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Simulating radio emission from air showers with CORSIKA 8

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CORSIKA 8 (C8) is a new framework for air shower simulations implemented in modern C++17, based on past experience with existing codes like CORSIKA 7. It is a project structured in a modular and flexible way that allows the inclusion and development of independent modules that can produce a fully customizable air shower simulation. The calculation of radio emission from the simulated particle showers is incorporated as an integral module of C8, including signal propagation and electric field calculation at each antenna location using the "Endpoint" and ZHS formalisms simultaneously. Due to C8's flexibility, the radio functionality can be used both to validate other physics modules and to investigate specific physical scenarios. In this work, we are going to present air shower simulations generated with C8 and compare their predicted radio emission with corresponding air showers simulated with CORSIKA 7 and ZHAireS. The incorporation of both calculation formalisms in the same code also allows detailed comparisons for the same underlying shower, which we will discuss as well.

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1. Introduction

The radio detection technique of extensive air showers has undergone an impressive renaissance over the past 20 years [1] and has become a promising technique competitive with particle and fluorescence detection. Extensive air showers are very complex and the analysis of experimental data in order to reconstruct the main properties of the shower and of the primary particle, make detailed simulations of the radio emission necessary. CoREAS [2] (implemented in CORSIKA 7 [3]) and ZHAireS [4] are the state of the art simulation software tools for radio emission that the community heavily relies on currently. These tools implement two different formalisms for calculating the radio emission from the particle tracks in the extensive air shower, namely the "Endpoint" formalism [5, 6] and the "ZHS" [7] formalism, respectively. However, these implementations inherit the limitations of their underlying shower codes and do not provide the flexibility nor take advantage of new computing technologies to perform simulations for the diverse array of current and future experiments. In addition, the calculation of the radio emission is one of the most computationally expensive modules (especially for ultra high-energy showers) and this is going to be a stumbling block for the proposed next-generation experiments since they are growing significantly in size and number of radio detectors. To address these limitations, we have implemented the first radio emission module for the CORSIKA 8 (C8) simulation framework [8]. It is designed to be highly configurable, user-extensible and ready to quickly adapt technologies like multithreading to directly address the limitations of the current simulation tools and support the next generation of radio detection experiments.

2. The architecture of the radio module

Based on the main ideas of C8 which are modularity and flexibility, our module builds upon them and consists of four top level, user-configurable and swappable components. These separate components construct a *radio process* which is added in C8's process sequence (see Figure 1) and gives access to all particle tracks in order to extract the necessary information for the radio emission calculation. These components are programmed under flexible and clear guidelines that makes them easily updatable even by users who want to tailor the simulation to their specific experimental needs. These are the *track filter*, the *formalism*, the *propagator* and the *antenna*.

Filter This serves as a distinction mechanism for relevant particles and tracks from C8 to be pushed into the radio emission calculation. For example, the radio module processes only e^+ and e^- and ignores the rest of the particles. Also, tracks with specific characteristics can be selected like a specific atmospheric depth range for the signal pulse calculation and so on.

Formalism This is responsible for the main calculation of the radio emission. The electric field vector can be calculated by two fully implemented formalisms, namely the CoREAS algorithm [2] which uses the "Endpoints formalism" [5, 6] and the "ZHS" algorithm [7]. Direct comparisons between the two formalisms are feasible since they are both developed in the same underlying shower code (C8) and will be shown along with comparisons in their original implementations in CoREAS [2] in CORSIKA 7 and in ZHAireS [4]. Previous comparisons between the two

