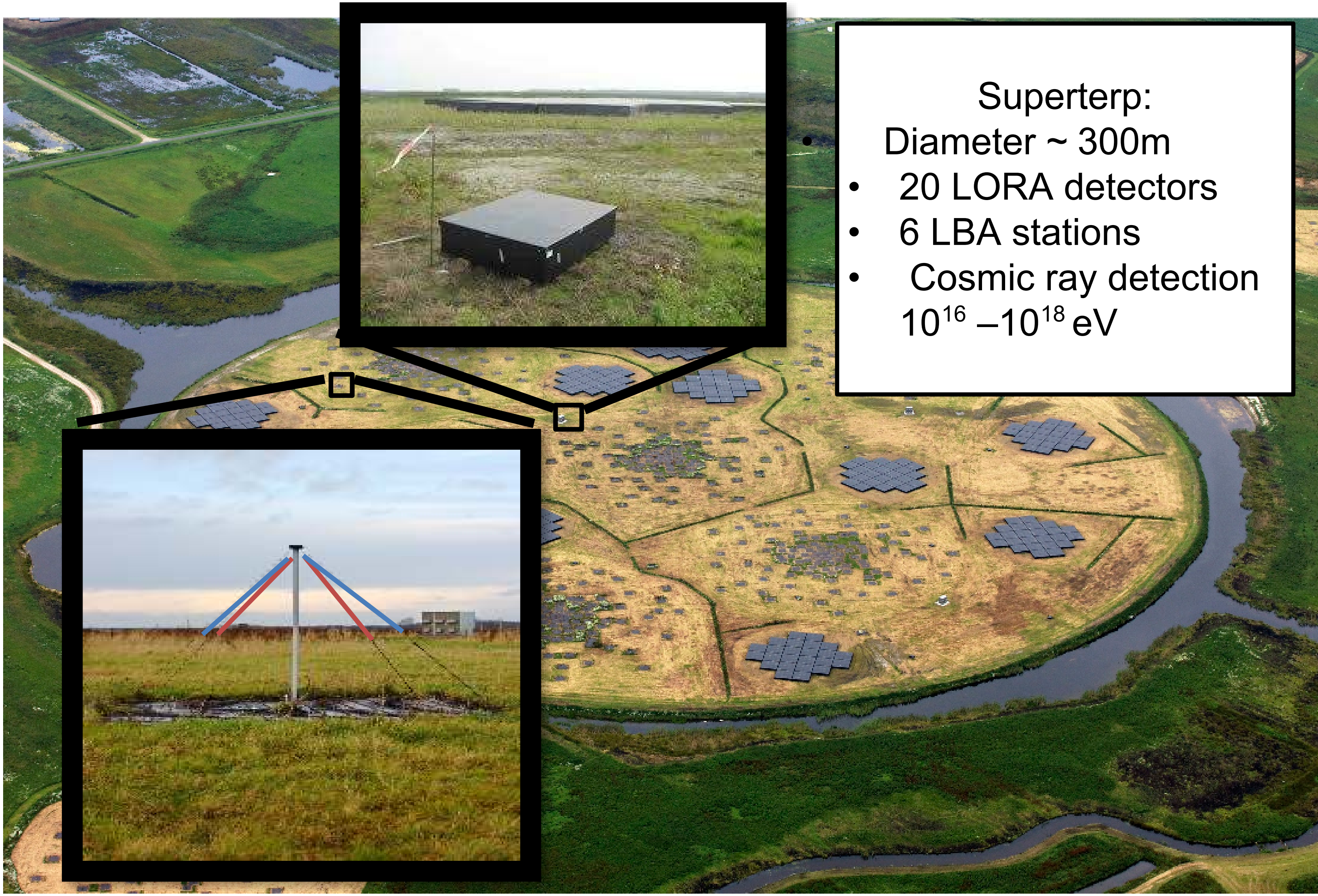
LOFAR

LOw Frequency ARay

- Fully digital radio telescope
  - 50+ stations in Northern Europe
  - Dense core of 24 stations in the Netherlands
    - 96 Low-Band (10 – 90 MHz) antennas
    - 768 High-Band (110 – 240 MHz) antennas



LOFAR Superterp



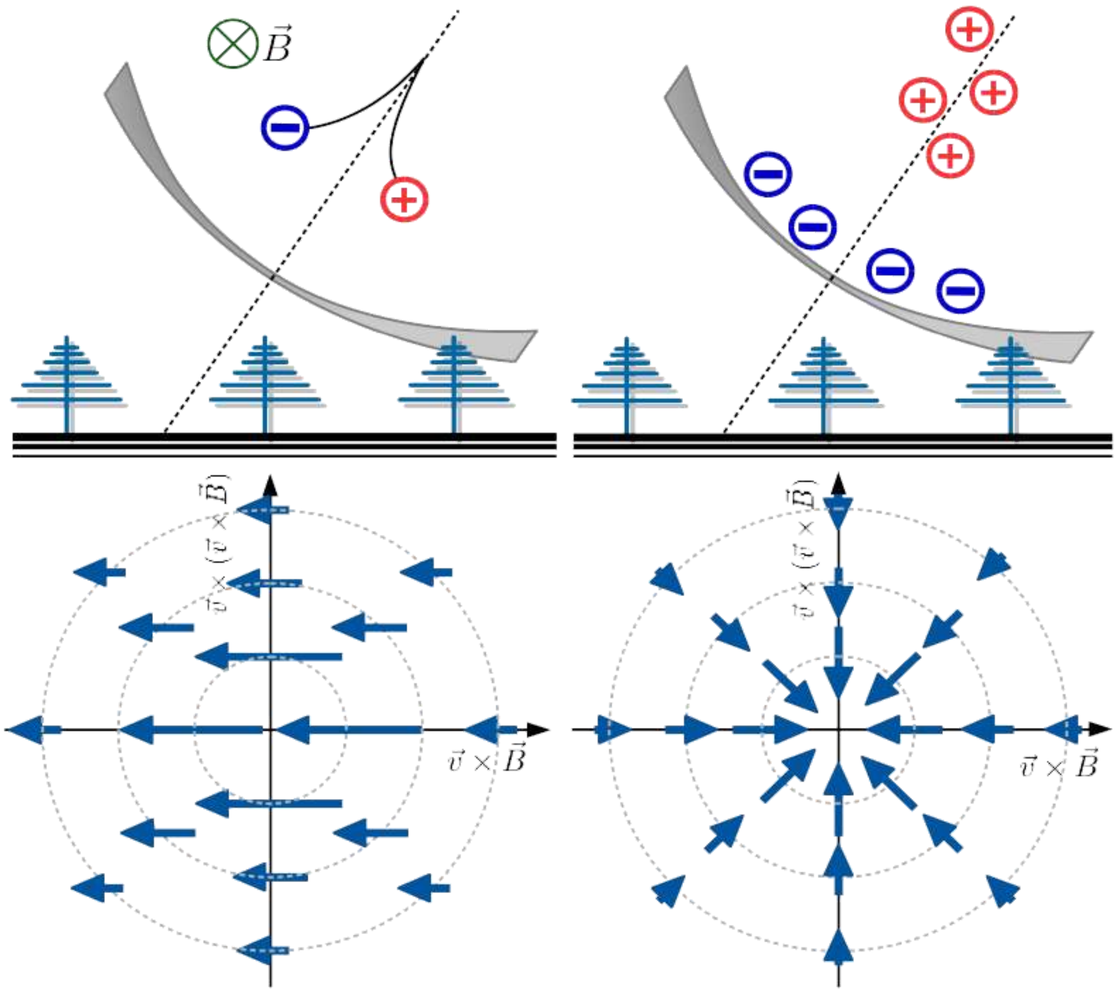
Superterp:

Diameter ~ 300m

- 20 LORA detectors
- 6 LBA stations
- Cosmic ray detection $10^{16} - 10^{18}$ eV

