Producing realistic atmospheres for radio simulations of EAS using GDAS

AtmoHEAD2018

LOw Frequency ARay

International LOFAR Telescope (ILT)

- 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

\[
\begin{align*}
X_{\text{max}} &= 630 \text{ g/cm}^2 \\
X_{\text{max}} &= 700 \text{ g/cm}^2
\end{align*}
\]
Xmax reconstruction

Measured antenna power fitted to a 2D simulated radio map

- Dedicated simulation set for each event.
- Minimum of fitted parabola $\rightarrow$ reconstructed $X_{\text{max}}$

SB et al. PRD 90082003 (2014)
Systematics on Xmax

- Zenith angle dependence
  \( \sim 16 \text{ g/cm}^2 \)
- Hadronic interaction model
  \( \sim 5 \text{ g/cm}^2 \)
- Atmospheric effects

S.B et al Nature 513,70,2016
Effect of atmosphere on $X_{\text{max}}$

- 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 $N = (n-1) \times 10^6$ 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: $\cos \alpha = 1/\beta n$
- 10% higher N underestimates $X_{\text{max}}$ 17 g/cm$^2$

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

A. Corstanje et al
arXiv:1701.07338v1
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.
Towards realistic profile: GDAS

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GDAS Atmospheric Profiles

- Profile for 5 events.
- Huge variance at LOFAR site.
GDAS Atmospheric Profiles

Relative humidity vs altitude

- High cloud
- Low cloud
Events with same ground pressure could see different atmosphere over height.

Full atmospheric description over correction to ground pressure.
GDAS Profile: Refractivity

Relative refractivity:
\[
\frac{(N_{\text{gdas}} - N_{\text{us}})}{N_{\text{us}}}
\]

- 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

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

CoREAS:
Replaces on-the-fly calculation of RI with look up table

File: Atmosphere.dat
Atmosphere layer definitions
Tabulated RI

CORSIKA:
New: option in input file:
ATMF: atmosphere.dat
Implementation of GDAS to CORSIKA/CoREAS

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

- CORSIKA:
  - New: option in input file: ATMF: atmosphere.dat

- CoREAS:
  - Replaces on-the-fly calculation of RI with look up table

Released in CORSIKA v-76300

File: Atmosphere.dat
- Atmosphere layer definitions
- Tabulated RI

creates
reads
Implementation of GDAS to CORSIKA/CoREAS

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

File: Atmosphere.dat
- Atmosphere layer definitions
- Tabulated RI

Can be used at any location
Implementation of GDAS to CORSIKA/CoREAS

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

File: Atmosphere.dat
- Atmosphere layer definitions
- Tabulated RI

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

• 5 layer atmospheric model
  \[ X(h) = a + b \exp(-h/c) \]
  \[ \rho(h) = \frac{b}{c} \exp(-h/c) \]
• Boundary condition: \( X(h), \rho(h) \) 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: $\Delta \text{density/density data}$
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$^2$

- Too small effect to be visible in data
- Cherenkov like emissions more prominent; 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 $\Rightarrow$ same Xmax

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

30-80 MHz (LOFAR)

- Too small effect to be visible in data

50-350 MHz (SKA-low)

- Cherenkov like emissions more prominent; sensitive to N
- Higher effects $\sim 10\%$
Humidity profile: event
Atmosphere profile: last Pressure bin (high P)
Atmosphere profile: 2nd last Pressure bin
## Bias Test

<table>
<thead>
<tr>
<th>Set</th>
<th>Mean Xmax Humidity=low</th>
<th>Mean Xmax Humidity=high</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New</strong></td>
<td>661.8</td>
<td>659.9</td>
</tr>
<tr>
<td><strong>Old corrected old</strong></td>
<td>666.3</td>
<td>663.8</td>
</tr>
<tr>
<td></td>
<td>663.4</td>
<td>665.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Set</th>
<th>Zenith=low</th>
<th>Zenith=high</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New</strong></td>
<td>655.6</td>
<td>666.6</td>
</tr>
<tr>
<td><strong>Old corrected old</strong></td>
<td>659.6</td>
<td>670.5</td>
</tr>
<tr>
<td></td>
<td>659.5</td>
<td>669.2</td>
</tr>
</tbody>
</table>
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 $X_{\text{max, reco}} - X_{\text{max, real}}$: humidity effect.
- 50 event sets; each ~ 50-100 simulations.
Humidity Effects: From MC studies

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- 50 event sets; each ~ 50-100 simulations.

- no visible effect of humidity
- Further investigation