Contribution of Statistics to Human Exposure Assessment

Wiart Joe [1,2,5], Kersaudy Pierric[1,2,3], Gahmni Amal[1,2,3] , Marjorie Jala [1,2,5], Anis Krayni[1,2,5] , Varsier Nadege[1,2], Hadjem Abdelhamid[1,2], Odile Picon [3], Shermila Mostarshedi[3] Bruno Sudret[4] , Alain Sibille[5], Eric Moulines[5] , Isabelle Bloch [5]

1 WHIST Lab Institut Mines -Telecom, Paris
2 Orange Issy les Moulineaux
3 Universite Marne la Vallée PRES EST
4 ETH Zurich
5 Telecom ParisTech, Paris

(Email: wiart@telecom-paristech.fr)

http://whist.mines-telecom.fr

outline

I Introduction

II From determinist to statistical approach of the human RF Exposure

III Surrogate models in EMF exposure assessment

IV Conclusion

Introduction

- Large numbers of users > 5 billions worldwide
- Versatile use surf, talk, play
- Larger and larger duration of use surf is increasing and <talk> is > 150min/month

- Risk perception about the EMF exposure.

- Protection limits exist

Basic restrictions	Public	Workers
Whole body SAR (W/kg)	0.08	0.4
Local SAR (W/kg) Head - Trunk	2	10
Local SAR (W/kg) Limbs	4	20

- Large efforts to check the compliance to limits but the risk perception is still important

Euro-barmoter 2010 :

- 70% say that mobile phone masts have some effects on health.
- 67 % think that mobile telephones have some effects on their health.

Assess the real exposure is a key question for sanitary authorities as well as for industry

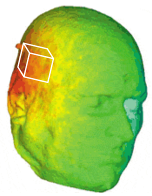
EMF Human Exposure

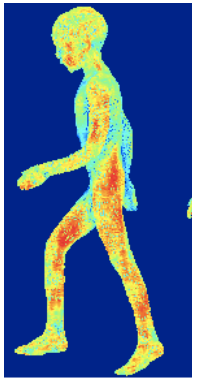
Fundamentally the exposure is link to the power absorbed.

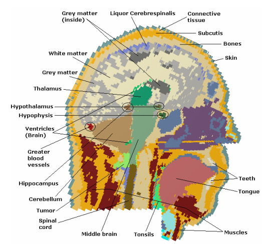
The power absorbed per unit of mass characterize such exposure .

→ Specific Absorption RateSAR

The SAR is often averaged over the whole body or over a small mass (eg 1 or 10 g)





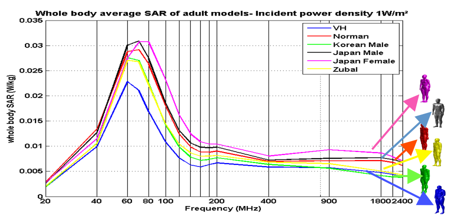


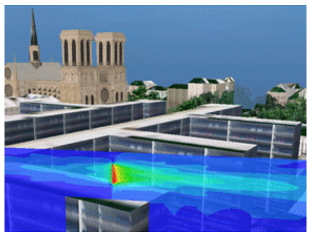
$$SAR = \frac{d\left(\frac{dW}{dm}\right)}{dt}$$

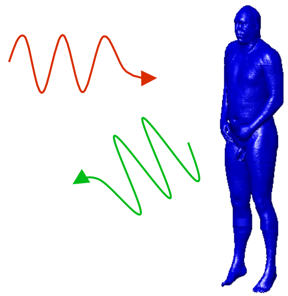
$$SAR = \frac{\sigma E^2}{2\rho}$$

For the whole body the exposure is often discussed in v/m but the incident field and the whole body exposure are linked by a transfer function

- The absorption depends on
  - Shape
  - Tissues
  - Frequency

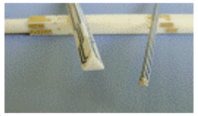






Large efforts dedicated to dosimetry since 20 years

- Experimentally. Probe, liquids, phantoms and protocols have been developped and implemented in standards



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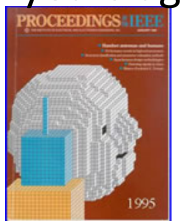
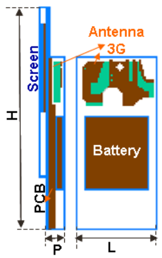
- Numerically: with HPC, GPU,.. simulations that can be achieved are larger and larger, faster and faster
  But is still facing limitation

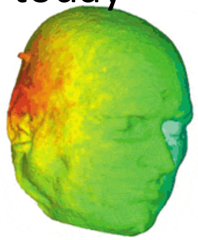
30 years ago



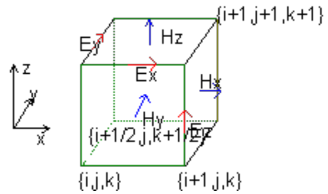
$$SAR = \frac{\sigma E^2}{2\rho}$$

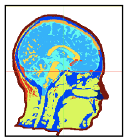
today

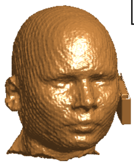


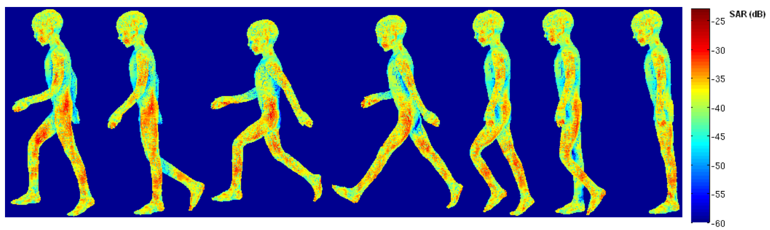


FDTD









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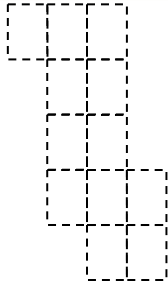
Numerical SAR assessment

In Bio-electromagnetism, the FDTD (Finite Difference in Time Domain) is the most popular method to solve the Maxwell PDE

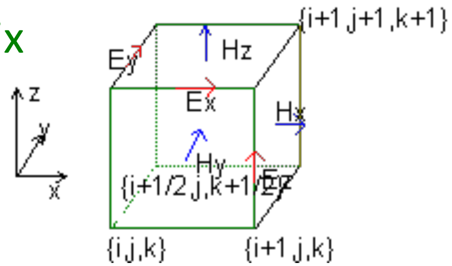


$$rot\vec{E} = -\frac{\partial(\mu_0 \vec{\mu}_r * \vec{H})}{\partial t}$$

Solve the Maxwell PDE over an orthogonal grid

$$rot\vec{H} = \frac{\partial(\varepsilon_0 \vec{\varepsilon}_r * \vec{E})}{\partial t} + \vec{\sigma}\vec{E}$$

