

# Radio-detection of neutrino-induced air showers: the influence of topography

V. Decoene, N. Renault-Tinacci, O. Martineau-Huynh, Didier Charrier, K. Kotera, S. Le Coz, V. Niess, M. Tueros, A. Zilles

### ► To cite this version:

V. Decoene, N. Renault-Tinacci, O. Martineau-Huynh, Didier Charrier, K. Kotera, et al.. Radiodetection of neutrino-induced air showers: the influence of topography. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2021, 986, pp.164803. 10.1016/j.nima.2020.164803 . hal-02101669

## HAL Id: hal-02101669 https://hal.science/hal-02101669

Submitted on 24 Oct 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

## Radio-detection of neutrino-induced air showers: the influence of topography

## V. Decoene<sup>a</sup>, N. Renault-Tinacci<sup>a</sup>, O. Martineau-Huynh<sup>b,c,a</sup>, D. Charrier<sup>d</sup>, K. Kotera<sup>a</sup>, S. Le Coz<sup>c</sup>, V. Niess<sup>e</sup>, M. Tueros<sup>f,a</sup>, A. Zilles<sup>a</sup>

5	<sup>a</sup> Sorbonne Université, CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98 bis bd
6	Arago, 75014 Paris, France
7	<sup>b</sup> Sorbonne Université, Université Paris Diderot, Sorbonne Paris Cité, CNRS/IN2P3,
8	LPNHE, Paris, France
9	<sup>c</sup> National Astronomical Observatories of China, Chinese Academy of Science, Beijing
10	100012, P.R. China
11	<sup>d</sup> Université de Nantes, IMT-Atlantique, CNRS/IN2P3, SUBATECH, Nantes, France
12	<sup>e</sup> Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France

<sup>f</sup>Instituto de Física La Plata - CONICET, Argentina

#### 14 Abstract

1

2

13

<sup>15</sup> Neutrinos of astrophysical origin could be detected through the electromag-<sup>16</sup> netic radiation of the particle showers induced in the atmosphere by their <sup>17</sup> interaction in the Earth. This applies in particular for tau neutrinos of en-<sup>18</sup> ergies  $E>10^{16}$  eV following Earth-skimming trajectories. The ~1° beaming <sup>19</sup> of the radio emission in the forward direction however implies that the radio <sup>20</sup> signal will likely fly above a detector deployed over a flat site and would <sup>21</sup> therefore not be detected.

We study here how a non-flat detector topography can improve the detection probability of these neutrino-induced air showers. We do this by computing with three distinct tools the neutrino detection efficiency for a radio array deployed over a toy-model mountainous terrain, also taking into account experimental and topographic constraints. We show in particular that ground topographies inclined by few degrees only induce detection efficiencies typically three times larger than those obtained for flat areas for favorable trajectories. We conclude that the topography of the area where the detector is deployed will be a key factor for an experiment like GRAND.

- 22 Keywords: ultra-high-energy cosmic-rays, ultra-high-energy neutrinos,
- <sup>23</sup> radio-detection, air-showers.

Preprint submitted to Elsevier (V. Decoene)

October 7, 2020

#### 24 1. Introduction

<sup>25</sup> Ultra high energy neutrinos (UHE  $\nu$ ) are valuable messengers of violent <sup>26</sup> phenomena in the Universe ([1, 2] and references therein). Their low interac-<sup>27</sup> tion probability with matter allows them to carry unaltered information from <sup>28</sup> sources located at cosmological distances, but, on the other hand, makes their <sup>29</sup> detection challenging: non-negligible detection probability can be achieved <sup>30</sup> only with large volumes of dense targets.

At neutrino energies targeted here  $(E > 10^{16} \text{ eV})$ , the Earth is opaque 31 to neutrinos. Therefore only Earth-skimming trajectories yield significant 32 probability of neutrino interaction with matter, leading to a subsequent tau 33 decay in the atmosphere, eventually inducing an extensive air-shower (EAS). 34 The detection of these EAS has been proposed as a possible technique to 35 search for these cosmic particles [3]. The progress achieved by radio-detection 36 of EAS in the last 15 years [4, 5, 6, 7, 8, 9] combined with the possibility to 37 deploy these cheap, robust detectors over large areas open the possibility to 38 instrument giant radio arrays designed to hunt for neutrino-induced EAS as 39 proposed by the GRAND project [2, 10]. 40

An EAS emits a radio signal via two well understood mechanisms : the *Askaryan effect* [11, 12] and the *geomagnetic effect* [13, 14], which add up coherently to form detectable signals in the frequency range between tens to hundreds of MHz. The interplay between these two effects induces an azimuthal asymmetry of the electric field amplitude along the shower axis [15, 16].

The nearly perfect transparency of the atmosphere to radio waves, combined with the strong relativistic beaming of the radio emission in the forward direction [17] make it possible to detect radio signals from air showers at very large distances from their maximum of development  $X_{\text{max}}$ : a  $2 \times 10^{19}$  eV shower was for example detected by the Auger radio array with a  $X_{\text{max}}$  position reconstructed beyond 100 km from shower core [18]. This is obviously an important asset in favor of radio-detection of neutrino-induced air showers.

The strong beaming of the radio signal also implies that the topography of the ground surface may play a key role in the detection probability of the induced EAS. The primary objective of this article is to perform a quantitative study of the effects of ground elevation on the detection probability of neutrino-induced air showers. To do this, we use a toy configuration where a radio array is deployed over a simplified, generic topography. We compute the response of this setup to neutrino-induced showers with three



Figure 1: General structure of the three simulation chains (*microscopic*, *Radio Morphing* and *Cone* models) used in this study. The sections where their various elements are described are indicated in parenthesis. The trigger condition for the *microscopic* and *Radio Morphing* methods is fulfilled if five antennas or more with peak-peak voltages larger than a threshold value  $V_{th}$  set to 5 times (conservative) or twice the minimal background noise level. For the *Cone model*, the trigger condition is fulfilled if five antennas or more are within the volume of the cone modeling the shower radio emission.

different simulation chains, ranging from a fast and simple estimation using 61 a parametrization of the expected signal amplitude, to a detailed and time 62 consuming Monte-Carlo. This is motivated by the fact that full Monte-Carlo 63 tools are CPU-intensive treatments, to the point of becoming prohibitive 64 when it comes to simulating radio detection by large antenna arrays. The 65 secondary purpose of this paper is therefore to determine if reliable results 66 can be obtained with faster treatments than full Monte-Carlo simulation 67 codes. 68

In section 2 we present the general principle of our study, in section 3 we detail the implementation of the three simulation chains used, and finally in section 4 we discuss the results.