Radio emission from air showers

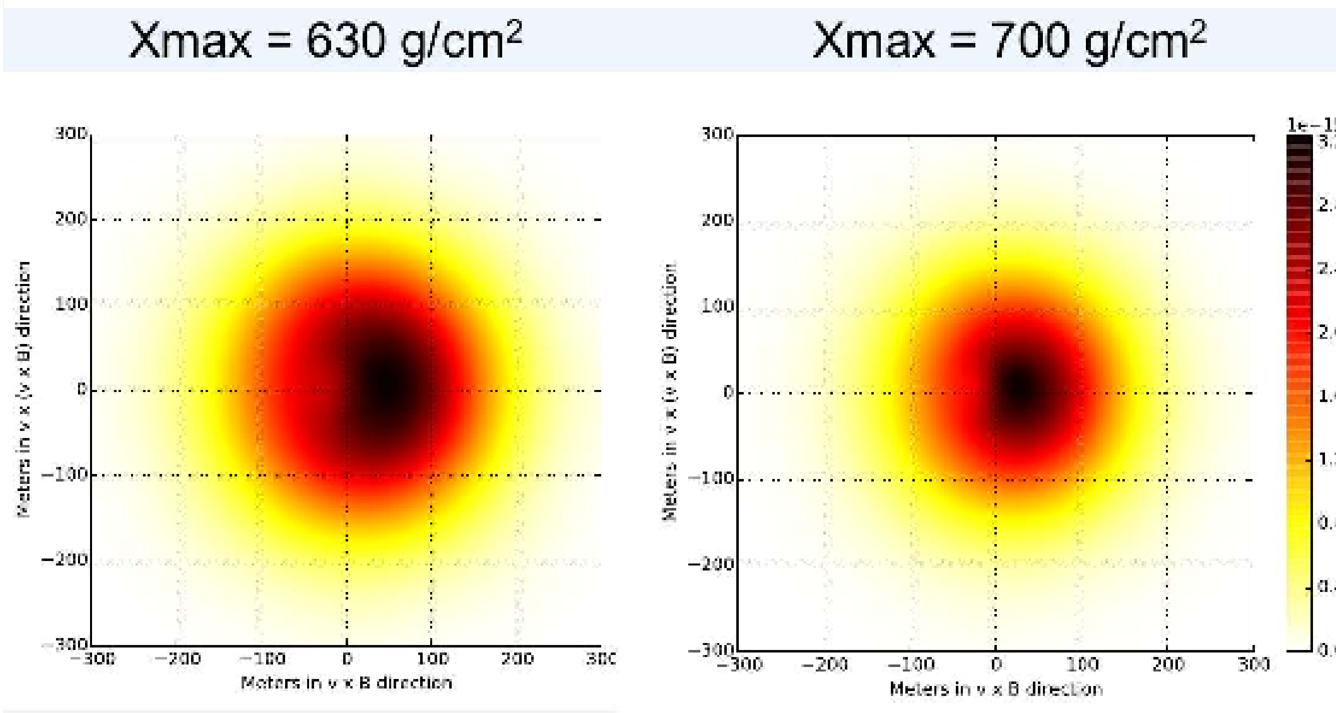
Geomagnetic **Charge excess**



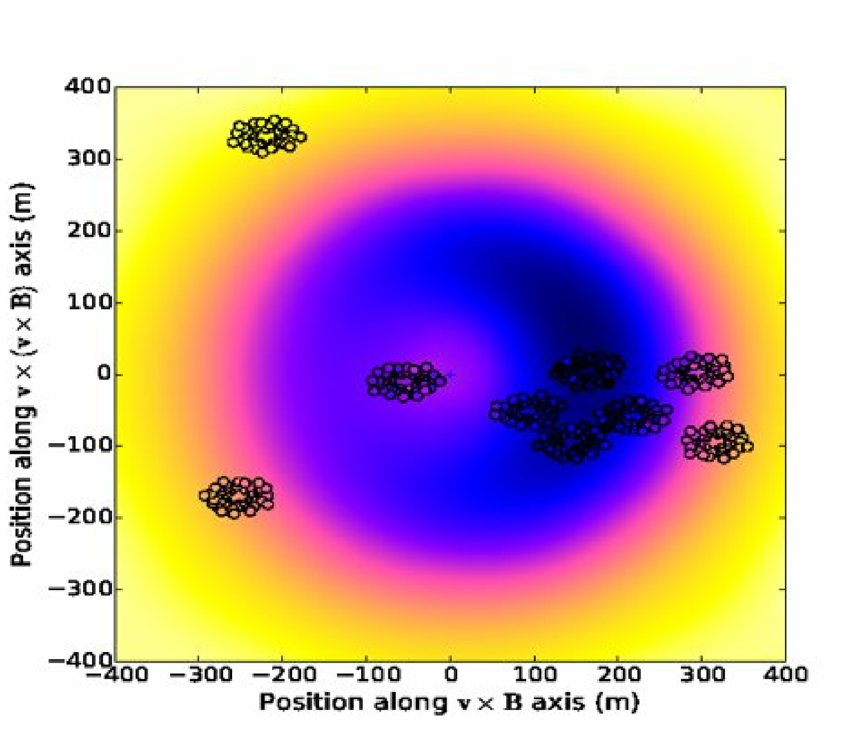
Combined effect results in asymmetry in radio profile

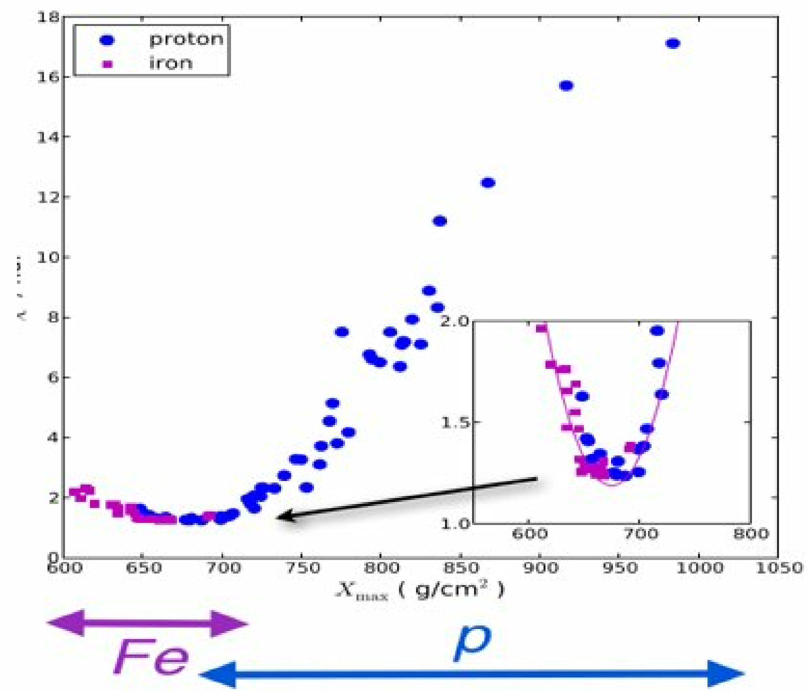
Radio footprint

Size depends on Xmax: deeper shower results in smaller footprint



Xmax reconstruction



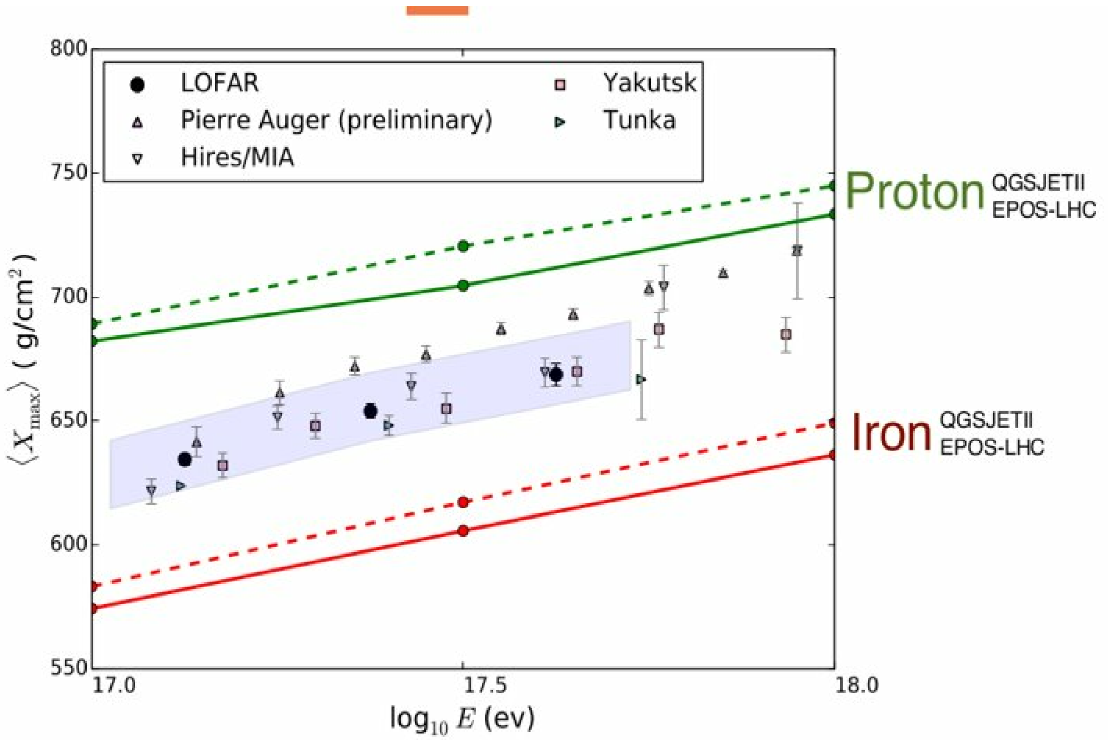


Measured antenna power fitted to a 2D simulated radio map

- Dedicated simulation set for each event.
- Minimum of fitted parabola →reconstructed Xmax

