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Detection Simulation of UHE neutrinos with RDSim

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Neutrino-induced extensive air showers can be detected with arrays of antennas on the ground, such as the Radio Detector extension of Auger (Auger-RD). But these neutrino showers depend on extra variables that are unique to them, such as the atmospheric depth of the neutrino interaction or the tau-lepton decay. This makes the phase space of neutrino events much larger than that of hadronic showers. Blindly exploring such a vast phase space would need a truly astronomical number of full simulations. In order to investigate the relevant phase space, we have developed a fast and comprehensive framework for the simulation of the radio emission and its detection, called RDSim. This framework uses simplified approaches to drastically reduce the number of full simulations needed to investigate the vast neutrino event phase space in detail. The RDSim framework makes it possible to investigate events with a very low trigger probability, as well as many geometrical effects due to the array layout.

In this work, we also present first estimates of the Auger-RD apertures for neutrino events, as obtained with RDSim, leading to a better understanding of the strengths and weaknesses of the detector. It also constrains the phase space of detectable events, allowing the optimization of dedicated full simulation libraries needed for future, more detailed studies of the Auger-RD neutrino performance.

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1. RDSim

RDSim is a fast and comprehensive framework for simulating the radio emission and detection of downgoing air showers. The emission model used in RDSim is an extension of the one presented in [1], which is based on the superposition of the Askaryan and geomagnetic components of the radio emission. ZHAireS [2] simulations, with just a few antennas, are used as input by the emission model to estimate the peak electric field anywhere on the ground. This toymodel-like emission model also allows for a single simulation to be reused for multiple events, as it can be scaled in energy and rotated in azimuth, taking into account all relevant emission effects. This drastically cuts down the computing time needed to produce complete sets of input simulations. RDSim takes into account, in a simplified manner, the main characteristics of the detector, such as trigger setups, thresholds and antenna patterns. It is also capable of simulating events induced by neutrino CC and NC interactions and tau-lepton decays. In this work we will focus on some preliminary results for neutrino events at the Auger-RD array, as well as new additions to the code, such as the capability to simulate mountain tau-lepton events. We refer the reader to [3] for more detailed descriptions of RDSim and its models.

1.1 Simulation of mountain tau induced events

When a ν_τ enters a mountain, it can interact and create a tau-lepton, which in turn can exit the mountain and create a shower in the atmosphere that can be detected by an antenna array. In this work we call these events mountain events.

Given a shower axis, defined by an arrival direction and a core position, we use topographic data from the Shuttle Radar Topography Mission [4] to establish which parts of the axis, if any, crosses the mountain. This calculation is done on the shower plane, using angular steps in a spherical coordinate system with origin at the center of the Earth. For each angular step, which matches the resolution of the topographic map, we establish if the axis falls below the topography. A geometrical scheme of the procedure is shown on the left panel of Fig. 1. From this we obtain two key quantities: the total distance DRock propagated inside the rock, which is important for the ν_τ propagation inside the mountain; and the distance faceD from the core to the intersection of the axis with the mountain face, i.e., the point from which a tau-lepton would emerge, which is important for the propagation and decay of the exiting τ in the air. On the middle and right panels of Fig. 1 we show the values obtained for DRock (middle) and faceD (right) for several directions, all with the core at Malargue, Argentina, close to the edge of the Auger observatory. One can see that DRock starts small for the lower zenith angles, since these arrival directions just graze the tops of the highest peaks, and tends to increase with zenith angle, as the directions start to traverse more of the main core of the mountain. On the faceD plot (right), one can see a shadowing effect of the closest mountains over the more distant ones. But a few very high and distant peaks are still visible, e.g., at around $\phi = 90°$.

