Equivalent Dipole Model optimized by Ant Colony Optimization Algorithm for Modeling Antennas in their Context

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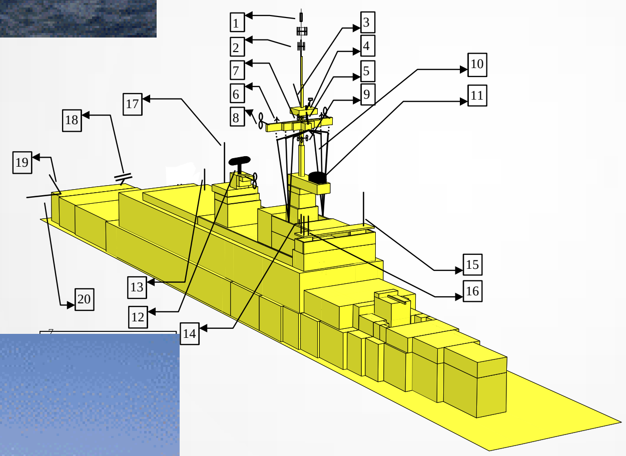
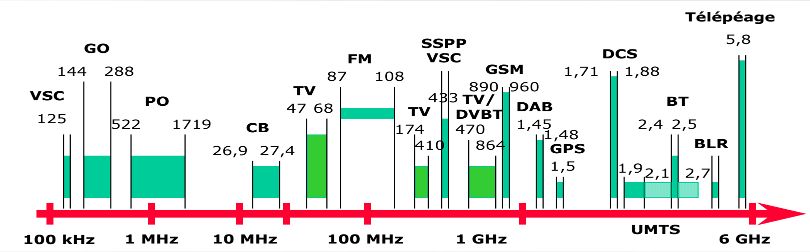
Introduction

Increasing number of embedded antennas……





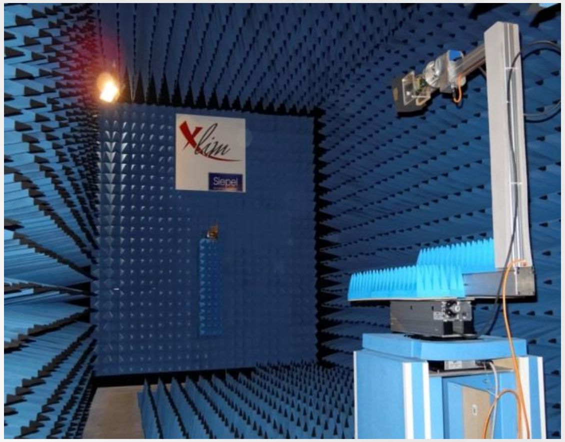
Introduction

Problem to be solved:

Generally antennas are characterized alones: :

→ S11 matching coefficient

→ S21 radiation pattern

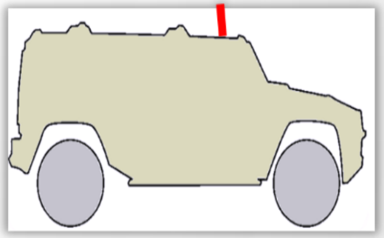


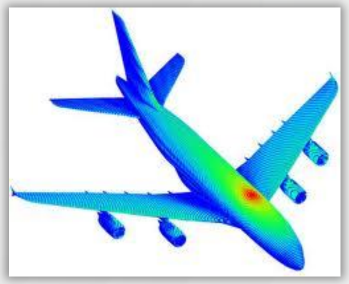
⇒ What becomes the behavior of the antenna when embedded ?

→ effect of the environment (carrier)

→ coupling between antennas

How to realize theoretical prediction of their behavior ?





Difficulty of modeling:

→ modeling to the scale of the antenna

→ modeling to the scale of the carrier

=> Necessity of finding a model able to reproduce the same behavior as the original antenna

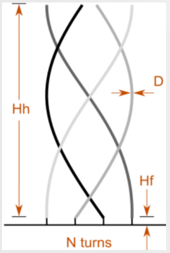
Proposed approach

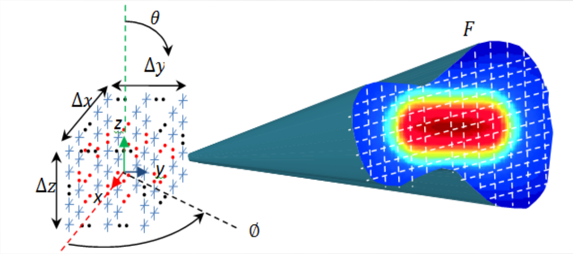
Méthodology:

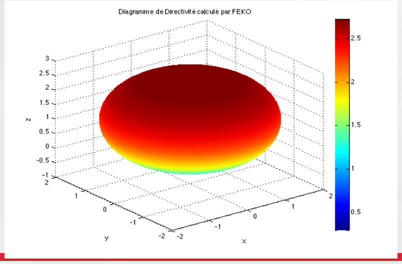
Replacing the antenna by a collection of elementary electrical dipoles

Knowledge of the radiated field for a given antenna

Radiation of a distribution of triaxial elementary dipoles equivalent to the antenna from radiation point of view.







Comparison between the two patterns

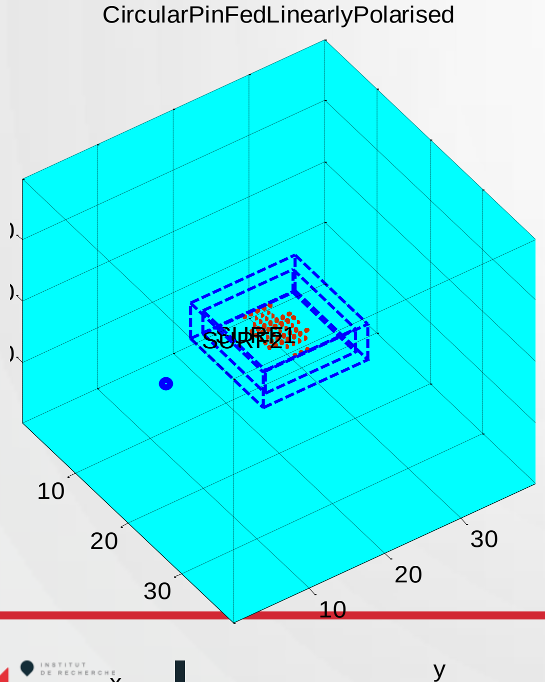
Proposed approach

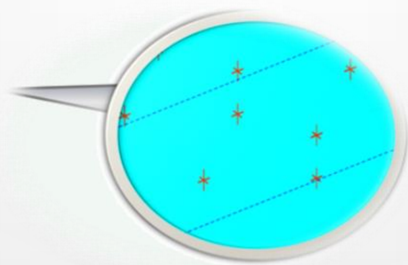
After the optimization phasis, introduction of dipolar source model in a FDTD software

