ZHAireS 1.0.30 Manual Draft

M. Tueros for the ZHAireS people of the world

This Document is the draft of the user manual i intend to format following the AIRES manual. So dont pay attention to formating.

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ZHAireS is distributed worldwide as "wineware" for all scientists working in educational/research non-profit institutions, as long as they cite:

1] J. Alvarez-Muñiz, W. Rodrigues, A. Romero-Wolf, M. Tueros and E. Zas, Astropart. Phys., 35, 325, (2012), and all our future papers regarding ZHAireS.

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Current Limitations:

ZHAIRES SUPPORTS ONLY 1 shower per task

Aires has the capability to run several showers in 1 task (i.e. with one input file). ZHAireS does not support this. **Be sure to set TotalShowers 1.**

Fixed zeinith and azimuth angles

Aires has the capability of specifying a range of primary zenith and azimuths, and a random value folowing a certain distribution is chosen at run time. ZHAireS does not support this. You must explicitly set the Zenith and Azimuth values

Dense Media Has not been tested nor validated:

Although Aires supports the simulation on an homogeneous media with arbitrary density, and ZHAireS supports entering an arbitrary fixed refraction index (which could be used to simulate radio-emission in ice for example) this has not been tested nor validated. Do not use it lightly.

Fixed Energies Recommended

Aires has the capability of specifying a range of energies, and a random value folowing a certain distribution is chosen at run time. ZHAireS support this, but the python functions used externally to produce HDF5 files do not.

Summary: What is ZHS. Who are the original Authors. What does it do? How is it embeeded in AIRES to do ZHAireS (and why?). Who started with this and why i am now in charge?. Its a long story...that i will write eventually

Implementation References:

[1] "Coherent Cherenkov radio pulses from hadronic showers up to EeV energies" J. Alvarez-Muñiz, W. Rodriguez, M. Tueros and E. Zas, Astropart. Phys., 35, 325, (2012).
[2] "Calculations of electric fields for radio detection of ultrahigh energy particles." D. García-Fernández, J.Alvarez-Muñiz,W.R.Carvalho Jr., A. Romero-Wolf, E. Zas. Physical Review D 87, 023003 (2013)
[3] "Monte Carlo simulations of radio pulses in atmospheric showers using ZHAireS" J. Alvarez-Muñiz, A. Romero-Wolf, E. Zas, Phys. Rev. D 81,123009 (2010).
[4] "Electromagnetic pulses from high-energy showers: Implications for neutrino detection" E. Zas, F. Halzen, T. Stanev, Phys. Rev. D 45, 362 (1992).
[5] "Radiodetection of cosmic neutrinos. A numerical, real time analysis" F. Halzen, E. Zas, T. Stanev, Phys. Lett. B 257, 432 (1991).

What is new?.

The biggest difference is that now we are based on AIRES 19.06.00, that includes many improvements in shower simulation including the post-LHC hadronic models.

But along with it came a lot of technical improvements, including

-- Making ZHAireS an external module suported natively by AIRES, making it much easier to install.
-- Now ZHAireS benefits from AIRES simulation restart capabilities, meaning that you can configure it to save its results periodically and in case the simulation is stopped, you can restart it from the last checkpoint.
-- CoREAS friendly output (although in international units)

Physics: Describe the algorithms. Make a resume of the papers. Show plots.

ZHAires is an implementation of the algorithms developed by Zas-Halzen-Stanev in the well-known and well-tested ZHS code [3,4] to calculate the components of the electric field produced by charged particle tracks in the shower. These algorithms are obtained from first principles from the Lienard-Wiechert potentials, so no emission mechanisms or models are presupposed. The full derivation can be seen in [3] for the frequency domain and in [4] for the time domain.

The radio emission calculations are done in parallel to the AIRES shower simulation: as each charged particle in the shower is propagated by AIRES in steps. These steps are taken as a single particle tracks and their contribution to the radio emission is calculated and added to the total electric field in both the time and frequency domains. This procedure naturally accounts for the radio emission from any kind of deflection, scattering and from the creation or annihilation of charged particles in all of the physical processes used to simulate the shower, including interference effects associated to the different space-time positions of the particles in the shower.

