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Reconstructing air shower parameters with LOFAR using event specific GDAS atmospheres

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Abstract

The limited knowledge of atmospheric parameters like humidity, pressure, temperature, and the index of refraction has been one of the important systematic uncertainties in reconstructing the depth of the shower maximum from the radio emission of air showers. Current air shower Monte Carlo simulation codes like CORSIKA and the radio plug-in CoREAS use various averaged parameterized atmospheres. However, time-dependent and location-specific atmospheric models are needed for the cosmic ray analysis method used for LOFAR data. There, dedicated simulation sets are used for each detected cosmic ray, to take into account the actual atmospheric conditions at the time of the measurement. Using the Global Data Assimilation System (GDAS), a global atmospheric model, we have implemented time-dependent, realistic atmospheric profiles in CORSIKA and CoREAS. We have produced realistic event-specific atmospheres for all air showers measured with LOFAR, an event set spanning several years and many different weather conditions. A complete re-analysis of our data set shows that for the majority of data, our previous correction factor performed rather well; we found only a small systematic shift of 2 g/cm^2 in the reconstructed X_{max} . However, under extreme weather conditions, for example, very low air pressure, the shift can be up to 15 g/cm^2 . We provide a correction formula to determine the shift in X_{max} resulting from a comparison of simulations done using the US-Std atmosphere and the GDAS-based atmosphere.

Keywords: LOFAR, Cosmic Ray, EAS, Radio detection technique, Atmosphere, GDAS, Index of refraction, Effects of humidity, X_{\max} reconstruction

1. Introduction

1 In recent years, the field of radio detection of air showers has advanced quite rapidly [1, 2].
2 Estimating the depth of the shower maximum, X_{\max} , with improved accuracy is of great
3 interest for the study of the primary particle composition [3, 4]. The development of the air
4 shower induced by a cosmic ray is governed by the interactions and decays of the secondary
5 particles. The secondary electrons and positrons in the air shower undergo charge separation
6 as they travel through the magnetic field of the Earth. This leads to a time-varying transverse
7 current, producing radio emission. There is another small contribution to the radiation
8 from the excess of negative charge accumulated at the shower front, known as the ‘Askaryan
9 effect’ [5]. The emission reaches the ground as a short pulse on the order of 10 to 100 ns
10 with a specific lateral intensity distribution, or footprint, that depends on X_{\max} ; X_{\max} is
11 calculated in terms of total atmospheric matter traversed by the air shower from the top of
12 the atmosphere to the point where the particle number reaches the maximum. It is therefore
13 important to know the altitude-dependent air density. Another atmospheric parameter that
14 plays a crucial role in the radio emission is the refractive index of air. If for a given emission
15 region along the shower axis an observer is located at the corresponding Cherenkov angle,
16 radiation emitted from all along this region arrives simultaneously. This results in a highly
17 compressed signal in time, forming a ring-like structure on the ground [6, 7]. The refractive
18 index determines the propagation velocity of the radio signal at different altitudes and
19 influences the time compression [8, 9]. For observers located on the Cherenkov ring, pulses
20 are coherent up to GHz frequencies [10]. The angle at which Cherenkov emission is emitted is
21 inversely proportional to the refractive index. At higher frequencies pulses are more sensitive
22 to the refractive index. In general, at all frequencies, the variations in the refractive index
23 lead to changes in the radio intensity footprint [11]. Both the density and the refractive
24 index of air are dependent on air temperature, humidity and pressure. Thus, having a good
25 understanding of these atmospheric variables is crucial.

26 The radio detection technique can be used in combination with established techniques
27 such as fluorescence detection and surface detection with scintillators and water Cherenkov
28 detectors. Dense antenna arrays like the core of the LOFAR radio telescope [12] provide
29 the opportunity to investigate the radio footprint, i.e. the lateral intensity distribution, in
30 close detail and enable the measurement of X_{\max} up to a precision of < 20 g/cm². The
31 precision is sensitive to the choice of an atmospheric model included in the Monte Carlo air
32 shower simulation codes. There are several parameterized atmospheric models incorporated
33 in the CORSIKA air shower simulation code, based on averaged profiles: U.S. standard

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34 atmosphere parameterized according to J. Linsley [13], parameterized atmospheres for the
 35 Pierre Auger Observatory near Malargüe (Argentina) by M. Will and B. Keilhauer [14],
 36 South Pole atmospheres parameterized by P. Lipari and D. Chirkin etc. So far, the US
 37 standard atmosphere has been used in LOFAR analyses, through CORSIKA simulations
 38 [13] and the CoREAS extension [13] which is used to calculate the radio emission of the air
 39 showers.

40 A first order linear correction to the US standard atmosphere has been applied to account
 41 for the fact that the US-standard atmosphere does not reflect the realistic atmospheric
 42 conditions at a given time. It is preferable to integrate a realistic atmosphere directly into
 43 the simulations. In particular, the reconstruction of X_{\max} depends on the refractive index
 44 of air, and so a realistic refractive index profile needs to be included.

45 The effects of the refractive index, n , on the reconstructed X_{\max} have been previously
 46 reported in Ref.[15] and Ref.[11], using different simulation codes. In Ref.[11], CoREAS
 47 was used to simulate two ensembles of showers, one with a globally higher refractivity
 48 $N = (n - 1) 10^6$, another with standard values. A Monte Carlo based approach was taken
 49 to study the systematic shift in reconstructed X_{\max} by comparing the set of simulations
 50 with higher refractivity to the standard ones. The shift in the reconstructed X_{\max} from the
 51 default value was found to be proportional to the geometric distance to X_{\max} . The effect
 52 was stronger in the high frequency band of 120–250 MHz than in the 30–80 MHz band.
 53 In Ref.[15], a more realistic profile of the refractivity was constructed for one particular
 54 day using information from the Global Data Assimilation System, GDAS, a global weather
 55 database. The differences between this atmosphere and default atmospheres were studied
 56 using the SELFAS radio emission simulation code [16]. The results showed that correcting
 57 for the realistic density is the most important factor in the accurate reconstruction of X_{\max} ,
 58 causing about 30 g/cm² bias in X_{\max} . And the second most important correction was through
 59 the inclusion of the high frequency refractivity formula, applicable at radio frequencies,
 60 contributing about 5 g/cm² bias in X_{\max} . The effects of the increased refractivity on the
 61 time traces and the lateral distribution function (LDF) were also reported. In the 20–80
 62 MHz frequency band, relatively small differences in the amplitude of the electric field and
 63 LDF were found, whereas considerable differences were found studying the high frequency
 64 band between 120–250 MHz. These results were in agreement with Ref.[11]. While both
 65 works paved the way for the understanding of atmospheric effects on radio simulations, a
 66 direct application to real data using simulations with realistic atmospheric conditions was
 67 not addressed.