SB *et al.* PRD 90082003 (2014)

Systematics on Xmax



S.B et al Nature 513,70,2016

- Zenith angle dependence ~ 16 g/cm^2
- Hadronic interaction model~ 5 g/cm2
- **Atmospheric effects**

Effect of atmosphere on Xmax

- Monte Carlo simulation codes for air shower like CORSIKA/ CoREAS uses default US stdA or averaged profiles.
- The variation of refractive index in the atmosphere important for radio detection.
- Refractivity $N=(n-1)\,10^6$ depends on pressure, temperature and relative humidity in radio frequencies -

$$N = 77.6890\frac{p_d}{T} + 71.2952\frac{p_w}{T} + 375463\frac{p_w}{T^2}$$

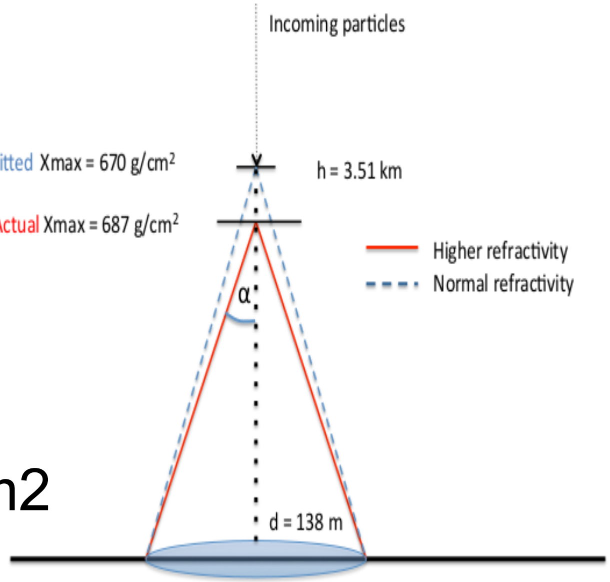
[after J.Rueger]

- Effect of humidity in N important in radio regime

Effect of refractive index on Radio Footprint

Toy Model

- Radio pulses compressed in time ~ Cherenkov like emission.
- Opening angle scales : **Cosα =1/βn**
- 10% higher N underestimates Xmax 17 g/cm2

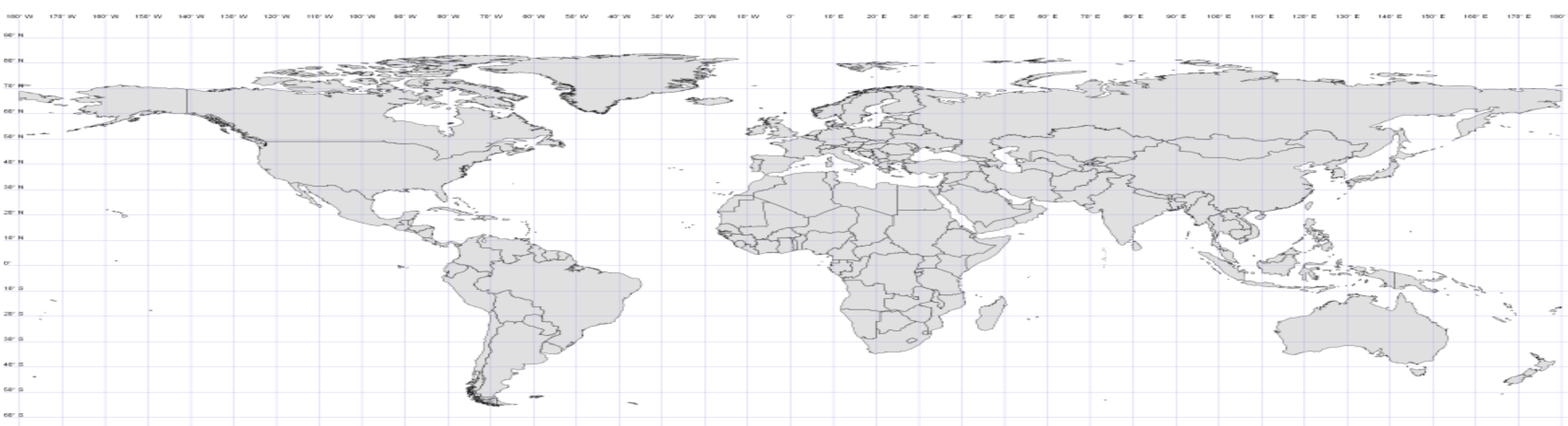


A.Corstanje et al
arXiv:1701.07338v1

Limitations: considers only local RI. Integrated RI important for propagation effects.

Towards realistic profile: GDAS

- Global Data Assimilation System:
  database of atmospheric data used for weather forecasting.
- 1°x1°, 3 hour grid.
- 23 constant pressure level data.
- Altitude profiles of temperature, pressure, humidity.
- Calculated the density and refractive index for use in
  the simulations.



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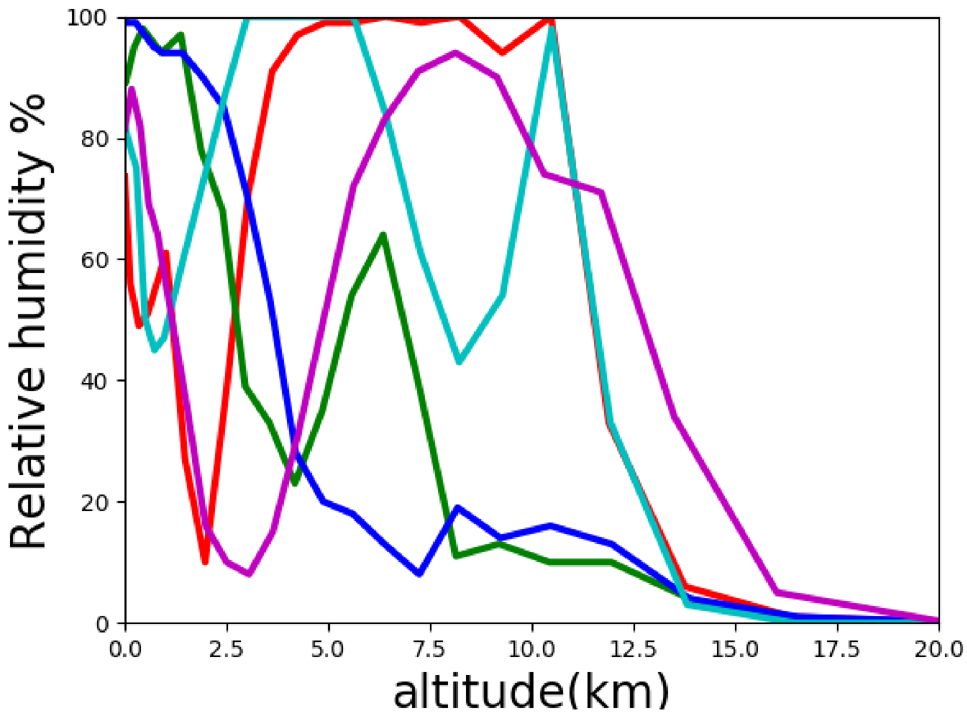
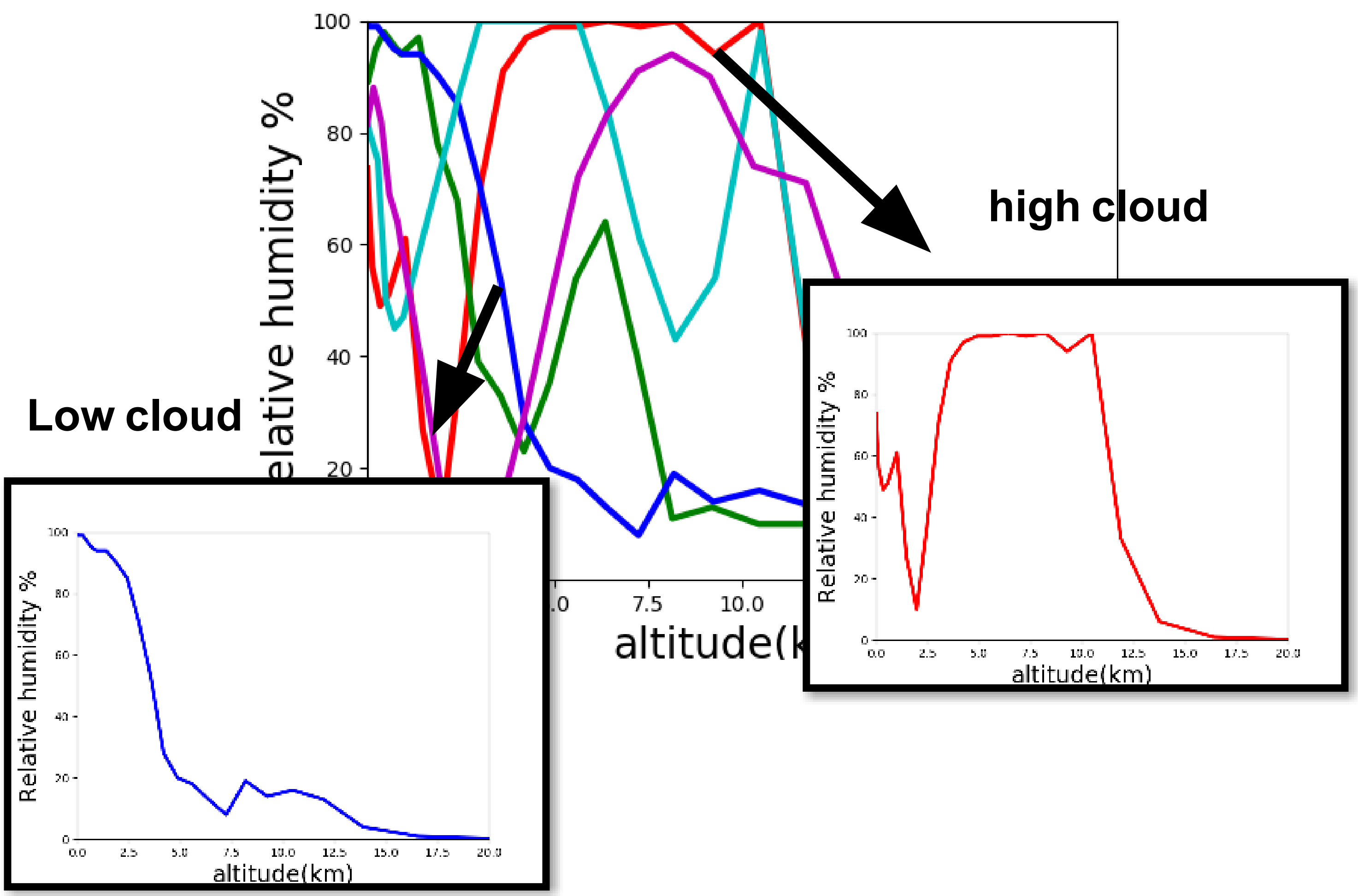
GDAS Atmospheric Profiles