Explicit formulation does not require any matrix innversion

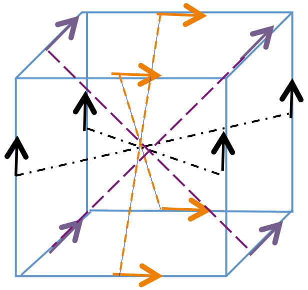


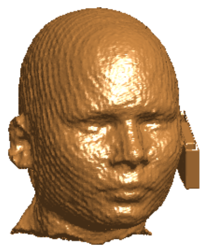
Finite Difference in Time Domain

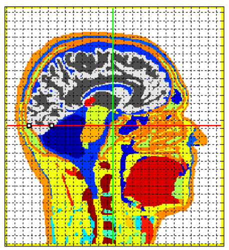
$$E_x^n(i-1/2,j,k) = E_x^{n-1}(i-1/2,j,k) + \frac{\Delta t}{\varepsilon_0 \varepsilon_r} \cdot \frac{H_z^{n-1/2}(i-1/2,j+1/2,k) - H_z^{n-1/2}(i-1/2,j-1/2,k)}{\Delta y} - \frac{\Delta t}{\varepsilon_0 \varepsilon_r} \cdot \frac{H_y^{n-1/2}(i-1/2,j,k+1/2) - H_y^{n-1/2}(i-1/2,j,k-1/2)}{\Delta z}$$

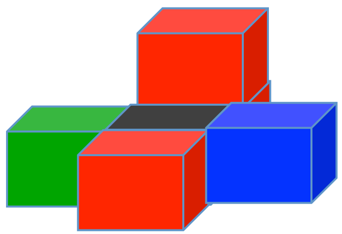
Divide the resolution by 2 the time computation by 2

$$P_{abs} = \frac{1}{2}\iiint \sigma E^2 dv$$



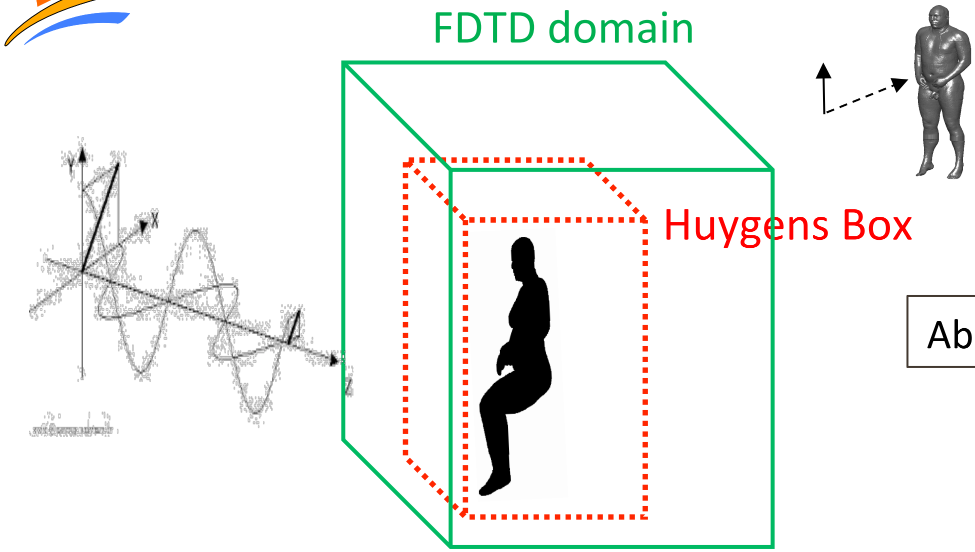


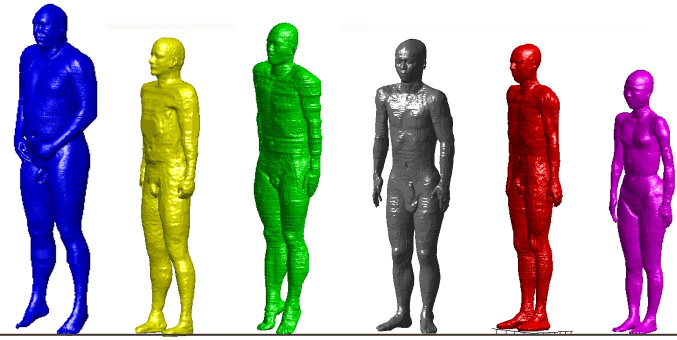




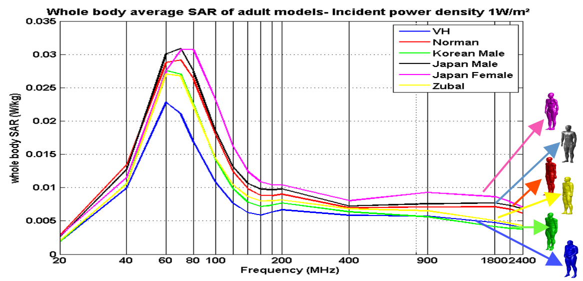
$$SAR = \frac{\sigma E^2}{2\rho}$$

Whole Body exposure from a far and close sources





Absorbed power divided by the weight vs frequency



Huygens Box Principle

- The exposure induced by the incident field can be be performed using the equivalent principle
- With the E.P. only the incident field at the surface is required to assess the field inside the box.