68 In this work, for the first time, GDAS-based atmospheric profiles, automatically included in
 69 CoREAS simulations are applied to LOFAR data. The effects of atmospheric parameters
 70 like pressure and humidity on the reconstructed X_{\max} are studied and compared to the
 71 results of previously used linear corrections. A new GDAS-based correction is introduced
 72 and compared to previous methods. Furthermore, a tool is developed to extract GDAS
 73 atmospheric parameters which are then interfaced with CORSIKA. The utility of this tool
 74 is not only limited to LOFAR. This code, called ‘gdastool’, has been available for public
 75 use since the release of CORSIKA version 7.6300. It is flexible and ready to be adapted by
 76 the users to obtain parameterized atmospheric profiles for user-specified time and location.

77 Sections 2 and 3 describe the processing of GDAS data to extract the atmospheric state
 78 variables and examples of atmospheric profiles at the LOFAR site, respectively. Section 4
 79 covers the details of the implementation of GDAS in CORSIKA. In sections 5 and 6, LOFAR
 80 cosmic ray data are evaluated with the GDAS atmospheric profiles, the GDAS-correction
 81 factor is introduced and the explicit effects of humidity on shower parameters are discussed.
 82

83 2. Extracting atmospheric variables from GDAS data

84 The Global Data Assimilation System (GDAS) developed at NOAA's¹ National Centers
 85 for Environmental Prediction (NCEP) is a tool used to describe the global atmosphere. It is
 86 run four times a day (0, 6, 12, and 18 UTC) and provides a 3-, 6- and 9-hour forecast based on
 87 the interpolation of meteorological measurements from all over the world including weather
 88 stations on land, ships and airplanes as well as radiosondes and weather satellites [17]. The
 89 three hourly data are available at 23 constant pressure levels, from 1000 hPa (roughly sea
 90 level) to 20 hPa (≈ 26 km) on a global 1° spaced latitude-longitude grid (180° by 360°).
 91 Each data set is complemented by data at the surface level. The data are stored in weekly
 92 files and made available online. In order to model a realistic atmosphere one needs to obtain
 93 the suitable atmospheric parameters from GDAS. Parameters like temperature (K), height
 94 (m) relative humidity (H) and pressure (hPa) can be directly extracted from the database.
 95 In the GDAS data, the altitude is in geopotential units with respect to a geoid (mean sea
 96 level). This is an adjustment to geometric height or elevation above mean sea level using
 97 the variation of gravity with latitude and elevation. To convert from geopotential height h
 98 (m) to standard geometric altitude z (m) we use the formula

$$z(h, \Phi) = (1 + 0.002644 \cdot \cos(2\Phi)) \cdot h + (1 + 0.0089 \cdot \cos(2\Phi)) \left(\frac{h^2}{6245000} \right) \quad (1)$$

99 where Φ is the geometric latitude [18]. To calculate the air density, the relative humidity
 100 is to be converted into water vapor pressure. The following approximation of the empirical
 101 Magnus formula is used to calculate the water vapor pressure (hPa) in terms of humidity
 102 and temperature [18]:

$$e = \frac{H}{100\%} \times 6.1064 \times \exp\left(\frac{21.88 t}{265.5 + t}\right) \quad \text{for } t \leq 0^\circ C \quad (2)$$

103 and

$$e = \frac{H}{100\%} \times 6.1070 \times \exp\left(\frac{17.15 t}{234.9 + t}\right) \quad \text{for } t \geq 0^\circ C. \quad (3)$$

104 The density can be calculated from the ideal gas law as

$$\rho = \frac{P M_{\text{air}}}{R T} \quad (4)$$

¹National Oceanic and Atmospheric Administration.

105 where P is the atmospheric pressure in Pa, T is temperature in K and R is the universal gas
 106 constant, having a value of $8.31451 \text{ J K}^{-1} \text{ mol}^{-1}$ and M_{air} is the molar mass of air. Moist
 107 air can be decomposed into three components to calculate its molar mass: dry air, water
 108 vapor and carbon dioxide. The molar mass of humid air is the sum of the molar masses of
 109 the components, weighted with the volume percentage ϕ_i of that component [18],

$$M_{air} = M_{dry} \cdot \phi_{dry} + M_{water} \cdot \phi_{water} + M_{CO_2} \cdot \phi_{CO_2}. \quad (5)$$

110 The molar masses of dry air, water vapor and CO_2 are 0.02897 , 0.04401 and $0.01802 \text{ kg}\cdot\text{mol}^{-1}$
 111 respectively. The volume percentage of CO_2 is taken as 385 ppmv , the percentage of water
 112 ϕ_{water} is the partial pressure of water vapor divided by the pressure P ; the dry air makes up
 113 the rest.

114 The refractivity, defined as $N = (n - 1) 10^6$, is a function of humidity, pressure and
 115 temperature can be expressed as

$$N = 77.6890 \text{ K hPa}^{-1} \frac{p_d}{T} + 71.2952 \text{ K hPa}^{-1} \frac{p_w}{T} + 375 463 \text{ K}^2 \text{ hPa}^{-1} \frac{p_w}{T^2} \quad (6)$$

116 with p_w , p_d and T being the partial water vapor pressure ($p_w = e \times 100 \text{ Pa}$), partial dry air
 117 pressure and temperature respectively [19]. The effect of humidity is important for our study
 118 as it tends to increase the refractivity in comparison to that of dry air at the radio frequencies.
 119 There are differences between the refractivities obtained in radio and the ones in the visible,
 120 near the infrared and UV ranges as described in [18]. To account for the uncertainties in
 121 GDAS data one needs to perform in situ measurements with weather balloons. Since this
 122 is beyond the scope of this work and we refer to [18], which provides a comparison between
 123 GDAS data and weather balloon measurements in Argentina. Since global atmospheric
 124 models are typically more precise in the Northern hemisphere where more weather data is
 125 available we assume that the intrinsic uncertainty of GDAS at the LOFAR site is similar
 126 to that in Argentina. Various relevant uncertainties are: $\pm 0.5 \text{ }^\circ\text{C}$ for temperature, 0.5 hPa
 127 for pressure, and 0.05 hPa for water vapor pressure and less than 1 g/cm^2 in atmospheric
 128 depth over the altitude range from 3 to 6 km . The uncertainty in water vapor pressure
 129 translates to $2 - 7\%$ uncertainty in humidity. The resulting relative uncertainty in N due
 130 to these parameters is around 0.5% at the same altitude range. The GDAS data have a
 131 resolution of 1° by 1° in latitude longitude. This can be roughly approximated as a distance
 132 of 100 km between two adjacent grid points. For highly inclined showers the distance to
 133 the region of shower development from the observation site can be larger than the distance
 134 between two grid points. For air showers coming from 70° zenith this distance is around
 135 70 km and for zenith $> 75^\circ$ it is about 100 km . In these cases, the choice of an exact grid
 136 point becomes complicated. Also at this point, for zenith angles $> 70^\circ$ the correction due
 137 to curved atmosphere becomes important. This does not occur for LOFAR as the detected
 138 cosmic rays are limited to within a $< 55^\circ$ zenith angle due to the particle detectors used for
 139 triggering. In this regime the GDAS model works well.