#### 72 2. General principle

Three simulation chains are used in this study. Their general principles are presented in sections 2.1 to 2.3, and summarized in Figure 1. In section 2.4, we present the toy detector configuration used for the study.

#### 76 2.1. End-to-end microscopic simulation

77

The first simulation chain consists of four independent steps:

(i) We produce a fixed number of tau decays induced by cosmic tauneutrinos ( $\nu_{\tau}$ ) interacting in a spherical Earth. This is done for two neutrino energies ( $E_{\nu} = 10^9$  and  $10^{10} \,\text{GeV}$ ) with a dedicated Monte-Carlo engine: DANTON [19, 20], further described in section 3.1.

(ii) We compute the electromagnetic field induced at the location of the
detection units by the showers generated by these tau decays. This is
done through a full *microscopic simulation* of the particles in the EAS
and of the associated electromagnetic radiation using the ZHAireS [21]
simulation code (see section 3.2.1 for details).

(iii) The voltage induced by the radio wave at the antenna output is then
 computed using a modelling of the GRAND HORIZONANTENNA [2] per formed with the NEC4 [22] code. This is detailed in section 3.3.

(iv) If the peak-to-peak amplitude of the output voltage exceeds the defined
threshold for five antennas or more, then the neutrino is considered as
detected (see section 3.4 for more details). This threshold value is
either twice (aggressive scenario) or five times the minimal noise level
(conservative scenario).

#### 95 2.2. Radio-Morphing

Monte-Carlo simulations of the electric field provide the most reliable estimate of the detection probability of a shower, and are therefore used as a benchmark in this work. They however require significant computational resources: the CPU time is mainly proportional to the number of simulated antennas and can last with ZHAireS up to  $\approx$  72 h on one core for 1000 antennas given our simulation parameters.

An alternative simulation chain therefore uses the so-called *Radio Morphing* method [23] instead of ZHAireS for the electric field computation. *Radio Morphing* performs a very fast, semi-analytical computation of the electric field (see section 3.2.2 for details). The antenna response and the trigger computation are simulated in the same way as for the *microscopic simulation* chain. The gain in computation times allows to study a larger number of configurations than with the *microscopic* approach.



Figure 2: Layout of the toy-setup considered in this study. A tau particle decays at a location represented as a star, producing an air shower. The radio signal emitted by the shower impinges the detector plane, tilted by an angle  $\alpha$  from the horizontal. The intersection between the detector plane and the horizontal plane is set at a horizontal distance D from the decay point. The parameter D is therefore a measurement of the amount of free space in front of the detector.

#### 109 2.3. Cone Model

Even if significantly faster than the microscopic method, the Radio Mor-110 *phing* treatment still requires that the antenna response is computed, and 111 thus implies that hundreds of time traces for electric field and voltage need 112 to be handled for each simulated event. A third, much lighter method is 113 therefore used in this study. It is based on a geometric modeling of the 114 volume inside which the electromagnetic field amplitude is large enough to 115 trigger an antenna. We give to this volume the shape of a cone, oriented 116 along the shower axis, with its apex placed at the  $X_{\text{max}}$  position, half-angle 117  $\Omega$  and height H. Values of  $\Omega$  and H depend on shower energy, and are ad-118 justed from ZHAireS simulations (see section 3.5 for details). A shower is 119 considered as detected if at least five antennas are within the cone volume. 120 A similar *Cone Model* was used to compute the initial neutrino sensitivity 121 of the GRAND detector [24]. Being purely analytical, this method produces 122 results nearly instantaneously and requires only minimal disk space and no 123 specific simulation software, an attractive feature when it comes to perform 124 simulation for thousands of detection units covering vast detection areas. 125 126

#### 127 2.4. Toy detector configuration

The detector considered in this study is presented in Figure 2. It is a rectangular grid with a step size of 1000 m between neighbouring antennas. This large step size is a distinct feature of the envisioned dedicated radio array for the detection of neutrino-induced air showers [17]. It is a compromise between the need for very large detection areas imposed by the very low event rates expected for one part, and the instrumental and financial constraints which limit the number of detection units for the other.

In our study we use a simplified, toy setup configuration where the an-135 tenna array is deployed over a plane inclined by an adjustable angle  $\alpha$  (also 136 called "slope" in the following) with respect to an horizontal plane. We 137 restrict our treatment to showers propagating to the North, i.e. directly to-138 wards the detector plane. For other directions of propagation, the size of 139 the shower footprint on ground —hence its detection probability— would 140 directly depend on the width of the detector plane. Defining a specific value 141 for this parameter would be highly arbitrary, given the great diversity of to-142 pographies existing in reality. For showers propagating towards the detector 143 however, the shower footprint is aligned with the detector longitudinal axis 144 (see Figure 2), and the detector width then has a negligible effect on the 145 shower detection efficiency. This motivates our choice to restrict ourselves to 146 this single direction of propagation. The horizontal distance between the tau 147 decay point and the foot of the detector, D, can be understood as the amount 148 of empty space in front of the detector over which the shower can develop and 149 the radio signal propagate. It is therefore closely related to the topography 150 of the detection site. The reference ground elevation is chosen to be 1500 m 151 above sea level (a.s.l.). A maximum altitude of 4500 m a.s.l. is set for the 152 antennas, as larger elevation differences are unrealistic. The vertical devia-153 tion due to Earth curvature can be estimated by  $2\delta h \approx R_{\text{earth}} (L/R_{\text{earth}})^2 \,\text{km}$ , 154 where  $L \ll R_{\text{earth}}$  is the longitudinal distance between the maximum devel-155 opment of the shower and the observer. For L = 50 km, we find  $\delta h < 100$  m. 156 A flat Earth surface is therefore assumed in this toy setup configuration. 157

The slope  $\alpha$  and the distance D are the two adjustable parameters of the 158 study. Values of  $\alpha$  vary from 0 to 90° and D ranges between 20 and 100 km, 159 covering a wide variety of configurations. As will be detailed in section 4.2, 160 larger values of D are irrelevant because most showers would then fly over 161 the detector (see Figure 12 in particular), an effect that would furthermore be 162 amplified if the Earth curvature was taken into account. Values of  $\alpha$  larger 163 than  $30^{\circ}$  are also not realistic, because steeper slopes are not suitable to host 164 a detector, but they are included in our study for the sake of completeness, 165 and because these extreme cases will help us interpret the results of the study. 166 For each pair of values  $(\alpha, D)$ , we process the two sets of tau decays of 167 energies  $E_{\nu} = 10^9 \,\text{GeV}$  and  $E_{\nu} = 10^{10} \,\text{GeV}$  with the three methods micro-168



Figure 3: Distributions of tau decay elevation angles of particle trajectory measured with respect to a horizontal plane (*left*), height above ground at tau decay point (*center*) and shower energy (*right*) for the two sets of primary  $\nu_{\tau}$  energy considered in this study.

scopic, Radio Morphing and Cone Model. We then use the fraction of tau decays inducing a trigger by the detector to perform a relative comparison between  $(\alpha, D)$  configurations. This treatment allows to directly assess the effect of topography on neutrino-induced shower detection efficiency —the purpose of this paper— for a reasonable amount of computing time, given the large number of configurations  $(\alpha, D)$  considered in this study.