We then perform a simulation of the ν_τ propagation inside the mountain. For this we created a fast simplified version of NuTauSim [5] that only takes into account CC interactions and disregards neutrino regeneration. Here we use the middle $\sigma_{\nu_\tau - N}$ cross-section for the neutrino interaction and the ALLM parametrization for the tau-lepton energy loss (see [5] for details). In this simulation, the ν_τ is propagated inside a constant density andesite block of length DRock. If the neutrino interacts,

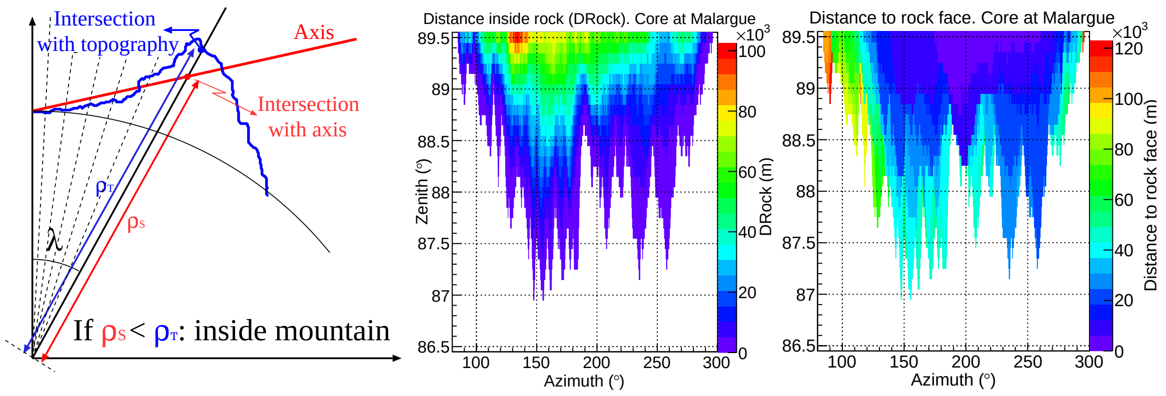


Figure 1: Left: Geometrical scheme of the topographic calculation. Middle: Values of DRock for several arrival directions for the shower core at Malargue. Right: Same as left left, but for faceD (see text).

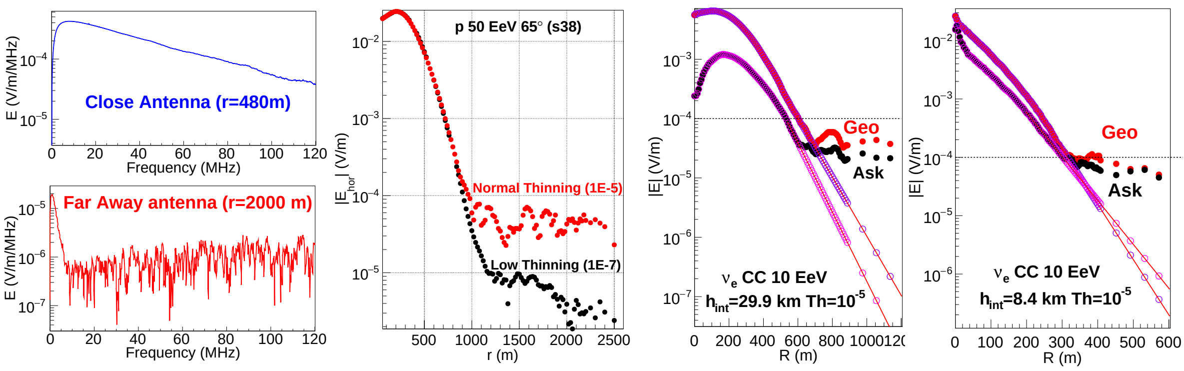
a tau-lepton that carries, on average, around 80% of the neutrino energy is created. This τ is then propagated in steps, taking into account energy losses and the probability of decay. At each step, the τ will either leave the mountain, decay or loose energy. If it leaves the mountain, the final energy E_τ is recorded and it is further propagated in air (disregarding energy losses) until it decays or reaches the ground. If it decays above ground, we record its decay depth and choose a suitable tau-lepton decay emission toymodel for the given energy and decay depth. At this point, the RDSim procedure to simulate the event becomes exactly the same as for regular downgoing showers.

