Détection et suivi d'aiguille de biopsie en échographie 3D temps réel

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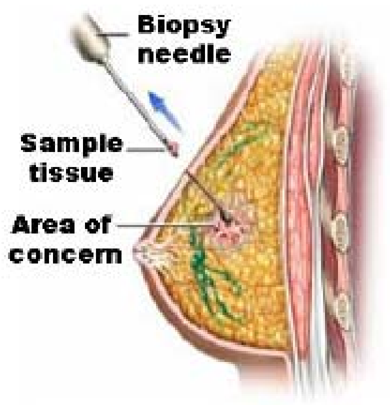
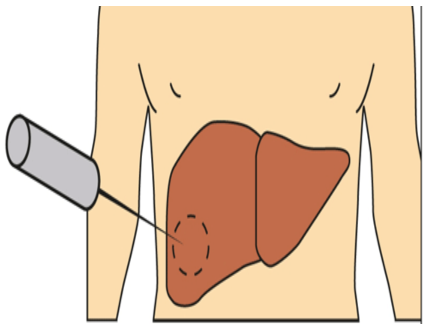
Outline

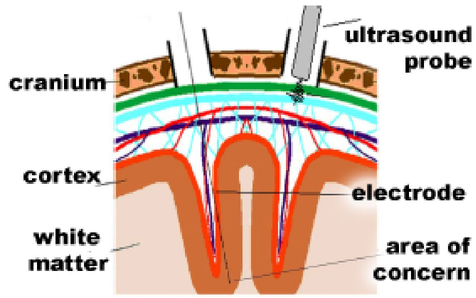
- Medical context
- 2D US probe for 3D imaging
- Needle detection and tracking
- Future work

Contexte médical

- **Suivi de micro-outils**
  - Prélèvement ciblé (tumeur) ou non (maladie diffuse)
    - o aiguille de biopsie
    - o foie/prostate/sein/thyroïde
  - Thérapie, aiguille (RF ou micro-ondes) , foie
- **Enjeux**
  - Biopsie du foie:
    - o prélever au bon endroit , éviter les mauvais diagnostics
    - o éviter les structures vasculaires , risque d'hémorragie et/ou dissémination
    - o limiter les trajets dans le parenchyme hépatiques , risque de lésions
  - Traitement par aiguille RF
    - o positionner au bon endroit : traitement complet de la tumeur plus marge saine

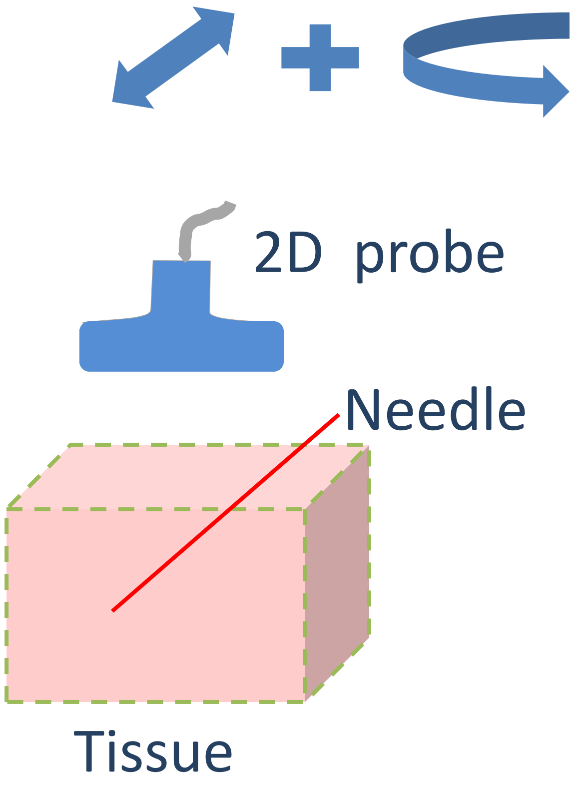


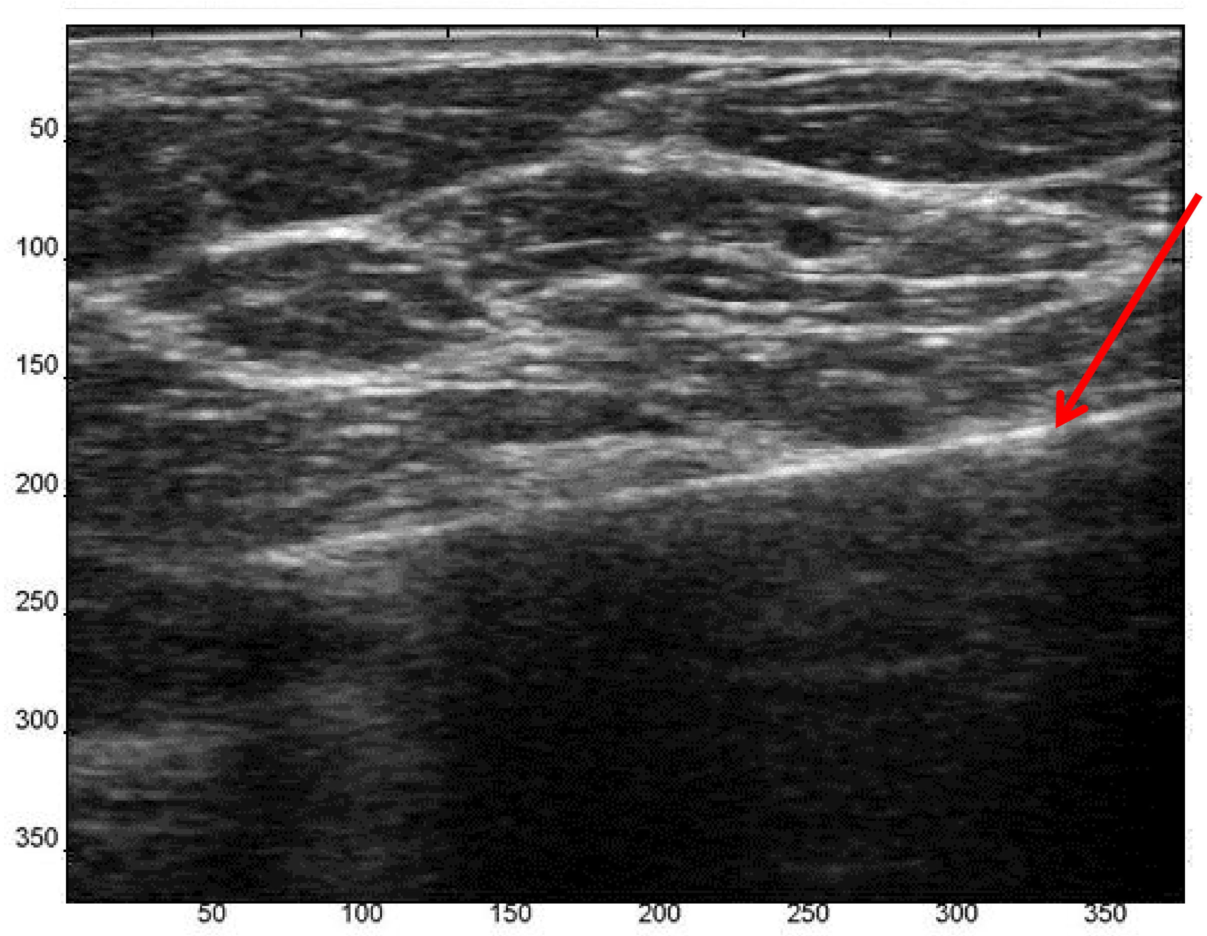




Biopsie: where is the needle?