#### 176 3. Computational methods

We present in the following the implementation of the methods described in sections 2.1 to 2.3.

#### 179 3.1. Production of the shower progenitors

The production of the shower progenitors was performed with the DAN-180 TON software package [19, 20]. DANTON simulates interactions of tau neu-181 trinos and tau energy losses. It produces results compatible with similar 182 codes [25]. Additionally DANTON offers the possibility to run simulations 183 in backward mode (i.e. from tau decay upwards, with appropriate event 184 weight computations), an attractive feature for massive simulations, and it 185 also allows us to take into account the exact topography of the Earth sur-186 face [26]. It is however operated here in forward mode, i.e. as a classical 187 Monte-Carlo. The primary neutrino source is set as mono-energetic and 188 isotropic. A spherical Earth is used with a density profile given by the Pre-189 liminary Reference Earth Model (PREM) [27], but with the sea layer replaced 190 by Standard Rock [28]. Two energy values are used for the primary neutrino 191 flux:  $E_{\nu} = 10^9$  GeV and  $10^{10}$  GeV. The characteristics of the tau lepton 192

resulting from the interaction of the neutrino with the Earth and of all the
particles produced during the decay of the tau in the atmosphere are also
computed: decay position, list of products and their associated momenta.

For this study one million primary neutrinos were simulated per energy 196 value. Those inducing tau decays in the atmosphere were then selected if the 197 subsequent showers had energies above  $5 \times 10^7$  GeV, because lower energies 198 can hardly lead to detection for such a sparse array [5, 15]. In Figure 3, we 199 show the distribution in energy, elevation angle and height of the two sets 200 of tau decays. Among the surviving set, 100 were randomly chosen for each 201 energy. This value is a good compromise between computation time and 202 statistical relevance. 203

#### 204 3.2. Simulation of the electric field

#### 205 3.2.1. Microscopic method

In the *microscopic* method, the extensive air showers initiated by the by-206 products of the tau decay, and the impulsive electric field induced at the 207 antenna locations were simulated using the ZHAireS software [21], an imple-208 mentation of the ZHS formalism [29] in the AIRES [30] cascade simulation 209 software. To allow for geometries where cascades are up-going and initiated 210 by multiple decay products, we implemented a dedicated module called RAS-211 PASS (Radio Aires Special Primary for Atmospheric Skimming Showers) in 212 the ZHAireS software. 213

#### 214 3.2.2. Radio Morphing

Radio Morphing [23] is a semi-analytical method for a fast computation of the expected radio signal emitted by an air shower. The method consists in computing the radio signal of any *target* air shower at any target position by simple mathematical operations applied to a single *generic* reference shower. The principle is the following:

- i) The electromagnetic radiation associated with the *generic* shower is simulated using standard microscopic tools at positions forming a 3D mesh.
- ii) For each *target* shower, the simulated signals are scaled by numerical factors which values depend analytically on the energy and geometry of
- the *target* and *generic* showers.
- iii) The *generic* 3D mesh is oriented along the direction of propagation ofthe target shower.

iv) The electromagnetic radiation expected at a given *target* position is computed by interpolation of the signals from the neighbouring positions of this 3-D mesh.

This technique lowers the required CPU time of at least two orders of magnitude compared to a standard simulation tool like ZHAireS, while reproducing its results within  $\sim 25\%$  error in amplitude [23].

#### 233 3.3. Antenna response

In order to compute the voltage generated at the antenna output for 234 both *microscopic* and *Radio Morphing* methods, we choose in this study the 235 prototype antenna for the GRAND project: the HORIZONANTENNA [2]. It 236 is a bow-tie antenna inspired from the *butterfly antenna*[31] developed for 237 the CODALEMA experiment [32], later used in AERA [33] and adapted to 238 GRANDProto35 [34]. As for GRANDProto35, three arms are deployed along 230 the East-West, South-North and vertical axes, but the radiating element is 240 half its size to better match the  $50 - 200 \,\mathrm{MHz}$  frequency range considered 241 for GRAND. As the *butterfly antenna*, the HORIZONANTENNA is an active 242 detector, but in the present study, we simply consider that the radiator is 243 loaded with a resistor  $R = 300 \Omega$ , with a capacitor  $C = 6.5 \times 10^{-12} \text{ F}$  and 244 inductance  $L = 1 \,\mu\text{F}$  in parallel. The HORIZONANTENNA is set at an height 245 of 4.5 m above ground in order to minimize the ground attenuation of the 246 radio signal. 247

The equivalent length  $\vec{l}_{eq}^k$  of one antenna arm k (where k = EW, NS, Vert) is derived from NEC4 [22] simulations as a function of wave incoming direction  $(\theta, \phi)$  and frequency  $\nu$ . The voltage at the output of the resistor Rloading the antenna arm is then computed as:

$$V^{k}(t) = \int \vec{l}_{eq}^{k}(\theta, \phi, \nu) \cdot \vec{E}(\nu) e^{2i\pi\nu t} d\nu$$
(1)

252

where  $\vec{E}(\nu)$  is the Fourier transform of the radio transient  $\vec{E}(t)$  emitted by the shower.

The equivalent length was computed for a vertical antenna deployed over a flat, infinite ground. The ground slope of the toy setup can then be accounted for by a simple rotation of this system by an angle  $\alpha$ , which translates into a wave effective zenith angle  $\theta^* = \theta - \alpha$ , to be used in Eq. 1.

#### 259 3.4. Trigger

The last step of the treatment consists in determining whether the shower could be detected by the radio array. For this purpose, we first apply a Butterworth filtering of order 5 to the voltage signal in the 50 – 200 MHz frequency range. This mimics the analog system that would be applied in an actual setup in order to filter out background emissions outside the designed frequency range.

Then the peak-to-peak amplitude of the voltage  $V_{\rm pp}$  is compared to the level of stationary background noise  $\sigma_{\rm noise} = 15\mu V$ , computed as the sum of Galactic and ground contributions (see [2] and [9] for details). If  $V_{\rm pp} \geq N\sigma_{\rm noise}$ , then we considered that the antenna has triggered. Here N = 2in an aggressive scenario, which could be achieved if innovative triggering methods [35, 36] were implemented, and N = 5 in a conservative one.

If at least five antennas trigger on a same shower, then we consider it as detected.