In the original ZHS algorithms [3,4], the field calculation was performed in the Fraunhofer approximation. In this case the observer "sees" the radiation arriving from all the points in the shower at the same angle, and changes in the phase from each track are taken into account through a simple projection. This approach works well for showers in dense media, such as ice, since the size of the shower is much smaller than the typical distance to the antennas. In the case of air showers, the distance to the observer is usually of the order of the shower size, and thus the Fraunhofer approximation is no longer valid. In order to make the method valid for the closer observers in air showers, we allow the distance and direction to the observer to change from one track to the next, but we still use the Fraunhofer approximation inside each track. In the simulation, the vast majority of tracks satisfy the Fraunhofer condition for frequencies up to 300 Mhz. If a particular track in the simulation does not satisfy this condition, e.g. a track passes very close to an antenna, it is further divided into several sub-tracks,in order to always guarantee the validity of the Fraunhofer approximation while working in what would macroscopically be the Fresnel zone.

To obtain the radio signal at each antenna for the shower as a whole, the contributions of each particle track to the vector potential A are added up. This net vector potential is then differentiated with respect to time to obtain the net electric field as a function of time for each antenna. In the far field, this formalism is equivalent to the one used in [17[2]], as shown in [37[2]].

Is this a place to speak about the diference with the endpoints formalism?

Atmosphere: Delve into the diference between the Linsley and the pure exponentials. Show plots.

ZHAireS uses an exponential model to take into account the strong dependence of the index of refraction n on temperature, presure and humidity. Motivated by the exponential decrease of density with altitude, we parametrize the refractivity R ($[n(h)-1]\times 10^6$) with height h as

$R(h) = R_s \exp(-K_r h)$ (?)

with the default values $R_s = R(h = 0) = 325$ and $K_r = 0.1218$ km^{-1}. These values reproduce the refractivity calculated in [39 [2]] up to h ~ 10 km within less than ~ 1%. The values in [39[2]] take into account the humidity dependence of the refractivity, which increases the refractivity at low altitudes where the effect of a variable index of refraction is most important, since the shower has a larger number of particles. At higher altitudes, the exponential model slightly overestimates the refractivity, but the effect of the variable index of refraction at these altitudes is much less important, since above 20 km the shower has barely started developing and the number of particles is small. It is also worth noting that since R depends on temperature and humidity, there are large seasonal and even daily variations in the refractivity that are associated to atmospheric conditions. Rs and Kr can be changed by the user using the directives **RefractionIndex** and **RefractionIndexKr** to accomodate for this.

The variable atmospheric refractive index would in principle make the radio emission follow a curved path. However, in [20[2]] it was shown that the effect of the deviation from a straight path on the time structure of the pulse is negligible, and thus in ZHAireS its assumed that the radio emission follows a straight path from the emission point to the antenna. The effect of a variable refractive index in the propagation time of the signal is taken into account using the effective refractive index along the line of sight from the antenna to the track.

Caveat:

The Exponential atmosphere is not consistent with AIRES density profile (this is the first big thing to solve, along with the speed in the calculation)
Timing accuracy with variable index of refraction is guaranteed to 0.15ns accuracy down to 1000km from the core. Closer is better of course.
In any case, AIRES spherical geometry is guaranteed to 1100km (10 geogr degrees) This will make working with 0.5ns time bins safe, thus allowing frequencies of 1Ghz. If your cascades and antennas are closer to the origin than 100km, acuracy doubles. In any case, keep in mind that the accuracy in the model of the index of refraction is much lower than that (at this level of precision you should care of humidity, clouds, inversion layers, etc)

A NOTE ON COORDINATE SYSTEMS

Note that, on .dat and .emp output, ZHAireS express the X and Y coordinate as in per the AIRES coordinate system, but the Z is measured from the injection point. So if the injection point was set at 100km, a z at 1000m above sea level will be output as 99000m. This comes from historical legacy from the original ZHS code, and might be changed to match the AIRES coordinate system in future releases.