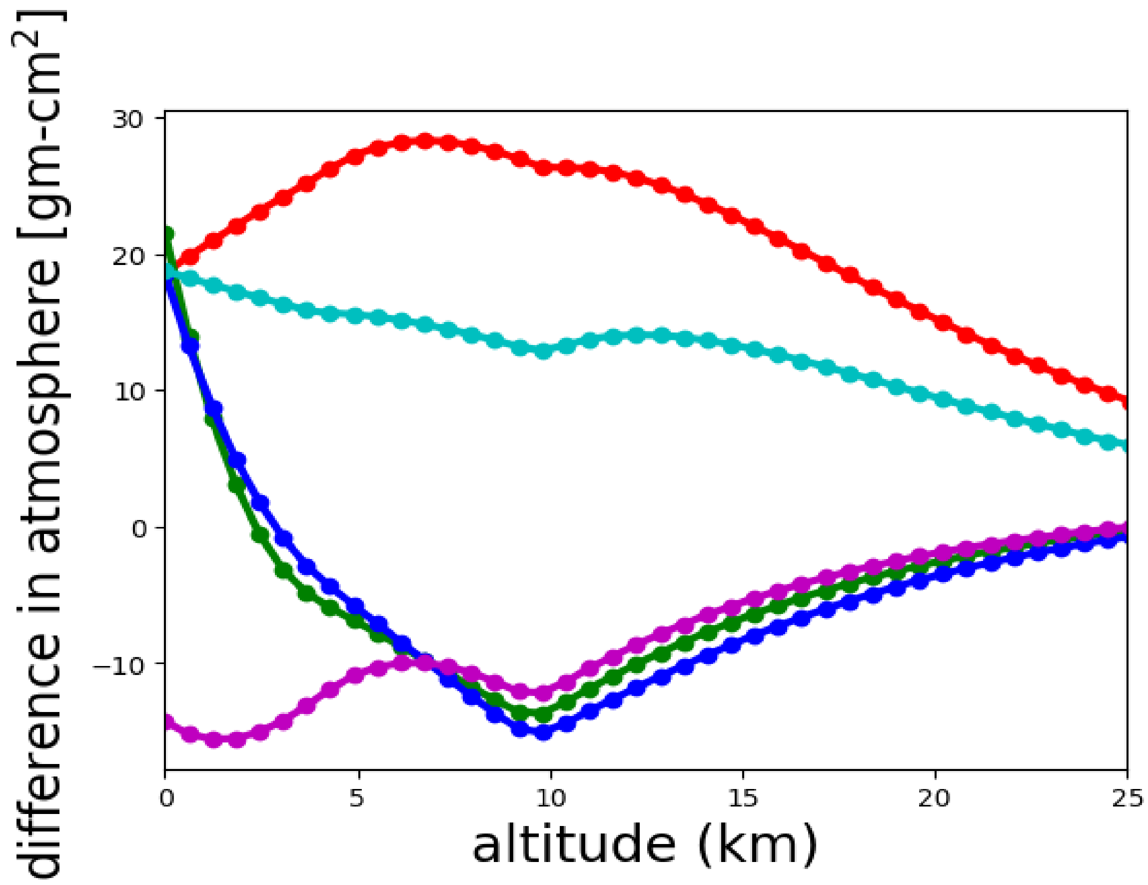
- Profile for 5 events.
- Huge variance at LOFAR site.

GDAS Atmospheric Profiles



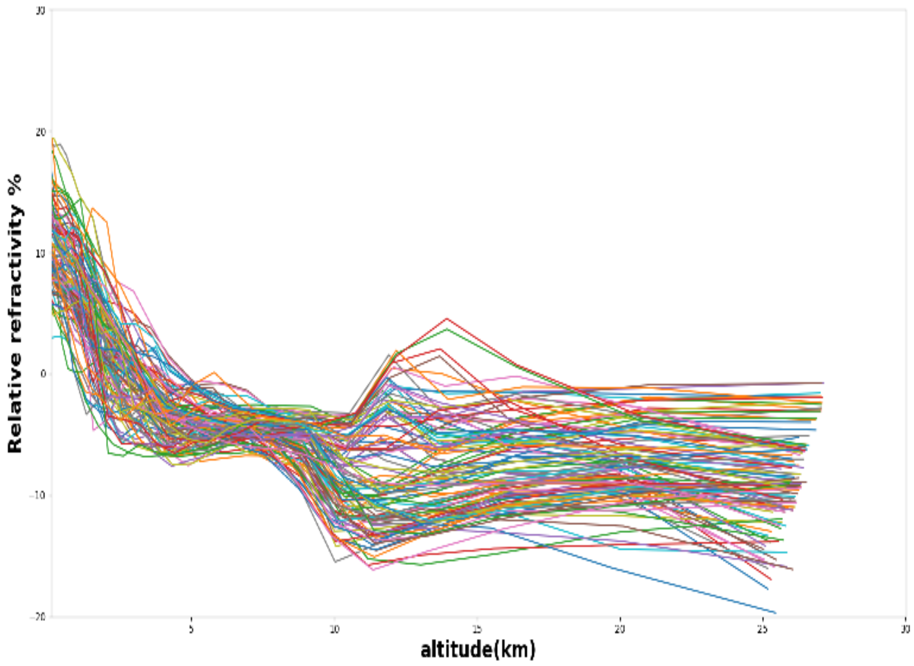
GDAS Profile: Atmosphere

GDAS- Us stdA atmosphere.



- Events with same ground pressure could see different atmosphere over height.
- Full atmospheric description over correction to ground pressure.

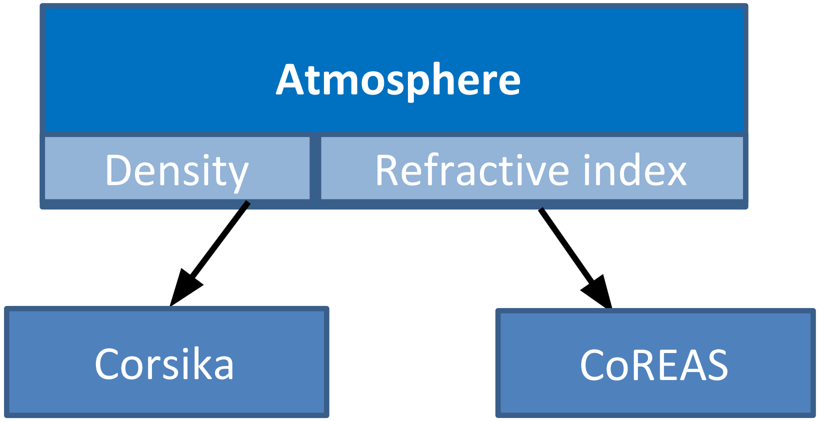
GDAS Profile: Refractivity



Relative refractivity:
$(N_{gdas} - N_{us})/N_{us}$

- profile for 100 different CR events recorded at LOFAR.
- 3-5 % variation at 5-8 km ~ region of shower maximum.
- Integrated relative refractive index ~ 7-10 % between the same region.

