First version: OMH, Friday April 26, 2019

Hands-on micro-session "GRAND scripts"

Abstract:

This hands-on can be divided into two parts: one consists in a step-by-step progression through the computation of the antenna response to an electromagnetic transient signal, and the other in getting accounted with signals produced at antenna output, where you will study for example how the filtering frequency band may affect time traces and amplitude pattern at ground from a shower simulated on the GRANDProto300 detector.

Disclamer: I start writing this file exactly 11 hours before the session starts. It is therefore certainly full of mistakes!!

Exercice n°1: find and correct them ☺

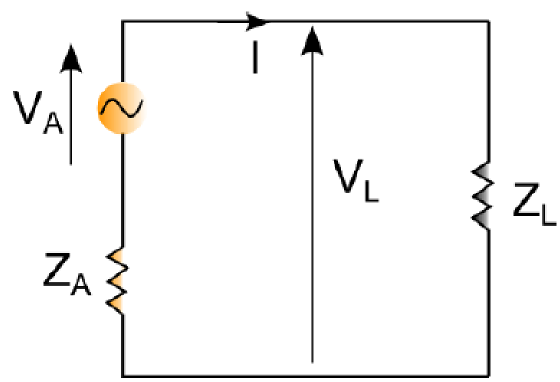
Note: the time needed to complete this "GRAND scripts" micro-session largely exceeds the nominal 1.5 hours. So feel free to skip any boring part! The exercises allowing to get a broad idea of the topic are tagged in green.

A- Antenna response computation

TextBook antenna theory

Let's first introduce a few basics of radio detection (for a complete reference, you may want to check Balanis :

An antenna is often represented as a voltage generator V_A associated with a (complex) impedance $Z_A=R_A+iX_A$ (with R_A and X_A the antenna resistance and impedance respectively). In reception mode, the voltage V_A is generated at the antenna output by the electromagnetic wave passing through the antenna. Note here that Z_A is a ***radiative impedance***, and has nothing to do with the actual electric impedance of the wire composing the antenna. The real part of the radiative impedance allows in particular to compute the power radiated by the antenna in emission mode when a current *I* flowing through: $P_{rad} = R_A \, \mathrm{I}^2$.



First version: OMH, Friday April 26, 2019

One of the important parameter of an antenna is its ***directional gain* G(θ,ϕ)**. It is defined in emission mode as the ratio of the intensity of a signal emitted in direction (θ,ϕ) to the total power injected in the antenna.

It is related to the ***antenna effective area*** by the following formula:

$$A_{eff}(f,\theta,\varphi) = \frac{f^2}{4\pi c^2} G$$

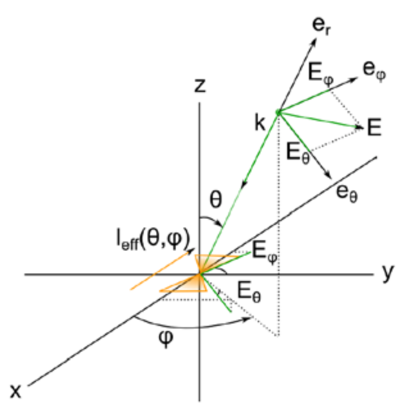
The antenna effective area measures its equivalent collection surface to an input electromagnetic flux. You may use the effective area to compute the power received by an antenna from the sky through:

$$P = \int_{4\pi} B_\nu(\theta,\phi,\nu) A_{eff}(\theta,\phi,\nu) \sin\theta d\theta d\phi$$

where *B* is the spectral radiance of the Galaxy (in units of W/m2) (see section 3.2 of the [2019 TREND paper]() for details)

As we are detecting electrical fields -a vectorial information-, a more natural quantity to use in GRAND is the *antenna effective length*, defined as:

$$V_A = \overrightarrow{l_{eff}} \times \vec{E} \qquad (1)$$



where V is the voltage generated at the antenna output by an incoming field $\vec{E}$. The vectorial quantity $\overrightarrow{l_{eff}}$ is complex (phase and module), and just like the effective area, it depends on the frequency and direction of origin of the wave. It therefore concentrates a lot of information. It is often decomposed on the local base $(\overrightarrow{e_r}, \overrightarrow{e_\theta}, \overrightarrow{e_\varphi})$ (see Fig. n°2) through $\overrightarrow{l_{eff}} = l_{eff}^{\theta}\overrightarrow{e_\theta} + l_{eff}^{\varphi}\overrightarrow{e_\varphi}$.