The field radiated by a source can be expanded over

- plane waves
- spherical waves (that are an orthogonal base as the plane waves are)

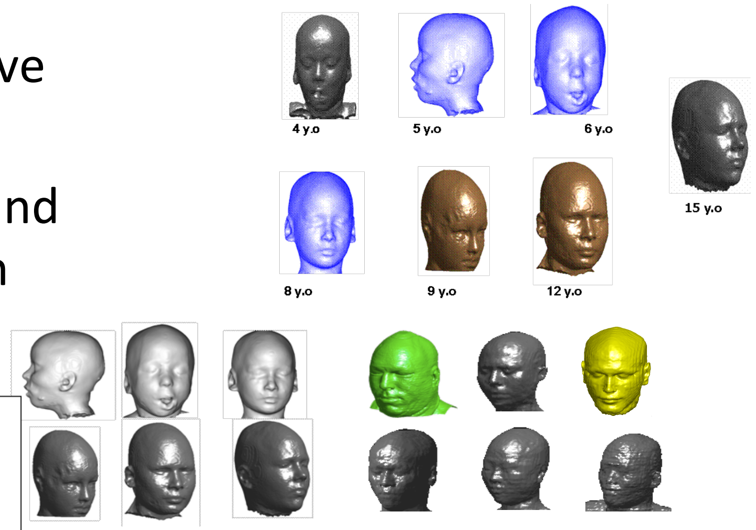
$$\vec{E}(r,\theta,\varphi) = \sum_k Q_k \vec{F}_k(r,\theta,\varphi)$$

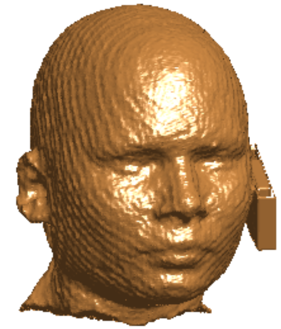
Computational effort:

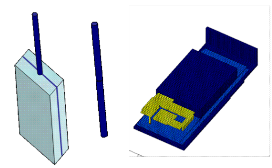
- **A single simulation (1 phantom, 1 fre) = 8 h**
- **16 freq x 6 phantoms → 768 hours… 32 days…**

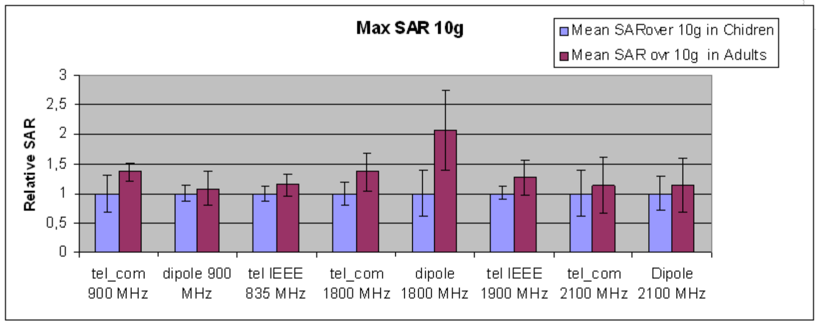
Children vs Adults exposure

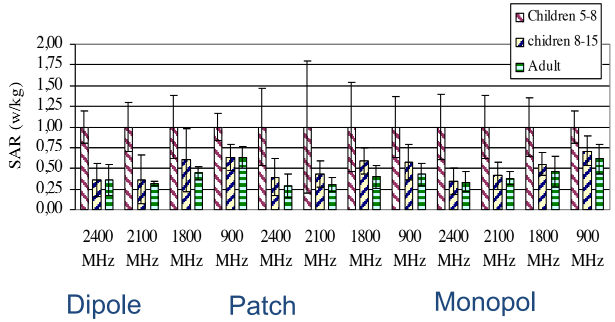
- Head models, MRI based, have been developped
- Comparison between adult and child head models have been conducted .











Analysis of RF exposure in the head tissues of children and adults
J. Wiart, A Hadjem, M F Wong and I Bloch, Phys. Med. Biol. 53 (2008) 3681–3695

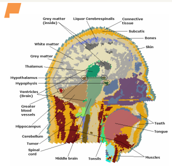
Computational effort:

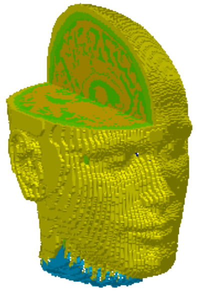
- **A single simulation (1 heab phantom, 1 fre) > 0.5 h**
  → Computation time= 72 *0.5 = 36 h
- **Simulation preparation (put the phone close to the head) → 1 h …**

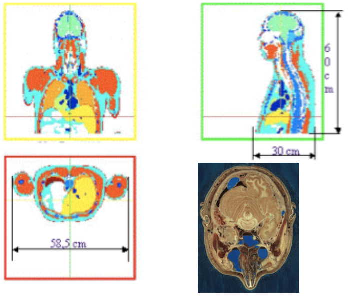
3 phones, 6 head → 18h

The Human body structure: evolving, deformable, heterogeneous and dispersive..