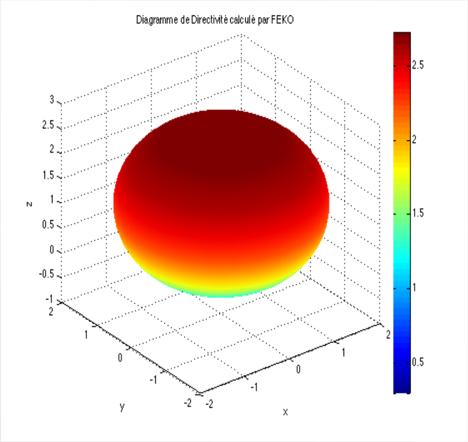
→ Position, magnitude and phases of dipole sources (at f0 frequency)
→ Time Domain Analytical formula for the near field calculation (E and H) on a Huygens surface surrounding the electrical dipole model

$$(\vec{E},\vec{H}) = f(Idl_x, Idl_y, Idl_z)$$

→ Radiation of the Huygens surface in 3D space thanks to the FDTD method







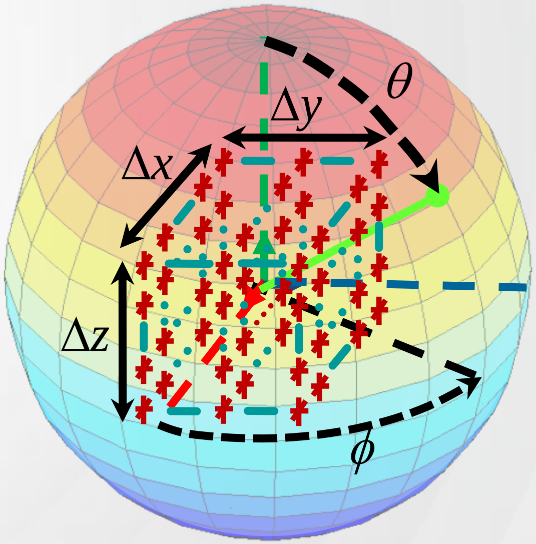
Méthodology

Initial Data :

* Antenna: geometry
* Working Frequency f_0
* Complex far field radiated in all the direction of the 3D space.

Angular step $(\Delta\theta, \Delta\phi)$ ⟹ $N_\theta \times N_\varphi$ components $\left(E_\theta, E_\varphi\right)$

Gridding of the space containing the sources:



Dimensions of the volume surrounding the antenna $L_x \times L_y \times L_z$

Definition of a regular grid: $\Delta x \times \Delta y \times \Delta z$

Definition of elementary triaxial dipoles at each node Mi of the regular grid

$$p_i = \left(p_{x_i}, p_{y_i}, p_{z_i}\right) = \left(Idl_{xi}, Idl_{yi}, Idl_{zi}\right)$$

Calculation of the magnitude of dipolar momentum

Direct function: radiation of dipoles

Analytical formula for the radiation of an elementary electrical dipole whose momentum is $p_i = Idl_i$

$$\vec{E}_j(r_j,\theta_j,\varphi_j) = \frac{jk\eta}{4\pi r_j}\frac{e^{-j\vec{k}.\vec{r}_j}}{r_j} e^{j\vec{k}.\vec{r}_i}(\vec{r}_j \times \vec{p}_i \times \vec{r}_j)$$

Far field approximation: $\vec{k}.\vec{r}_{ij} \approx kr_j - \vec{r}_i.\vec{r}_j \longrightarrow E_i\left(r_j\right) = \frac{jk\eta}{4\pi r_j} e^{-j\vec{k}r} e^{j\vec{k}\left(\hat{r}_i \cdot \hat{r}_j\right)}\left(\hat{r}_j \times p \times \hat{r}_j\right)$

Components of the far electric field radiated by a triaxial dipole at an Mi point

$$\begin{bmatrix} E_{xj} \\ E_{yj} \\ E_{zj} \end{bmatrix} = \begin{bmatrix} G_{xxji} & G_{xyji} & G_{xzji} \\ G_{yxji} & G_{yyji} & G_{yzji} \\ G_{zxji} & G_{zyji} & G_{zzji} \end{bmatrix} \begin{bmatrix} p_{xi} \\ p_{yi} \\ p_{zi} \end{bmatrix} \Rightarrow [G][P]=[F]$$

Choice of an optimization method:

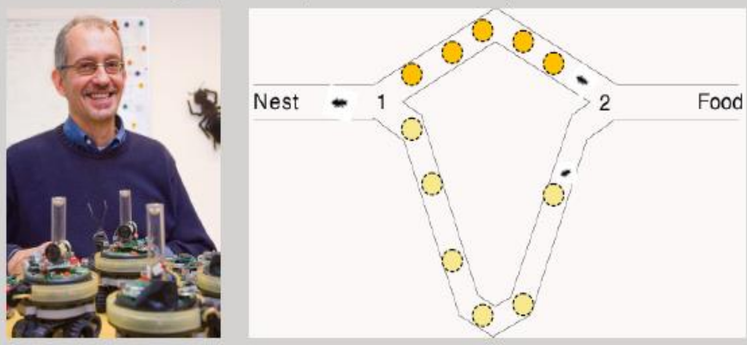
Optimization using metaheuristic approaches for inverse problems : genetic, Simulated Annealing, PSO, Ant Colony Optimization …

Definition of the objective function

$$f = \frac{\sum_{\theta}\sum_{\phi}\left|E(\theta,\phi) - E_{ref}(\theta,\phi)\right|^2}{\sum_{\theta}\sum_{\phi}\left|E_{ref}(\theta,\phi)\right|^2}$$

Origins of the ACO Algorithm

Marco Dorigo (1991) – PhD thesis



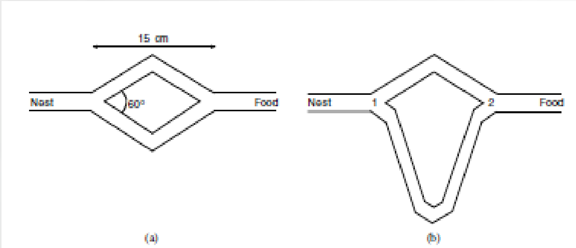
The objectif of M. Dorigo (Ant System Algorithm 1992):

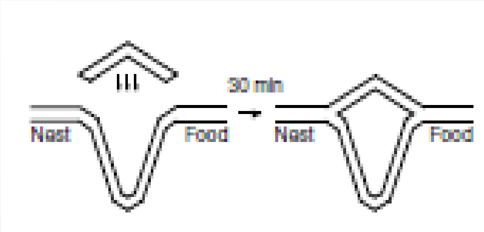
→ Resolution of the TSP problems that consists in finding the shortest path in a graph.

Each Ant try to find a path between its nest and the food location.