Quiz question: why isn't there any component of $\overrightarrow{l_{eff}}$ along $\overrightarrow{e_r}$?

Answer: because we work in the (far-field) approximation where the waves are supposed to be plane, i.e. with electromagnetic fields perpendicular to the direction of propagation. There is therefore no need to compute the antenna response in a direction where there is no signal.

First version: OMH, Friday April 26, 2019

Effective length computation

Here we do very boring stuff to compute $\overrightarrow{l_{eff}}$ ☺

The response of the GRAND HorizonAntenna (see section IV.B of the GRAND white paper) was computed by Didier Charrier with a dedicated electromagnetic simulation program called NEC (Numerical Electromagnetic Code). NEC calculates the electric field emitted by the antenna for an excitation current of given frequency and amplitudes.

Quiz question n°2: how come we simulate the antenna behavior in emission mode, while we are using it in reception mode??

Answer: because of the reciprocity principle which states that antennas work identically in emission and reception mode: a current I inducing an electric field E in emission mode will be identical to that produced by the antenna receiving this very same electric field in reception mode.

The output file *HorizonAntenna_X.out* is available in the *data* directory[1] and can be edited. It is composed of different sections: in the first one (structure specification), the antenna geometry is described.

Exercise n°2: write a python script displaying the antenna geometry (difficulty: moderate)

NEC computes the electric field emitted in directions (θ, ϕ) (following angular conventions given in Fig. 2) for excitation currents *I* of various frequencies in the 20-300MHz range, as well as its associated antenna gain and impedance.

Exercise n°3: here we realize that the parameter we look for -$\overrightarrow{l_{eff}}$ – is not computed by NEC ☹… Help us to solve that by writing the formula allowing to compute ||$\overrightarrow{l_{eff}}$|| and then l_{eff}^{θ} and l_{eff}^{φ} (difficulty: hard)

Hint: it can be demonstrated (for example here) that effective length and effective area are related by the following formula:

$$A_{eff} = ||l_{eff}||^2 \frac{Z_0}{R_A}$$

where Z_0 is the impedance of free space and R_A the antenna resistance.

In order to read the antenna's response, it has to be connected to an electronic circuit, which is seen by the antenna as a load of impedance Z_L (see Fig. 1). The "usefull" voltage generated at antenna output is

[1] The data folder is too large to be stored in the GitHub repository. It is therefore available on the GRAND sps directory @ IN2P3 computing center only: . Copy it locally. The location where the data folder is stored is noted *$DATADIR* in this document and has to be replaced by its actual name when executing the exercises.

therefore V_L (see Fig. 1) and rather than $\overrightarrow{l_{eff}}$, the relevant quantity for us is $\overrightarrow{l_{eq}}$, defined as:

$$V_L = \overrightarrow{l_{eq}} \times \vec{E}$$

Exercise n°4: compute the analytical formula giving $\overrightarrow{l_{eq}}$ as a function of $\overrightarrow{l_{eff}}$ for a load $Z_L = R_L + iX_L$. You may use formula (1) (difficulty: easy)

Answer: open necoutputreader2.py and compare your results of exercises n°3 & 4 to lines #148-152 (author: S. Le Coz)

Exercise n°5: in order to optimize the readout of the antenna signal, the power transmitted to the electric circuit loading the antenna has to be maximized. Show that the transmitted power can be written as:

$$P = {V_A}^2 \frac{R_L}{\|Z_A + Z_L\|^2}$$

for a given voltage at antenna output V_A. Then demonstrate that this power is maximized for impedance matching conditions: $R_L = R_A$ and $X_L = -X_A$ (difficulty: moderate).

Exercise n°6: Write a python script computing R_L and X_L if the load is composed of a resistor R in parallel to a capacitor L and an inductance L and plot these two quantities as a function of frequency (difficulty: easy). Then retrieve values of R_A and Z_A from the NEC output file and compute values of R, L, C which maximize the ratio $\left\|\overrightarrow{\mathbf{l_{eq}}}\right\| / \|\overrightarrow{\mathbf{l_{eff}}}\|$ (difficulty: moderate). Comment on the chosen values for GRAND HorizonAntenna: R = 300 Ω, L = 10^{-6} H, C = 6.5 10^{-12} F.