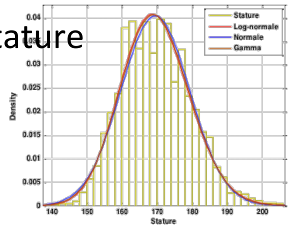
Heterogeneous

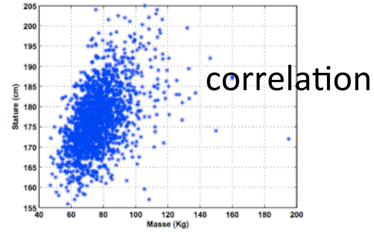


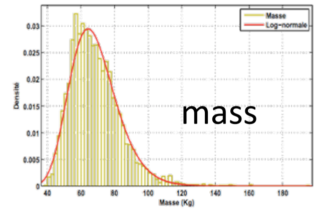




Human variability

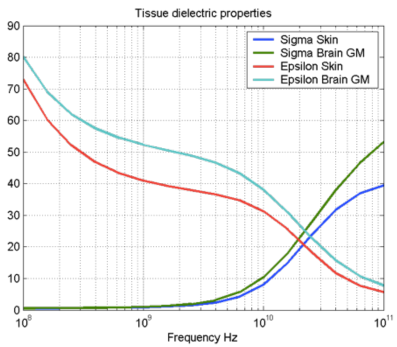






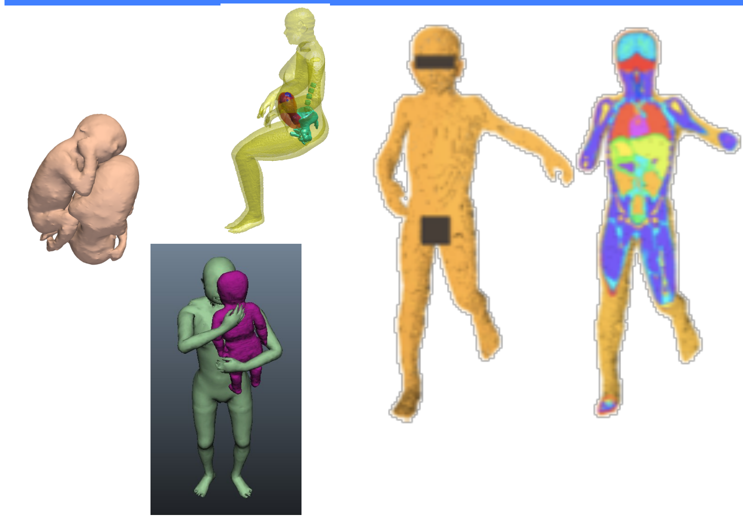
Dispersive, Lossy and variable

e.g. at F= 900 MHz



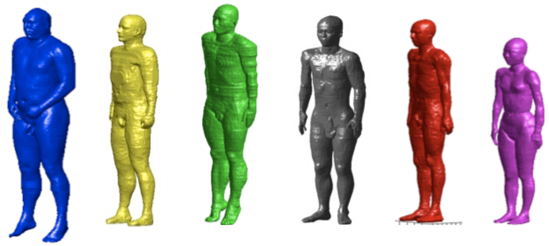
Tissue	Epslon	Sigma
Blood	61.3	1.53
Bone_Cortical	12.4	0.14
Bone_Marrow_Infiltrated	11.2	0.22
Bone_Marrow_Not_Infilt	5.5	0.04
Cartilage	42.6	0.78
Cerebro_Spinal_Fluid	68.6	2.41
Eye_Tissue(Sclera)	55.2	1.16
Fat	5.4	0.05
Grey_Matter	52.7	0.94
Muscle	55.0	0.94
Nerve(Spinal_chord)	32.5	0.57
Skin(Dry)	41.4	0.86
Skin(Wet)	46.0	0.84
Tongue	55.2	0.93
White_Matter	38.8	0.59

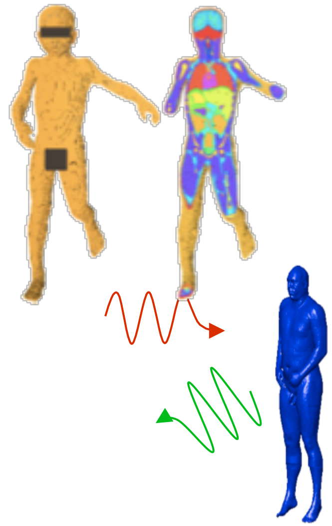
Deformable and evolving structure



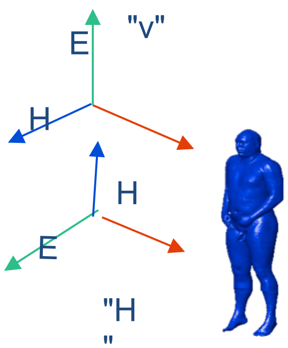
Exemple of influence of morphology and posture

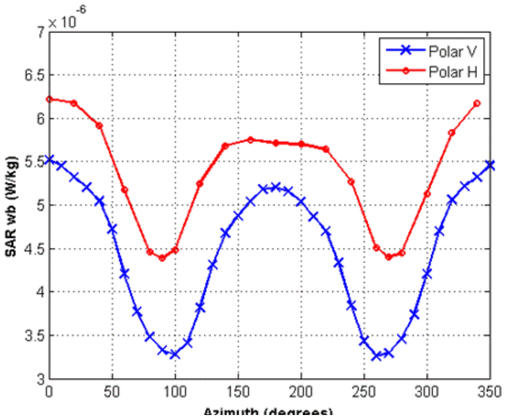
Total absorbed power divided by the weight



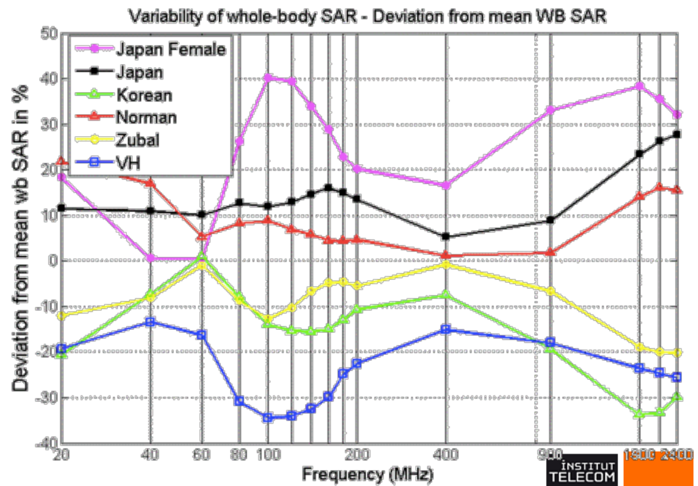


Large Variability





2.1 GHz



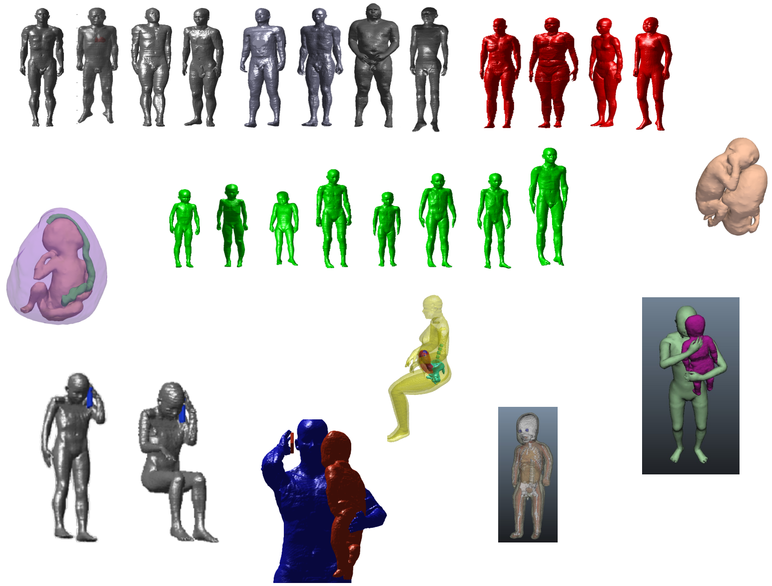
Wireless technologies evolve.
RF source are more and more complex.
Usages are versatile

Complex and evolving technologies

Versatile use

And the time of consciousness has come.