3. GDAS atmospheric profiles at the LOFAR site

In this section several GDAS atmospheric profiles extracted at the LOFAR site are discussed. Fig-1 (**left**) shows humidity as a function of altitude for 5 arbitrary atmospheric profiles for different days in the year 2011, between June and November. A significant day-to-day fluctuation is seen. The red solid and blue dashed lines indicate two very different weather conditions; the red solid line having high saturating humidity between 5 – 8 km suggests higher cloud coverage and the blue dashed line with low humidity in that range indicates low cloud coverage. Fig-1 (**right**) shows the difference in atmospheric depth profile between the US standard atmosphere and the GDAS atmospheres at LOFAR for 8 profiles over the years 2011 – 2016. The GDAS atmospheres vary significantly from the US atmosphere. Atmospheric profiles with similar atmospheric depth at ground can evolve differently higher in the atmosphere. This is important for calculating the correct distance to the shower maximum. Fig-2 shows the mean profile for the relative difference in refractivity $\Delta N_{\text{relative}}$ between GDAS and the US standard atmosphere as a function of altitude for over 3 years for 100 cosmic rays recorded at LOFAR. It is defined as $\Delta N_{\text{relative}} = (N_{\text{GDAS}} - N_{\text{US}})/N_{\text{US}}$, where N_{GDAS} is calculated from Eq-6 using GDAS atmospheres at LOFAR. N_{US} is obtained from the linear relation $N_{\text{US}} = \frac{\rho_{\text{us}}}{\rho_{\text{sealevel}}} N_{\text{sealevel}}$, with $N_{\text{sealevel}} = 292$. This is the default option for calculating refractivity in CoREAS as well.

The absolute value of the mean $\Delta N_{\text{relative}}$ is around 10% near ground and around 3 – 8% between 3 to 10 km of altitude, the region important for shower development.

Approximately 75% of the atmospheric matter and 99% of the total mass of water vapor and aerosols are contained within the troposphere, the lowest layer of Earth's atmosphere. Within the troposphere the temperature drops with altitude, reaching a constant value in the tropopause, the boundary region between troposphere and stratosphere. In the US standard atmosphere the troposphere ends at 11 km and tropopause extends to an altitude of 20 km. For the local GDAS atmospheres these boundaries are not sharply defined. The flat part in the mean $\Delta N_{\text{relative}} > 10$ km in Fig-2 is the result of constant temperature in the tropopause. However contribution from this region to the radio emission is minimal. To consider the effects of refractive index in the propagation time of radio signal it is important to calculate the effective N [1, 8]. This is defined as

$$N_{\text{eff}} = \frac{\int N(h)dh}{D} \quad (7)$$

where D is the distance between the line of emission and observer. The values of relative effective refractivity $\Delta N_{\text{relative}}^{\text{eff}}$ between the GDAS and US standard atmosphere are around 7 – 10 % in the range of altitude mentioned above, for observers within < 100 m of the shower axis.

4. Implementation in CORSIKA/CoREAS

To incorporate the atmospheric parameters extracted from GDAS in CORSIKA and CoREAS we have developed a program named 'gdastool' that downloads the required GDAS

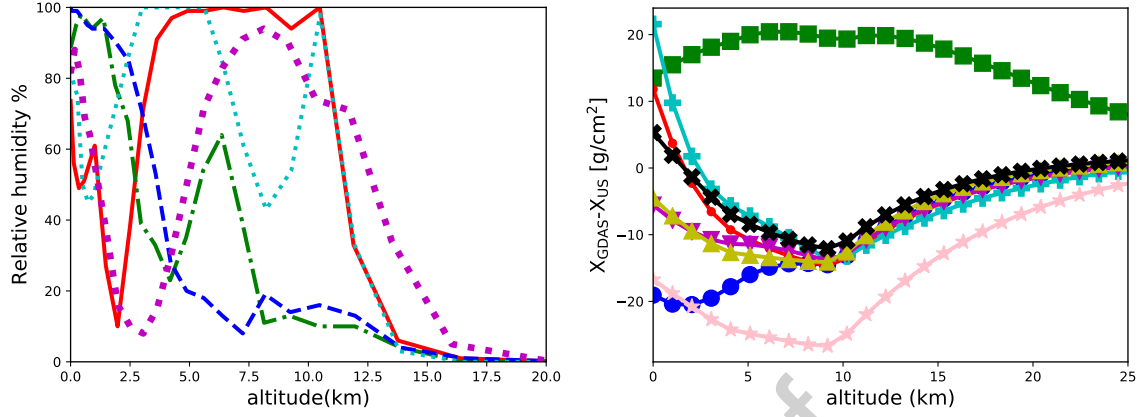


Figure 1: Atmospheric profiles at LOFAR. **Left:** Example of 5 humidity profiles between June to November during the year 2011. **Right:** 8 profiles for the difference in atmospheric depth between US standard atmosphere and GDAS atmospheres as a function of altitude between the years 2011 – 2016.

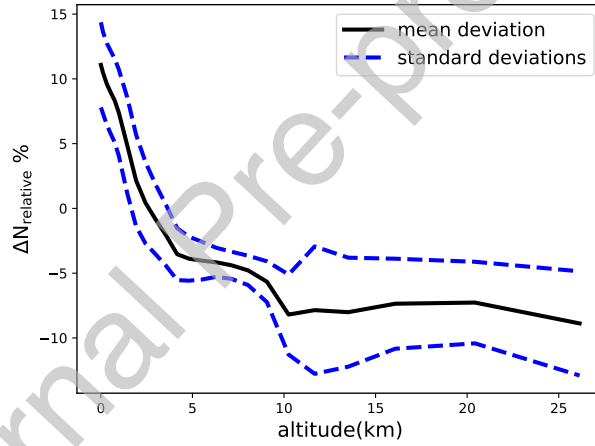


Figure 2: Mean relative refractivity, defined as $\Delta N_{relative} = \frac{N_{GDAS} - N_{US}}{N_{US}}$; profiles for 100 recorded cosmic rays at LOFAR spanning over the years 2011 to 2014. The black solid line denotes the mean profile and the blue dashed lines show the standard deviations.

178 file given the time and location of observation of the event and returns refractive indices
 179 between ground and the highest GDAS level. It also fits the density profile according to
 180 the standard 5 layer atmospheric model used in CORSIKA [13]. In this model the density
 181 $\rho(h)$ has an exponential dependence on the altitude leading to the functional form of mass
 182 overburden $T(h)$ which is the density integrated over height (km) as

$$T(h) = a_i + b_i e^{-10^5 h/c_i} \quad i = 1, \dots, 4. \quad (8)$$

183 Thus, the density is

$$\rho(h) = b_i/c_i e^{-10^5 h/c_i} \quad i = 1, \dots, 4. \quad (9)$$

184 In the fifth layer the overburden is assumed to decrease linearly with height. The parameters
 185 a_i , b_i and c_i are obtained in a manner such that the function $T(h)$ is continuous at the layer
 186 boundaries and can be differentiated continuously. The first three layers constitute of the
 187 24 density points obtained from GDAS data. The first layer consists of 10 points, second
 188 layer of 7 points and the third layer of 7 points. Since GDAS provides data on constant
 189 pressure levels, not of constant heights, the layer boundaries vary slightly between different
 190 atmospheric profiles. The mean values of the boundaries for the conditions of 100 cosmic ray
 191 events are 3.56 ± 0.11 km, 9.09 ± 0.23 km, 26.27 ± 0.56 km from boundary 1 to 3, respectively.