#### 274 3.5. Cone Model

The *Cone Model* proposes to describe the volume inside which the electromagnetic radiation is strong enough to be detected as a cone, characterized by a height and an opening angle varying with shower energy. The *Cone Model* allows for a purely analytical computation of the radio footprint at ground, and thus provides a very fast evaluation of the trigger condition, while it also allows for an easier understanding of the effect of ground topography on shower detection.

The parametrization of the cone height and opening angle as a function of shower energy needs to be computed once only for a given frequency range. This was done as follows for the 50 – 200 MHz band considered in this study:

1. We simulate with the ZHAireS code the electric field from one shower 285 at different locations set at fixed longitudinal distances L from the 286  $X_{\rm max}$  position (see Figure 4 for an illustration). Values  $L > 100 \,\rm km$  are 287 not simulated because the maximal value  $D = 100 \,\mathrm{km}$  chosen in our 288 study for the distance between the tau decay point and the basis of the 289 detector (see section 2.4) makes it unnecessary. As the  $X_{\text{max}}$  position 290 is reached  $\sim 15 \,\mathrm{km}$  after the decay, a distance L = 100 km allows to 291 simulate radio signals over a detector depth of 15 km at least. This is, 292 in the majority of cases, enough to determine if the shower would be 293 detected or not. 294



Figure 4: Position of the planes used to parametrize the *Cone Model*. These are placed perpendicular to the shower axis, at various longitudinal distances L from  $X_{\text{max}}$ . See section 3.5 for details.

295 2. In each of these antenna planes, identified by an index j in the following, 296 we compute the angular distance between the antennas and the shower 297 core. We determine the maximal angular distance to the shower core 298  $\Omega^{j}$  beyond which the electric field drops below the detection threshold, 299 set to 2 (aggressive) or 5 (conservative) times the value of  $E_{\rm rms}$ , the 300 average level of electromagnetic radiation induced by the Galaxy is 301 computed as:

302

$$E_{\rm rms}^{2} = \frac{Z_0}{2} \int_{\nu_0}^{\nu_1} \int_{2\pi} B_{\nu}(\theta, \phi, \nu) \sin(\theta) d\theta d\phi d\nu$$
(2)

where  $B_{\nu}$  is the spectral radiance of the sky, computed with GSM [37] 303 or equivalent codes,  $Z_0 = 376.7 \Omega$  the impedance of free space, and 304  $[\nu_0, \nu_1]$  the frequency range considered for detection. Here we choose 305  $\nu_0 = 50 \,\mathrm{MHz}$  and  $\nu_1 = 200 \,\mathrm{MHz}$ , the frequency range of the HORIZO-306 NANTENNA. The factor 1/2 arises from the projection of the (un-307 polarized) Galactic radiation along the antenna axis. We find  $E_{\rm rms} =$ 308  $22\,\mu\text{V/m}$ . Defining a detection threshold on the electric field amplitude 309 as done here —rather than the voltage at antenna output as usual— 310 allows to derive results that do not depend on a specific antenna de-311 sign. It is however not precise: by construction, the details of a specific 312 antenna response and its dependency on the direction of origin of the 313 signal are neglected here, and only the average effect is considered. The 314



Figure 5: Distribution of the electric field amplitude produced with ZHAireS as a function of  $\Omega$ , the angular distance to the shower axis, for antennas located at a longitudinal distance of 59 km from  $X_{\text{max}}$ . The amplitude dispersion at a given  $\Omega$  value is due to interplay between Askaryan and geomagnetic effects leading to an azimuthal asymmetry of the signal amplitude. For a shower energy  $E = 1.5 \times 10^8 \text{ GeV}$  (in blue) from the  $E_{\nu} = 10^9 \text{ GeV}$  dataset, we find for instance  $(\Omega^j_{\min}; \Omega^j_{\max}) = (0.1^\circ; 1.7^\circ)$  in the aggressive case and  $(0.8^\circ; 1.2^\circ)$  in the conservative one.

<sup>315</sup> *Cone Model* is therefore only an approximate method.

316

317

318

319

320

321

322

The distribution of the electric field amplitudes as a function of the angular distance to the shower axis is shown for illustration in Figure 5 for the plane j located at a longitudinal distance L = 59 km. As the Cherenkov ring induces an enhancement in the amplitude profile for  $\Omega \sim 1^{\circ}$ , we actually compute two values of the angle  $\Omega^{j}$ :  $\Omega^{j}_{\min}$  and  $\Omega^{j}_{\max}$ , thus defining the angular range inside which the electric field amplitude is above the detection threshold.

323 3. The value of  $\Omega^{j}$  does not vary significantly with L (see Figure 6). This validates the choice of a conical model for the trigger volume and allows to derive a single set of values  $(\Omega_{\min}; \Omega_{\max}) = (\langle \Omega_{\min}^{j} \rangle; \langle \Omega_{\max}^{j} \rangle)$  for one <sup>326</sup> specific energy.

4. A similar procedure is applied to determine the cone height H, set to be equal to the longitudinal distance L up to which the signal is strong enough to be detected.

Table 1: Parameters for the fitting functions given in Equations 3 and 4, for aggressive and conservative thresholds and maximal and minimum  $\Omega$  angles. Parameters *a* and *b* are in km, *c* and *d* in degrees.

,	2					
threshold	a	b	Ω	С	d	
aggressive	$109 \pm 15$	$116 \pm 3$	min max	$\begin{array}{c} 0.20 \pm 0.02 \\ 1.3 \pm 0.2 \end{array}$	$-2.4 \pm 0.2$ $1.00 \pm 0.02$	
conservative	$42 \pm 7$	$48 \pm 1$	min max	$1.2 \pm 0.2 \\ 1.0 \pm 0.3$	$-2.2 \pm 0.2$ $0.80 \pm 0.03$	

5. We repeat the treatment for various shower energies  $E_{\rm sh}$  by rescaling the signals amplitudes and thus obtain the distributions  $\Omega(E_{\rm sh})$  and  $H(E_{\rm sh})$  shown in Figures 7 and 8. We fit these distributions for shower energies larger than  $3 \cdot 10^7$  GeV with analytic functions given by

$$H|_{50-200\text{MHz}} = a + b \left(\frac{E_{\text{sh}} - 10^{17} \text{eV}}{10^{17} \text{eV}}\right), \qquad (3)$$

334

$$\Omega|_{50-200\text{MHz}} = c + d \log\left(\frac{E_{\text{sh}}}{10^{17}\text{eV}}\right).$$
(4)

with  $E_{\rm sh}$  expressed in eV in the formulas. Numerical values of a, b, c, dare given in Table 1.