The radiologist guides (moves) the probe to align the ultrasound plane with the axis of the needle

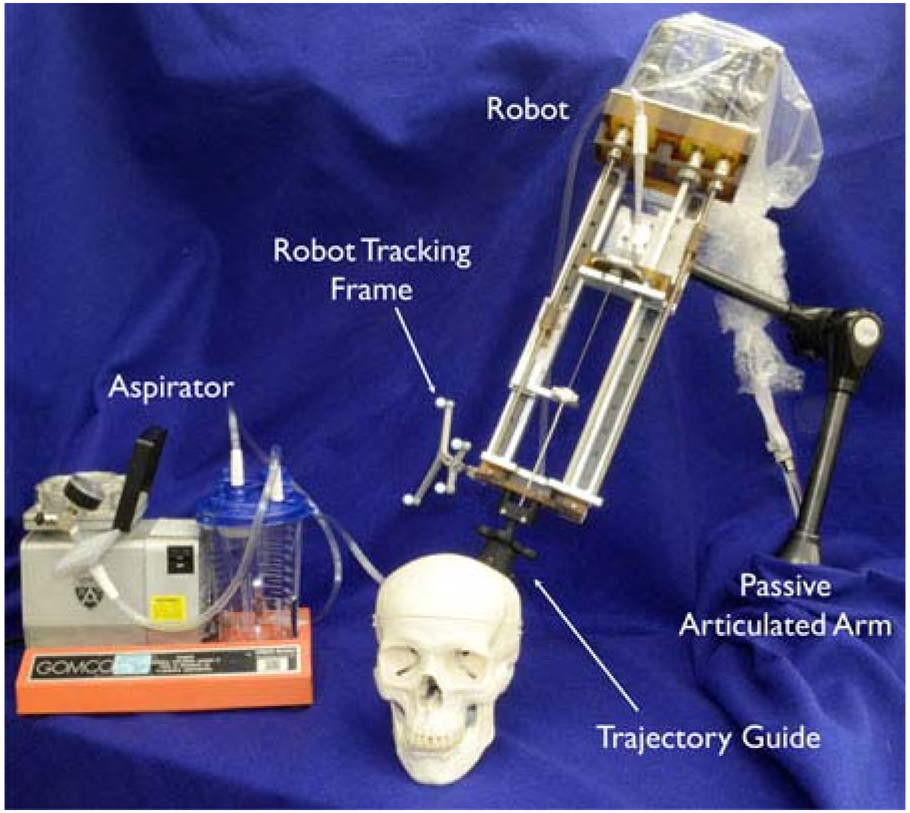




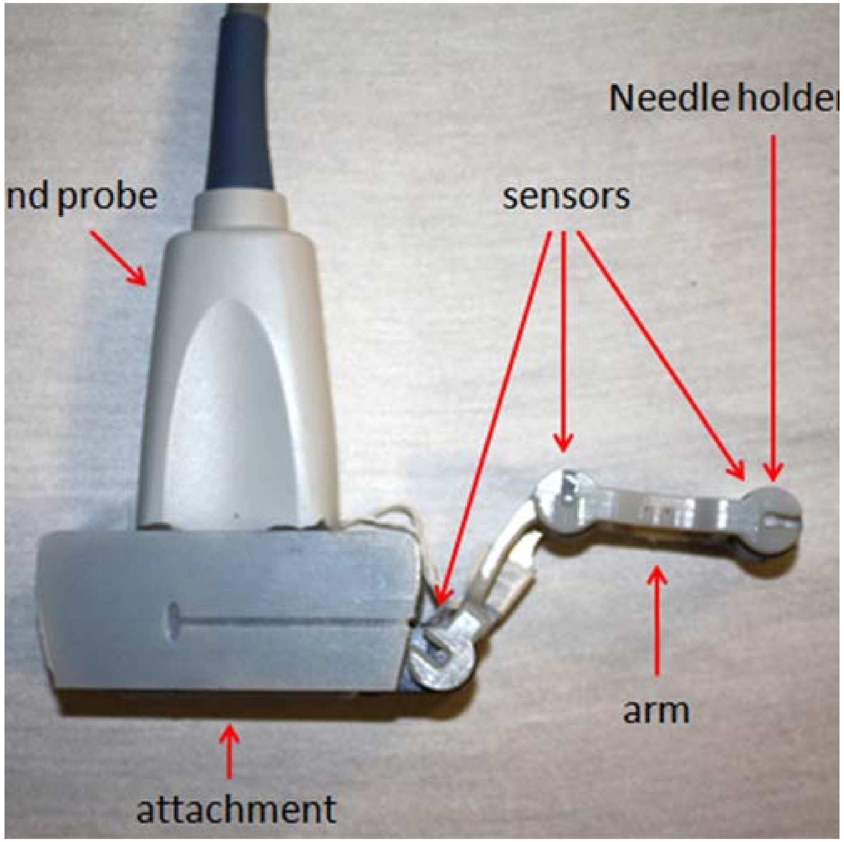
Real data from 2D ultrasonic image of breast

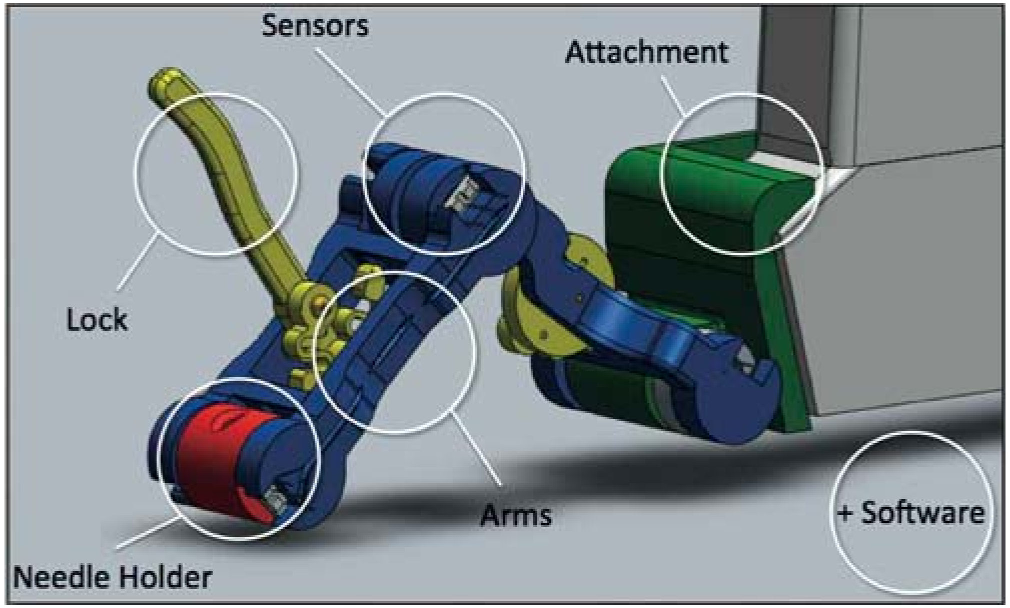
Robot and MRI

The Image-Guided Autonomous Robot (IGAR), which works in combination with a magnetic resonance imaging (MRI), aims to make breast biopsies more precise and automated. It has a precision to insert the needle within about 8 mm.