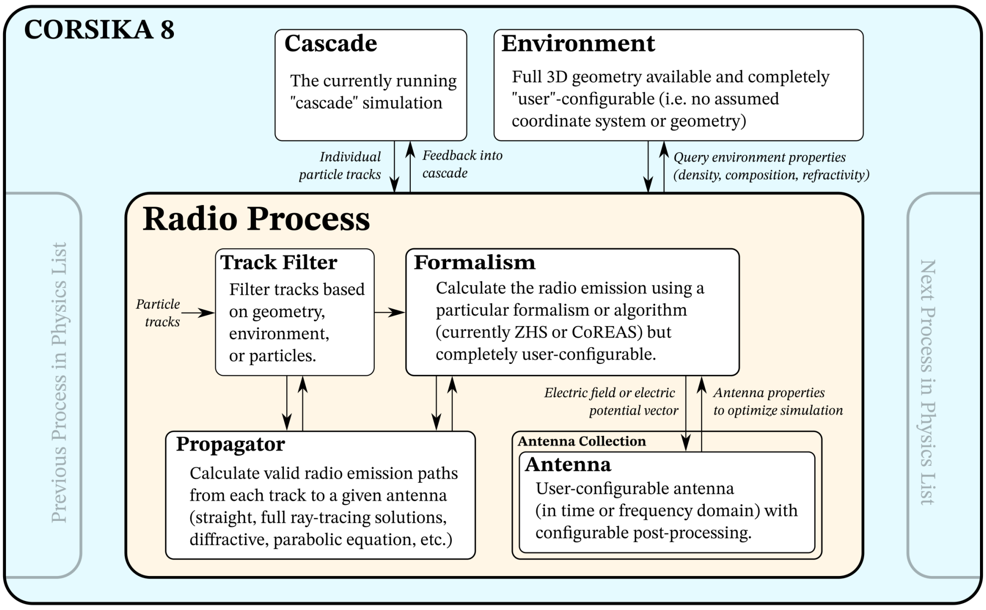

Figure 1: A schematic diagram of the radio process currently implemented in C8 and how it integrates with the C8 framework.

formalisms have been made [9], although these studies inherit the differences of the shower code they rest upon (CORSIKA 7 for COREAS and ZHAireS for ZHS).

Propagator This is called by the *Formalism* to calculate the (potentially multiple) valid radio signal propagation paths from every particle track to each antenna. The two propagators that are implemented at the moment use a straight-ray approximation (similar to C7 and ZHAireS) including: 1) an analytic ray path solver that can only be used in media with uniform or exponential refractive indices; and 2) an *integrating* propagator that numerically integrates the time delay along each propagation path and can therefore work in arbitrarily complex media where no analytic solution exists. The separation of the signal propagator from the emission formalisms, allows the implementation of more advanced propagation techniques (e.g. full raytracing or parabolic equation methods) or more complex simulation scenarios (such as cross-media showers) without altering the underlying emission formalisms.

Antenna The *Antenna* instance is storing, processing, and managing an individual antenna in the simulation. Multiple instances of independent antennas with the same or different configurations make up an *antenna collection*. Currently, a standard time-domain *perfect* antenna (frequency-domain can also be supported) has been implemented whose characteristics are the sampling rate, detection start time, and a time window within which the signal shall be calculated.

It is worth noting that our radio module has separate validation tests which are performed in every update of our code, that simulate the synchrotron emission from one electron performing a circular loop in a uniform magnetic field utilizing a "manual" and C8's tracking algorithm as discussed in [11]. An updated validation test is shown in Figure 3. This gives us the confidence to perform a full scale comparison between the simulation software codes mentioned above.

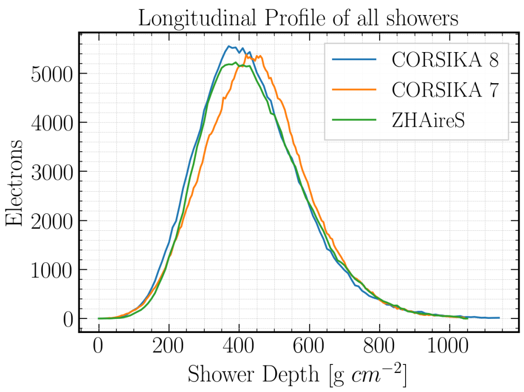

Figure 2: The longitudinal profile of all 3 showers are shown. We can see that their profiles are relatively close so this allows us to compare them.