The three parameters  $\Omega_{\min}$ ,  $\Omega_{\max}$  and H allow to define a hollow cone, with an apex set at the shower  $X_{\max}$  location and oriented along the shower axis. Any antenna located inside this volume is supposed to trigger on the shower according to the *Cone Model*.

As mentioned in the introduction, the interplay between the geomag-342 netic effect and the charge excess induces an asymmetry on the electric 343 field amplitude as a function of antenna angular position w.r.t. the 344 shower core. This can be seen on Figure 5, for instance, where the 345 dispersion in field strength at a given angular distance is the exact 346 illustration of this phenomenon. The *Cone Model* however assumes a 347 rotation symmetry around the shower axis and thus neglects this asym-348 metry. This is still acceptable if we are only interested in the average 349

number of triggered antennas by the shower —which is the case here—
and not in the amplitude pattern of the radio signal.

Once this parametrization is completed, the *Cone Model* is applied to the selected set of tau decays: the values of the cone parameters are computed for the energy and geometry of each shower and the intersection between the resulting cone volume and the detection area is calculated. If at least five antennas fall within this intersection, then we consider that the shower is detected.

#### 358 4. Results

We have computed the detection efficiency for our toy setup through the three independent simulation chains presented in section 2. Detection efficiency is defined here as the ratio of the number of showers detected to the total of 100 selected tau decays. The parameters ranges explored initially are distances  $D = \{20, 30, 40, 60, 80, 100\}$  km and slopes  $\alpha = \{0, 5, 10, 15, 20, 45, 90\}$ degrees. This coarse step is mainly motivated by computation time and disk space considerations for the *microscopic* simulation.

We first show a relative comparison of the different methods before discussing the effects of the topography on the detection efficiency.

#### 368 4.1. Relative comparison

Figure 9 shows that the *Radio Morphing* treatment induces trigger ef-369 ficiencies at most 15% higher than *microscopic* simulations. This confirms 370 results obtained in [23] and qualifies the *Radio Morphing* chain as a valid 371 tool for the study presented in this article. Taking advantage of the factor 372  $\sim 100$  gain in computation time of *Radio Morphing* compared to *microscopic* 373 simulations [23] we then decrease the simulation step size down to  $2^{\circ}$  for slope 374  $\alpha$  and 5 km for the distance to decay D, allowing for a more detailed study 375 of the effect of topography on the array detection efficiency. 376

This refined analysis is presented in Figure 10, where results of the *Cone Model* are also shown. The distribution of the *Cone Model* detection efficiency in the  $(\alpha, D)$  plane follows a trend similar to the *Radio Morphing* one, with differences within  $\pm 20\%$  for most of the parameter space  $(\alpha, D)$ . There are however some differences, in particular a significant under-estimation with the *Cone Model* in the ranges  $(\alpha > 30^{\circ}, D > 80 \text{ km})$  and  $(\alpha < 20^{\circ}, D < 30 \text{ km})$ . There is also a flatter distribution as a function of slope for the conservative trigger hypothesis, which results in an over-estimation for  $(\alpha > 30^{\circ}, D < 40 \text{ km})$  for the *Cone Model*, also visible on Figure 11.

Discrepancies are not surprising since the *Cone Model* is an approximate 386 method as already pointed out in section 3.5. One should however be re-387 minded that slopes  $\alpha > 30^{\circ}$  correspond to extreme cases, very rare in reality 388 and which cannot be considered for actual deployment. For realistic slope 389 values  $\alpha < 30^{\circ}$ , the *Cone Model* detection efficiencies differ from those of 390 the *microscopic* approach by -30% at most. The *Cone Model* can thus safely 391 be used to provide in a very short amount of time a rough and conservative 392 estimate of the neutrino sensitivity for realistic topographies. This result 303 also provides an *a posteriori* validation of the initial computation of the 394 GRAND array sensitivity [24], even though the cone was then parametrized 395 from showers simulated in the 30-80 MHz frequency range. 396

#### 397 4.2. Toy-setup discussion

Below we study how the topography affects the detection potential of neutrino-induced air showers by a radio array. To do that, we use the results of the *Radio Morphing* chain, which provide at the same time good reliability and fine topography granularity as explained in the previous section.

Despite statistical fluctuations obviously visible in Figures 10 and 11, general trends clearly appear. Four striking features can in particular be singled-out:

• A significant increase of the detection efficiency for slopes varying from 0 degree up to few degrees: the detection efficiency for a flat area is lower by a factor 3 compared to an optimal configuration  $(\alpha, D) \approx (10^{\circ}, 25 \text{ km})$ . This result is consistent with the study presented in [2], where the effective area computed for a real topography on a mountainous site was found to be four times larger than for a flat site.

• Limited variation of the detection efficiency for slopes between  $\sim 2^{\circ}$  and  $_{412} \sim 20^{\circ}$ .

• An efficiency slowly decreasing for slopes larger than  $\sim 20^{\circ}$ . This is in <sup>414</sup> particular valid for distances D shorter than 40 km, where the detection <sup>415</sup> efficiency is nearly null.

• A slow decrease of the detection efficiency with increasing value of D.

To interpret these results, we may first consider that two conditions have to be fulfilled to perform radio-detection of showers: first the radio beam must hit the detector, then enough antennas (five in this study) have to trigger on the corresponding radio signal. In order to disentangle these two factors —one mostly geometrical, the other experimental—, we display in Figure 12 the fraction of events reaching the detector as a function of the parameters ( $\alpha$ , D). These events are defined by a non-null intersection between the detector plane and a 3° half-aperture cone centered on the shower trajectory, a conservative and model-independent criterion.

It appears from Figure 12 that the large fraction — around 90%— of 426 showers flying above the detector is the main cause of the limited efficiency 427 of a flat detection area. As a corollary, the steep rise of detection efficiency 428 with increasing slope is clearly due to the increasing fraction of intercepted 429 showers. Figures 10 and 12 however differ significantly for configurations 430 corresponding to  $\alpha > 20^{\circ}$  and D < 40 km: the fraction of intercepted events 431 varies marginally with  $\alpha$  at a given D, while the detection efficiency drops. 432 This means that the first condition for detection —detector inside the ra-433 dio beam— is fulfilled for these configurations, but the second —sufficient 434 number of triggered antennas— is not, because the tau decay is too close, 435 and the radio footprint at ground consequently too small. The situation may 436 be compared —with a  $90^{\circ}$  rotation of the geometry of the problem— to the 437 radio-detection of "standard" air showers with zenith angle  $\theta < 60^{\circ}$ , which 438 suffers from limited efficiency for sparse array [9]. A larger density of detec-439 tion units would certainly improve detection efficiency, but the need for large 440 detection areas, imposed by the very low rate of neutrino events, discards 441 this option. 442

Finally the slow decrease in efficiency with increasing value of D is mostly due to geometry, as the fraction of intersecting events diminishes with D in similar proportion.