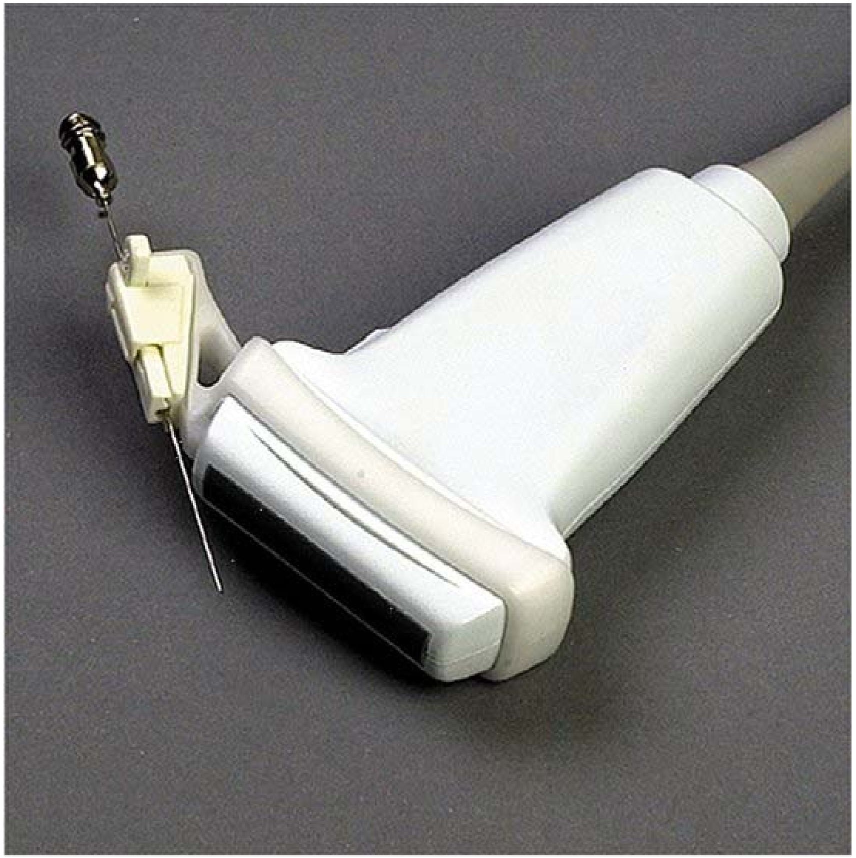


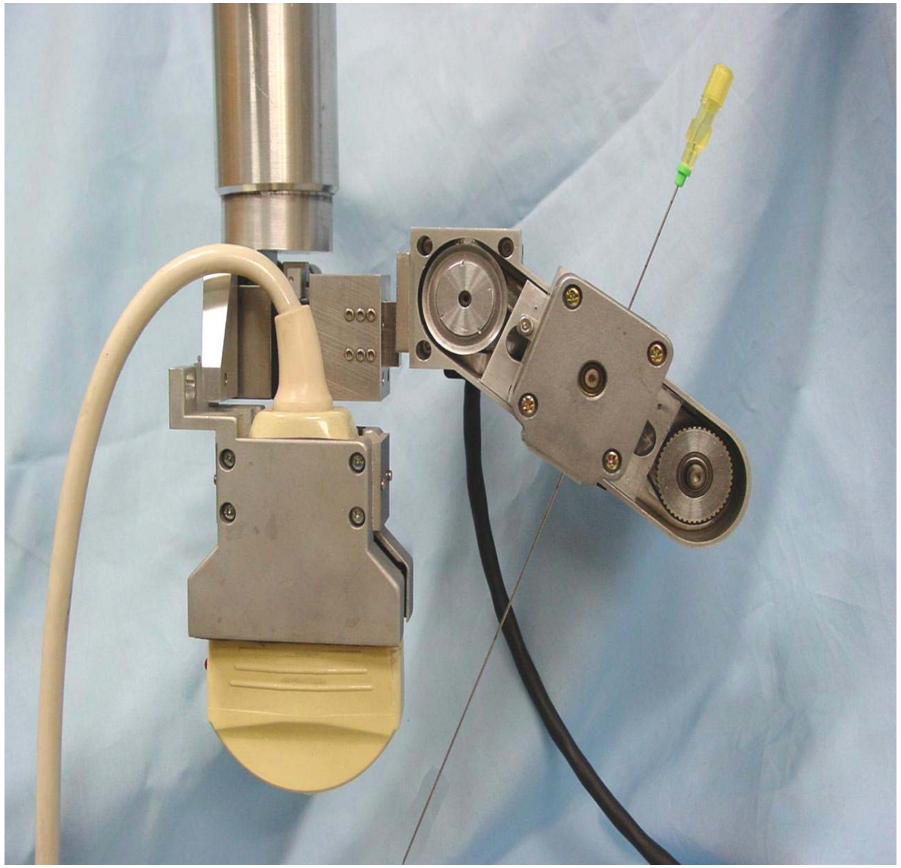
A steerable needle robot setup attached to a phantom skull. This robot is designed for treating brain clots. An ultrasound imaging combined with a computer model of deformation of brain tissue could be implemented in future work [J. Burgner, 2013].





An Ultrasound needle guided devices with a robotic arm attach to the ultrasound probe (left) and its diagrammatic sketch (right) [L. Brattain, 2011]





Different kinds of guide attached to the ultrasound probe

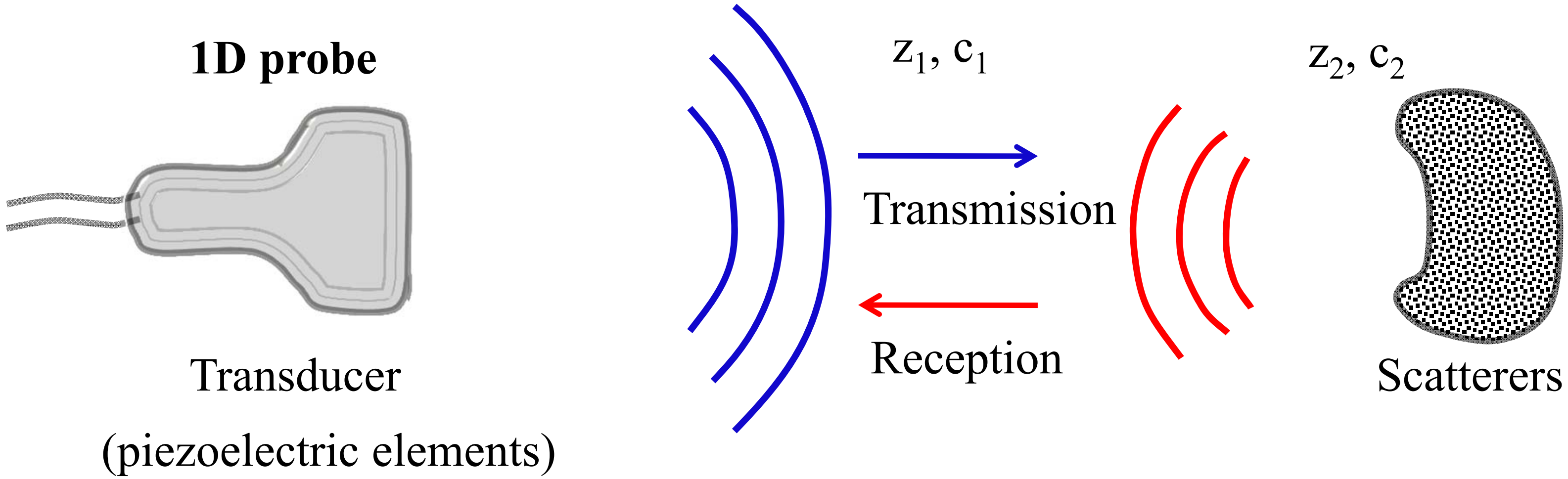
Contexte médical: biopsie

- **Sous contrôle ultrasonore**
  - non invasif,
  - peu couteux
  - imagerie temps réel
- **Limites actuelles**
  - Imagerie 2D alors que l'orientation est 3D : nécessite une grande expertise
  - simple visualisation, pas d'aide au geste
- **Objectifs**
  - imagerie ultrasonore 3D
  - aide au geste (segmentation tumeur, détection et suivi aiguille, indication de trajectoire)
  - modification minimale du système: pas de système de navigation ou autre dispositif