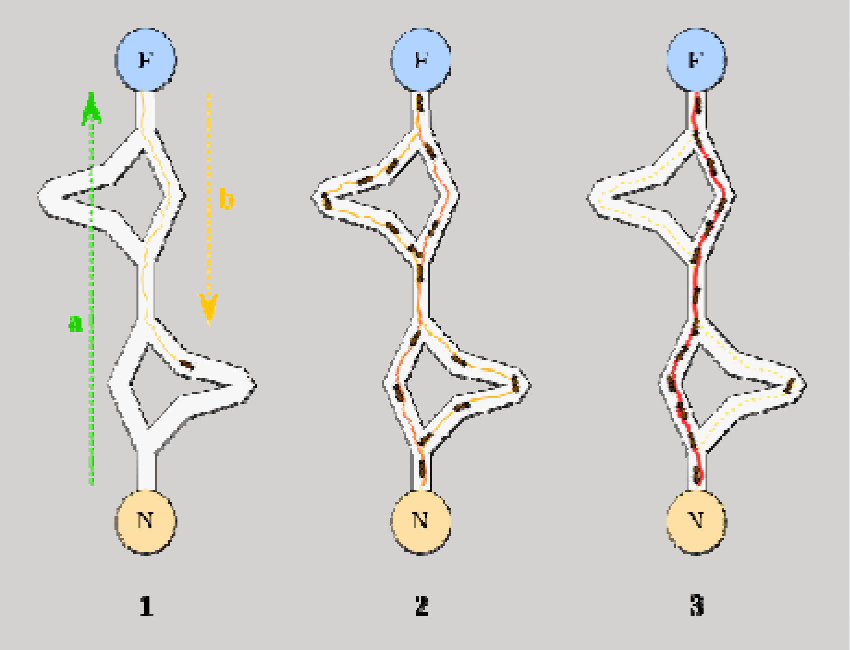
Experiment of Jean Louis Deneubourg (with « Iridomyrmex humilis ») :

=> Proves the capability of adaptation of the ants according to the problem to be solved





Process in the case of real ants



- An ant chooses at random a path to go from N to F, then come back from F to N.
- Pheromone deposit
- Next ants → follow the path with more pheromone

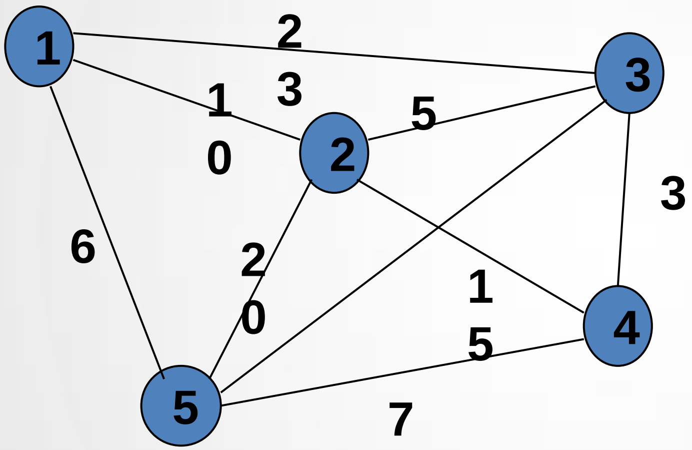
→ After some iterations, the shortest path is followed by the ants (in term of travel time)

How to avoid local minima ?
→ Evaporation phenomenon

Resolution of a discrete problem

Application to artificial ants of the Traveling Salesman Problem

Presentation of the problem



Objective: searching an Hamiltonian path – the shortest path traveling in all town one and only one time.

Resolution of a discrete problem

Algorithm

- **Definition of the nodes in the graph**
- **Considering N ants starting from a node of the graph**
- **Each ant follows a closed circuit that goes through all towns**
- **If the ant k goes through the (i,j) segment, pheromone is deposited on this**

$$\Delta\tau_{ij}^{k}(t) = \begin{cases} \dfrac{Q}{L^{k}(t)} & if\ (i,j) \in T^{k} \\ 0 & \text{else} \end{cases}$$

$Q = \text{constant}$

$L^{k}(t) = Total\ length\ of\ the\ path$

- **Calculation of the pheromone all along all the segments for all ants**

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \sum_{k=1}^{m} \Delta\tau_{ij}^{k}(t)$$

Term for taking evaporation phenomena into account

Pheromone increasing

Resolution of a discrete problem

- **At the following iteration: the probability for the k ant to chose the xy path becomes:**

$$\begin{cases} p_{xy}^{k}(t) = \dfrac{\tau_{xy}^{\alpha}\eta_{xy}^{\beta}}{\sum_{ij}\tau_{xy}^{\alpha}\eta_{xy}^{\beta}} & si \;\; j \in T_{x}^{k} \\ 0 & \text{sinon} \end{cases}$$

$\eta = \dfrac{1}{d}$ **d= distance between two nodes**

$\alpha = 0$ **Only the visibility of nodes will be taken into account**

$\beta = 0$ **Only the pheromone deposit will have an influence**

Adaptation to the continuous case

Approach due to SOCHA (2008) : ACO-R

Methodology:

The idea is to keep a similar algorithm as in the discrete case (combinational optimization) to mix continuous and discrete variables: mixed optimization

- **Definition of an archive table for the storage of parameters value**

ith parameter ↓

kème ant ⟶

$$Tab = \begin{bmatrix} s_1^1 & & \cdots & & s_1^N \\ \vdots & \ddots & & & \vdots \\ s_k^1 & & s_k^i & & s_k^N \\ \vdots & & & \ddots & \vdots \\ s_K^1 & & \cdots & & s_K^N \end{bmatrix}$$

Value of the objective function :

$$F = \left[\, f(s_1)\; f(s_2) \ldots f(s_k) \ldots \; f(s_K) \,\right]^T$$

Performance of each ant

$$\omega = \left[\omega_1 \;\; \omega_2 \; \ldots \; \omega_k \; \ldots \; \omega_K\right]^T$$

Adaptation to the continuous case

Initialization:

- **For each parameter: definition of a means value and of a standard deviation :**

$$\mu_k^i = a_i + (2k-1)\frac{b_i - a_i}{2K} \qquad \sigma_k^i = \frac{b_i - a_i}{2K}$$

- **Definition of an evolutive probability law for each parameter (multi gaussian kernels) :**

$$P(x^i) = \sum_{k=1}^{K} \omega_k . g(x^i, \mu_k^i, \sigma_k^i)$$ **with:** $$\omega_i = \frac{1}{qK\sqrt{2\pi}} e^{-\frac{(i-1)^2}{2q^2K^2}}$$

- **Probability of ant selection all along the iteration process :**

$$p_k = \frac{\omega_k}{\sum_{j=1}^{K} \omega_j} \qquad \sigma = \xi \sum_{p=1}^{K} \frac{\left| s_p^i - s_j^i \right|}{K-1}$$

The standard deviation parameter is decreasing as the time increases that is t say when the number of iteration increases.