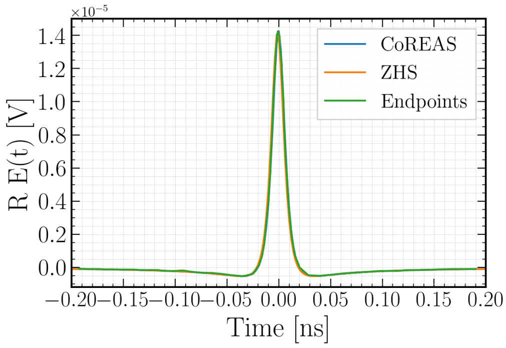

Figure 3: The radio pulse produced from an electron in a uniform magnetic field performing a circular loop. This serves as a validation test of the radio module in C8 and is compared to a reference pulse calculated analytically in [5].

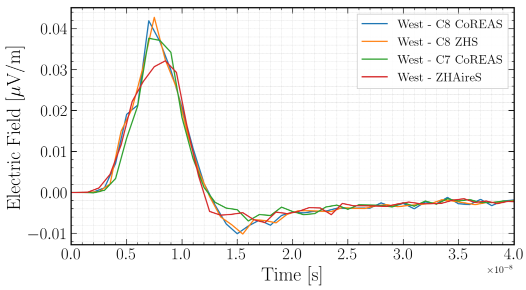

Figure 4: Signal pulse comparison for antenna at 50 m from the shower core - West polarization.

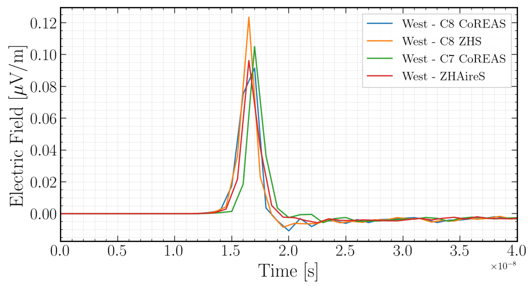

Figure 5: Signal pulse comparison for antenna at 200 m from the shower core - West polarization.

3. An extensive air shower simulation comparison

In this section we simulate one electron induced 10 TeV vertical extensive air shower with CORSIKA 8, CORSIKA 7 and ZHAireS with no thinning applied. In more detail, we simulate showers in the "US Standard atmosphere" with a uniform refractive index ($n = 1.000327$), and a constant horizontal geomagnetic field of 50 µT aligned in the x direction. The electromagnetic interaction model that C8 uses, and therefore was used in our simulations, is PROPOSAL v.7.2.1 [10]. For the antenna array we use a star-shaped pattern of 160 antennas located at the ground, in 20 concentric rings spaced equally from 25 m to 500 m from the shower axis with 8 antennas distributed azimuthally in each ring (exact locations are shown in the fluence maps in Table 12). Since we are comparing only three showers, we plot their longitudinal profiles in Figure 2. From that, we can see that the three showers made with C8, C7 and ZHAireS behave similarly and their depth of shower maximum (X_{max}) is close to $430 g/cm^2$, which renders these showers comparable for further analysis. The particle energy cuts are set to relatively high values of $5 MeV$ due to limitations of the version of PROPOSAL we used. However, it is worth noting that such limitations have been addressed and fixed in newer versions of PROPOSAL.

In our previous work [11] a similar comparison was made in which, and although our results

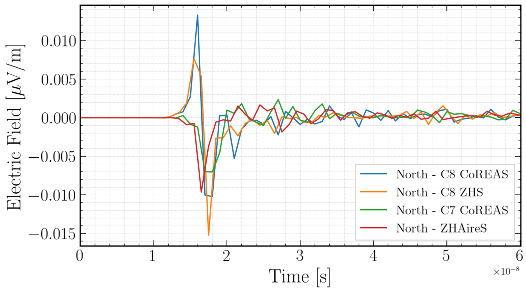

Figure 6: Signal pulse comparison for antenna at 200 m from the shower core - North polarization.