Voxel body models and deformation methods have been developped



But

- What is the representativeness of these phantoms?
- What is the influence of posture on exposure ?
- What is the impact of uncertainties/variability on SAR distribution?
- What is the influence of versatile use with longer duration?
- What is the influence of multiple source, multiple networks, multiple questions

From deterministic to statistical

For a specific person, age, posture, usage, phone….
At a given time, the **relationship** between theses parameters and
SAR is determinist
SAR=**f**(sources [design, location, frequency technology..] , body [composition, geometry, posture,…])

In real word age, posture, usage, phone…. Can change, evolve …
The SAR is dependent on a large number of **variable inputs x_i**

$$SAR = f(x_1, x_2, \ldots x_i, x_{i+1}, \ldots x_n)$$

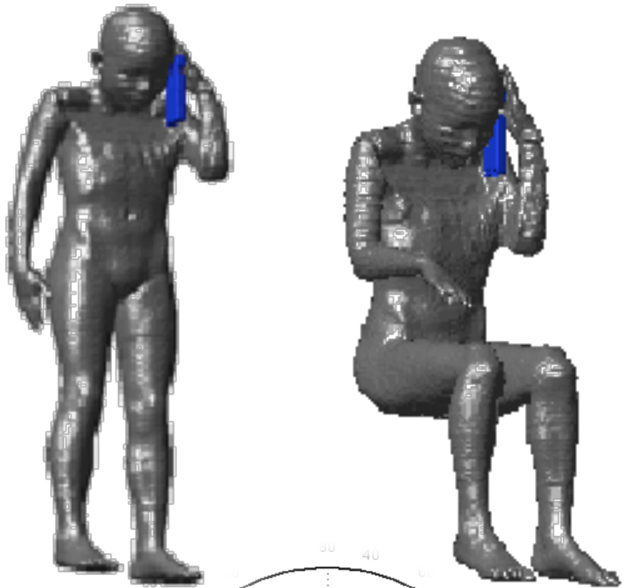
$$SAR(\omega) = f(x_1(\omega), x_2(\omega), \ldots x_i(\omega), \ldots x_n(\omega))$$

$$where\ \ \omega \in \Omega\ \ \ with\ \Omega\ \ the\ \ space\ of\ \ \ possibility$$

Large number of inputs:
- dielectric properties of tissues
- Posture description
- Source localisation
- …

Stochastic dosimetry started in the 2000's

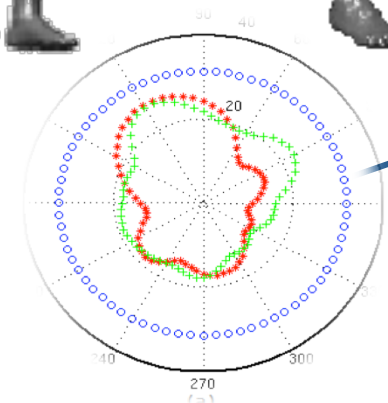
Variable SAR induced by the variable gain of the couple mobile+user

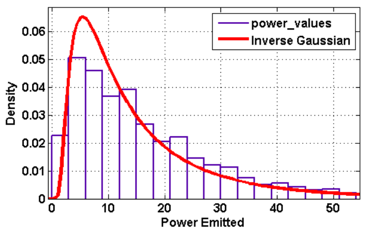


- The pattern antenna (gain) of « mobile +user » depends on the posture and location of the phone
- The human exposure (SAR) depends on the power radiated by the phone

$$P_e * G_e * \underbrace{PL * G_r}_{constant} = \underbrace{P_r}_{fixed}$$

$$P_e * G_e(\theta_{LOS}, \phi_{LOS}) = 1$$





Considering PE x GE known, what is the variation of SAR. In this case is the relative position of the phone is fixed so SAR depend only the power emitted:

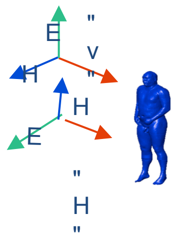
$$P_e = \frac{1}{G_e(\theta_{LOS}, \phi_{LOS})}$$

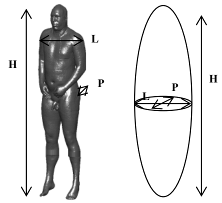
Surrogate modeling
first engineering approach

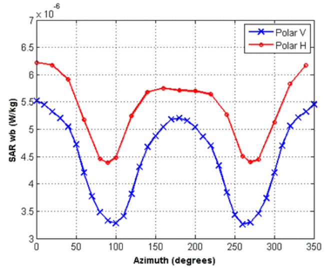
FDTD simulation cost does not allow large number of sampling, surrogate model is needed.

- In the RF domain there is no resonnance, then the whole body SAR is is proportional to the surface cross section

- Human body can be approximated using Ellipsoid







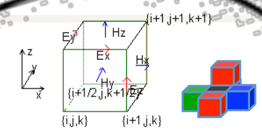
Based on simulations performed vith VH $P(W) = 0.72 * S(m^2) * DSP\left(\frac{W}{m^2}\right) \pm 5\%$

$$surface = \pi \frac{H}{2} \sqrt{\frac{L^2}{2} \cos(\theta)^2 + \frac{P^2}{2} \sin(\theta)^2}$$

Representativeness?

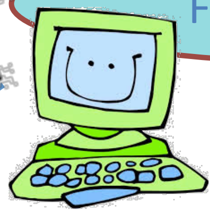
A method is needed to built the surrogate models

Challenges of the stochastic dosimetry



$$rot\vec{E} = -\frac{\partial(\mu_0\vec{\vec{\mu}}_r * \vec{H})}{\partial t}$$

$$rot\vec{H} = \frac{\partial(\varepsilon_0\vec{\vec{\varepsilon}}_r * \vec{E})}{\partial t} + \vec{\vec{\sigma}}\vec{E}$$



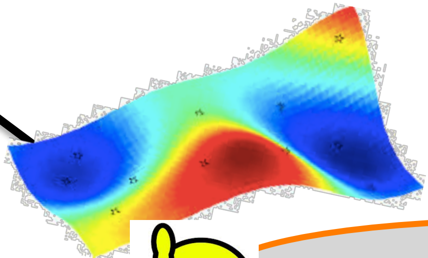
FDTD : **high cost**

Vector of input variables

$x \in \Re^M$

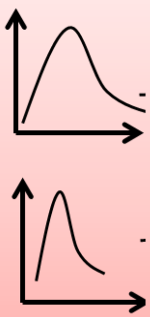
Vector of output variables

$y = \mathcal{M}(x)$



Low cost surogate model

- User variables
  - morphology
  - posture
- Usage variables
  - devices
  - type of service
- Network variables
  - load
  - type of cells
  - RAT
- …



- Surrogate model
  - analytical model
  - **polynomial chaos**
  - **gaussian process**
  - krieging
  - …

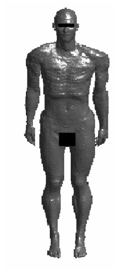
- Global variable whole body SAR
- Local variables
  - 10g SAR
  - brain SAR
  - …
- …

First Challenge: Characterise the input

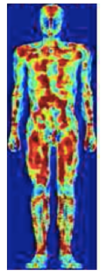
Main Challenge: built surrogate model with the minimum cost

surrogate modeling using Polynomial Chaos

height,
shoulders,
chest size
lap belt



Input
$\mathbf{X}(\Omega_i)$



$\mathbf{Y_i = SAR_i}$

SAR statistical distribution

$$Y = M(X)$$ With $$E(Y^2) < \infty$$

$$Y = \sum_k \beta_k \Psi_k(X)$$

Where β_k are the coefficients of the polynomial chaos expansion

Ψ_k are the basis of of the polynomial chaos.