Implementation of GDAS to CORSIKA/CoREAS



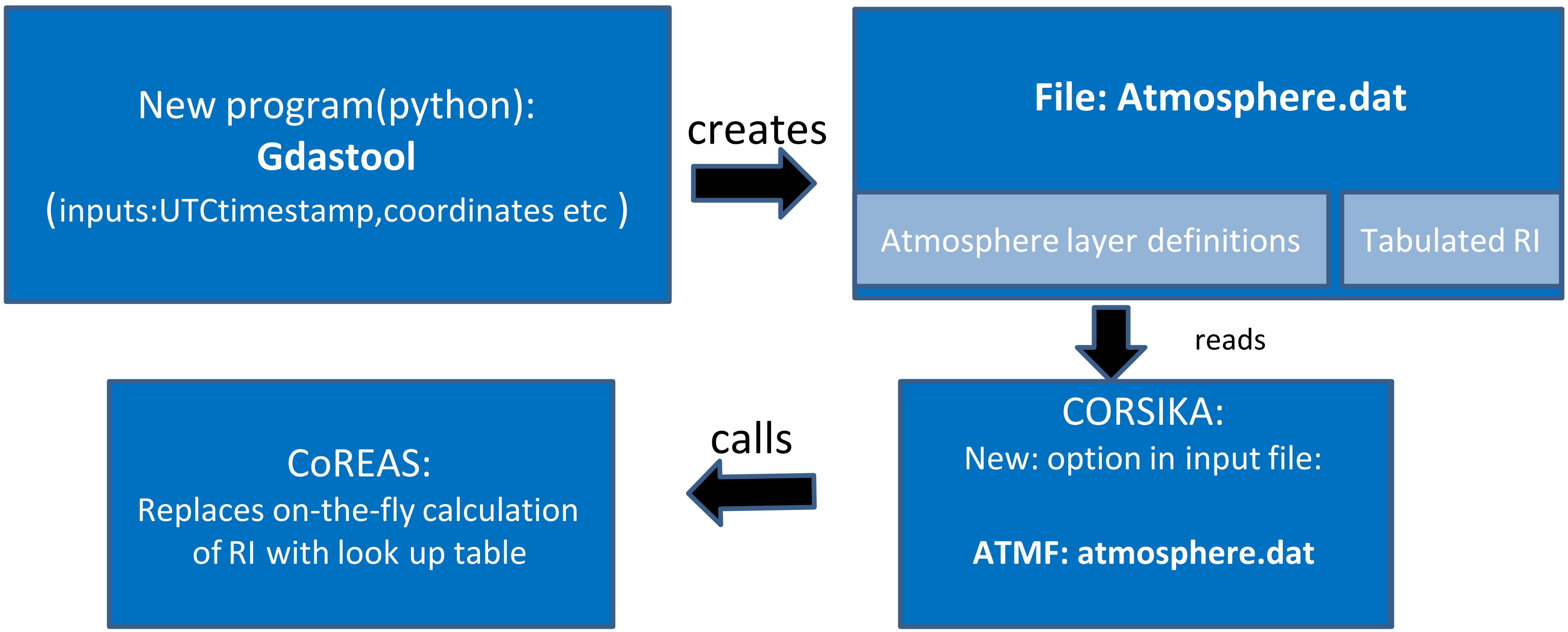
CORSIKA

- Fit layered atmosphere model to GDAS data.
- Feed fit parameters unto simulation.

Coreas

- Replace calculation of RI with look up table.
- Read RI data from file.

Implementation of GDAS to CORSIKA/CoREAS



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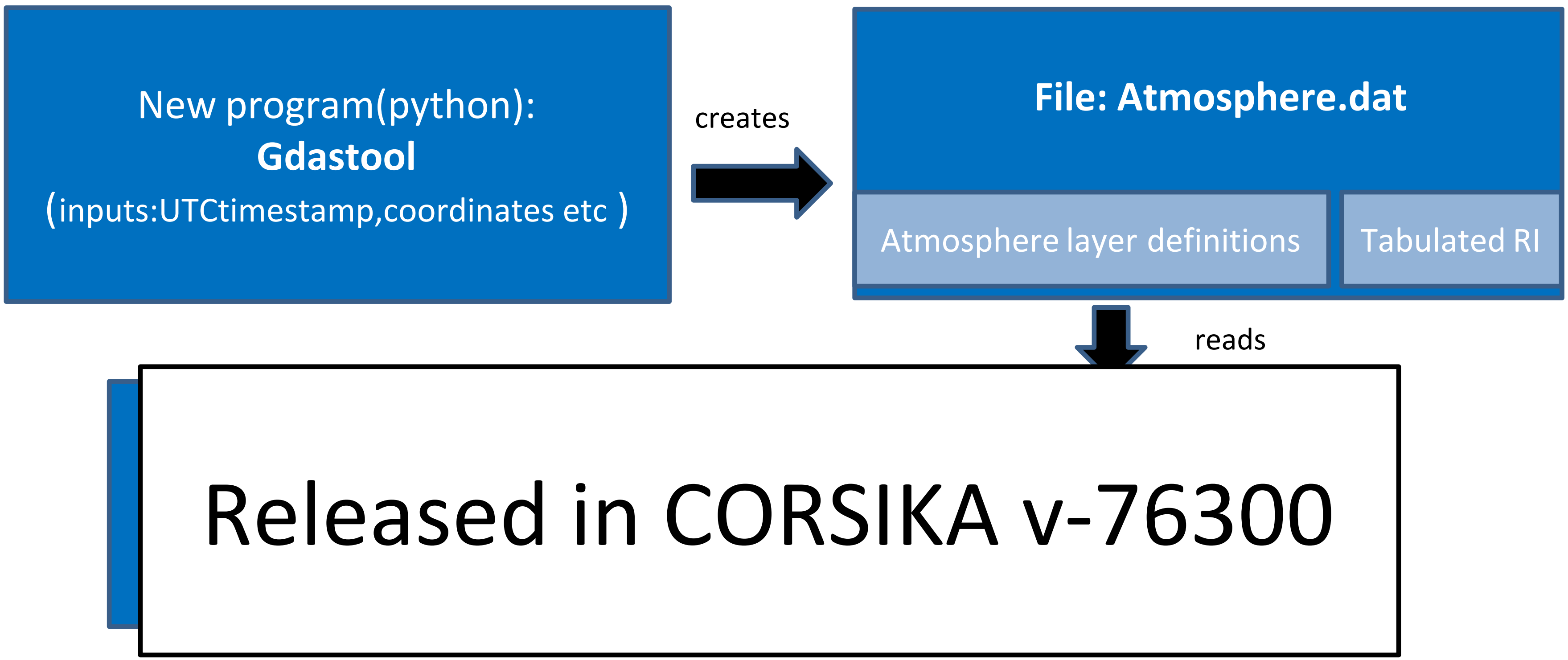

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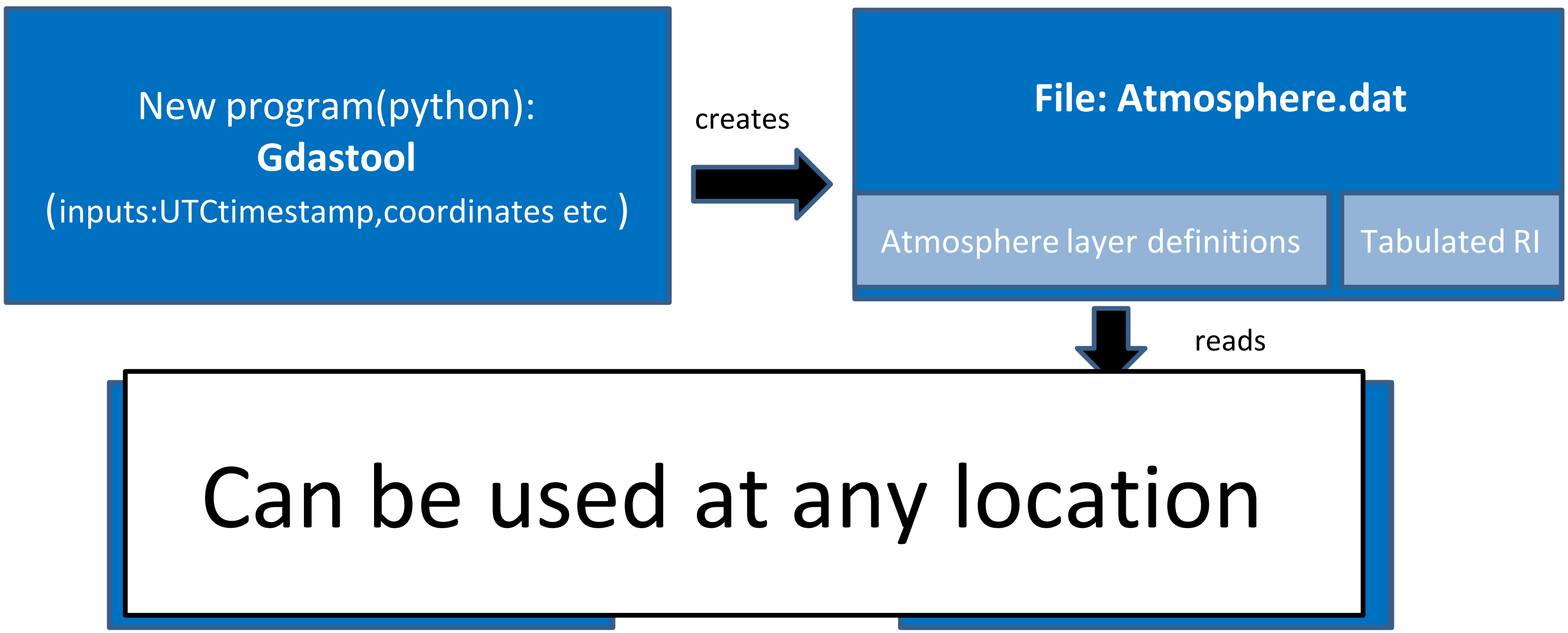