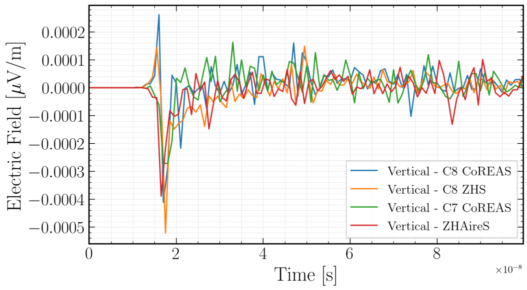

Figure 7: Signal pulse comparison for antenna at 200 m from the shower core - Vertical polarization.

were encouraging, we noticed some unexplained effects in the C8 calculations. First, in order to produce fine radio signal pulses we were previously forced to reduce the tracking step size (to a maximum deviation in the magnetic field of 0.0001 radians), which had a large impact on the computation time. Secondly, although close to the shower axis C8 had a good agreement with C7 and ZHAireS, as we were moving further away from the axis, discrepancies in the amplitude of the C8 pulses with respect to C7 and ZHAireS were noticeable and in many cases could reach 50%. Finally, as observed by the frequency spectra, the C8 radio simulations would lack in high frequency content for antennas at larger distances from the shower axis. After thoroughly investigating the tracking algorithm used in C8 we confirmed that it works as intended. The bug was identified in C8's main algorithm, *Cascade*, where there was a slight inconsistency when crucial information like particle time and position were updated. This issue was found, addressed and fixed using our radio module as the coherent emission it calculates is very sensitive to time and position information. Hence, the results we present here are updated and no longer affected by this bug.

When comparing the simulations from C8, C7 and ZHAireS one must take into consideration that each shower code uses a different tracking algorithm and different electromagnetic interaction models, so a 100% agreement is unrealistic since the showers will not be the same. In Figures 4 and 5 the West polarization is plotted for C8-CoREAS, C8-ZHS, C7 and ZHAireS for antennas at 50 m and 200 m from the shower axis, respectively. The amplitudes agree within 20% and the pulses have the same shape and length. Moving to the other polarizations, in Figures 6 and 7 the north and vertical polarization for an antenna at 200 m from the shower core is plotted. Although all pulses show a similar trend in terms of shape, amplitude agreement gets worse within 50% and we notice a differing behavior in the C8 radio pulses. In north and vertical polarizations C8 produces a bipolar structure in both formalisms which is absent in C7 and ZHAireS. We have investigated in detail C8's core code and PROPOSAL and we concluded that multiple scattering is so far not taken into account properly due to an interface conflict in C8. There is ongoing work to solve this issue by introducing a more consistent and precise particle/track interface and preliminary studies are encouraging but still under development.

Advancing through our comparisons, in Figures 8 and 9 we plot the frequency spectra for the West polarization of antennas at 50 m and 200 m from the shower axis, respectively. We observe a significant improvement over what we had presented in [11] and an overall good agreement with C7 and ZHAireS. It is interesting to note that C8-CoREAS and C8-ZHS slightly diverge for

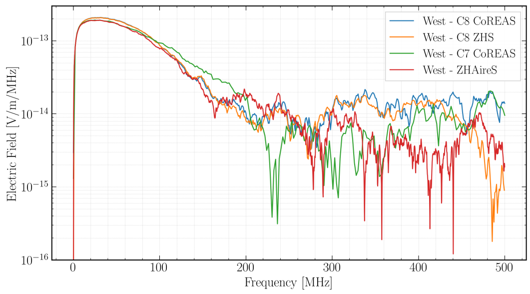

Figure 8: Frequency spectra comparison for antenna at 50 m from the shower core - West polarization.

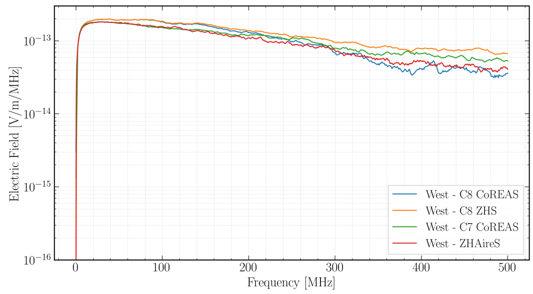

Figure 9: Frequency spectra comparison for antenna at 200 m from the shower core - West polarization.