Exercise n°7: write a better code to replace necoutputreader2.py (difficulty: hard)

Effective length display

Here we display beautiful plots of effective length (© S. Le Coz).

Exercise n°8; run "python display_leff.py $DATAPATH/HorizonAntenna_X.out 50" which does exactly what its name says (where $DATAPATH has to be replaced by the path where your data directory lies). Difficulty: easy.

Go have a coffee while it runs.

Quizz questions: why is the maximum of l_{eff} along the EW direction? Why do we observe this funny shape?

Answer: maximum sensitivity is along the antenna major axis. Destructive interferences between direct and reflected waves take place for specific incoming directions which correspond to multiples of wavelength (and thus inducing more complex lobes for larger frequencies)

First version: OMH, Friday April 26, 2019

Exercise n°8b: do the same for different frequencies and admire the beauty of antenna physics. Do the same after changing the NEC file name to HorizonAntenna_Y and HorizonAntenna_Z. Quizz question: is everything normal here? Difficulty: easy.

To be added: play with antenna height and tilt…

Antenna response computation

Now that we have computed the matrixes $l_{eq}^{\theta}(f,\theta,\varphi)$ and $l_{eq}^{\varphi}(f,\theta,\varphi)$, it is possible to compute the antenna response to a given electric field. To do that, we first have to write the electric field time traces [E_X(t), E_Y(t), E_Z(t)] in the referential $(\overrightarrow{e_r}, \overrightarrow{e_\theta}, \overrightarrow{e_\varphi})$.

Exercise n°9 (only for masochists): write a python code to do this conversion (difficulty: moderate).

Hint: use the following (standard) projections:

$\overrightarrow{e_r} = \sin\theta(\cos\varphi\,\overrightarrow{e_x} + \sin\varphi\,\overrightarrow{e_y}) + \cos\theta\,\overrightarrow{e_z}$

$\overrightarrow{e_\theta} = \cos\theta(\cos\varphi\,\overrightarrow{e_x} + \sin\varphi\,\overrightarrow{e_y}) - \sin\theta\,\overrightarrow{e_z}$

$\overrightarrow{e_\varphi} = -\sin\varphi\,\overrightarrow{e_x} + \cos\varphi\,\overrightarrow{e_y}$

The detailed implementation is given lines #137-138 of computeVoltage.py.

Quizz question: why is line 136 commented?

Answer: see quizz question n°1.

After this is done, the next step is to actually perform the scalar product

$$V_L = \overrightarrow{l_{eq}} \times \vec{E}$$

Problem: $l_{eq}^{\theta}(f,\theta,\varphi)$ and $l_{eq}^{\varphi}(f,\theta,\varphi)$ are computed as a function of frequency while our signal $\vec{E}$ is broadband!!!

Exercise n°10: propose a solution to this annoying problem and implement it (difficulty: very hard).

Answer: see lines #199-237 of computeVoltage.py ©S. Le Coz

Exercise n°11: compute your first GRAND antenna response using either the simulated E field traces you produced in the "simulation" micro-session, or using the traces available in the data folder, by calling:

- ***python computeVoltage.py ./$DATADIR/exampleShowerGP300 manual theta phi 0 0 ID***

Note: here theta and phi need to be given in the -soon former- GRAND conventions:

First version: OMH, Friday April 26, 2019

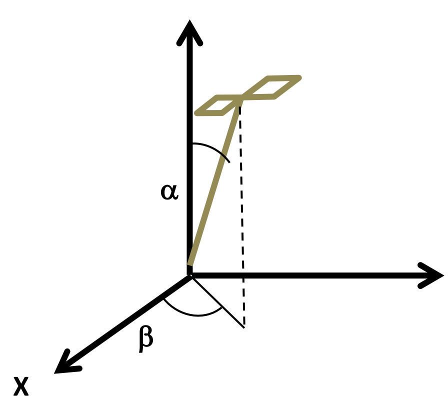
theta = 180-theta_CR
phi = 180+phi_CR
where (theta_CR, phi_CR) are the angular parameters from the ZHAireS .inp file.
and ID corresponds to the antenna ID you prefer (if you are using $DATADIR/exampleShower, select ID=22)…
Also set wkdir (line #15 in code) to your $DATADIR

What do you think about the result?