Implementation of GDAS to CORSIKA/CoREAS

New program(python):
Gdastool
(inputs:UTCtimestamp,coordinates etc)

creates

File: Atmosphere.dat

Atmosphere layer definitions

Tabulated RI

reads

Execution: gdastool [-h] [-t UTCTIMESTAMP] [-o OUTPUT] (--observatory {lofar,aera} | -c COORDINATES COORDINATES)

Fitting Procedure

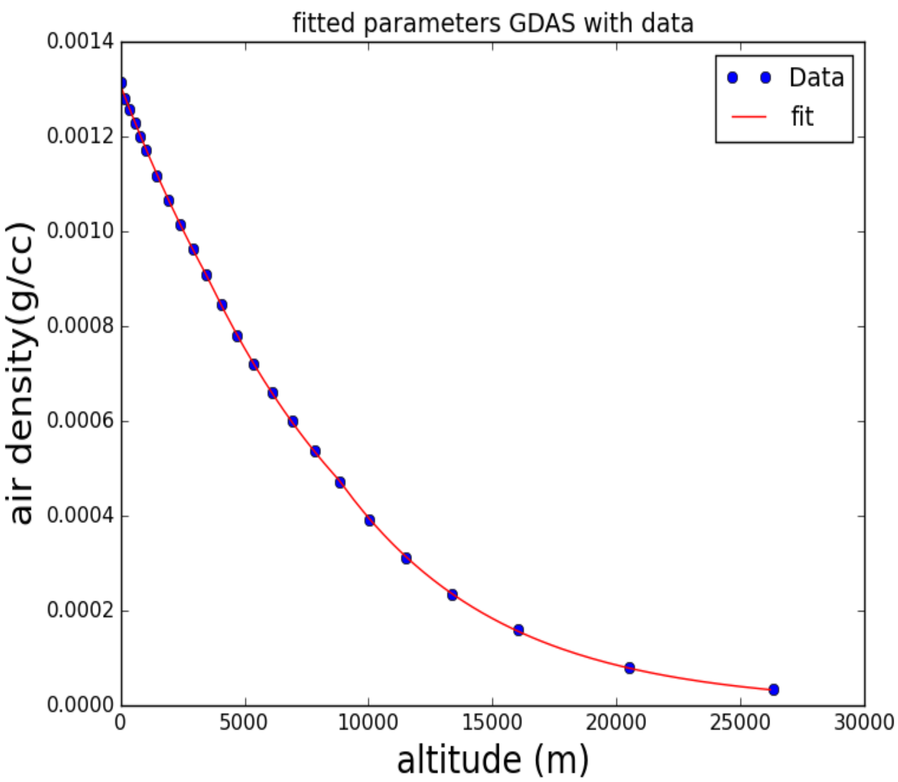
- 5 layer atmospheric model

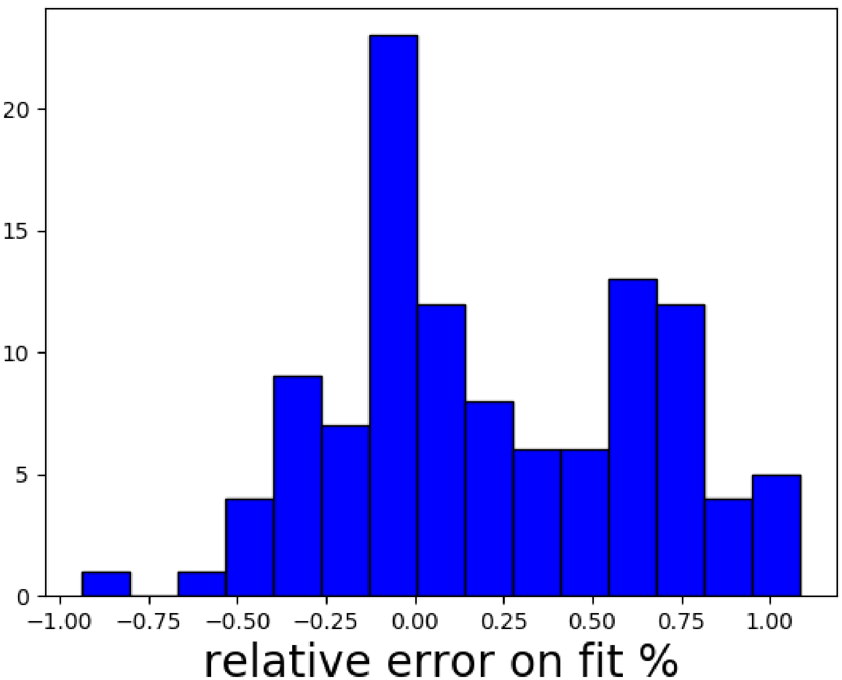
$$X(h) = a + b \exp(-h/c)$$

$$\rho(h) = b/c \exp(-h/c)$$

- Boundary condition: **X(h)**,**ρ(h)** should be continuous at layer boundary
- Choosing boundary layers-24 GDAS points divided into 3 layers
- Fit density profile for **b**,**c**
- Analytically solve for **a**

gdastool : Output Example





Relative error: Δdensity/ density data

Simulation with LOFAR data

- New simulation with LOFAR events.
- 123 for this analysis
- New GDAS atmosphere .
- Xmax reconstruction with radio only fitting
- Compare between event sets:

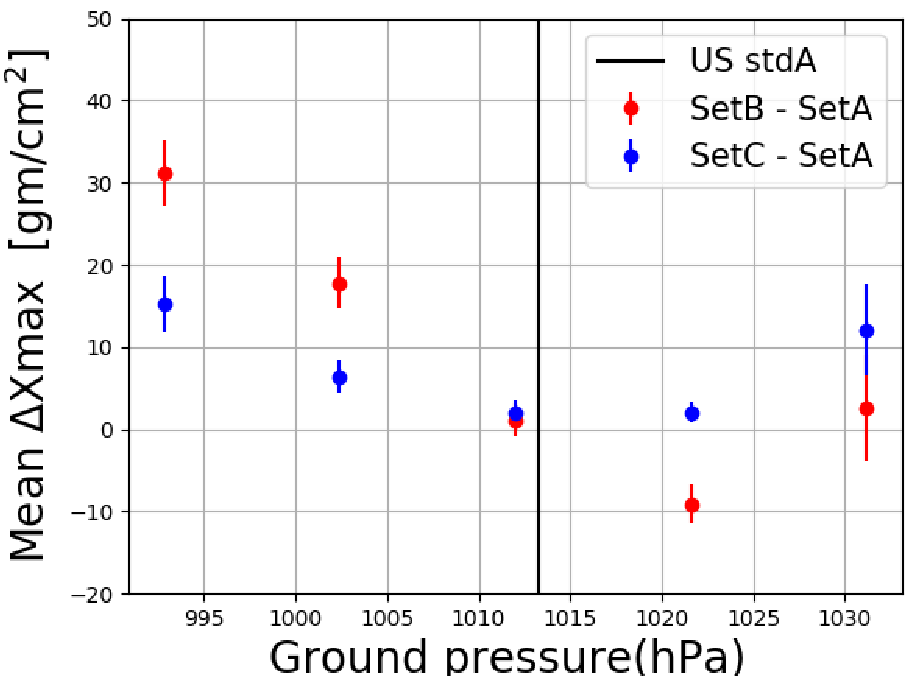
Set- A
GDAS atm + CORSIKA-new

Set- B
US stdA + CORSIKA-old

Set-C
US stdA +atm correction+ CORSIKA-old

CORSIKA-old: v 74385
CORSIKA-new: v 76300
Offset = g/cm2

Mean Xmax vs ground pressure



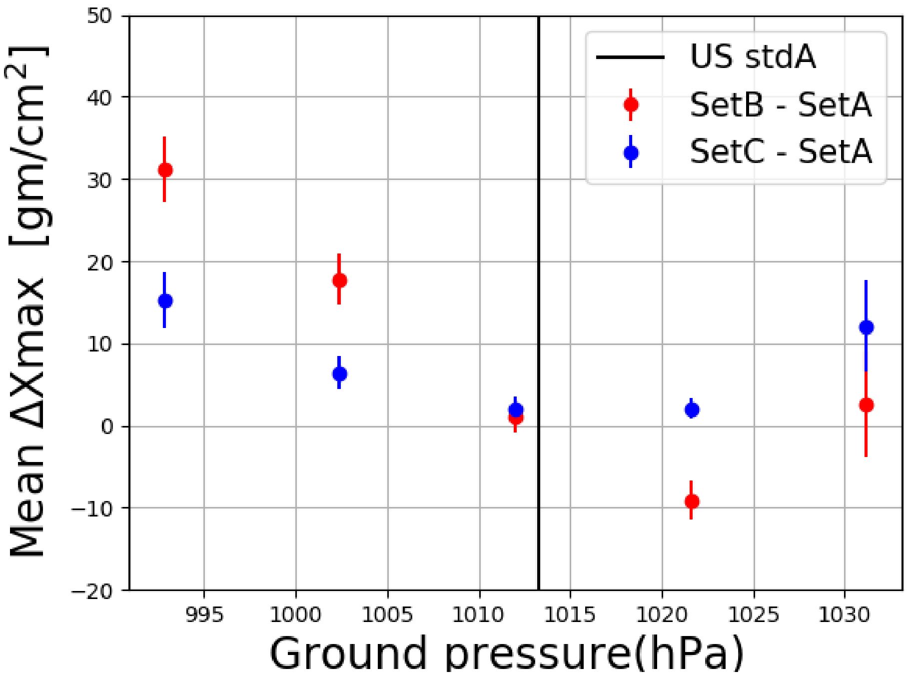
Difference in mean Xmax between

Set- A
GDAS atm + CORSIKA-new

Set- B
US stdA + CORSIKA-old

Set-C
US stdA +atm correction+ CORSIKA-old

Mean Xmax vs ground pressure



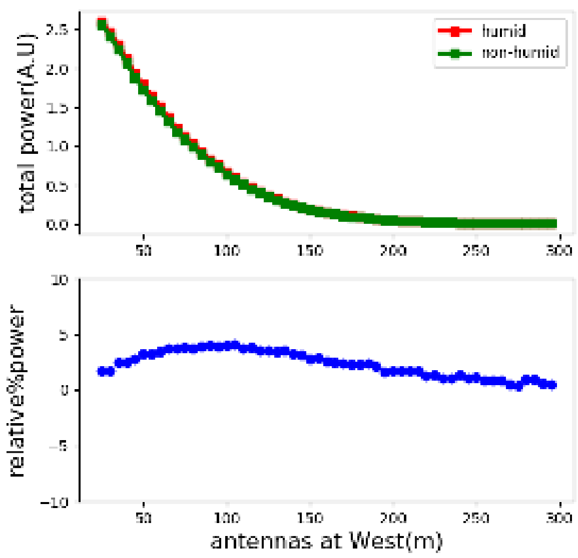
- Correction for pressure is important.
- Linear correction is not sufficient at lower pressure.
- full GDAS-based simulations required.

Effects of humidity on radio LDF

- 2 simulation sets: GDAS **N** profile with and without humidity
- Density profile same ⟶ same Xmax

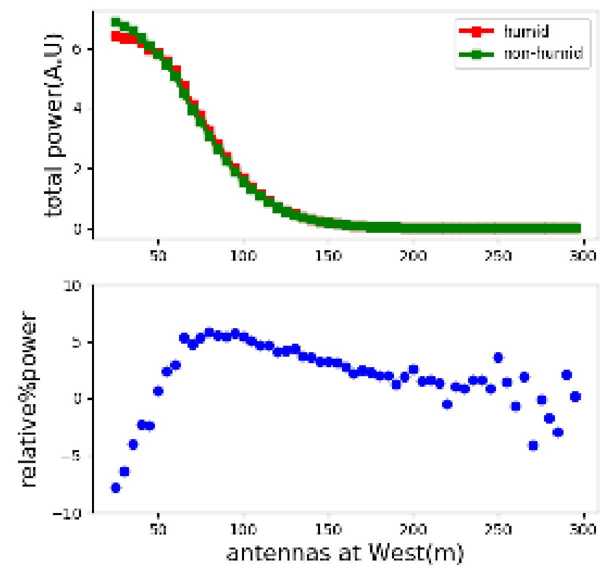
10^{17} eV proton shower,zenith 0, Xmax=604 g/cm^2

30-80 MHz(LOFAR)



- Too small effect to be visible in data

50-350MHz(SKA-low)



- Cherenkov like emissions more promin sensitive to **N**
- Higher effects ~ 10%

Conclusions

- GDAS atmosphere included in **CORSIKA-v76300**

- A Stand-alone script "**gdastool**" provides local real time atmospheric profiles (density + RI) for any location.
- LOFAR data simulated with GDAS atmosphere.

- Full GDAS atmospheric profile is required over Linear correction to US stdA.

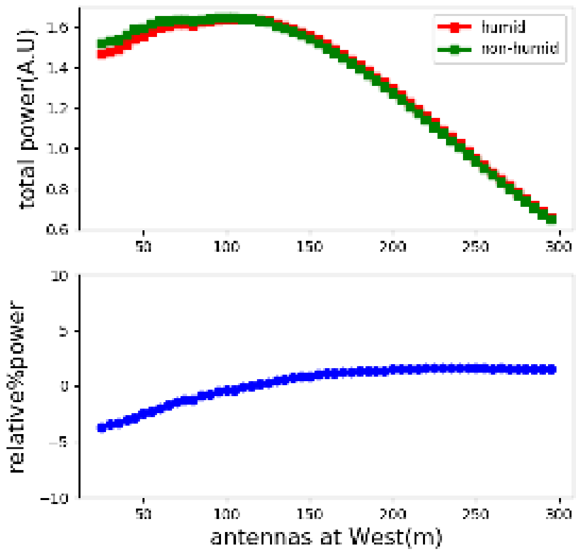
Back ups

Effects of humidity on radio LDF

- 2 simulation sets: GDAS **N** profile with and without humidity
- Density profile same ⟶ sameXmax

10^{17} eV proton shower,zenith 45, Xmax=593 g/cm^2

30-80 MHz(LOFAR)



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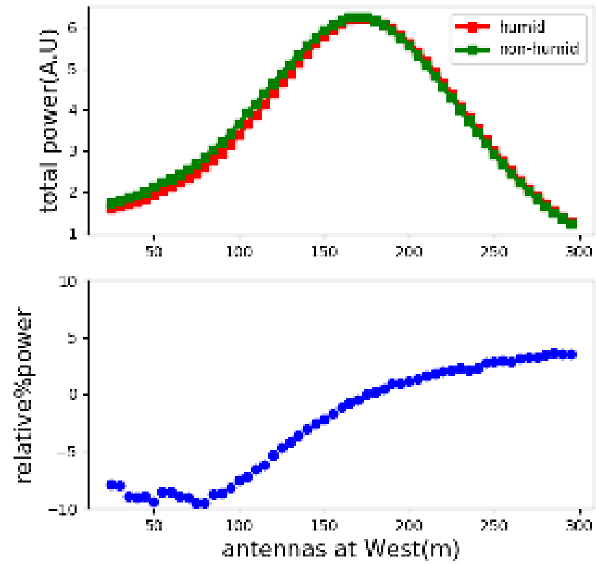