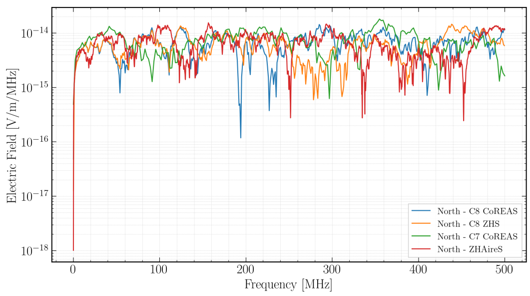

Figure 10: Frequency spectra comparison for antenna at 200 m from the shower core - North polarization.

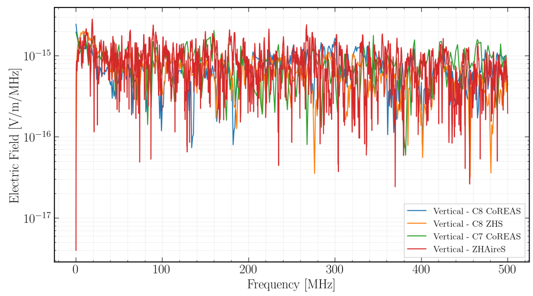

Figure 11: Frequency spectra comparison for antenna at 200 m from the shower core - Vertical polarization.

frequencies larger than $420MHz$ for the antenna at 50 m and for frequencies larger than $200MHz$ for the antenna at 200 m. We also look into the frequency spectra of the antenna at 200 m in North and Vertical polarizations, Figures 10 and 11 respectively. When looking at the corresponding pulses of these polarizations, Figures 6 and 7, the bipolar structure we mentioned earlier is evident. In the frequency spectra though there is no clear indication towards this unexpected behaviour or a strong disagreement between the three showers that were simulated.

By exploiting the fact that the differences in the underlying shower codes of C7 and ZHAireS vanish within the context of C8 we are able to directly compare the two formalisms as has been presented in the plots so far. We can see that they agree within 5% considering the pulse amplitude for antennas at 50 m (Figure 4) and within 25% and 50% for antennas at 200 m, Figures 5, 6 and 7 respectively. To draw more general conclusions about the agreement, detailed studies with increased statistics need to be performed where our module can be used.

As a final comparison, we calculate and plot 2D maps of the energy fluence in the 30-80 MHz band for both C8 formalisms as well as C7 and ZHAireS in Figure 12. The absolute scale and polarization characteristics of all results agree qualitatively well, although slight differences become apparent, in particular an offset from the symmetry axis in the $\vec{v}\times(\vec{v}\times\vec{B})$ polarization in the C8 and ZHAireS results which is not present in C7. Furthermore, when considering polarizations $\vec{v}\times\vec{B}$ and $\vec{v}$ it is evident that the C8 maps for both CoREAS and ZHS are much more symmetrical than those of C7 and ZHAireS. This is likely related to the problematic bipolar pulse structure in the