Adaptation to the continuous case

Iterations:

$$Tab = \begin{bmatrix} s_1^1 & & \cdots & & s_1^N \\ \vdots & \ddots & & & \vdots \\ s_k^1 & & s_k^i & & s_k^N \\ \vdots & & & \ddots & \vdots \\ s_K^1 & & \cdots & & s_K^N \end{bmatrix}$$

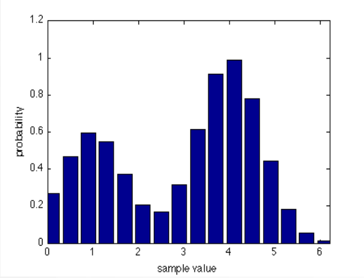
- **selection if random numbers for the parameters as function of the position in the table**
- **Construction of r supplementary ants**
- **Ranking the solutions and sorting using the objective function**
- **Forgotten the r last solutions**

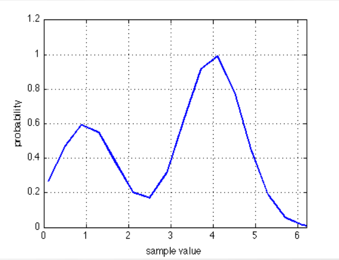
Remarks:

- The number of ants is always the same all along the iterations,
- The suppression of the r lasts acts as an evaporation process

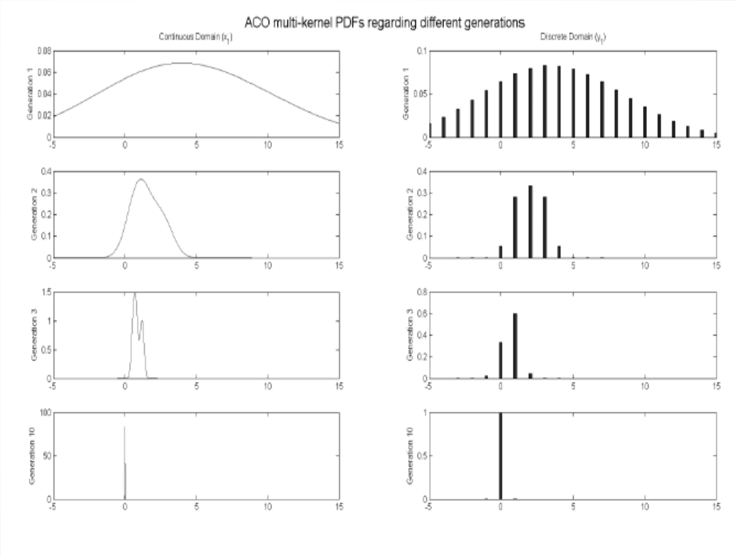
Adaptation to the continuous case

From the discrete case to the continuous case





Example of parameters variations all along the iteration process



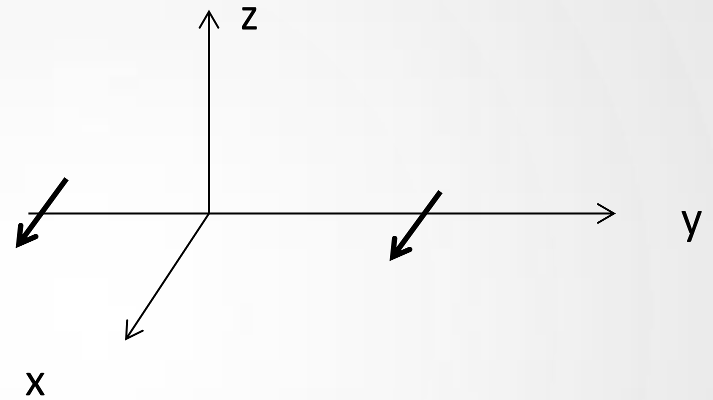
Martin Schlueter, « *Nonlinear mixed integer based Optimization Technique for Space Applications* » Thesis submitted to the University of Birmingham for the degree of Doctor of Philosophy - December 2011

Validation on an array of two dipoles

The case of a 2 dipoles array in the xoy plane oriented in the x direction is considered → formation of the diagram in the yoz plane (H plane)

$$Idx_1 = Idlx_2 = 1$$

$$dx_1 = dx_2 = 0.3\,m$$

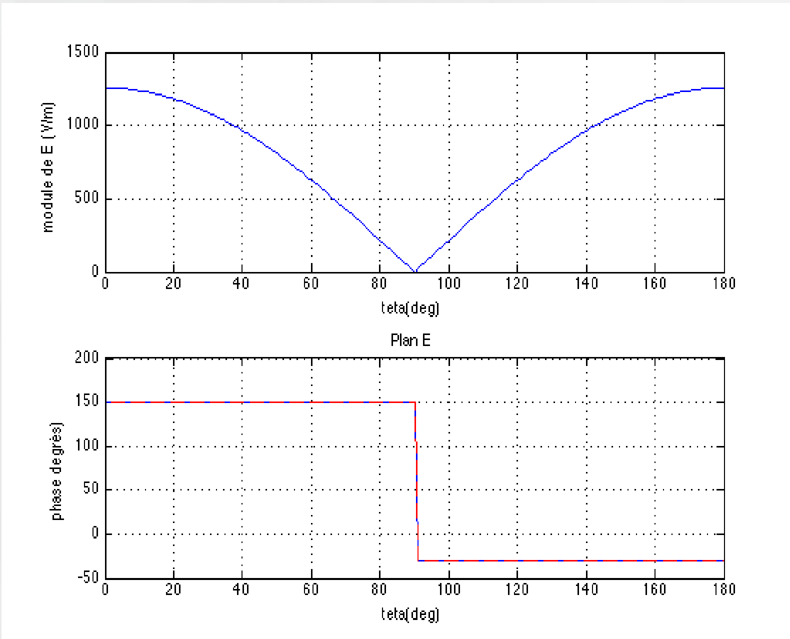



```
--------------------------------------------
[EVAL:     30000, TIME:    14.90, IFAIL:    1]
--------------------------------------------
F(X) =                    0.000007072149592600
--------------------------------------------        ---BOUNDS-PROFILER---
X(   1) =                 0.999996849810914190     !  ____________x_______
X(   2) =                 0.999996854963096760     !  ____________x_______
X(   3) =                 0.000000085570233441     !  __________x_________
X(   4) =                 0.000000128234711033     !  __________x_________
X(   5) =                -0.000000008576101837     !  __________x_________
X(   6) =                -0.000000008279563937     !  __________x_________
X(   7) =                 0.000049314257684684     !  __________x_________
X(   8) =                 0.000049201359720919     !  __________x_________
X(   9) =                -0.000000027127221718     !  __________x_________
X(  10) =                 0.000000030661306357     !  __________x_________
X(  11) =                 0.000000018173738767     !  __________x_________
X(  12) =                 0.000000298031256776     !  __________x_________
```

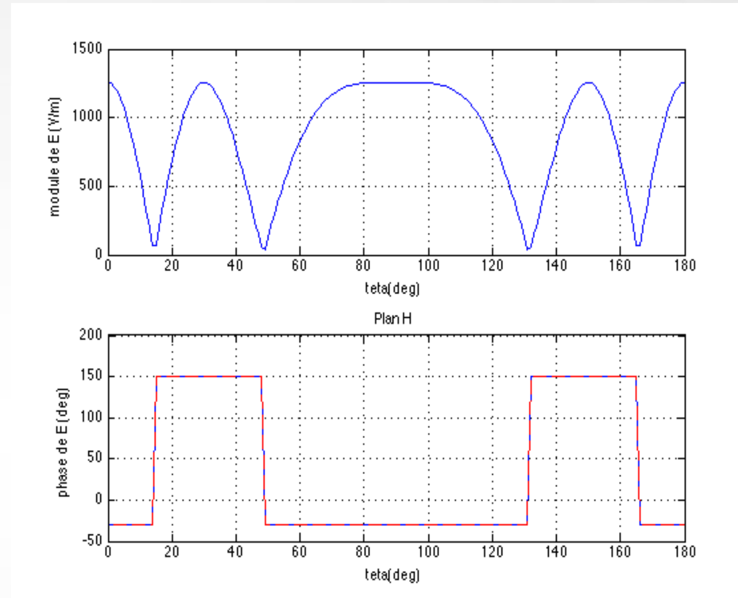
Midaco software screenshot (Martin Schlueter)