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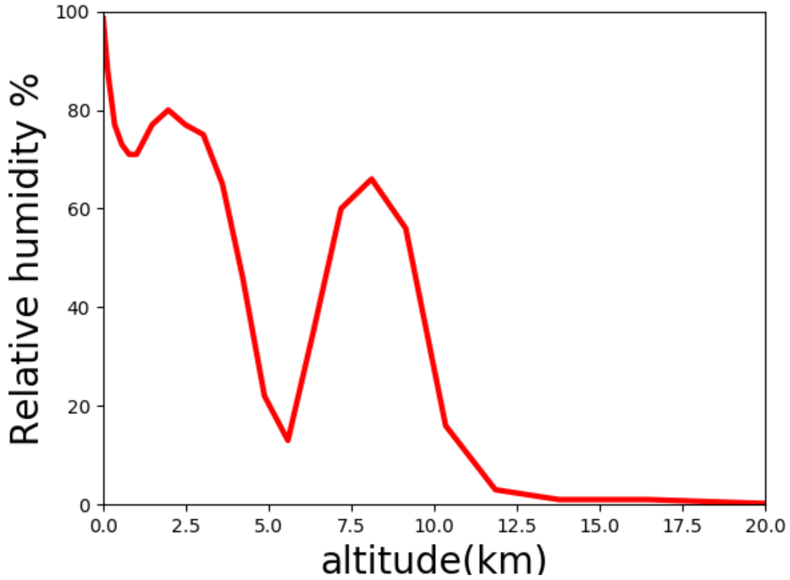
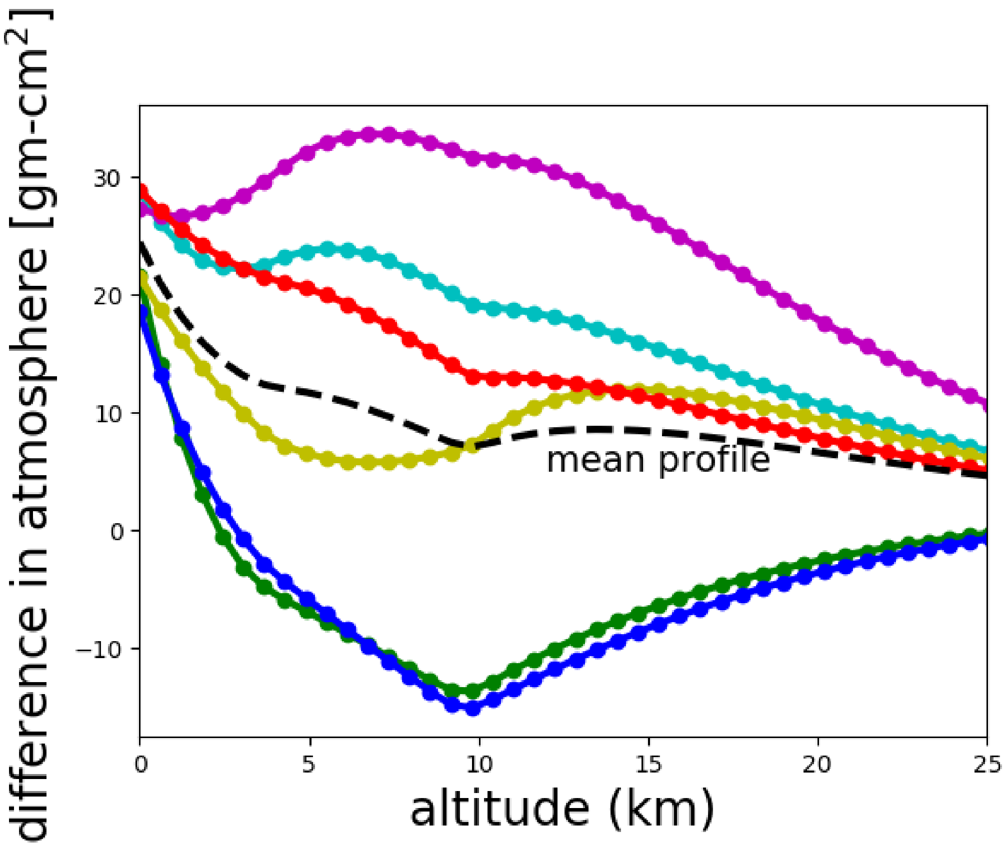
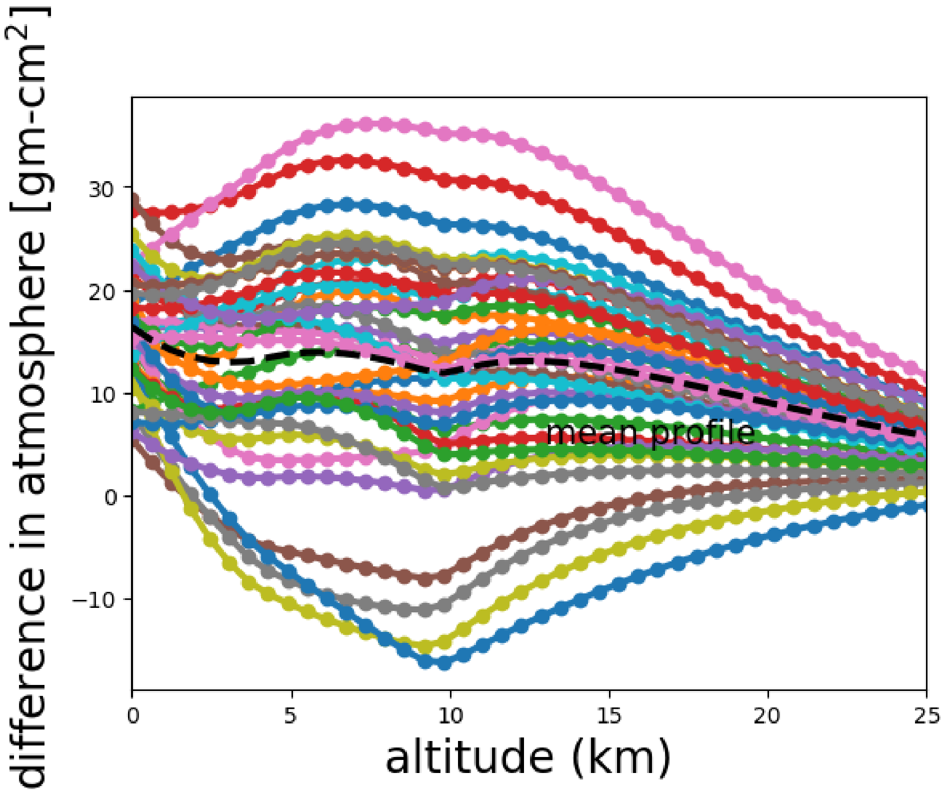
Humudity profile:event



Atmosphere profile: last Pressure bin(high P)



Atmosphere profile: 2nd last Pressure bin



Bias Test

Set	Mean Xmax Humidity=low	Mean Xmax Humidity=high
New	661.8	659.9
Old corrected old	666.3 663.4	663.8 665.3

Set	Zenith=low	Zenith=high
New	655.6	666.6
Old corrected old	659.6 659.5	670.5 669.2

Humidity Effects: From MC studies

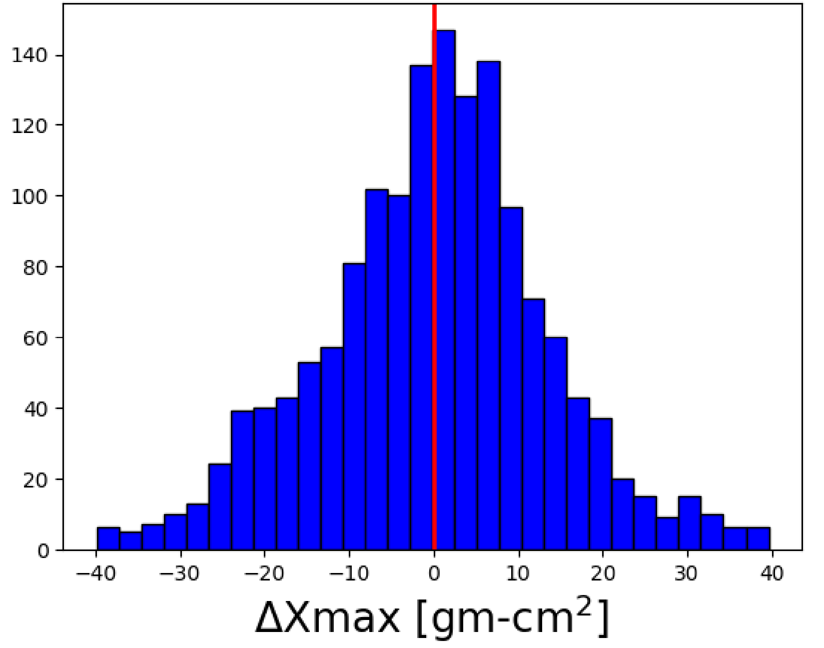
Set1

- New CORSIKA/CoREAS
- No humidity

Set2

- New CORSIKA/CoREAS
- With humidity

- Take one shower from **Set2** as "fake data"
- Fit showers from **Set1** to it.
- Difference $Xmax_{reco} - Xmax_{real}$: humidity effect.
- 50 event sets; each ~ 50-100 simulations.



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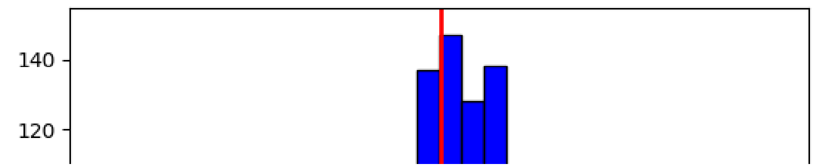

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- no visible effect of humidity
- Further investigation