Yet, one could argue that this result is biased by the detector layout 446 defined in our toy-setup. The infinite width of the detection plane combined 447 with a limit on the detector elevation (3000 m above the reference altitude, 448 see section 2.4) indeed implies that a detector deployed over mild slopes is 449 larger than one deployed over steeper ones in this study. A value  $\alpha = 10^{\circ}$  for 450 example allows for a detector extension of  $3/\sin\alpha \sim 17$  km, while  $\alpha = 70^{\circ}$ 451 implies a value six times smaller. Considering a constant detector area for all 452 configurations ( $\alpha$ ,D) and comparing their effective area —or expected event 453 rates— would avoid such bias, but would require a complete Monte-Carlo 454 simulation. This is beyond the scope of this study, and would be useful only 455 if real topographies were taken into account. 456

It is however possible to estimate this bias by studying how the *constant* 457 area detector efficiency varies with slope. This quantity is defined as the 458 detection efficiency averaged over D and weighted with a factor  $\sin \alpha$ . As D 459 measures the amount of empty space in front of the detector (see section 2.4), 460 averaging the efficiency over all values of D allows us to take into account all 461 possible shower trajectories for a given slope value. The factor  $\sin \alpha$  corrects 462 for the variation of the detector area with slope. The *constant area detector* 463 *efficiency* can therefore be understood as a proxy for the event rate per unit 464 area of a detector deployed on a plane of slope  $\alpha$ , facing an infinite flat area. 465 The constant area average efficiency computed from the Radio Morphing 466 results is displayed as a function of slope on Figure 13. 467

Beyond a certain threshold (~ 20° for the conservative case, ~ 30° for the aggressive one), there is no significant variation of its value with  $\alpha$ , because the poor performance of steep slopes for close-by showers (i.e. small values of D) compensates for the larger area factor sin  $\alpha$ . Figure 13 also confirms the clear gain of a slope — even mild— compared to a detector deployed over flat ground.

Only showers propagating towards the slope were considered in this study, 474 but one can deduce from Figures 11 and 12 that the opposite trajectory 475 (corresponding to a down-going slope, i.e.  $\alpha < 0$ ) results in a  $\sim 0$  detection 476 probability. For showers traveling transverse to the slope inclination (i.e. 477 along the East-West axis in our configuration), basic geometric considerations 478 allow to infer that the situation is probably comparable to horizontal ground. 479 The boost effect of value 3 determined for showers propagating towards the 480 detector plane thus certainly corresponds to a best-case scenario. Computing 481 the net effect of a non-flat topography on the neutrino detection efficiency 482 for random direction of arrivals cannot be performed with this toy-setup 483 configuration (see section 2.4 for details). However we note that a study 484 presented in Ref. [2] points towards a boost factor of  $\sim 2$  on the detection of 485 upward-going showers for the specific site used in that work. 486

#### 487 5. Conclusion

We have studied the impact of the topography for radio-detection of neutrino-induced Earth-skimming air showers. For this purpose, we have developed a toy setup with a simplified topography for the detector, depending on two parameters: the distance between the air shower injection point and the detector array, and the ground slope of the detector array. We have <sup>493</sup> computed the neutrino detection efficiency of this toy detector configuration <sup>494</sup> through three computation chains: a microscopic simulation of the shower <sup>495</sup> development and its associated radio emission, a radio-signal computation <sup>496</sup> using *Radio Morphing* and an analytical treatment based on a *cone model* of <sup>497</sup> the trigger volume.

The comparison of these three independent tools confirms that *Radio Morphing* is a reliable method in this framework, while the *Cone Model* offers a fast, conservative estimate of the detection efficiency for realistic topographies. The latter can thus be used to perform in a negligible amount of time a preliminary estimate of the potential for neutrino detection of a given zone, and the former can then be used to carry out a detailed evaluation of selected sites instead of full Monte-Carlo simulations.

More importantly, the results presented here show that ground topog-505 raphy has a great impact on the detection efficiency, with an increase by a 506 factor  $\sim 3$  for angles of just a few degrees compared to a flat array and for an 507 optimal case where shower trajectories face the detector plane. This boost 508 effect is very similar for any slope value ranging between  $2^{\circ}$  and  $20^{\circ}$ . The 509 other noticeable result of this study is the moderate effect of the distance on 510 the detection efficiency, with comparable values for tau decays taking place 511 between 20 and 100 km from the detector. 512

Two slopes facing each other with tens of kilometers between them may 513 therefore constitute the optimal configuration for neutrino detection, as they 514 would correspond to enhanced rates for the two directions perpendicular to 515 the slopes. Wide valleys or large basins could offer such topographies and 516 will consequently be primarily targeted in the search for the optimal sites 517 where the  $\mathcal{O}(10)$  sub-arrays composing the GRAND array could be deployed 518 to optimize its neutrino detection efficiency. An effort in this direction has 519 been initiated in the framework of the GRAND project. 520

#### 521 Acknowledgments

We are grateful to Clementina Medina and Jean-Christophe Hamilton for suggesting this study. This work is supported by the APACHE grant (ANR-16-CE31-0001) of the French Agence Nationale de la Recherche. We also thank the France China Particle Physics Laboratory for its support. The simulations were performed using the computing resources at the CC-IN2P3 Computing Centre (Lyon/Villeurbanne France), partnership between CNRS/IN2P3 and CEA/DSM/Irfu.