Validation on an array of two dipoles

E plane



H plane



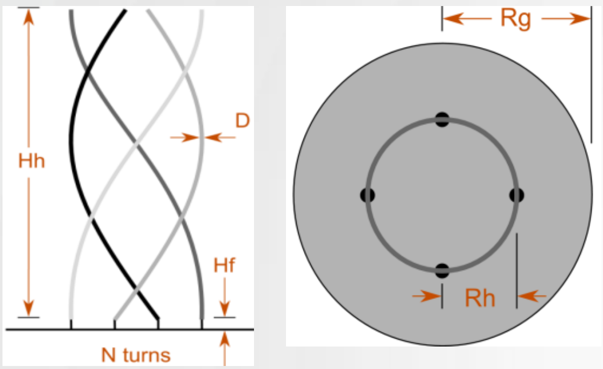
It is interesting to remark: that a phases variation of π can be observed from one lobe to the following in the far field magnitude

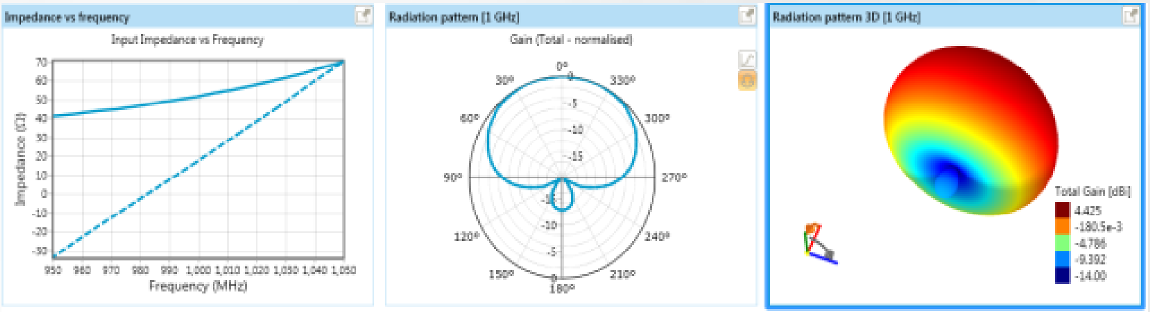
.

→ It is possible to optimize by knowing only the magnitude using the phases reconstruction (generally only magnitude can be available to measurements)

Validation of the approach on a model of complex antenna

Quadrifilar helicoïdal antenna





FEKO software computation ➔ field components (E_θ, E_ϕ)

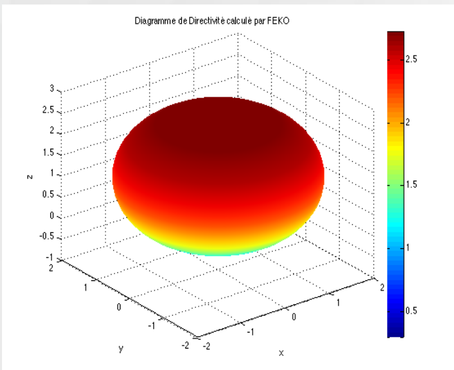
Computation volume 83.2 mm * 83.2 mm * 214.5 mm

Frequency 1 GHz.