Projection and Quadrature approach to get the coef

Ψ_k are orthogonal

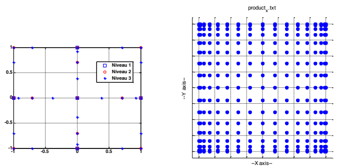
Modal description is often used in electromagnetism and therefore the projection can be considered as “natural” in dosimetry.

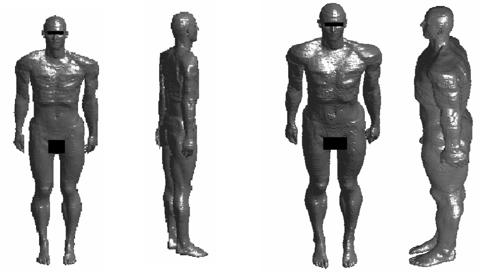
This approach is useful to assess accurately a coefficient but, in the human exposure domain, even with quadrature, in the human exposure domain the projection approach leads to have large number of FDTD simulations. (large number of input and quite large order of polynomial)

Sparse Quadrature : « Clenshaw Curtis » and Smolyak tensorisation

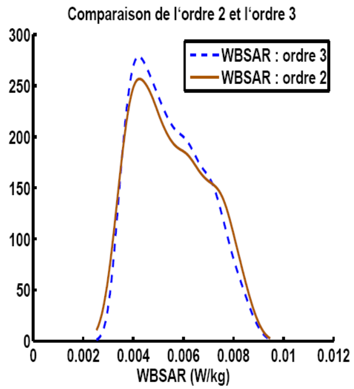
4 input parameters to create Morphed human models

height, shoulders, chest size, Lap belt



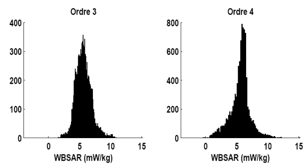


	3 D	4 D
Ordre 1	7	9
Ordre 2	25	41
Ordre 3	69	137
Ordre 4	177	401
Ordre 5	441	1105



Phd A El Habachi
& Statistical analysis of whole-body absorption depending on anatomical human characteristics at a frequency of 2.1 GHz
A El Habachi et al 2010 Phys. Med. Biol. 55 pp 1875 -1887

Phs J Silly Carette
& Variability on the Propagation of a Plane Wave Using Stochastic Collocation Methods in a Bio Electromagnetic Application
Silly-Carette et al IEEE MWCL 2009



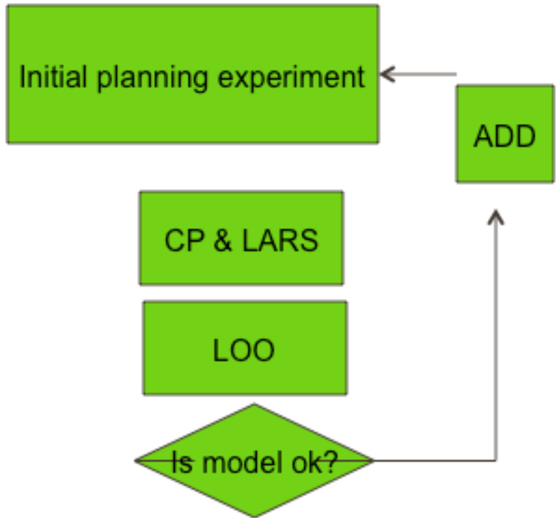
Coefficients assessment using Regression

Regression and LOOCV seems to be more suitable for dosimetry

$$\hat{Y} = \sum_{k=1}^{N} \beta_k \Psi_k(X)$$

$$\hat{y} = \begin{pmatrix} \hat{y}_0 \\ \hat{y}_1 \\ \vdots \\ \hat{y}_P \end{pmatrix} \qquad Z = \begin{pmatrix} \Psi_0(\xi^{(1)}) & \Psi_1(\xi^{(1)}) & \dots & \Psi_P(\xi^{(1)}) \\ \Psi_0(\xi^{(2)}) & \Psi_1(\xi^{(2)}) & \dots & \Psi_P(\xi^{(2)}) \\ \vdots & \vdots & \ddots & \vdots \\ \Psi_0(\xi^{(n)}) & \Psi_1(\xi^{(n)}) & \dots & \Psi_P(\xi^{(n)}) \end{pmatrix}$$

$$\hat{\beta} = (Z^T Z)^{-1} Z^T y$$



Leave one out to analyse the global accuracy of such model

If the model is not as expected then a new experiment has be added

Influence of the phone position closed to the head using Polynomial Chaos

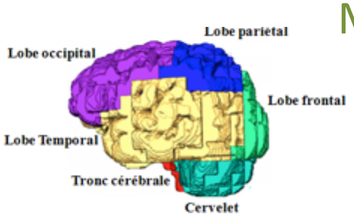
Latin hyper sampling

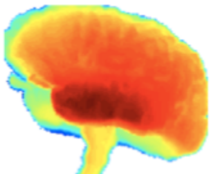
Uniform

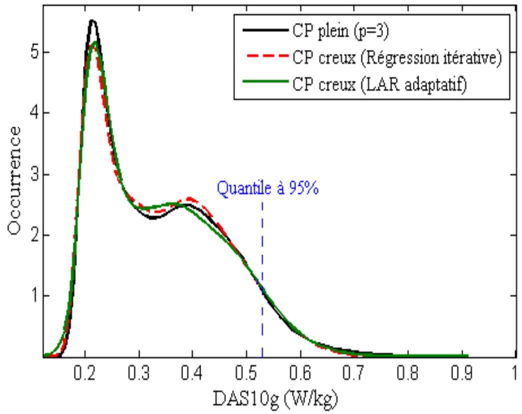
	θ	Φ	Δx	Δz
	[0 -30°]	[-15°+15°]	[5 - 30 mm]	[-10 +10mm]