#### 529 6. References

- [1] K. Fang, K. Kotera, M. C. Miller, K. Murase, F. Oikonomou, Identifying ultrahigh-energy cosmic-ray accelerators with future ultrahighenergy neutrino detectors, JCAP 12 (2016) 017. arXiv:1609.08027, doi:10.1088/1475-7516/2016/12/017.
- [2] J. Alvarez-Muñiz, et al., The Giant Radio Array for Neutrino Detection
   (GRAND): Science and Design, Sci. China Phys. Mech. Astron. 63 (1)
   (2020) 219501. arXiv:1810.09994, doi:10.1007/s11433-018-9385-7.
- [3] D. Fargion, A. Aiello, R. Conversano, Horizontal tau air showers from mountains in deep valley: Traces of uhecr neutrino tau, in: Proceedings, 26th International Cosmic Ray Conference, August 17-25, 1999, Salt Lake City: Invited, Rapporteur, and Highlight Papers, 1999, p. 396, [2,396(1999)]. arXiv:astro-ph/9906450.
- [4] H. Falcke, et al., Detection and imaging of atmospheric radio flashes
  from cosmic ray air showers, Nature 435 (2005) 313–316. arXiv:astroph/0505383, doi:10.1038/nature03614.
- <sup>545</sup> [5] D. Ardouin, et al., Geomagnetic origin of the radio emis<sup>546</sup> sion from cosmic ray induced air showers observed by CO<sup>547</sup> DALEMA, Astropart. Phys. 31 (2009) 192–200. arXiv:0901.4502,
  <sup>548</sup> doi:10.1016/j.astropartphys.2009.01.001.
- [6] P. A. Bezyazeekov, et al., Measurement of cosmic-ray air showers with
  the Tunka Radio Extension (Tunka-Rex), Nucl. Instrum. Meth. A 802
  (2015) 89–96. arXiv:1509.08624, doi:10.1016/j.nima.2015.08.061.
- [7] A. Aab, et al., Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory, Phys. Rev. D 93 (12) (2016) 122005. arXiv:1508.04267, doi:10.1103/PhysRevD.93.122005.
- <sup>555</sup> [8] S. Buitink, et al., A large light-mass component of cosmic rays <sup>556</sup> at  $10^{17} - 10^{17.5}$  eV from radio observations, Nature 531 (2016) 70. <sup>557</sup> arXiv:1603.01594, doi:10.1038/nature16976.
- [9] D. Charrier, et al., Autonomous radio detection of air showers with
   the TREND50 antenna array, Astropart. Phys. 110 (2019) 15–29.
   arXiv:1810.03070, doi:10.1016/j.astropartphys.2019.03.002.

- [10] D. Ardouin, et al., First detection of extensive air showers by the
   TREND self-triggering radio experiment, Astropart. Phys. 34 (2011)
   717-731. arXiv:1007.4359, doi:10.1016/j.astropartphys.2011.01.002.
- <sup>564</sup> [11] G. Askaryan, Excess negative charge of an electron-photon shower and <sup>565</sup> its coherent radio emission, Sov. Phys. JETP 14, 441 (1962).
- <sup>566</sup> [12] G. Askaryan, Coherent radio emission from cosmic showers in air and <sup>567</sup> in dense media, Sov. Phys. JETP 21, 658 (1965).
- <sup>568</sup> [13] F. D. Kahn, I. Lerche, A. C. B. Lovell, Radiation from cosmic ray air
   <sup>569</sup> showers, P. Roy. Soc. A Math. Phy. A-289 (1966) 206.
- Scholten, K. Werner, F. Rusydi, A macroscopic descrip-|14| O. 570 tion of coherent geo-magnetic radiation from cosmic-ray air 571 showers, Astropart. Phys. 29 (2008) 94–103. arXiv:0709.2872, 572 doi:10.1016/j.astropartphys.2007.11.012. 573
- 574 [15] T. Huege, Radio detection of cosmic ray air showers in the
   575 digital era, Phys. Rept. 620 (2016) 1–52. arXiv:1601.07426,
   576 doi:10.1016/j.physrep.2016.02.001.
- 577 [16] F. G. Schröder, Radio detection of Cosmic-Ray Air Showers and
   578 High-Energy Neutrinos, Prog. Part. Nucl. Phys. 93 (2017) 1–68.
   579 arXiv:1607.08781, doi:10.1016/j.ppnp.2016.12.002.
- [17] J. Alvarez-Muñiz, W. R. Carvalho, D. García-Fernández, H. Schoorlemmer, E. Zas, Simulations of reflected radio signals from cosmic ray induced air showers, Astropart. Phys. 66 (2015) 31–38. arXiv:1502.02117, doi:10.1016/j.astropartphys.2014.12.005.
- [18] A. Aab, et al., Observation of inclined EeV air showers with the radio
   detector of the Pierre Auger Observatory, JCAP 1810 (10) (2018) 026.
   arXiv:1806.05386, doi:10.1088/1475-7516/2018/10/026.
- [19] V. Niess, O. Martineau-Huynh, DANTON: a Monte-Carlo sampler of  $\tau$ from  $\nu_{\tau}$  interacting with the Earth (2018). arXiv:1810.01978.
- <sup>589</sup> [20] V. Niess, Danton: Decaying taus from neutrinos, GitHub repository <sup>590</sup> (2017–2018).
- <sup>591</sup> URL https://github.com/niess/danton

- [21] J. Alvarez-Muñiz, W. R. Carvalho. E. Zas. Monte Carlo 592 simulations of radio pulses in atmospheric showers using 593 ZHAireS, Astropart. Phys. 35 (2012) 325 - 341.arXiv:1107.1189, 594 doi:10.1016/j.astropartphys.2011.10.005. 595
- <sup>596</sup> [22] G. Burke, Numerical Electromagnetics Code NEC-4, Method of
  <sup>597</sup> Moments, Part I: User's Manual, Lawrence Livermore National Lab.,
  <sup>598</sup> Rept. URCL-MA-109338 Pt. I (1992).
- 599 URL http://physics.princeton.edu/~mcdonald/examples/NEC\_ 600 Manuals/NEC4UsersMan.pdf
- [23] A. Zilles, O. Martineau-Huynh, K. Kotera, M. Tueros, K. de Vries,
  W. Carvalho Jr., V. Niess, N. Renault-Tinacci, V. Decoene, Radio Morphing: towards a fast computation of the radio signal from
  air showers, Astropart. Phys. 114 (2020) 10–21. arXiv:1811.01750,
  doi:10.1016/j.astropartphys.2019.06.001.
- [24] O. Martineau, K. Kotera, K. Fang, Z. Feng, C. Finley, Q. Gou,
  V. Niess, N. Renault-Tinacci, C. Timmermans, D. Charrier, S. de Jong,
  K. de Vries, J. Gu, H. HU, K. Murase, F. Oikonomou, J. Schmid,
  Z. Wang, X. Wu, J. Zhang, Y. Zhang, The Giant Radio Array for
  Neutrino Detection, in: Proceedings of The 34th International Cosmic Ray Conference PoS(ICRC2015), Vol. 236, 2016, p. 1143.
  doi:10.22323/1.236.1143.
- [25] J. Alvarez-Muñiz, W. R. Carvalho, K. Payet, A. Romero-Wolf,
  H. Schoorlemmer, E. Zas, Comprehensive approach to tau-lepton
  production by high-energy tau neutrinos propagating through the
  Earth, Phys. Rev. D 97 (2) (2018) 023021. arXiv:1707.00334,
  doi:10.1103/PhysRevD.97.023021.
- [26] V. Niess, A. Barnoud, C. Cârloganu, O. Martineau-Huynh, TURTLE:
   A C library for an optimistic stepping through a topography (2019).
   arXiv:1904.03435, doi:10.1016/j.cpc.2019.106952.
- [27] A. M. Dziewonski, D. L. Anderson, Preliminary reference earth model,
  Physics of the Earth and Planetary Interiors 25 (4) (1981) 297 356.
  doi:https://doi.org/10.1016/0031-9201(81)90046-7.