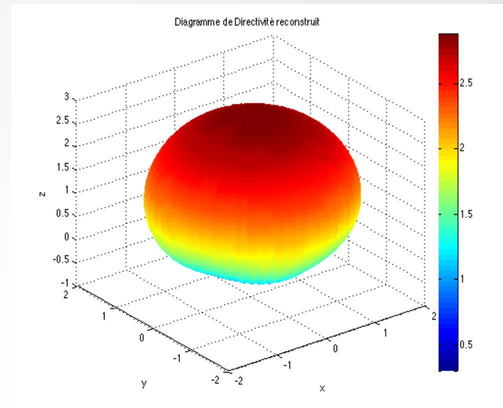
grid: 6*6*11 nodes ➔ 396 dipoles

Validation of the approach on a mode complex antenna

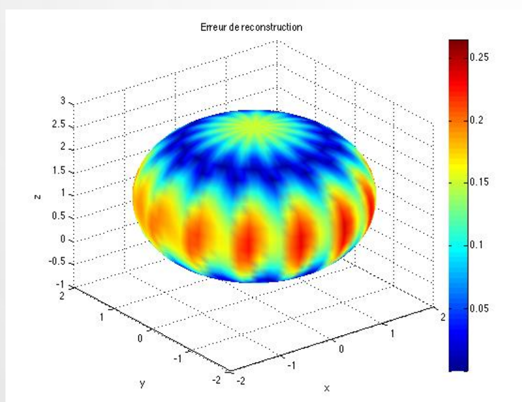
Reconstruction of the 3D diagram

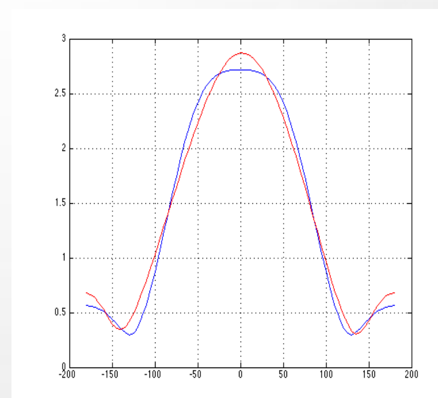


Original pattern



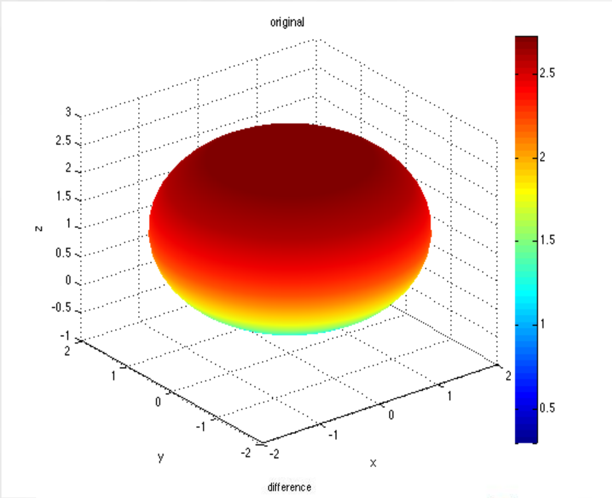
Reconstructed pattern



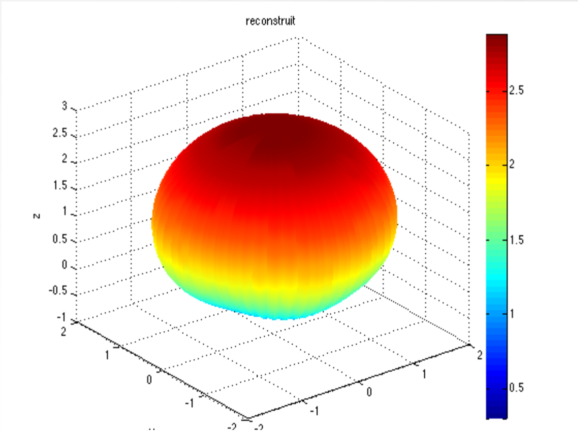


Reconstruction using only the two main planes

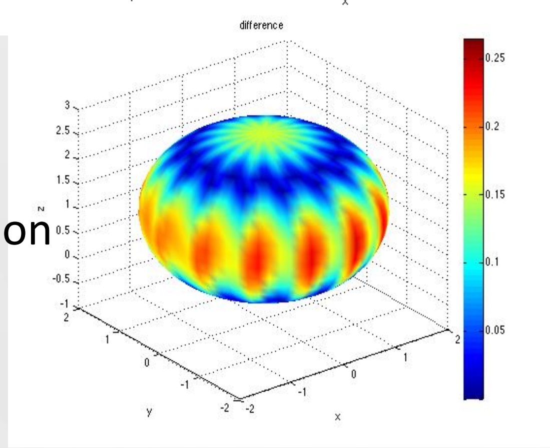
Original pattern



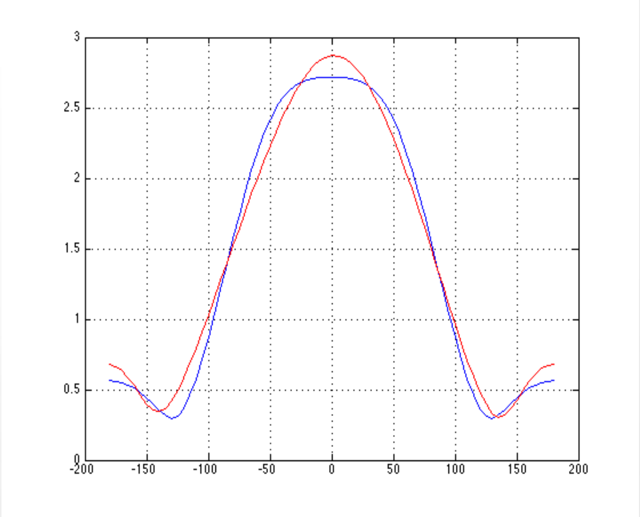
Reconstructed pattern



Reconstruction error

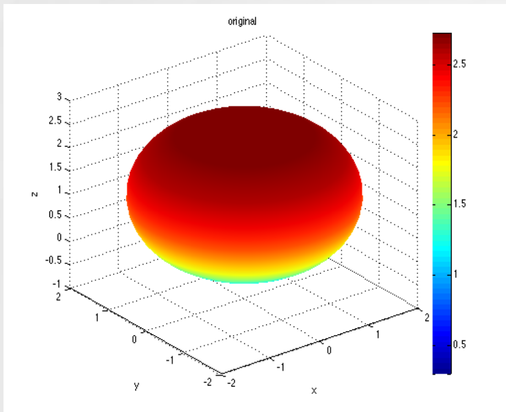


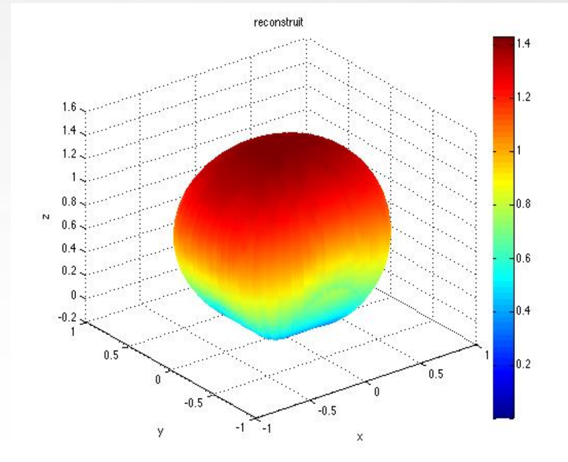
Pattern in one plane



Reconstruction using only the magnitude of far field in the two main planes (phases reconstruction)