2 axes de recherche

- Echographie 3D à partir de sonde matricielle
- Détection et suivi d'aiguille à partir de données ultrasonores 3D

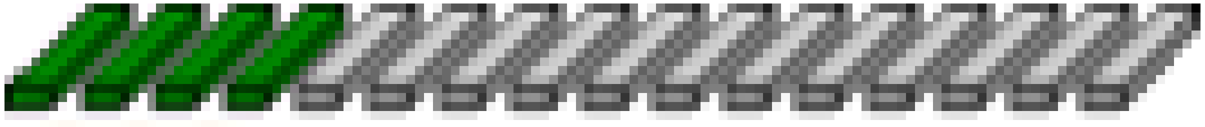
- **Frequency (f) range between 2 and 20 MHz**
- **Image is formed by echoes from the scatterers**

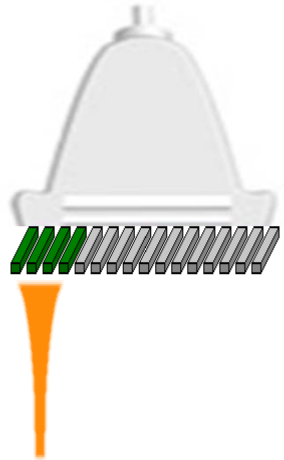


$\lambda = c/f$ Wavelength

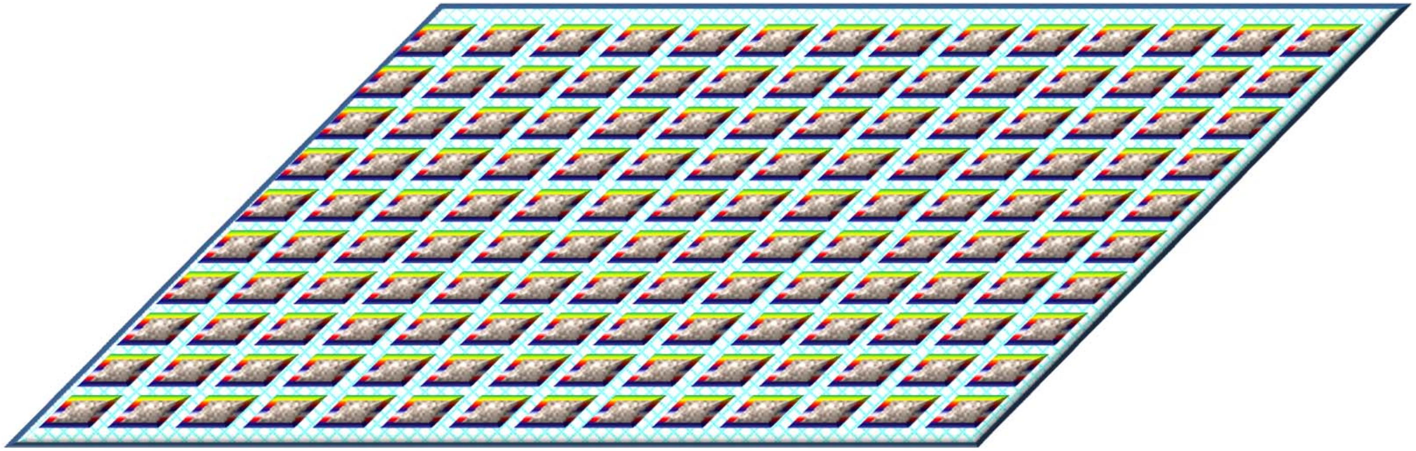
c Speed of sound (≅1540 m/s in soft tissues)

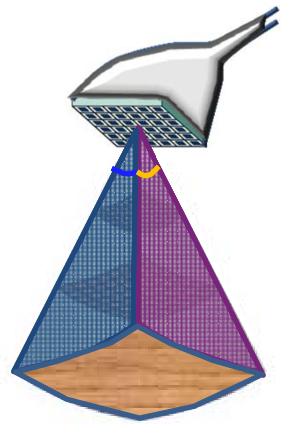
- **Barrette linéaire 1D**



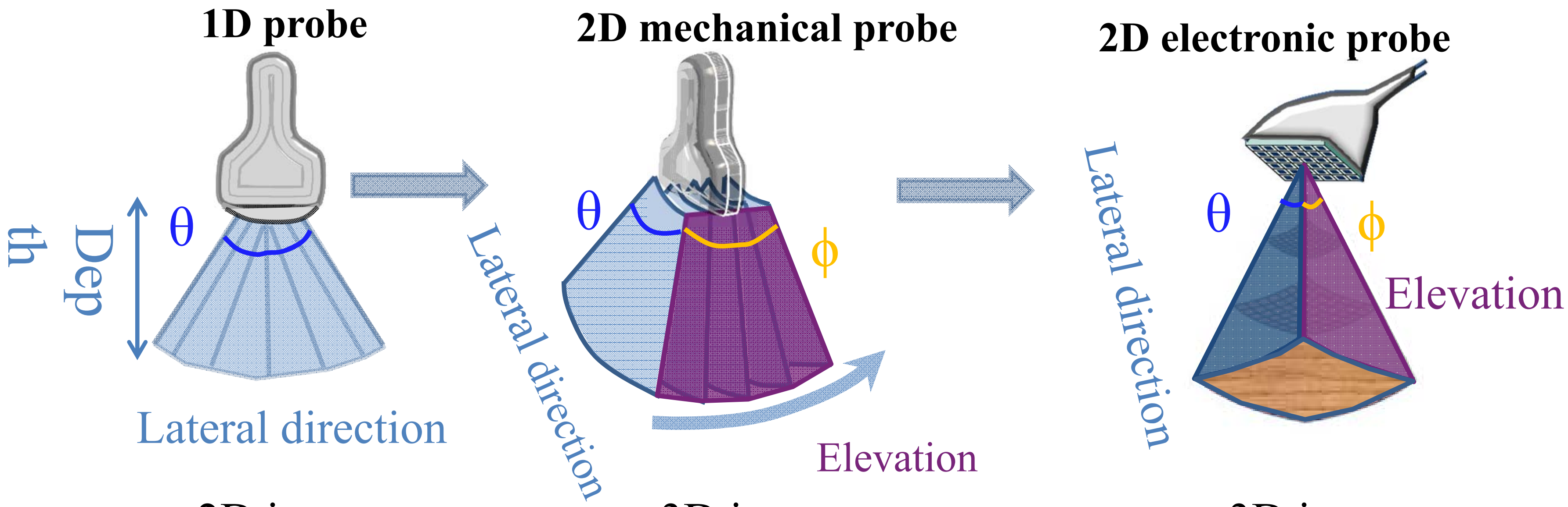


- **Matrice 2D**





3D ultrasound imaging



2D image | 3D image | 3D image

- 20 to 50 images/s
- Information only on slices

- 3D representation
- About 1 volumes /s

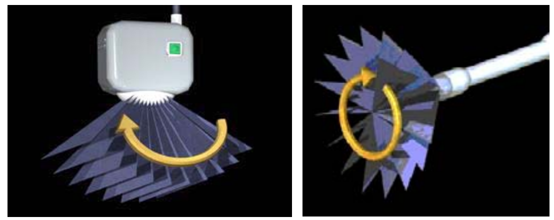
- 20 to 50 volumes/s
- Beam steering in space
- Too many elements