Exercise n°12: the function *inputfromtxt* in computeVoltage allows to read zenith and azimuth directly from the ZHAireS input file… But it is not fully implemented. Please complete that. Difficulty: moderate.

Bonus: slope!

A tilted antenna will have a different response than a vertical one to a wave coming from a same direction. Assuming that the antenna lobe (the map of $\overrightarrow{\mathrm{l_{eq}}}(\theta, \varphi)$, see exercise n°6) is not deformed when the antenna is titled[2], then the problem can be reduced to a simple rotation of the antenna axis $(\vec{X}, \vec{Y}, \vec{Z})$ with respect to the GRAND framework. The rotation matrix can be easily written from the parameters (α,β) of the antenna tilt. Note however that the X-axis antenna is always aligned along the N-S direction, which corresponds to an additional rotation. The transformation of a vector given in the GRAND referential to the antenna referential $(\vec{X}, \vec{Y}, \vec{Z})$ is done in modules:TopoToAntenna(). This will however be deeply simplified after the migration of the code to the new framework.



[2] This was verified up to 18°.

First version: OMH, Friday April 26, 2019

Exercice n°13: play a bit with the slope parameters alpha and beta and see how this affects the signal. Difficulty: easy.

For instance

- **python computeVoltage.py $DATADIR/exampleShowerGP300 manual theta phi -20 0 22**
  and
- **python computeVoltage.py $DATADIR/exampleShowerGP300 manual theta phi 20 0 22**
  or
- **python computeVoltage.py $DATADIR/exampleShowerGP300 manual theta phi 20 180 22**
  or
- **python computeVoltage.py $DATADIR/exampleShowerGP300 manual theta phi 20 90 22**

Quizz question: how mountain slopes may impact on the detection of the signals emitted by neutrinos?

Answer: they may help since attenuation for grazing angles is not as strong as for a flat site.

Bonus II: X_{max} computation

For a very extended array, the size of the footprint may become non negligeable compared to the distance to the source. Atop of that, Earth curvature implies that a given direction translates in different (θ,ϕ) values. For these reasons, the radio wave associated to a neutrino-induced shower cannot be described by a single direction (θ,ϕ) inside the GRAND detector. We instead consider that the source of the wave is located at the position $\overrightarrow{X_{\mathrm{max}}}$, and compute for each antenna $\overrightarrow{X_{\mathrm{ant}}}$ the “true” wave direction $\overrightarrow{u_{\mathrm{sh}}} = \overrightarrow{X_{\mathrm{ant}}} - \overrightarrow{X_{\mathrm{sh}}}$.

Exercise n°14: implement computation of $\overrightarrow{X_{\mathrm{max}}}$ and $\overrightarrow{u_{\mathrm{sh}}}$ (will be straightforward after code migration). Difficulty: moderate.

Noise

The main noise contribution to the antenna signal in the GRAND frequency range comes from the Galactic synchrotron emission (see white paper section IV.D, page 24). It results in a stationary Gaussian noise of RMS~15µV (see Fig. 21 in same paper).

Exercice n°15: simulate the galactic noise and add it to the signals (difficulty: moderate). Display the results. See how this affects detectability (difficulty: easy).

First version: OMH, Friday April 26, 2019

B- Electronics simulation

The DAQ will consist of a 50-200MHz filter and a 500MHz digitizer.

Exercise n°16: simulate these two elements (difficulty: moderate) and display the results. You may use for that the function signal_treatment:filters(). See how varying the high frequency limit affects the signals situated along the Cerenkov ring, and how the others depend on the low frequency limit. Difficulty: easy.

You have now completed the full GRAND simulation process!!! Congrats! ☺

C- Signal display

Here we do beautiful plots of the showers as they will be observed by GP300.

Exercise n°17: write a script displaying the max amplitude of the signals (Ex, Ey, Ez and E) as a function of antenna positions (so called amplitude pattern plot). Spot the Cerenkov ring. See how varying frequency changes the pattern. Difficulty: easy.

Hint: use script example_plot_2D.py as a guide and display a large event from the RadioMorphing micro-session. Still missing: a large GP300 event.

Exercise n°18: compute polarization angles (η,γ) and plot them as a function of position as well. Spot the geomagnetic/charge excess asymmetry. Difficulty: moderate.

Hint: use the matplotlib quiver() function