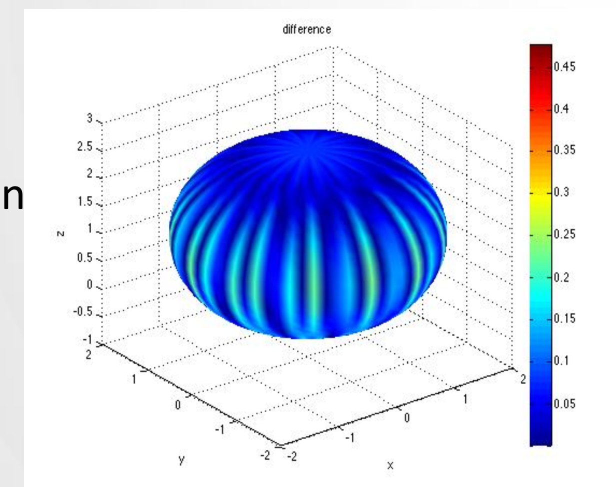
Original pattern

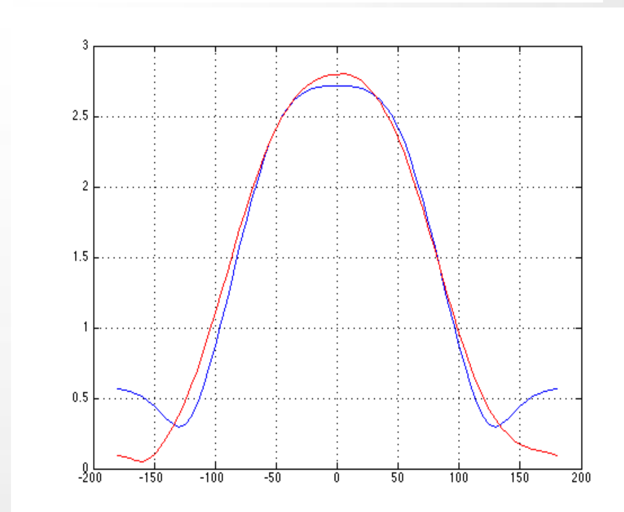




Reconstructed pattern

Reconstruction error

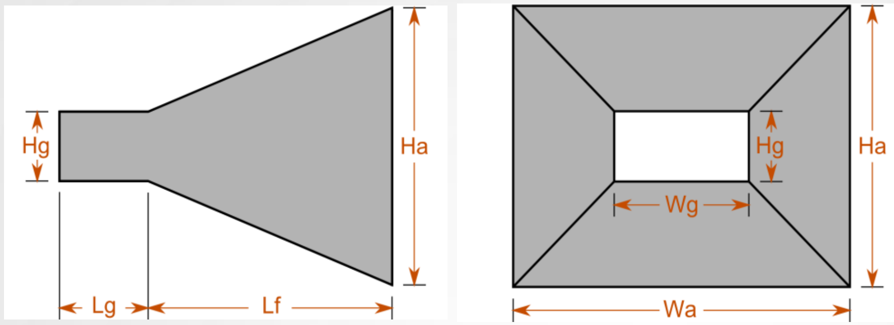




Pattern in one plane

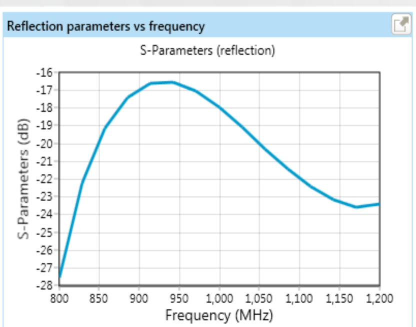
Study of a horn antenna

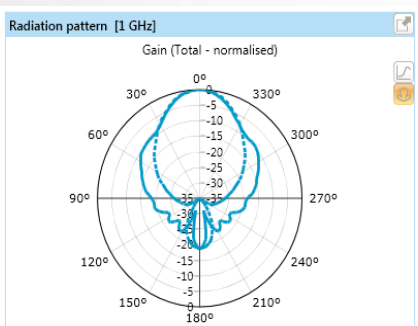
Characteristics of the horn

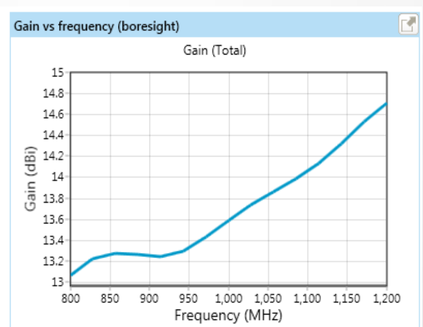


Parameter	Value
Frequency	1 GHz
Wg	235.3 mm
Hg	117.7 mm
Lg	449.7 mm
Wa	692.4 mm
Ha	507.1 mm
Lf	266.6 mm

Volume of the antenna = 692.4 mm × 507.1 mm × 716.3 mm

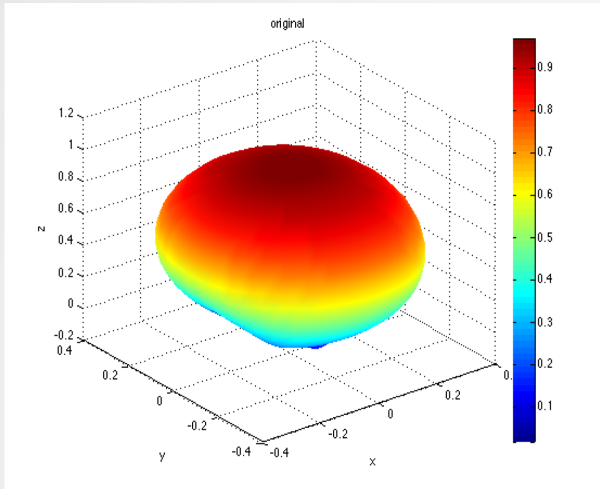


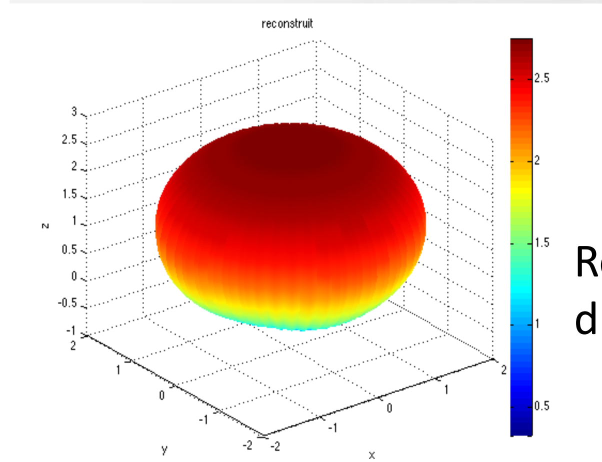




3D Reconstruction

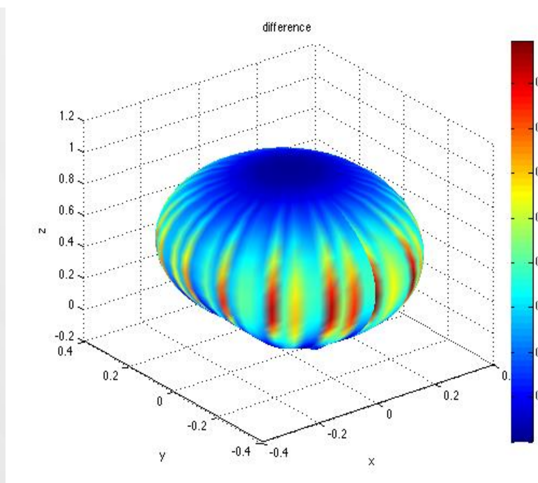
Original diagram





Reconstructed diagram

Reconstruction error



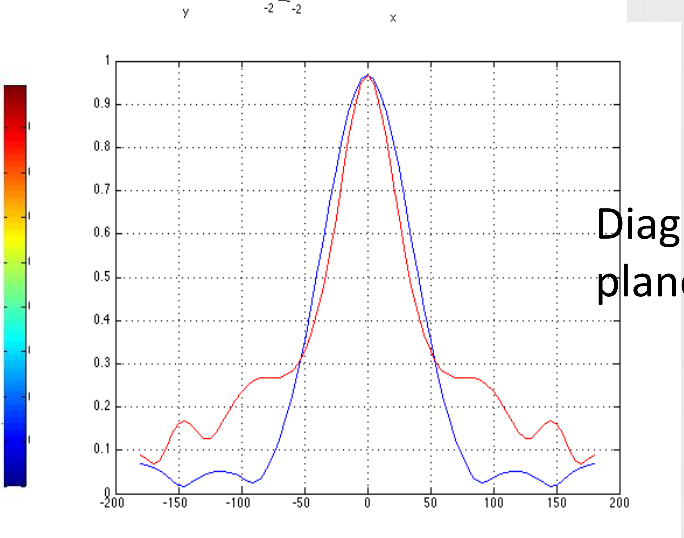
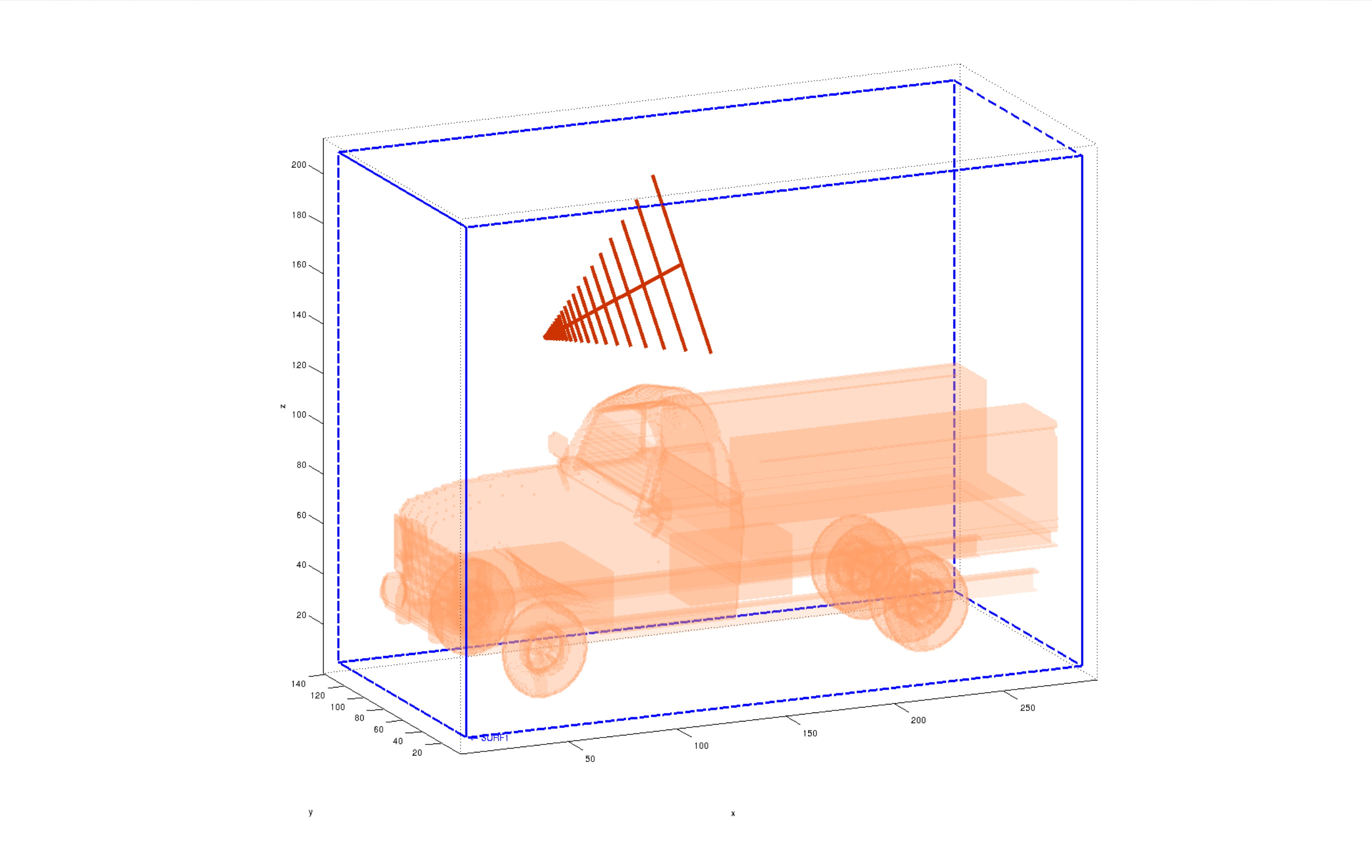