Principe de l'échographie 3D

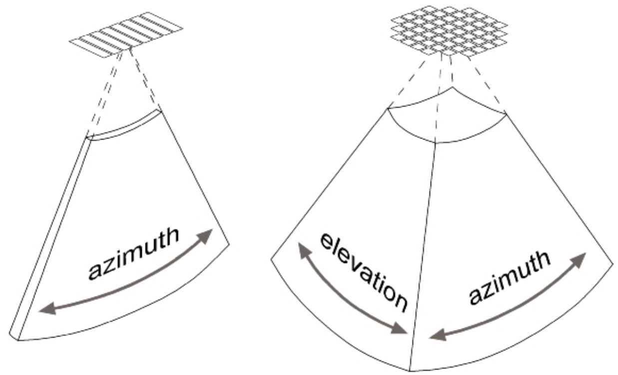
Un faisceau US balaye un volume 3D

- **Balayage manuel**

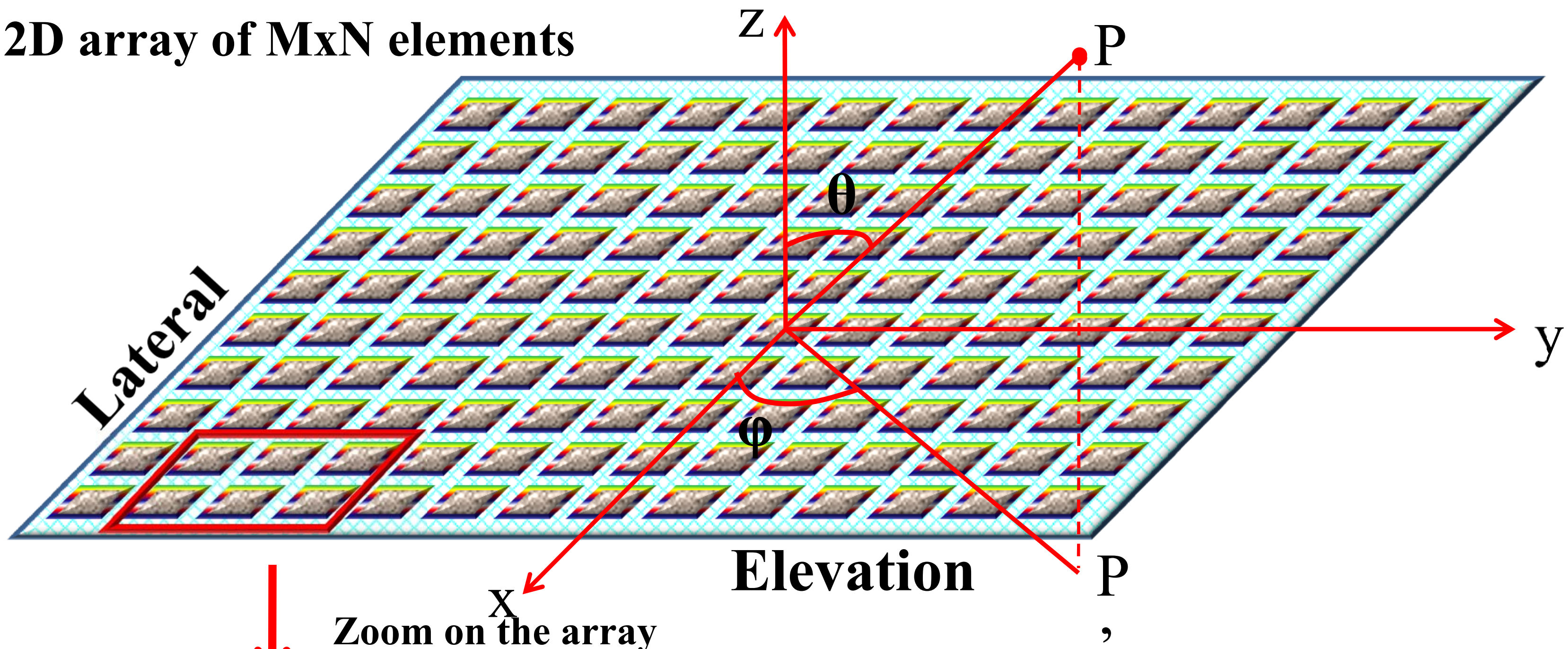
- **Balayage mécanique** (moteur pas à pas)
  - disponible sur les échographes commerciaux
  - lent (de l'ordre de 1 volume / seconde)

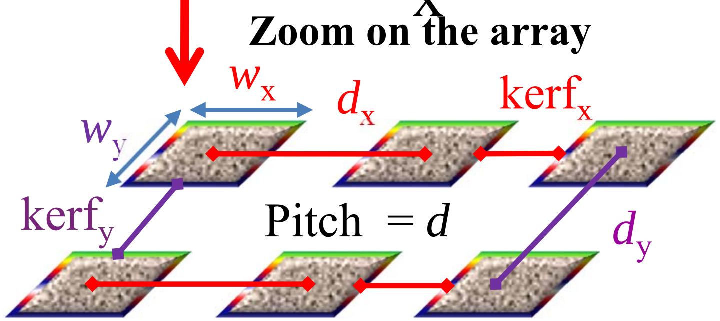


- **Balayage électronique: sonde matricielle, grand nombre d'éléments (64x64 = 4096)**
  - **connectique**
  - pilotage
  - matériel à développer