Usage: Describe the general Idea (to do)
Describe all the IDL commands (done)
Describe compilation time constants usage (to do)
Describe the output (to do)

#Basic ZHAireS IDL Directives

ZHAireS On/Off (Default:Off)

Enable/Disable the calculation of the electric field, as per the ZHS formalism

FresnelFreq On/Off (Default:Off)

Perform the field calculation on each antenna position (specified with the **AddAntenna** directive) in the frequency domain, using the Fresnel aproximation. You will need to specify the frequencies at which you want to compute the field witht the **AddFrequency** directive. Note that the CPU time to compute each frequency is of the order of computing the whole signal in the time domain...so if you want several frequencies you are better off using the time domain formalism and then making the fourier transform. Its unpractical, but usefull for consistency checks. With the default compilation options it is limited to 10 frequencies. If you need more, recompile after changing the appropiate parameter in src/zhaires/fieldcomm.f

FresnelTime On/Off (Default:Off)

Perform the field calculation on each antenna position (specified with the **AddAntenna** directive) in the time domain, using the Fresnel aproximation. You will need to specify the antenna time window with the **AntennaTimeMin** and **AntennaTimeMax** directives. You will also need to specify the time bin size with the **TimeDomainBin** directive. Note that the maximum number of time bins is controled by a parameter at compile-time.

AntennaTimeMin Value (Default:-200 ns)

lower edge of the signal time window at each antenna

AntennaTimeMax Value (Default:4800 ns)

upper edge of the signal time window at each antenna

Note that the antenna time window is set arround the time a plane wave in vaccum originating on the injection point would reach the antenna. This means that all signals should start at positive times, and further behind the plane wave as you go through denser atmospheres (bigger n) and farther away from the shower axis.

If the parameter **ExpectedXmaxDist** is set, ZHAireS will use instead a spherical wave emanating from a point located at the specified distance from the core along the shower axis (where you said xmax was going to be), taking into account the effective index of refraction from this point to each antenna, greatly increasing the acuracy for the positioning of the time window. Note that in this case, its posible for the signal to arrive before the spherical wave (for example, due to the finite size of the emision region some emision might happen from a point closer than the stated position of xmax). The closer is xmax, the bigger you will have to set the time window.

If you are planning on running many simulations, try running some extreme cases first to set the optimal window. Smaller time windows reduce significantly the amount of CPU time and disk space. The default values are set for safety, but keep in mind they are usually overkill.

ExpectedXmaxDist Value (Default: None)**[!new in ZHAireS 1.0.28]**

Set the expected distace to xmax for the shower, wich you can get beforehand by running the same input without radio (**ZHAireS Off**), if you manually set the seed for random number generator (see RandomSeed in Aires Manual). This will allow ZHAireS to fine tune the time windows, so that you can use tighter time windows and produce faster simulations, with smaller output.

TimeDomainBin Value (Default:1 ns)

Bin size of the time domain calculations. Be careful to use a bin size small enough as to comply with the Nyquist criteria if you plan to process the computed time signal with a Fourier transform.

With the default compilation options, you can have up to 10k time bins between **AntennaTimeMin** and **AntennaTimeMax.** If you need more, recompile after changing the appropiate parameter in src/zhaires/fieldcomm.f

RefractionIndex Value (Default:1.000325)

Value of the refraction index **AT SEA LEVEL.** The refraction index will change with with height using an exponential atmosphere, with the exponent given by **RefractionIndexKr.**(see eq. ???)

If you want the refraction index to be constant at all heights, please add the directive **ConstRefracIndex** On to the input.