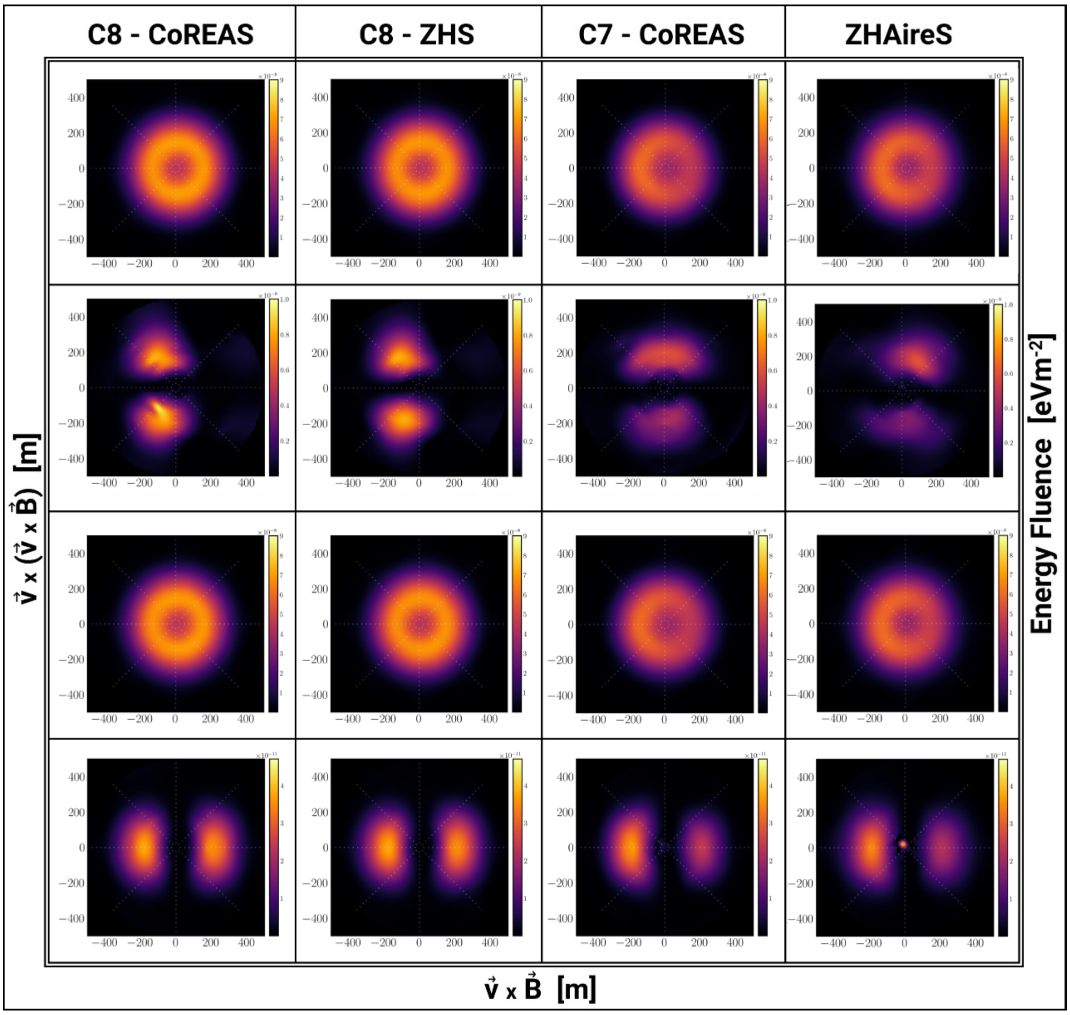

Figure 12: Table of energy fluence in different polarizations of the electric field for C8 both CoREAS and ZHS, C7 CoREAS and ZHAireS. The order of the polarizations we see starting from top to bottom is: all polarizations, $\vec{v} \times (\vec{v} \times \vec{B})$, $\vec{v} \times \vec{B}$ and $\vec{v}$.

charge-excess emission observed in Figures 6 and 7 which we are working towards fixing. As a final comparison remark, there is a "blip" in the $\vec{v}$ polarization only for ZHAireS, which we observed in our simulations.

4. Conclusions

The implementation of radio-emission calculations in C8 is presented. Both the CoREAS and ZHS algorithms have been ported very closely from their original versions in C7 and ZHAireS in a modern, modular structure that allows flexible extensions for the needs of current and future experiments.

We have performed significant updates to the core C8 code and we have fixed performance and agreement issues that were present in our previous results [11]. With every major update, either in the core code of C8 or in the radio code, low-level validation tests with single electrons undergoing circular motion in a uniform field are carried out to ensure that the radio-emission physics and the particle tracking in C8 work correctly. For our extensive air shower comparisons, we have simulated a vertical 10 TeV electron shower in a uniform refractive index medium with C8 (both formalisms), C7 and ZHAireS. We observe overall good agreement of C8 with the reference pulses, although the issue of C8 pulses having bipolar structure in the north and vertical polarizations is evident and there is ongoing work to fix that. Finally, we observe an agreement within 25% overall between the CoREAS and ZHS implementations in C8 which is a use case scenario of our flexible design that makes such comparisons possible.

Future work on the radio module will consist of advancements in performance and the development of more sophisticated signal propagation scenarios, for which we can take full advantage of the flexible environment and geometry of C8. After that, detailed comparisons of air showers with much higher energies along with statistical studies will be performed to establish the consistency of our module with earlier implementations and highlight its advantages.

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