2D array parameters

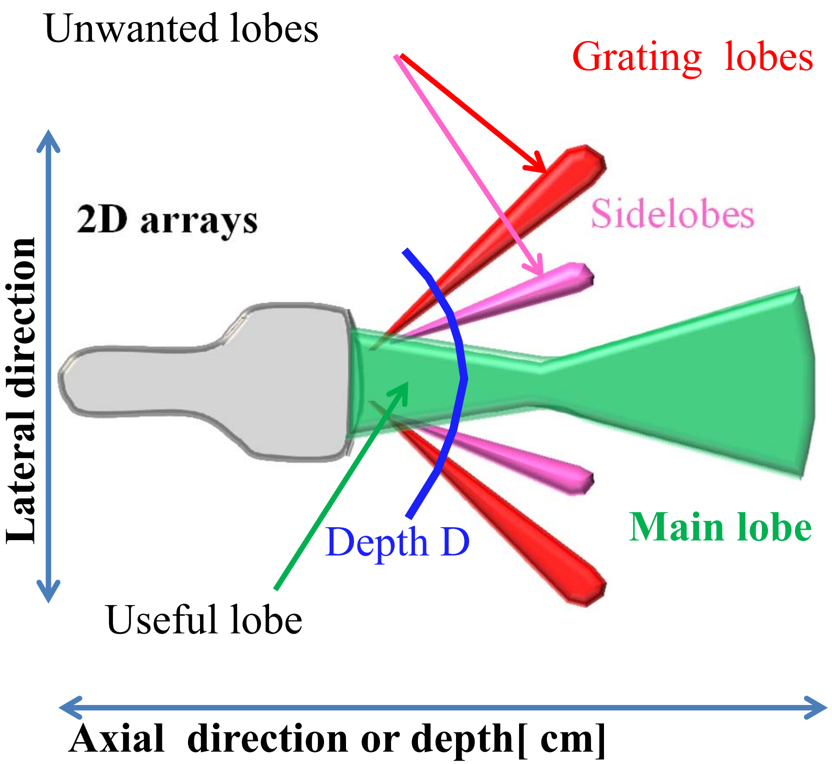


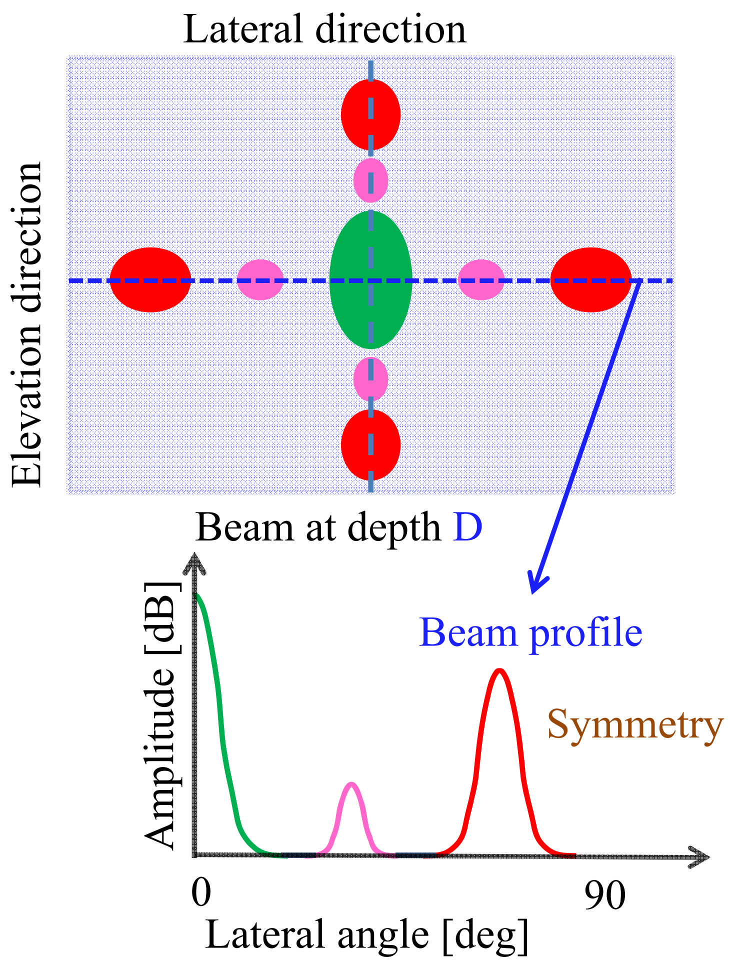


$$\text{Pitch} = w + \text{kerf}$$

Elements aligned
on a regular grid

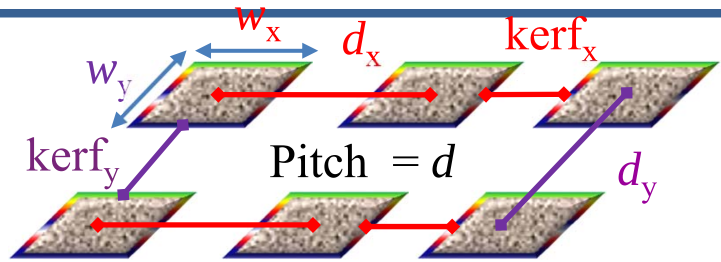
- **Beam visualization**





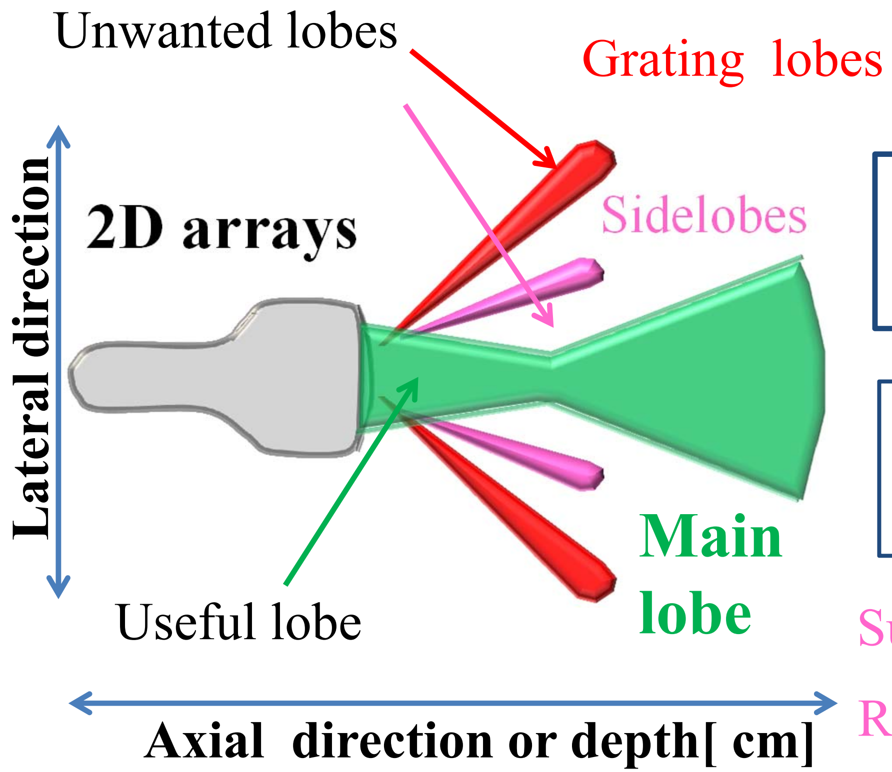
2D array beam

Regular positioning



Pitch $= w + \text{kerf}$

→ Pitch < λ/2 to avoid grating lobes



Small elements

- Huge element number → Connection challenge
- Poor sensitivity → Poor imaging properties