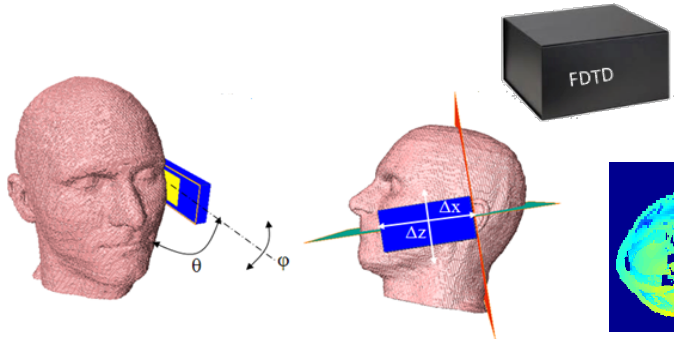
PC + LOO → 122 FDTD simulations

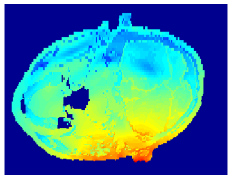
Maximum SAR over 10g in the head







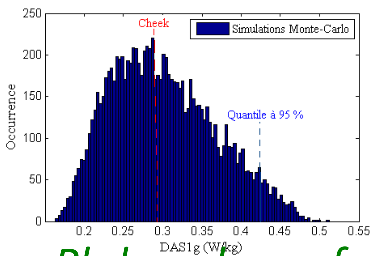


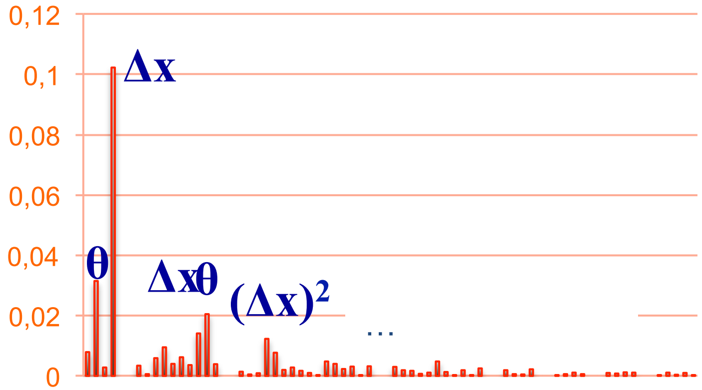


$Y_i = SAR_i$

Sensitivity analysis

Maximum SAR over 1g in the brain





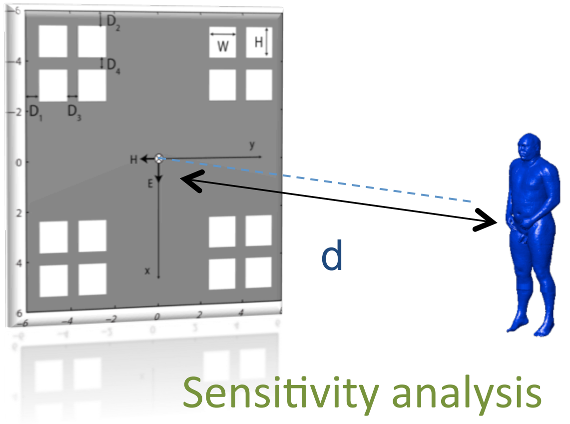
Phd works perfomed by A Ghanmi

Supervisors O Picon and J Wiart

INSTITUT TELECOM

orange

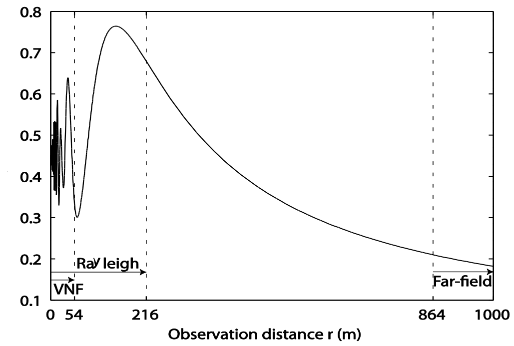
Exposure from reflection on wall



- 9 inputs
  - concrete and glass permittivity
  - height and width of windows
  - distance between windows
  - distance between windows and edges

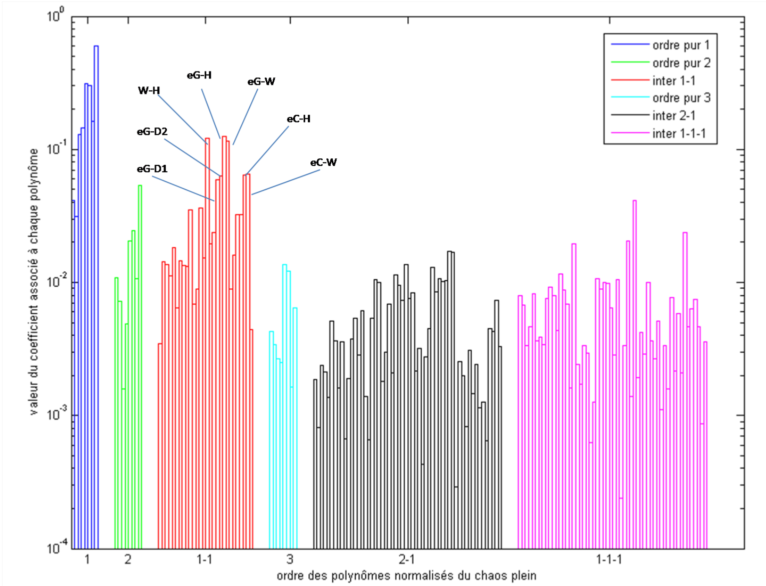
LHS

Deterministic approach

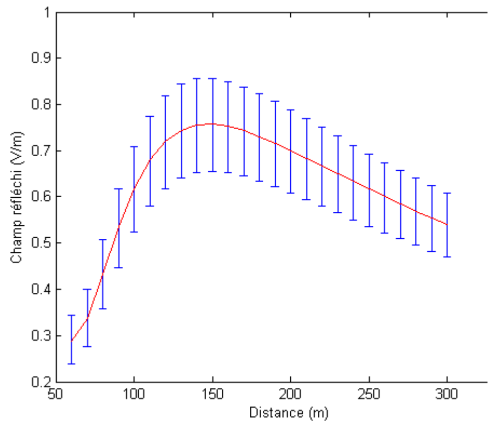


Sensitivity analysis

- Physical analysis: observation of the most inflent polynomials
- Prevalence of some interaction terms compared to the corresponding pure order terms



