Atmospheric effects on Radio detection of Cosmic Rays

Effect of atmosphere on Xmax

- Monte Carlo simulation codes for air shower like CORSIKA/CoREAS based on US stdA.
- Major systematic uncertainty arises from the variation of refractive index in the atmosphere.
- Refractivity $N=(n-1)\times10^6$ 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 RI on Radio Footprint

Toy Model

- Radio pulses compressed in time ~ Cherenkov-like emission.
- Opening angle scales: $\cos \alpha = \frac{1}{\beta n}$
- 10% higher $N$ underestimates $X_{\text{max}}$ 17 g-cm$^2$

Limitations: considers only local RI. Integrated RI important for propagation effects.
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
• Events with same ground pressure could see different atmosphere over height.

• Full atmospheric description over correction to ground pressure.

GDAS Profile: Atmosphere

GDAS- Us stdA atmosphere.
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.

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Fitting Procedure

• 5 layer atmospheric model:

\[ X(h) = a + be^{-h/c} \]
\[ \rho(h) = \frac{b}{c} e^{-h/c} \]

• 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 \( a \)
New program (python): 
Gdastool 
(inputs: UTC timestamp, coordinates etc)

File: Atmosphere.dat

Atmosphere layer definitions
Tabulated RI

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

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

create

calls

reads
Implementation of GDAS to CORSIKA/CoREAS

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

File: Atmosphere.dat
Atmosphere layer definitions
Tabulated RI

Released in CORSIKA v-76300

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Implementation of GDAS to CORSIKA/CoREAS

New program (python): Gdastool
(inputs: UTC timestamp, 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)
gdastool : Output Example

Relative error:
\[ \Delta \text{density} / \text{density data} \]

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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 = 1.67 gm-cm^2
Mean $X_{\text{max}}$ vs ground pressure

Difference in mean $X_{\text{max}}$ 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.
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

**Set1**
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- 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.

- **no visible effect of humidity**
- **Further investigation**
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
Atmosphere profile: last Pressure bin (high P)
Atmosphere profile: 2nd last Pressure bin
Effect of RI on E-field

US stdA: 0
GDAS : —

10^8 GeV p shower, coming from 20 zenith
measured at 100 m from core