RefractionIndexKr Value (Default:-0.1218 km^{-1})

Value of the constant Kr used in the exponent in the refraction index model (see eq. 1)

https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.453-11-201507-S!!PDF-E.pdf

#Antenna Possitions

AddAntenna Label X Y Z [m]

Add an antena at the specified location (in Aires coordinate system, **but with Z measured from the defined ground level**)

With the default compilation options, you can have up to 2k antennas. If you need more, recompile after changing the appropiate parameter in src/zhaires/fieldcomm.f. However, keep in mind that CPU time scales linearly with the number of antennas. If you are needing so many antennas it might be wise to run the same shower in several instances (using the same random seed) each instance with a fraction of the desired antennas. This will let you run the simulation using several CPU cores in paralell. Since the cost of the simulation of the cascade itself is more or less equivalent to the cost of simulating 1 antenna, simulating bunches of more than 100 antennas results in a minimal overhead.

AddAntenna Line x1 y1 z1 x2 y2 z2 nant

Add a line of antennas from point 1 to point 2 with nant antennas, including one in each extreme

AddAntenna Ring x1 y1 z1 radius[m] phi0[deg] nant

Add a ring of a givent radius centered at point 1, starting at azimuth phi0 [deg, magnetic]

AddAntenna None

Erases all the antennas defined previously. Only usefull in interactive mode.

#Frequencies

AddFrequency Freq [Mhz]

Add a specified frequency

AddFrequency Log Fmin Fmax nfreq

Adds nfreq frequencies from Fmin to Fmax (in Mhz) using a logarithmic step

AddFrequency Linear Fmin Fmax nfreq

Adds nfreq frequencies from Fmin to Fmax (in Mhz) using a linear step

AddFrequency None

Erases all the previously declared frequencies. Only usefull in interactive mode

#Output Control

CoREASOutput On/Off (Default:Off) **[!new in ZHAireS 1.0.25]**

Produce CoREAS style output, producing one .trace file per antenna containing the time, ex, ey and ez, and one antpos.dat file with the list of antennas, with its antenna labels and positions. Note that this output is still in uV/m, instead of the cgs units used by CoREAS.

EMPOutput On/Off (Defaiult:Off) **[!new in ZHAireS 1.0.25]**

Produce .EMP output (legacy format, kept for back compatibility but will not be maintained)

ReducedDATOutput On/Off (Default:Off) **[!new in ZHAireS 1.0.25]**

Normally, the program will produce .dat files with electric field, vector potential field, antenna position and time output that is easy to plot. However, this takes a lot of space. When you enable ReducedDATOutput, only antena number, time and electric field components are written.

RemoveZeroOutput On/Off (Default:Off) **[!new in ZHAireS 1.0.25]**

Remove time bins with no signal (i.e, electric field indentically null) to save up space

#Experimental Options

SumTracks On/Off (Default:Off)

Enable/Disable the calculation of the sum of track lengths, the number of tracks and other realated quantities.

IncludeLowEPcles On/Off (Default:Off) **[!new in ZHAireS 1.0.25]**

LowEPcles calculations are experimental should not be used for production. The idea is to make an estimation of how far a particle would travel in a stright line and include a "end of life" track. The objective of this would be to speed up the simulation by increasing the low energy limit (up to where is safe to ignore electron pair creation (few MeV). In its current implementation its too slow to be of any use.

IncludeHadrons On/Off (Default:Off) **[!new in ZHAireS 1.0.25]**

Hadrons calculations are experimental should not be used for production. The idea is to include heavy particles on the radio calculation (pions, protons and muons). By default only electrons and positrons are used.

SeparateContrib On/Off (Default:Off) **[!new in ZHAireS 1.0.25]**

Separate the contributions of e+/-,LowEPcles and Hadronic (will increase memmory usage)

EarthShadow On/Off (Default:Off) **[!new in ZHAireS 1.0.26]**

Consider the round earth shadow. When tracks are far away from the origin, they might not be visible from the other side due to earth curvature. This command was intended to speed up simulatinons, but assumes that the antenas are close to the origin, and that the earth curvature is negligible for the antenna positions. Since few tracks were afected by this, and the check is done on every track, the CPU gain was minimal, as well as the impact on the final result. This was by default **On** on old versions of ZHAireS, and is left for back compatibility but it might be removed in future releases. Use it with care.

A NOTE ON CPU Time: Include note on the effect of low energy cut,

and benchmarks