With PC



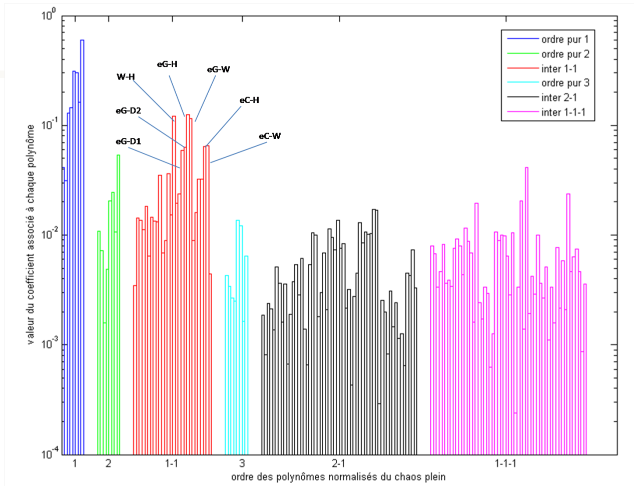
Phd works perfomed by P Kersaudy

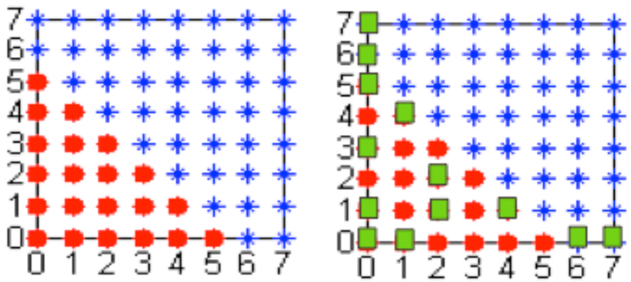
Supervisors O Picon, S Mostarshedi , B Sudret and J Wiart

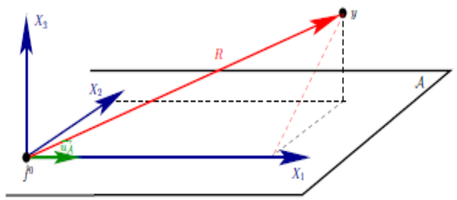
Limit the computationnal effort

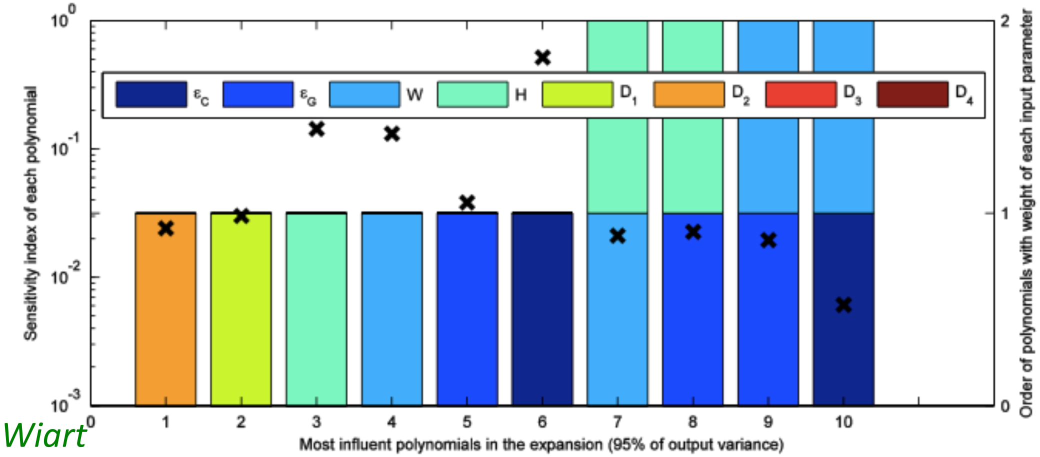
In Dosimetry Parsimony is not an option..

How select relevant polynomials?









Phd works perfomed by P Kersaudy

Supervisors O Picon, S Mostarshedi , B Sudret and J Wiart

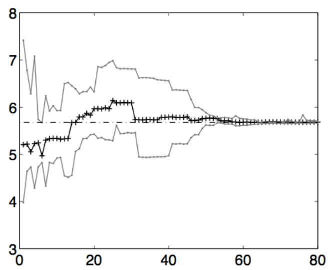
Least Angle Regression LARS

Sparse LARS truncation gives a significant reduction of the requested number of simulations

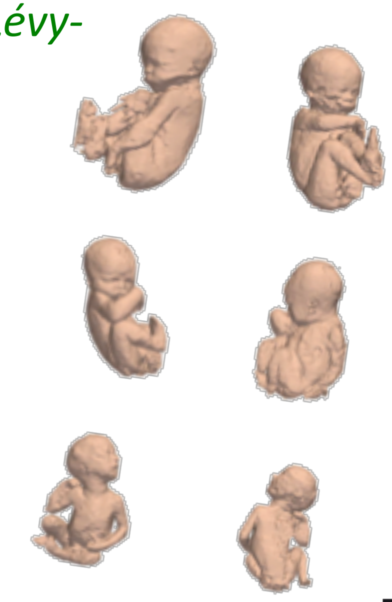
Next step : Parsimonious iterative experiment for quantile estimation

Challenge :
Built an iterative process able to monitor the uncertainty of specific quantile

- **Quantile estimation using Gaussian Process Shrunk (GPS)**

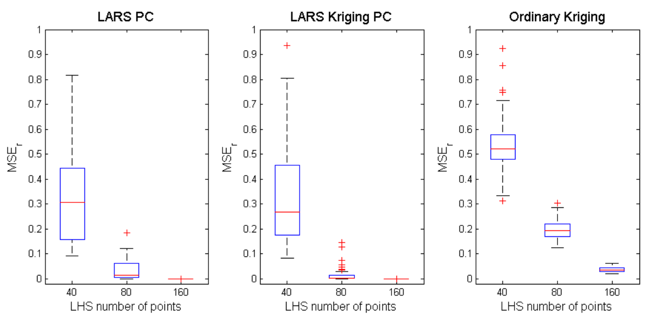


Phd works perfomed by M Jala
Supervisors : E Moulines, CLévy-Leduc, E Conil and J Wiar



- **Combination of Kriging with chaos polynomials**

Result with Ishigami function



As Final Conclusion

Dans la confusion trouver la simplicité

De la discorde faire jaillir l'harmonie

Au milieu de la difficulté se trouve l'opportunité

Albert Einstein,

Trois règles de travail