2. Notes on simulation of the radio emission of neutrino showers

It is well known [2, 6] that the thinning level of a simulation can greatly affect the calculated observables, such as the radio pulses and spectra. The thinning algorithm creates particle tracks with high weight that represent, on average, the many different particles tracks it excludes from the simulation. These excluded tracks would each contribute to the emission with a different phase. But the high-weight track that represents them contributes to the emission with a single phase and high weight, creating an unphysical “fake coherence” effect. At high frequencies, the overall coherent signal of the shower becomes very low, and these unphysical in-phase contributions of the high-weight tracks become dominant. Since the coherence of the emission also decreases with increasing observer distance, this “fake coherence” also occurs for observers far from the core, for the same reason (see Appendix A of [6] and section 4.4 of [2]). On panel (a) of Fig. 2 we show two spectra from a proton shower obtained with ZHAireS for an observer close (top) and far (bottom) from the Cherenkov cone. One can see that the the thinning artifact starts at a much lower frequency for the far away antenna than for the close one. Decreasing the thinning level used in the simulation can diminish this thinning artifact, as the weights will be lower. This can be seen on panel (b) of Fig. 2, where we show the peak amplitude as a function of antenna distance for two different thinning levels.

For the detection simulation, this thinning artifact becomes important if it artificially creates a signal that is above the detection threshold for the antennas. In the case of regular showers (p, Fe) simulated with ZHAireS at a thinning level of 10^{-5} and a trigger threshold of 100 $\mu V/m$, this artifact starts to become important at energies above ~40 EeV. If this artifact is not addressed above these energies, the result will be an artificially large detectable radio footprint, increasing the number of triggered antennas and thus the number of triggered events. At the highest energies, specially at low zenith angles and with a large antenna spacing, this would massively overestimate the apertures calculated by RDSim.

In the case of neutrino showers, which tend to start much lower in the atmosphere, the overall signal is increased due to the roughly $1/R$ scaling of the electric field amplitude, where R is the distance to X_{max}. This amplifies the effect of this "fake coherence", making neutrino showers, specially deep interacting ones, much more susceptible to thinning artifacts. These artifacts need to be addressed at a much lower energy in neutrino showers, if compared to regular ones. On panels (c) and (d) of Fig. 2 we show the reference lines, i.e., the peak amplitudes due to the geomagnetic (red dots) and the Askaryan (black dots) mechanisms. These reference lines are used by the emission model to calculate the net electric field and its polarization. Shown are two ν showers: a high interacting one at 29.9 km above the detector on panel (c) and a deeper one at 8.4 km on panel (d). One can see that, if we assume a 100 $\mu V/m$ threshold (dashed line), the artifact would create fake triggers in the case of the deep interacting neutrino shower[1].



(a) (b) (c) (d)

Figure 2: (a): Comparison between the spectra of antennas close (top) and far away from the Cherenkov Cone (bottom, $\psi \gtrsim 4\theta_{\text{Cher}}$). The signal of the far away antennas is overestimated, since it exhibits "fake coherence" inside the frequency range of the antenna (30 – 80 MHz for Auger-RD). (b): Peak amplitude as a function of antenna distance for a proton shower and for two different thinning levels. (c) and (d): Emission toymodel reference lines and the Cut&Fit approach (see text for details).

We have two options to address this problem in RDSim. The obvious one is to decrease the thinning level in the ZHAireS simulations used to create the emission toymodels. But this is impractical, as the thinning level required to eliminate the artifact for deep interacting neutrino showers at the highest energies is very low, massively increasing computing time. The second option is to eliminate the artifact by replacing it with an extrapolation of the expected behavior of the reference lines at lower distances, before the artifact starts, using a simple fit. We call this the

[1]The line with the assumed threshold of 100 $\mu V/m$ in the plots is just to guide the eyes, as the effect of the artifact would increase due to the superposition of the two emission mechanisms and any $\sin\alpha$ scaling performed during the toymodel rotation. That means that the strength of the effect would also depend on the exact shower geometry.

Cut&Fit approach, shown on panels (c) and (d) of Fig. 2. The red lines are the fits to the reference lines before the artifact kicks in, and the purple (magenta) circles are the new values used for the geomagnetic (Askaryan) reference lines. Note that the reference lines are only changed for distances just before the artifact. That means that the resulting electric field will only change for far away antennas, which are the ones susceptible to the artifact. For the creation of the neutrino toymodels used in this work we used a combination of a lower (but still sensible timewise) thinning level, and the Cut&Fit method where still needed. It is important to note that this artifact is not RDSim specific. It will affect any microscopic simulation of the radio emission that uses thinning.