- [28] See the following link to the pdg for a discussion about standard rock.
   URL http://pdg.lbl.gov/2015/AtomicNuclearProperties/
   standardrock.html
- [29] E. Zas, F. Halzen, T. Stanev, Electromagnetic pulses from high-energy
  showers: Implications for neutrino detection, Phys. Rev. D 45 (1992)
  362–376. doi:10.1103/PhysRevD.45.362.
- [30] S. J. Sciutto, AIRES: A system for air shower simulations (1999).
   arXiv:astro-ph/9911331, doi:10.13140/RG.2.2.12566.40002.
- [31] D. Charrier, CODALEMA Collaboration, Antenna development for astroparticle and radioastronomy experiments, Nucl. Instrum. Meth. A
  662 (2012) S142–S145. doi:10.1016/j.nima.2010.10.141.
- [32] A. Escudie, D. Charrier, R. Dallier, D. Garca-Fernndez, a. lecacheux,
  L. Martin, B. Revenu, From the Observation of UHECR Radio Signal
  in [1-200] MHz to the Composition: CODALEMA and EXTASIS Status
  Report, PoS ICRC2019 (2019) 246. doi:10.22323/1.358.0246.
- [33] P. Abreu, et al., Antennas for the detection of radio emission pulses from
   cosmic-ray, JINST 7 (2012) P10011. arXiv:1209.3840, doi:10.1088/1748 0221/7/10/P10011.
- [34] Q. Gou, et al., The GRANDproto35 experiment, PoS ICRC2017 (2018)
   388. doi:10.22323/1.301.0388.
- [35] F. Führer, T. Charnock, A. Zilles, M. Tueros, Towards online triggering for the radio detection of air showers using deep neural networks,
  in: Proceedings, Acoustic and Radio EeV Neutrino Detection Activities
  (ARENA 2018): Catania, Italy, June 12-15, 2018, Vol. 216, 2019, p.
  03004. arXiv:1809.01934, doi:10.1051/epjconf/201921603004.
- [36] M. Erdmann, F. Schlter, R. Smida, Classification and Recovery of Radio Signals from Cosmic Ray Induced Air Showers with Deep Learning, JINST 14 (04) (2019) P04005. arXiv:1901.04079, doi:10.1088/17480221/14/04/P04005.
- [37] H. Zheng, et al., An improved model of diffuse galactic radio emission
   from 10 MHz to 5 THz, Mon. Not. Roy. Astron. Soc. 464 (3) (2017)
   3486–3497. arXiv:1605.04920, doi:10.1093/mnras/stw2525.



Figure 6: Angular distances  $\Omega_{\max}^{j}$  computed following the method presented in Figure 5 as a function of longitudinal distance for various shower energies.  $\Omega_{\rm max}$  measures the maximum opening angle of the cone describing the triggering volume, while index j identifies the simulation plane perpendicular to the shower axis (see Figure 4). Here only the conservative case in shown.

The angle value varies marginally over the full range of longitudinal values considered for shower energies  $E = 1.1 \times 10^9$  and  $1.1 \times 10^{10}$  GeV, validating the choice of a cone model —with fixed opening angle  $\Omega_{\rm max} = \langle \Omega_{\rm max}^j \rangle$ for the trigger volume modeling. For  $E = 1.1 \times 10^8 \,\text{GeV}$ ,  $\Omega$  drops to 0 for  $L > 50 \,\mathrm{km}$  because the cone height H is equal to 50 km in the conservative case (see Figure 8). Similar treatment is applied to determine  $\Omega_{\min}$ .



Figure 7: Angles  $\Omega_{\text{max}}$  and  $\Omega_{\text{min}}$  as a function of shower energy  $E_{\text{sh}}$ ; and fit by Eq. 4. Angles  $\Omega_{\text{max}}$  and  $\Omega_{\text{min}}$  define the inner and outer boundaries of the hollow cone and are obtained by averaging the values  $\Omega_{\text{max}}^{j}$  and  $\Omega_{\text{min}}^{j}$  (see Figure 6)

. At the highest energies,  $\Omega_{\min}$  drops down to 0°, implying that the radio signal is above the detection threshold for all angular distances  $\Omega \leq \Omega_{\max}$ .



Figure 8: Cone height H as a function of shower energy  $E_{\rm sh}$  and fit by Eq. 3. Cone height saturates at values H = 100 km, because the antenna planes used to parametrize the *Cone Model* do not extend beyond this value. However points with values H < 100 km suffice to demonstrate that the cone heights scale linearly with energy, as one would naturally expect, since the electric field amplitude also scales linearly with energy. Cone height values H > 100 km are therefore extrapolated from the fit given in Eq. 3.



Figure 9: Left: Detection efficiency as a function of the distance D and slope  $\alpha$  for the simulation set with a primary neutrino energy of  $10^9$  GeV. Comparison between ZHAireS and Radio Morphing (respectively top and middle plots, while the difference is plotted at the bottom) and conservative thresholds (*left*) and aggressive thresholds (*right*). Right: Same for a primary neutrino energy of  $10^{10}$  GeV.



Figure 10: Left: Detection efficiency as a function of distance D and slope  $\alpha$  for the simulation set with a primary neutrino energy of  $10^9$  GeV. Results are plotted for the Cone Model (top) and Radio Morphing (middle), as well as the difference (Radio-Morphing - Cone Model) (bottom). Conservative (left) and aggressive (right) threshold hypothesis are also considered (right). Right: Same for a primary neutrino energy of  $10^{10}$  GeV.



Figure 11: Top: Detection efficiency as a function of slope  $\alpha$  for a distance D = 40 km for neutrinos energies of  $10^9$  (*left*) and  $10^{10} \text{ GeV}$  (*right*). Comparisons between the microscopic (solid lines), *Radio Morphing* (dashed lines) and *Cone Model* (dash-dotted lines), for conservative (black lines) and aggressive (red lines) threshold hypothesis. *Bottom:* Differences *ZHAireS-RadioMorphing* and *ZHAireS* - *Cone Model* for the data shown in the top pannel, following the same color code.



Figure 12: Left: Fraction of events intersecting the detection area as a function of distance D and slope  $\alpha$  for the simulation set with a primary neutrino energy of  $10^9$  GeV. Right: Same for a primary neutrino energy of  $10^{10}$  GeV.



Figure 13: *Left:* Average detection efficiency over a constant detector area as a function of slope for the simulation set with a primary neutrino energy of  $10^9$  GeV. *Right:* Same for a primary neutrino energy of  $10^{10}$  GeV. In both cases values are computed with the *Radio Morphing* treatment.