192 Next, we fit the data to Eq- 9 in the following way:

193 For layer 1 the density profile is fitted with two free parameters. Then the density ρ_1 at
 194 boundary 1 is calculated using Eq- 9 with the obtained parameters b_1 , c_1 . The condition that
 195 the density has to be continuous at the boundaries reduces the number of free parameters
 196 to 1 which is the parameter c . Thus the parameter b_2 for second layer can be expressed as
 197 a function of ρ_1 and c_2 with c_2 being the only free parameter. The same fitting procedure is
 198 repeated for the third layer. The fourth layer ranges from the highest GDAS altitude to 100
 199 km. At these altitudes there are no physical GDAS data. The parameter c_4 is obtained by
 200 fitting the last GDAS point and the density at 100 km from US standard atmosphere. At
 201 these altitudes the mass overburden is less than 0.1% of the value at ground. The important
 202 factor is to satisfy the boundary conditions throughout the atmosphere. Along with density
 203 the continuity of mass overburden is also preserved. For that, once a smooth profile for the
 204 density is obtained, the parameter a in Eq- 8 is solved for analytically, using the boundary
 205 conditions for the mass overburden. The parameterization for the fifth layer was adapted
 206 from the US standard atmosphere [13]. The ‘gdastool’ also returns a density profile plot
 207 with the best fit parameters as a function of altitude and the rms of the relative density
 208 difference between data and fit. The relative density is defined as $\frac{\rho_{\text{fit}} - \rho_{\text{data}}}{\rho_{\text{fit}}}$. Fig-3 (left)
 209 and its rms is used as a goodness of fit. Fig-3 (left) shows the example of a density profile
 210 between the fitted model and GDAS. The mean relative error in density for 100 profiles
 211 as a function of altitude is presented in Fig-3 (right). At lower altitudes the model fits
 212 the data very well; deviations $> 2\%$ start at altitudes higher than 15 km which are not so
 213 important for the shower development. A bump in the profile at 10 km is observed, this can
 214 be explained by the change in the atmosphere at the troposphere boundary as discussed in
 215 the previous section. There will be an error on the atmospheric depth introduced by the
 216 fitted model in Eq- 8. It is on the order of 2 g/cm^2 on average between the altitude range
 217 mentioned above with a variance of $4 - 5 \text{ g/cm}^2$.

218
 219 The ‘gdastool’ can be executed as a stand alone script within CORSIKA. Given the
 220 coordinate and UTC time stamp as input parameters it downloads the required GDAS files
 221 and extracts atmospheric data. It then returns an output file that contains fitted mass
 222 overburden parameters and tabulated refractive indices interpolated to 1 m intervals. This
 223 output file can be invoked through the CORSIKA steering file. When called, it replaces the
 224 default atmospheric parameters in CORSIKA with the new ones and the on-the-fly refractive
 225 index calculation in CoREAS with the look-up table.

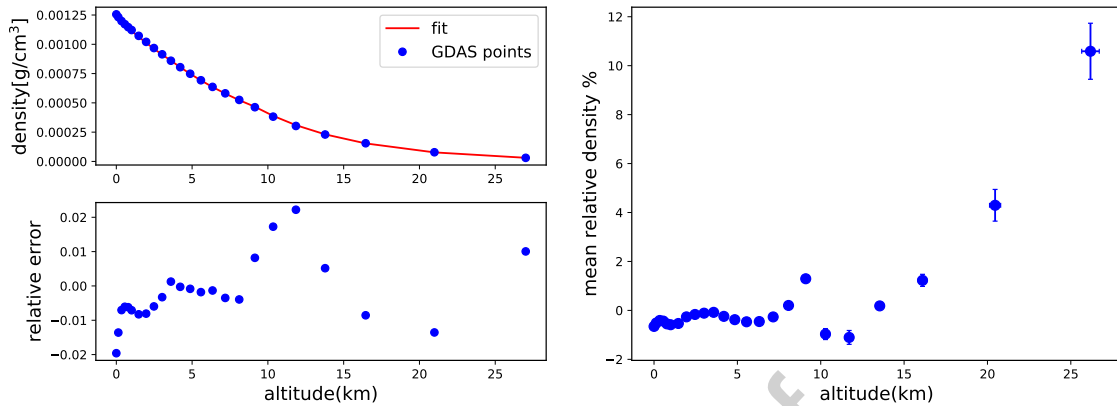


Figure 3: **Left:** Example of one density profile, GDAS and the fitted 5-layered atmospheric model. The bottom panel shows the relative error defined as $\frac{\rho_{\text{fit}} - \rho_{\text{data}}}{\rho_{\text{fit}}}$. **Right:** Mean relative error in density for 100 different atmospheric profiles. The mean is calculated at each of the 24 GDAS points for all the profiles. The error bars indicate the standard deviation.

226 5. Effects on the reconstruction of the depth of the shower maximum

227 The highest precision for the determination of X_{max} with the radio technique is currently
 228 achieved with the LOFAR radio telescope. Situated in the north of the Netherlands, the
 229 dense core of LOFAR consists of 288 low-band dipole antennas within a circle with a diameter
 230 of 320 meters, known as the Superterp. The radio emission from air showers in the frequency
 231 range 30–80 MHz is recorded by the LOFAR low-band antennas [12, 20]. An array of particle
 232 detectors installed on the Superterp provides the trigger for the detection of the air showers
 233 [21].

234
 235 The X_{max} reconstruction technique used at LOFAR is based on the production of dedicated
 236 simulation sets for each detected air shower. The number of simulations needed to reconstruct
 237 the shower maximum is optimized with CONEX [22]. A set of full CORSIKA simulations
 238 with proton and iron primaries is produced for each detected cosmic ray. The radio emission
 239 is simulated in a star-shaped pattern for antenna positions in the shower plane using
 240 CoREAS. An antenna model is applied to the simulated electric fields and compared to the
 241 measured signal in the dipole antennas [23]. The time integrated pulse power is calculated
 242 in a 55 ns window centered around the pulse maximum, summed over both polarizations.
 243 Finally, a two-dimensional map of the time integrated power is created by interpolating
 244 the star-shaped pattern [24]. In the previous analysis a hybrid fitting technique was used
 245 in which both the radio and particle data were fitted to the two-dimensional radiation
 246 map and the one-dimensional particle lateral distribution function simultaneously. In this
 247 work instead of the combined fit we fit only the radio data to the radio simulation. The
 248 advantage of switching to the radio only fitting method is that it results in reduced systematic
 249 uncertainties.