Suppressed by apodization in dense array

Reduced by optimization otherwise

Objectives of the study

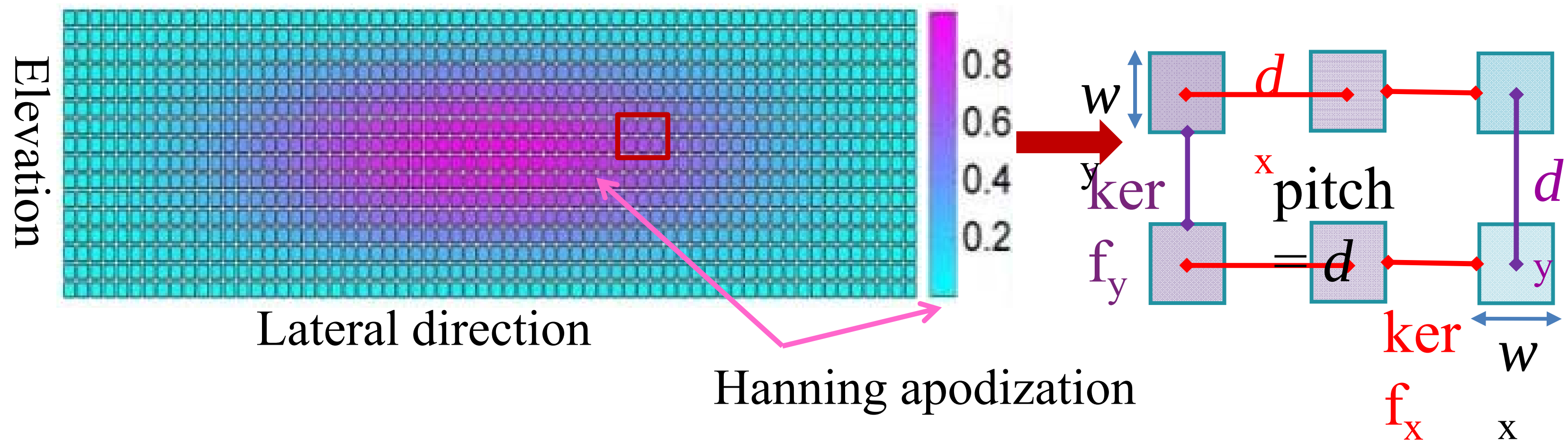
Three main barriers to break down

1. **Reduction of active element: 1024 à 4096** → **256 at most for easy connection**
   - To suit to current scanners
   - To have high volume rate
   - about 10 volumes/s
2. **Reduction of the energy loss** → **Energy loss as low as possible**
3. **Suppression of grating lobes** → **40 dB fewer than the main lobe**
   - Usual dynamic for echography

Illustration 2D array

- **Dense array**

16x64=1024 elements



Parameters	Values
Central frequency	3.5 MHz
Element number	64x16=1024
Element dimensions (*w*)	λ/2 = 0.22 mm
Pitch (*d*)	3λ/5 = 0.264 mm