Diagram in a plane

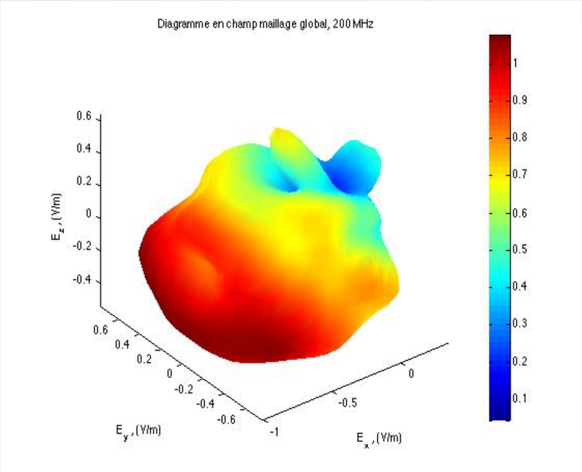
Embedded antenna

Modeling of log periodical antenna mounted on a vehicle

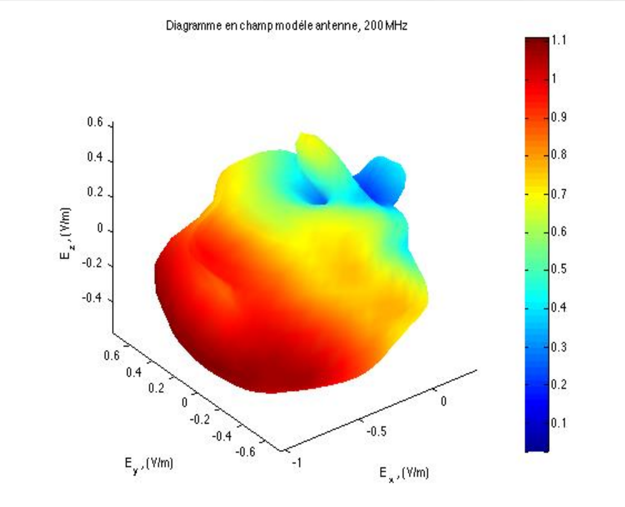


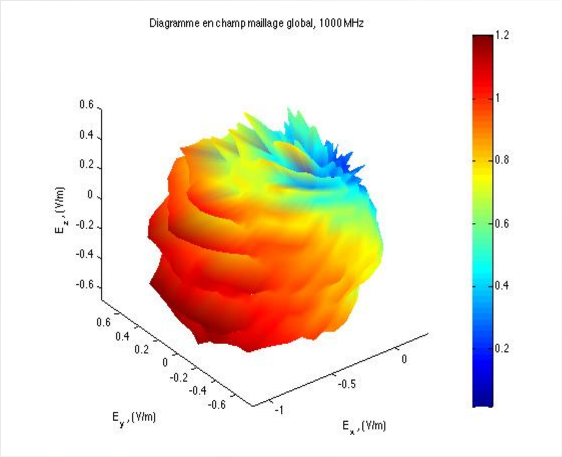
Modelling of an embedded log-periodical antenna

Radiation of the antenna mounted on the vehicle

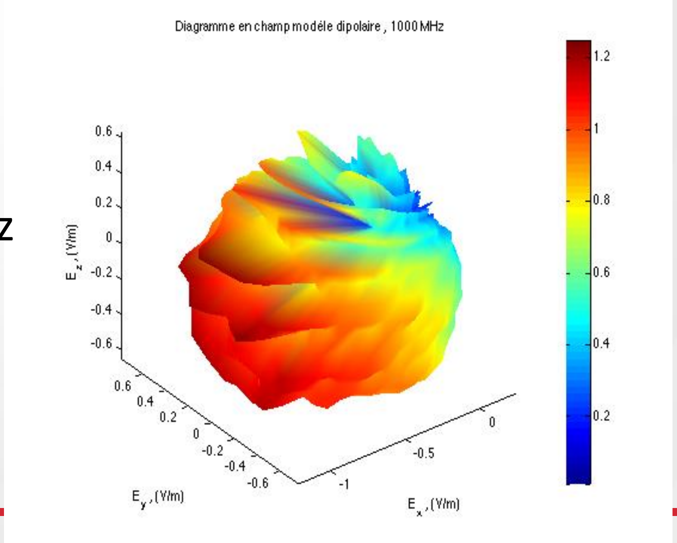


F=200 MHz





F=1000 MHz



Conclusion

→ New approach for the multiscale modeling of embedded antennas knowing their free space radiation pattern

→ Validation on different kind of antennas

Advantages:

→ first step: construction of an antenna library of equivalent dipoles

→ second step: introduction of the model in the FDTD grid, possibility of changing the orientation of the antenna without having to reconstruct the model

Imported fire ant workers.

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