250 Fig-4 shows the fit quality for an air shower detected with LOFAR as a function of X_{max}

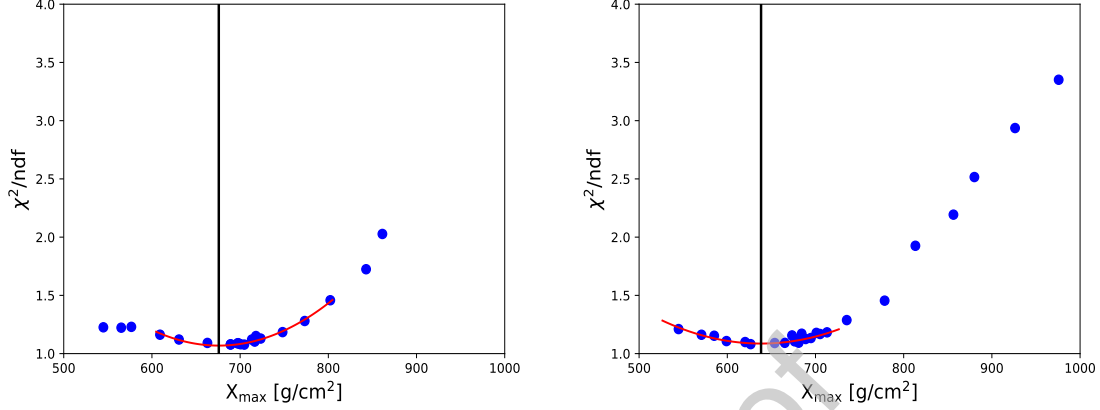


Figure 4: Quality of fit as a function of simulated X_{max} for a LOFAR event of energy 1.4×10^8 GeV, with a zenith angle of 38° . **Left:** simulated with default US standard atmosphere, reconstructed $X_{\text{max}} = 675.8$ g/cm^2 . Applying the linear first order atmospheric correction, the resulting $X_{\text{max}} = 658$ g/cm^2 . **Right:** simulated with GDAS atmosphere, reconstructed $X_{\text{max}} = 638.3$ g/cm^2 , the reconstructed X_{max} in both the cases is indicated by solid black lines.

251 simulated with two different atmospheres - one with the corresponding GDAS atmosphere
 252 and the other with the US standard atmosphere. The reconstructed value of X_{max} is found
 253 from the minimum of the fitted parabola around the best fitted points. We chose a LOFAR
 254 event for which the ground pressure was much lower than the US standard atmosphere, by
 255 20 hPa. The atmospheric profile for this particular event is represented by the blue line
 256 with circles in Fig-1 (**right**). The reconstructed X_{max} with the US atmosphere corresponds
 257 to a much higher mass overburden than the reconstructed X_{max} using much thinner GDAS
 258 atmosphere. In this example this translates to a difference of around 37.5 g/cm^2 in the
 259 reconstructed X_{max} between the two cases. This large deviation is attributed to the extreme
 260 weather condition for the shower chosen in the example. In the previous LOFAR analysis a
 261 correction factor to the US atmosphere was used to account for the real atmosphere [3, 24].
 262 The simulations that are produced with US standard atmosphere would approximately yield
 263 the correct geometrical altitude to the shower maximum. Then the corrected X_{max} is
 264 calculated by integrating the GDAS density profile obtained at LOFAR, from the top of
 265 the atmosphere to the geometric altitude of X_{max} in the following way:

$$X(h) = \frac{1}{\cos \theta} \int_h^\infty \rho_{\text{gdas}}(h) dh. \quad (10)$$

267 The corrected X_{max} for this particular example is 658 g/cm^2 and the difference between the
 268 corrected and new X_{max} is about 20 g/cm^2 .

269

270 Using the same approach described above we have studied 123 air showers recorded with
 271 LOFAR with three simulation sets:

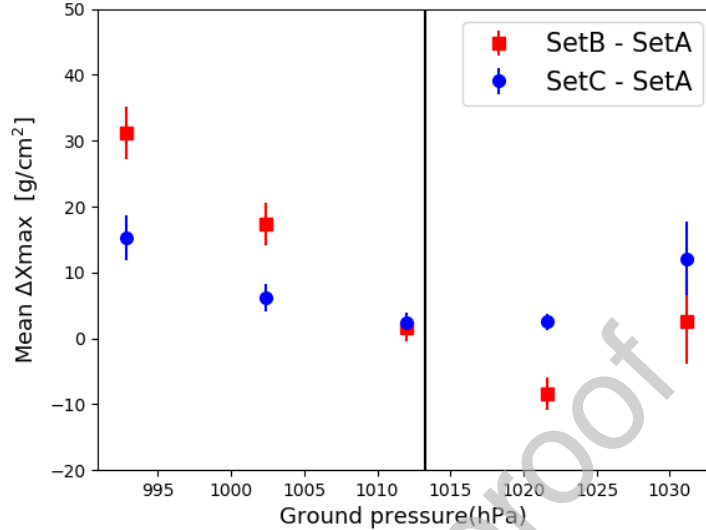


Figure 5: Difference in mean X_{\max} as a function of ground pressure. The total sample contains 123 air showers recorded at LOFAR. The black line denotes the U.S standard atmospheric pressure.

- 272 • **Set A**—the showers were simulated with CORSIKA v-7.6300 and GDAS atmosphere.
- 273 • **Set B**—the showers were simulated with CORSIKA v-7.4385 and US standard atmosphere.
- 274 • **Set C**—this set is identical to **Set B** but with the additional atmospheric correction
- 275 factor to it as described above.

276 The effect of using different CORSIKA versions on the reconstructed X_{\max} , irrespective of
 277 the atmospheric model, was probed. The difference in X_{\max} found using CORSIKA versions
 278 7.6300 and 7.4385 was found to be very small, around 1.4 g/cm². This confirms that the
 279 differences between Set-A, Set-B and Set-C are due to different atmospheric models, not
 280 any artifact arising from different versions of CORSIKA.

281 In Fig-5 the difference in mean reconstructed X_{\max} between the various simulation sets
 282 mentioned above is plotted against ground pressure bins obtained from GDAS. Both the blue
 283 circles and red squares converge to zero where GDAS pressure approaches the US standard
 284 pressure at 1013 hPa. The red squares have large ΔX_{\max} in general. This is expected as
 285 there is no atmospheric correction involved in Set-B. The blue circles however show a higher
 286 deviation both at low and high pressure values. This suggests that the linear first order
 287 correction added to the standard US atmosphere implemented in Set-C is not sufficient. As
 288 the refractive index effects can not be included in the linear first order correction, one needs
 289 full GDAS-based atmospheric profiles for more extreme atmospheric conditions.