3. Neutrino events at the Auger-RD extension

The Auger radio upgrade (Auger-RD) [7], part of the Auger Prime upgrade of the Observatory [8], is in its final stage of deployment. It consists of the installation of a short aperiodic loaded loop antenna (SALLA), with NS and EW polarizations, on each of the 1661 stations of the surface detector (SD) of the observatory. When finished it will, by far, be the biggest radio array in the world for cosmic-ray detection, with an area of 3000 km^2. This radio array will of course inherit the 1.5 km spacing of the SD. With this antenna spacing, only the large footprints of regular inclined events (p, Fe, $\theta \gtrsim 60°$) can be properly sampled. On the other hand, the SALLA antenna beam pattern decreases rapidly above $\sim 80°$ [7]. This means that very inclined events are harder to detect and need to be much more energetic in order to have a similar SNR as their less inclined counterparts.

In this work, we consider as detected events with at least 3 triggered antennas, using a threshold of $|E_{\text{hor}}| = 100\ \mu V/m$ for the amplitude of the horizontal component of the electric field (normalized by the antenna gains). The ability of an event to be detected will depend on the overall brightness (electric field amplitude) of its footprint, and on its size. An event will not be detected if its footprint is too small to cover at least 3 stations, or if it is not bright enough to trigger antennas. Also note that the rapid decrease of the gains of the SALLA antenna becomes very important for very inclined showers ($\gtrsim 80°$), effectively dimming the footprint. For normal showers, the size of the footprint increases with zenith angle, while its brightness decreases. In the case of neutrino events, besides the zenith dependence, there is another variable that changes the footprint, namely the ν interaction (or τ decay) depth. Showers that develop closer to the detector will have smaller, but brighter, footprints. The discrimination of neutrino events is greatly facilitated by their geometry. For example, since they develop much closer to the detector than normal showers, the curvature of their radio front is larger. We are currently working on a discrimination method, with promising results, that uses the arrival times of the signals to estimate this curvature and discriminate ν events.

Neutrino induced events at Auger can be divided into 3 classes: Downgoing neutrino events (section 3.1), Mountain tau neutrino events (section 3.2) and Earth skimming tau neutrino events. The geometry of all these 3 classes favors inclined events. Earth skimming events are generated when a ν_τ interacts in the Earth's crust, close enough to the surface for a tau-lepton to emerge. If this τ decays in the atmosphere, close to the detector, it creates an upgoing shower that could in principle be detected. The air density at Auger altitudes is so that the Cherenkov angle is of the order of 1°. Since the radio emission peaks close to the Cherenkov cone, this type of event favors very inclined showers ($\gtrsim 89°$), and τ decays very close to its exit point from the Earth. These high zenith angles make the detection very susceptible to the antenna beam pattern, requiring much larger shower energies in order to be detected. On the other hand, these higher energies greatly decrease the probability of the τ decaying close to the detector. The emission model in RDSim cannot handle upgoing showers, but we have performed full simulations of a few events. Based on these few simulations, we believe that the phase space for detection is so small, that even the much larger number of τs produced by this channel will not be enough to compensate for the geometrical shortcomings, i.e., we expect that Auger-RD will, for the most part, be blind to this class of event.

3.1 Downgoing neutrino events

Downgoing neutrino events are created by the interaction of a neutrino in the atmosphere. These events favor more inclined geometries, since the amount of matter traversed by a neutrino in the atmosphere increases drastically with increasing zenith angle. For a 1400 m ground altitude (Auger), it has a 3-fold increase from ~3300 g/cm^2 at 75° to ~9000 g/cm^2 at 85°, with a proportional increase in the probability of the ν interacting in the atmosphere. On the other hand, the interaction is much more likely to occur at lower altitudes, closer to the detector. This means that the radio footprints of ν events are generally much smaller, simply due to the projection effect of the Cherenkov cone on the ground. It is important to note that the large 1.5 km antenna spacing of Auger-RD has a big impact on its ability to detect these smaller neutrino footprints. These events will trigger fewer antennas or even land between stations, triggering none. This problem is compounded in the case of a tau neutrino, since the produced tau-lepton still has to propagate further from the interaction point until it decays and creates an atmospheric shower, or until it reaches the ground. This means that these tau induced showers not only tend to develop even closer to the detector, but are also less numerous, since many τs won't decay in air. These close showers have even smaller radio footprints that are even harder to detect due to the large antenna spacing.

On Fig. 3, we show three ν_e CC events simulated with RDSim, using its simplified trigger and emission models, and compare them with detailed full simulations of the Auger-RD detector. In the case of the full detector simulations, dedicated full ZHAireS simulations of all antennas were used as input, using the same energy, geometry and secondaries from the ν_e CC interaction as the corresponding RDSim event. One can see that there is a very good agreement between RDSim and the full simulation, specially considering the toymodel-like approach used by RDSim.

On the left panel of Fig. 4 we show a first estimate of the aperture of Auger-RD for downgoing events induced by ν_e CC interactions, as calculated by RDSim. The energy shown is shower energy and we assume that the neutrino interacts somewhere in the atmosphere, so there is no cross-section dependence on the plot. One can see that the apertures for the two lowest zenith angles almost completely saturate at around $10^{18.75}$ eV, and decrease fast for lower energies. This is due to the larger but fainter radio footprints at these high zenith angles. At the lowest energies, the footprints for most interaction depths at high zenith are too faint to trigger antennas, and only events very close to the ground will be bright enough to be detected. At higher energies, above $\sim 10^{18.75}$ eV, the electric fields of even distant events become large enough to trigger antennas, and the large footprints trigger a huge number of antennas. In the case of the lowest zenith angles ($\theta < 65°$), the showers develop even closer to the ground, creating much smaller, but brighter, footprints. In general, the hindrance to the detection of these low zenith angle events is a geometrical one, as most of their footprints are too small to trigger 3 or more antennas, except on the infill (with smaller

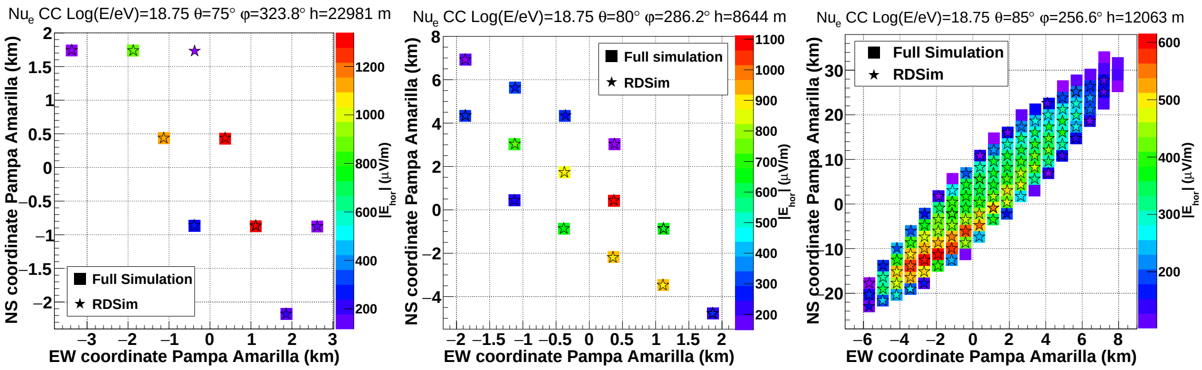


Figure 3: Comparison of events induced by ν_e CC interactions in the atmosphere simulated by RDSim (stars), with the same events simulated using full detailed simulations of both the shower and the Auger-RD detector (squares). The zenith angles of the events are 75° (left), 80° (middle) and 85° (right). The color scales inside the star and inside the square represent the electric field at each antenna, as obtained from RDSim and the full simulation, respectively.

antenna spacing) or regions of the array with double stations. This leads to an aperture that is smaller and less dependent on shower energy.

On the middle panel of Fig. 4 we show the RDSim estimated aperture for ν_τ induced events. The apertures, even at the peak ($10^{18.5}$ eV), are just a small fraction of the apertures for the ν_e CC case. This is due to the extra propagation of the tau-lepton, which needs to decay above the ground to create a shower. Also, these showers develop much closer, decreasing their footprint size. Increasing the energy further decreases the probability of the τ creating a shower, e.g., at 85° and 100 EeV, the average distance to the decay is ~5000 km, and less than 1% of the created tau-leptons decay above ground. For the lowest energies, the probability of creating a shower increases, but the footprints get dimmer and are harder to detect.