290

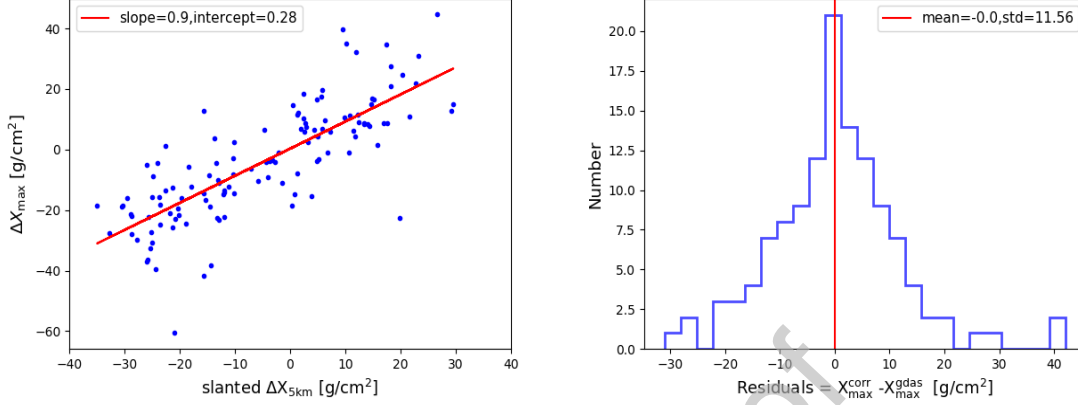


Figure 6: **Left:** scatter plot of $\Delta X_{\max} = X_{\max}^{\text{gdas}} - X_{\max}^{\text{us}}$ vs difference in slanted mass overburden $\Delta X_{5\text{km}} = X_{5\text{km}}^{\text{gdas}} - X_{5\text{km}}^{\text{us}}$. The red line is a linear fit to the profile. **Right:** Histogram shows the residual of fitted and actual X_{\max} ; residual = $X_{\max}^{\text{corr}} - X_{\max}^{\text{gdas}}$.

291 Here, we study the possibility to introduce a new global correction factor to the reconstructed
 292 X_{\max} with US standard atmosphere to correct for realistic atmospheres without having to
 293 run full GDAS-based CoREAS simulations. To achieve this we studied the correlation
 294 between X_{\max} , refractivity, and slanted mass overburden which is defined as the integrated
 295 density from the edge of the atmosphere to a given height at the slant of zenith angle, at
 296 different altitudes. It was seen that both the correlation between X_{\max} and refractivity and
 297 between X_{\max} and slanted mass overburden correlation are poor at ground and at lower
 298 altitudes. At the higher altitudes, between 4 - 6 km, X_{\max} and mass overburden show a
 299 higher correlation which is not prominent in X_{\max} vs refractivity profiles at these altitudes.
 300 We have found the strongest correlation at an altitude of 5 km. Fig-6 (left) shows the
 301 scatter plot of ΔX_{\max} defined as $X_{\max}^{\text{gdas}} - X_{\max}^{\text{us}}$ and difference in the slanted mass overburden
 302 $\Delta X_{5\text{km}} = X_{5\text{km}}^{\text{gdas}} - X_{5\text{km}}^{\text{us}}$. The precise correlation suggests the profile can be fit with a straight
 303 line and is used as a parameterization of global correction factor, provided by the equation:

$$X_{\max}^{\text{corr}} - X_{\max}^{\text{us}} = 0.9 \left(X_{5\text{km}}^{\text{us}} - X_{5\text{km}}^{\text{gdas}} \right) + 0.28. \quad (11)$$

304 The histogram in Fig-6 (right) shows the residual of the X_{\max}^{corr} from X_{\max}^{gdas} . The profile is
 305 symmetric with mean 0 g/cm² and standard deviation 11.56 g/cm². The fluctuations are
 306 within the typical systematic uncertainty of the reconstructed X_{\max} with LOFAR, which
 307 is around 17 g/cm² [24]. This correction factor can be used as a rule of thumb for the
 308 estimation of reconstructed X_{\max} with the following caveats. It is specific to LOFAR, as
 309 simulations were performed involving weather conditions, observation level, and magnetic
 310 field particular to LOFAR. Corresponding correction equations for other experiments can be
 311 constructed in the same manner and can yield different results depending on atmospheric
 312 parameters.

313 However, while this global correction factor is very useful when a fast reconstruction is

314 needed, we will use the full Monte Carlo approach in a future composition analysis. Simulations
 315 with event specific GDAS atmospheres are always more accurate than the correction factor.
 316 The correction factor might also introduce biases related to the mass of the primary particles.
 317 Proton primaries on average generate showers that reach maximum lower in the atmosphere
 318 than iron; these kind of effects are not taken into account.

319 6. Effects of humidity

320 As described in section 2, in the radio frequency regime, humidity increases the refractive
 321 index. For this study, two sets of simulations were produced. In one set the showers
 322 were simulated with the respective GDAS atmosphere and in the other with a GDAS
 323 atmosphere with vanishing humidity. This was achieved by hard-coding the partial water
 324 vapor pressure in Eq-3 to negligible values. For the GDAS atmosphere an extremely humid
 325 weather condition at the LOFAR site was chosen. The same atmospheric parameters are
 326 used in both cases to ensure that the particles evolve in a similar way in the atmosphere
 327 and produce same shower maximum. In this way the inclusion of humidity only influences
 328 the simulated radio pulses. The difference in the refractive index manifests in terms of
 329 propagation effects on the pulse arrival time and power. The pulse propagating through an
 330 atmosphere with higher refractive index will have a lower velocity compared to dry air. This
 331 results in a delayed arrival time of the signal, as seen in Fig-7. The difference in peak arrival
 332 time is less than 1 ns for an observer at 150 m. The effect is found to be less prominent
 333 for observers further away from the axis. The lateral distribution of the energy fluence,
 334 the time-integrated power per unit area, for different observer positions is also studied for
 335 different frequency bands for these two cases, as shown in Fig-8. In the low frequency band
 336 of 30–80 MHz relevant for LOFAR the difference in the fluence between the two sets is small,
 337 from around 4% closer to shower axis to 2% at a distance of 100 m from the axis. In the high
 338 frequency band of 50–350 MHz the values are larger, being around 8% at 100 m from the
 339 core. In the higher frequency band the Cherenkov-like effects become stronger and the signal
 340 is compressed along the Cherenkov ring [25]. A rough estimate of the radius of the ring can
 341 be obtained from the projection of a cone with an opening angle given by the Cherenkov
 342 angle starting from the shower maximum. The opening angle is strongly dependent on the
 343 index of refraction. This explains the higher difference in power in Fig-8. Similar effects in
 344 high and low frequency bands were also reported in [15] by studying the LDF of the electric
 345 field profiles. Inside the Cherenkov radius pulses are stretched due to refractive index effects.
 346 For higher refractive indices this will lead to lower pulse power which explains the negative
 347 sign in the relative fluence for observer distances close to the core.