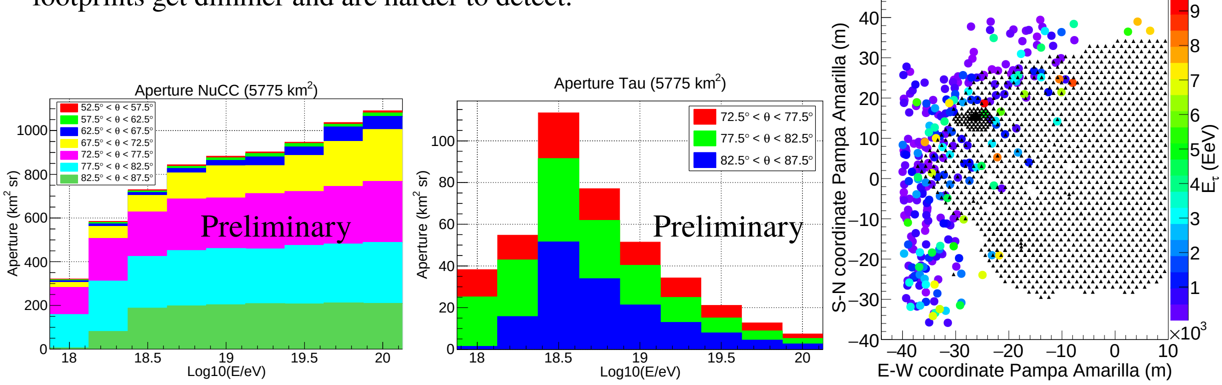


Figure 4: Left: Apertures for downgoing ν_e CC events at the Auger-RD estimated using RDSim. Middle: Same as left, but for ν_τ events. The displayed energy of both plots refers to shower energy. Right: Simulation of mountain τ events using RDSim, but without the actual detection simulation (see text).

3.2 Mountain tau events

In the case of mountain events (see section 1.1), the geometry at Auger-RD also favors very inclined events. Even at the westernmost region of the array, the one closest to the mountain range, only directions with zenith angles larger than ~87° can possibly cross the mountain. This can be seen on the middle and right panels of Fig. 1. At the center of the array, further away from the mountain, the minimum angle needed to just start crossing the top of the highest peaks increases to ~88°. The emerging mountain τs (with energy E_τ) still have to decay above ground to create a shower. High energy τs can create large showers, but are less likely to decay above ground, specially if the distance to the rock face (faceD on Fig. 1) is small. Lower energy tau-leptons are more likely to decay, but create less energetic showers that are much harder to detect, specially considering the very low gains of the SALLA antenna at these very large zenith angles. Unfortunately, this work is still ongoing and we were unable to finalize the needed simulations for the mountain event aperture calculations in time for this work. On the right panel of Fig. 4 we show an example simulation of mountain events. Except for the actual detection simulation, it includes all the steps described in section 1.1. The plot shows the core position and the energy of the decaying τ as a color scale. A total of 100k neutrinos of energy E_ν = 10 EeV crossing the mountain at a fixed zenith angle of 88° were simulated. But only 287 showers, about 0.3%, were created further than ~500 g/cm^2 from the shower core, in order to be at least partially developed before reaching the ground. The average energy of the decaying τs was $< E_\tau >$=1.7 EeV and the average height of the decay above ground level was $< h_{\text{decay}} >$=1.1 km (equivalent to ~26 km, or 2400 g/cm^2 from the core, along the shower axis). The allowed core positions encompass an area that contains the whole detector and is about twice as large. As expected, most showers are created for core positions close to the mountain range (western, and to some extent, northern parts of the plot). Also note that only 3 events were recorded East of the center of the array (0,0), since in this region, for the most part, we would need zeniths larger than 88° to cross the mountain. It is still unclear the fraction of these showers that can be detected. We will address the detection simulation of this class of event in a future work.

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