348 The radiation energy is the total energy contained in the radio signal. It scales quadratically
 349 with the cosmic ray energy, thus can be used as a cosmic ray energy estimator [26, 27]. The
 350 surface integral over the radio LDF mentioned above yields the radiation energy. The relative
 351 difference in the integrated LDF between the humid and non-humid profiles for both the
 352 low and high frequency regimes is smaller than 1%. This indicates that humidity has almost
 353 no effect on the estimated cosmic ray energy as determined from the radiation energy which
 354 was also concluded in [28].

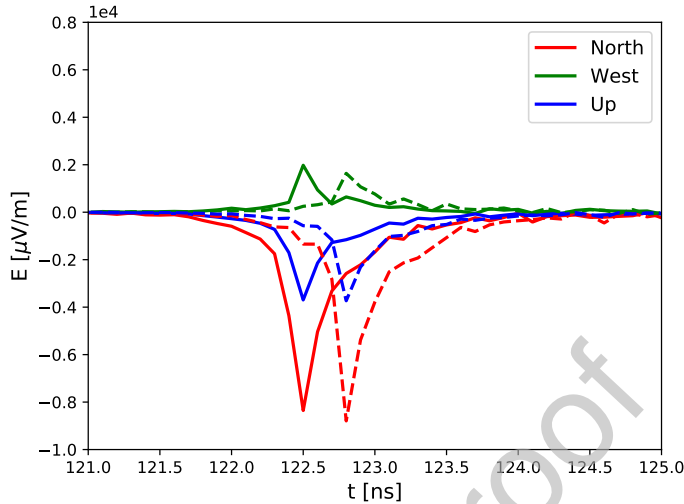


Figure 7: Unfiltered electric field components of a CoREAS pulse in time for two different refractive index profiles for a 10^{17} eV proton shower with a zenith angle of 45° coming from east for an observer at 150 m from the axis. The solid and dashed lines represent the profiles with lower and higher refractive indices respectively.

355 Next, to investigate the effect of humidity on X_{\max} measurements we have performed
 356 a Monte Carlo comparison study between two sets of simulations that deals with the
 357 atmospheres in a similar way as described in the beginning of this section. For each of
 358 these cases we have used a set of 40 simulated events with different energy, zenith and
 359 azimuth angles. Each of these sets consist of an ensemble of proton and iron initiated
 360 showers based on CONEX selection criteria. One shower from the set with higher humidity
 361 is taken as reference and all the simulated showers from the set with zero humidity are used
 362 to perform the reconstruction. This yields a reconstructed X_{reco} that can be compared to
 363 the actual X_{real} of the reference shower. The same method is repeated for all the showers
 364 in the set with higher humidity. Showers with extreme values of X_{\max} were not included in
 365 the fit. The range of the fit was taken as ± 50 g/cm² of the actual X_{\max} for the test shower.

366 The difference $X_{\text{reco}} - X_{\text{real}}$ estimates the effect of humidity on the reconstructed X_{\max} . We
 367 do not observe any significant shift in X_{\max} in this study. This indicates that these effects
 368 are most likely smaller than the overall resolution in reconstructed X_{\max} in the LOFAR
 369 frequency band. We also performed the same study in a higher frequency band between 50
 370 and 350 MHz, corresponding to the SKA-low band. There, an overall shift of 6.8 g/cm² in
 371 the reconstructed X_{\max} was observed. These results, shown in Fig-9, are in line with the
 372 LDF studies described earlier in this section.

373 In Ref.[11], larger shifts of about 10 to 22 g/cm² in reconstructed X_{\max} in the high frequency
 374 band of 120–250 MHz for 4% higher refractivity and 3.5 to 11 g/cm² in the low frequency
 375 band of 30–80 MHz were reported. A toy model was used to describe the effects. The toy

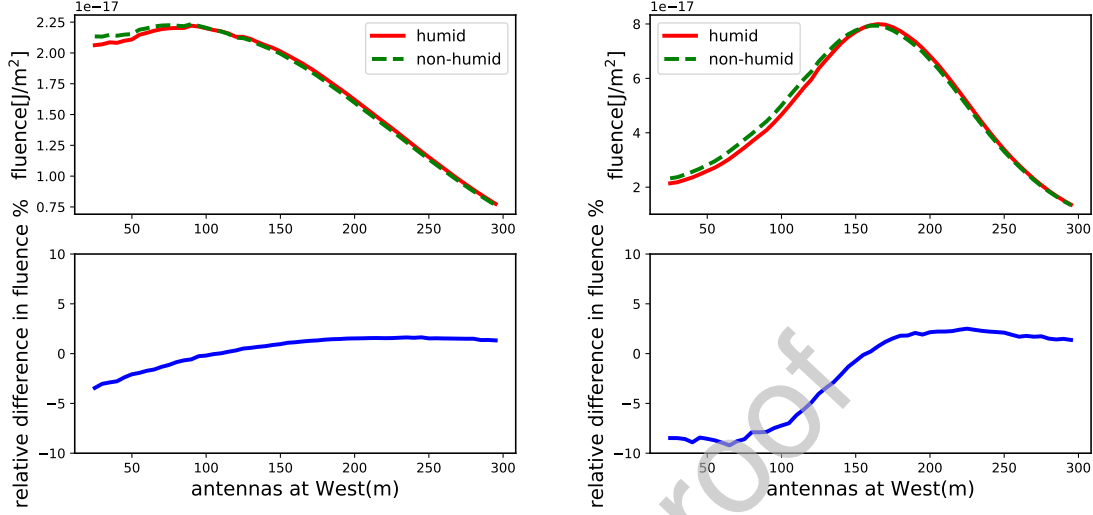


Figure 8: LDF profiles for a 10^{17} eV proton shower coming from zenith 45° with $X_{\max} = 593\text{g/cm}^2$. Observers are located to the west of the shower axis. **Left**: low frequency band between 30–80 MHz, **Right**: high frequency band between 50–350 MHz. The upper panel shows the LDF of total fluence for the humid and non-humid sets, the lower panel shows the relative difference between these two.

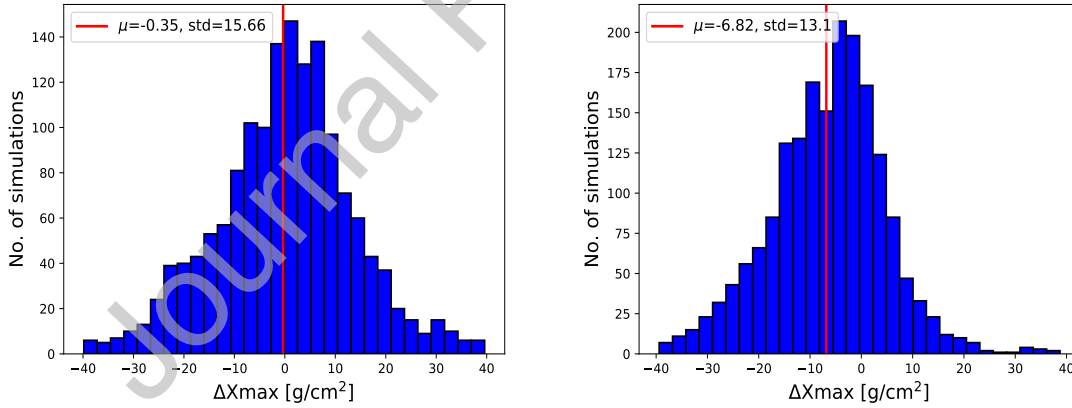


Figure 9: Histogram for the $\Delta X_{\max} = X_{\text{reco}} - X_{\text{real}}$ between the reconstructed and true value of the X_{\max} obtained from the Monte Carlo study between the humid and non-humid simulation sets. **Left**: for the low frequency band of 30–80 MHz. **Right**: for the high frequency band of 50–350 MHz. The shift in the X_{\max} is significant at 2σ level.

376 model was based on the assumptions that the size of the radio footprint on the ground would
 377 be proportional to the geometric distance to X_{\max} and to the Cherenkov angle at the altitude
 378 of X_{\max} . The effect of constant higher refractivity would correspond to a higher Cherenkov

379 angle resulting in an underestimation of X_{\max} . This then leads to a clear linear relation
 380 between shift in X_{\max} and distance to X_{\max} . Without having prior knowledge of individual
 381 atmospheric conditions, an overall scaling of the refractivity profile had to suffice. However,
 382 the realistic scenario is quite different. There are strong interplays between humidity,
 383 pressure, and temperature which are reflected in refractivity. The relative refractivity profile
 384 in Fig-2 shows that the shift is not a constant, but is altitude dependent. From near ground
 385 to higher altitudes it switches from being a higher value than US standard atmosphere to a
 386 lower value. This makes an one-to-one comparison to Ref.[11] hard. However, we can argue
 387 that qualitatively same trait in the high and low frequency band has been found in both the
 388 works.

389 The effects of different zenith angles, true X_{\max} and energy were probed for the shift in
 390 X_{\max} for both the frequency bins. The simulation set was divided in two groups, each group
 391 belonging to high and low values of the parameters mentioned above. No significant effect
 392 was seen.

Frequency band	Zenith	ΔX_{\max} (g/cm ²)
50–350 MHz	low < 30°	-6.24±0.30
50–350 MHz	high > 30°	-6.19± 0.37
30–80 MHz	low < 30°	0.10±0.50
30–80 MHz	high > 30°	-0.05±0.46
Frequency band	True X_{\max} (g/cm ²)	ΔX_{\max} (g/cm ²)
50–350 MHz	low < 624	-6.78±0.41
50–350 MHz	high > 624	-6.30± 0.32
30–80 MHz	low < 624	-0.61±0.51
30–80 MHz	high > 624	0.51±0.46
Frequency band	Energy(GeV)	ΔX_{\max} (g/cm ²)
50–350 MHz	low < 2.18 × 10 ⁸	-6.86±0.35
50–350 MHz	high > 2.18 × 10 ⁸	-6.92± 0.38
30–80 MHz	low < 2.18 × 10 ⁸	-0.48±0.48
30–80 MHz	high > 2.18 × 10 ⁸	0.±0.49

Table 1: Shift in X_{\max} for different zenith, energy and X_{\max} bins for different frequency bands.

393 7. Conclusion and discussion

394 Simulating air showers with realistic atmospheres is important for the precise reconstruction
 395 of X_{\max} with the radio technique. The GDAS database is a useful platform to extract
 396 atmospheric parameters for a given time and location. Atmospheric effects on radio simulations
 397 were previously studied in Refs. [11] and [15]. The studies demonstrated the role of correct
 398 description of atmospheric density and refractive index when included in the radio simulation
 399 codes. However, the application of simulations with realistic atmospheres to real data was
 400 not addressed.

401 We report, for the first time, the application of GDAS-based atmospheric profiles, automated
 402 in CoREAS simulation to cosmic ray data. By systematically performing GDAS-based
 403 CoREAS simulations for the LOFAR dataset, we have done comparison between GDAS-based
 404 atmospheres and a linear geometrical first order correction to the US standard atmosphere
 405 on X_{\max} . While the linear correction is sufficient for the bulk of the events, it becomes
 406 indispensable to use full GDAS based atmospheres for extreme values of the air pressure.
 407 When the air pressure at ground level differs by less than 10 hPa from the US standard
 408 atmosphere value, the reconstructed X_{\max} value including the linear correction agrees with
 409 the full GDAS-based reconstruction value within 2 g/cm². However, when the ground
 410 pressure is more than 10 hPa from the US standard atmosphere, this difference grows
 411 significantly up to 15 g/cm².

412
 413 We have also introduced a GDAS-based correction factor for X_{\max} reconstructed with
 414 US standard atmosphere without having to run full GDAS-based CoREAS simulations. It
 415 is specific to LOFAR, but similar relations can be worked out for other experiments as well.
 416 The uncertainty on the predicted X_{\max} using the correction factor is about 12 g/cm²; this
 417 is within the typical X_{\max} reconstruction uncertainty with LOFAR, around 17 g/cm².

418
 419 We have probed the effects of humidity on the lateral distribution of radio power by
 420 comparing two profiles with high and low humidity. We performed this study for different
 421 frequency bands. In the LOFAR frequency band of 30–80 MHz the relative difference
 422 in power is small. For a higher frequency band of 50–350 MHz the same effects are
 423 comparatively larger, up to 10%. We also estimated the radiation energy from the LDF
 424 profiles to see the effects of humidity on the reconstructed energy. No significant difference
 425 was found for either frequency regime which indicates that humidity does not influence the
 426 estimated energy. A Monte Carlo study on the reconstructed X_{\max} was also done for these
 427 frequency bands. No significant effect of humidity is found on the reconstructed X_{\max} for the
 428 low frequency band relevant for LOFAR; for the higher frequency band a mean difference
 429 on the order of 7 g/cm² is observed. This could be important for the high precision X_{\max}
 430 measurements for the cosmic ray detection with the SKA experiment [29].

431
 432 In the process of implementing GDAS-based parameterized density and refractive index
 433 profile in CORSIKA/CoREAS, we have developed a tool, called ‘gdastool’, which has been
 434 available for public use since the release of CORSIKA version 7.6300, and is already being
 435 used by other experiments in the community around the globe.

436
 437 In the previous LOFAR analysis the effects of refractive index were included within the
 438 systematic uncertainties on the reconstructed X_{\max} . The improved atmospheric correction
 439 will lead to a reduced systematic uncertainty. An update on the mass composition results
 440 is not within the scope of this study. It will be discussed in a future publication, which
 441 involves, along with atmospheric corrections, improved calibration of the radio antennas,
 442 energy scale, and new X_{\max} reconstruction techniques.

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Declaration of research statement

The authors declare no competing financial interests.

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