Simulations with
FIELD II software

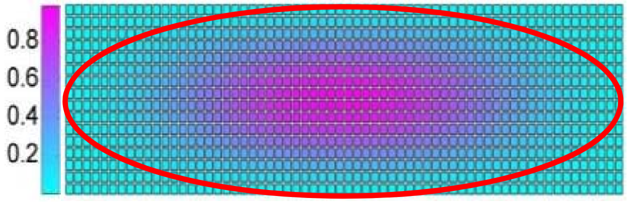
Jensen et *al*, 1992

Jensen, 1996

Edge deactivation

Edge elements contribute less to the beam ➡ **Apodization**

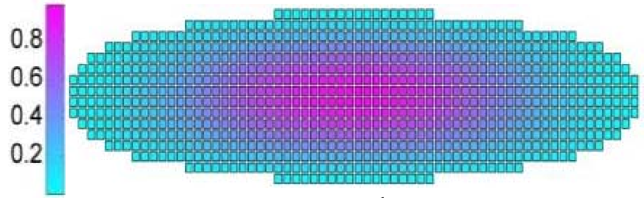
Dense array



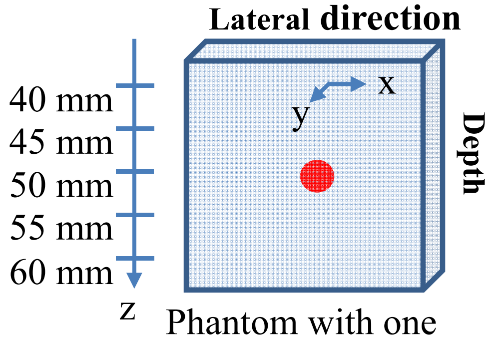
64x16 array of 1024 elements

20% to 30%

Ellipsoidal array



828 elements



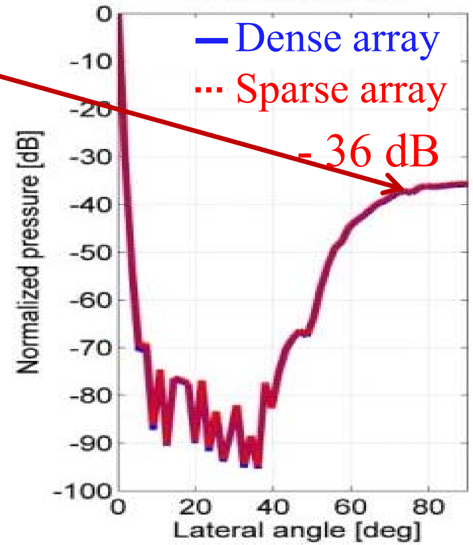
Phantom with one scatterer at 50 mm

Simulations

Field II

Energy loss ~ 0 dB

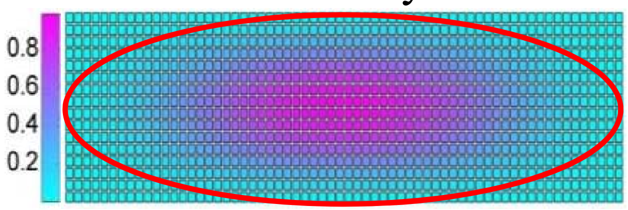
Grating lobes



Edge deactivation

Edge elements contribute less to the beam → **Apodization**

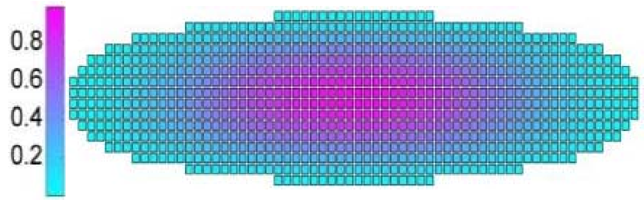
Dense array



64x16 array of 1024 elements

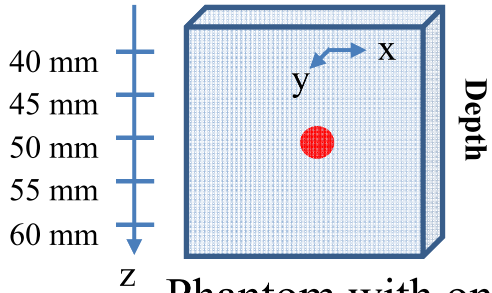
20% to 30%

Ellipsoidal array



828

Lateral direction

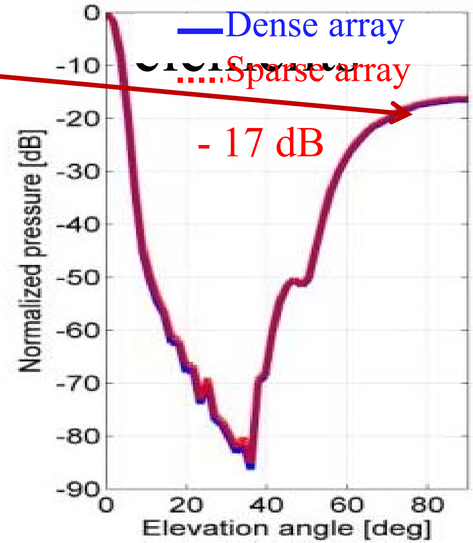


Phantom with one scatterer at 50 mm

Simulations

Field II

Grating lobes



Energy loss ~ 0 dB

Not enough

Maintained in the rest of the study

Other methods

Sparse array

Sparse array means an array containing more zeros than any other value

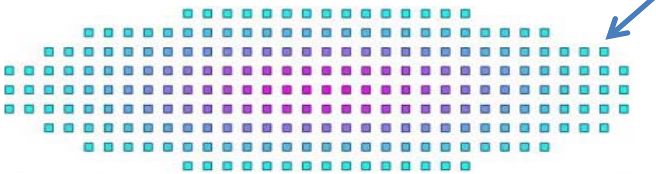
There are two types of sparse array

- The periodic sparse array
- The random sparse array

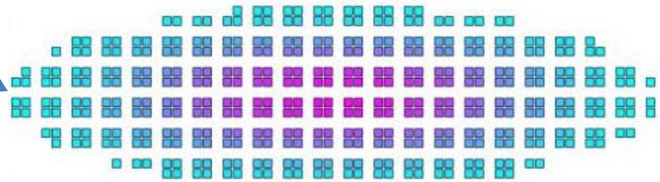
Periodic sparse array

Creatis

1 element active out of 2



2 elements active out of 3



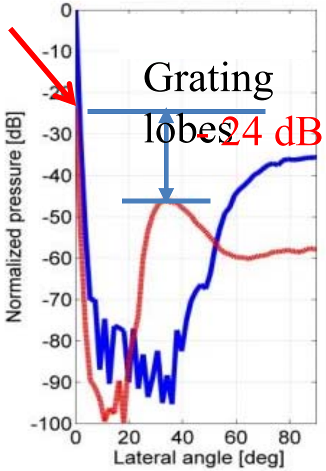
232 elements

409 elements

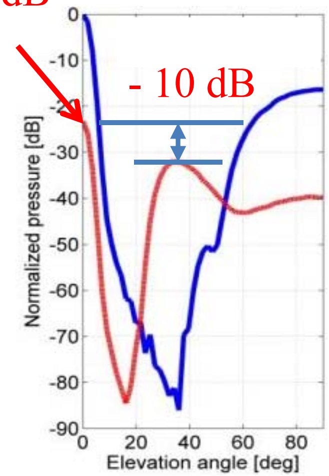
— Dense array

··· Sparse array

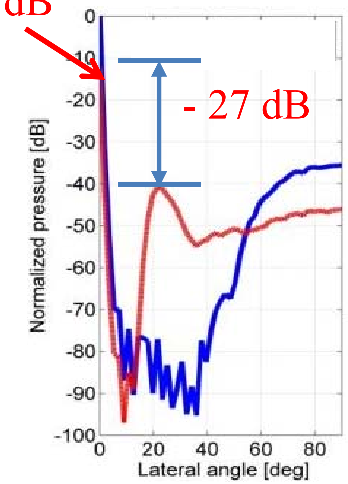
- 23 dB Lateral



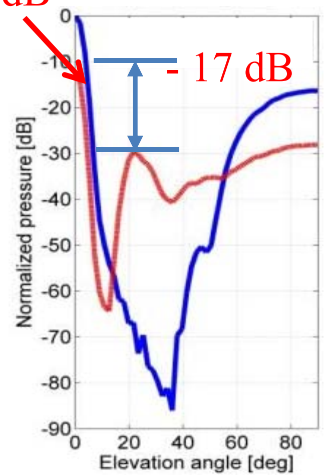
- 23 dB Elevation



- 13 dB Lateral



- 13 dB Elevation



Element number 232

Energy loss 23 dB

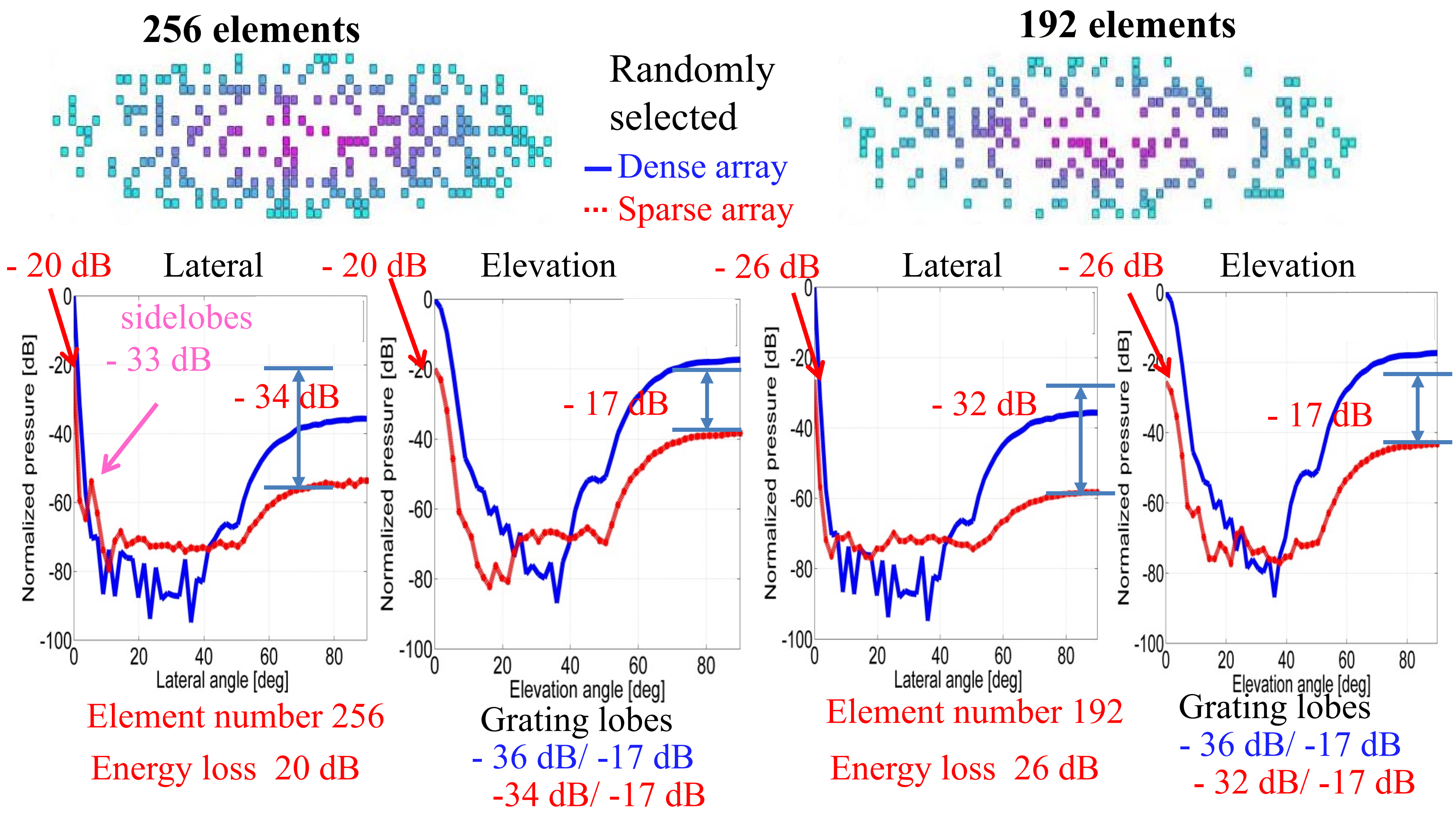
Grating lobes
- 36 dB/ -17 dB
- 24 dB/ -10 dB

Element number 409

Energy loss 13 dB

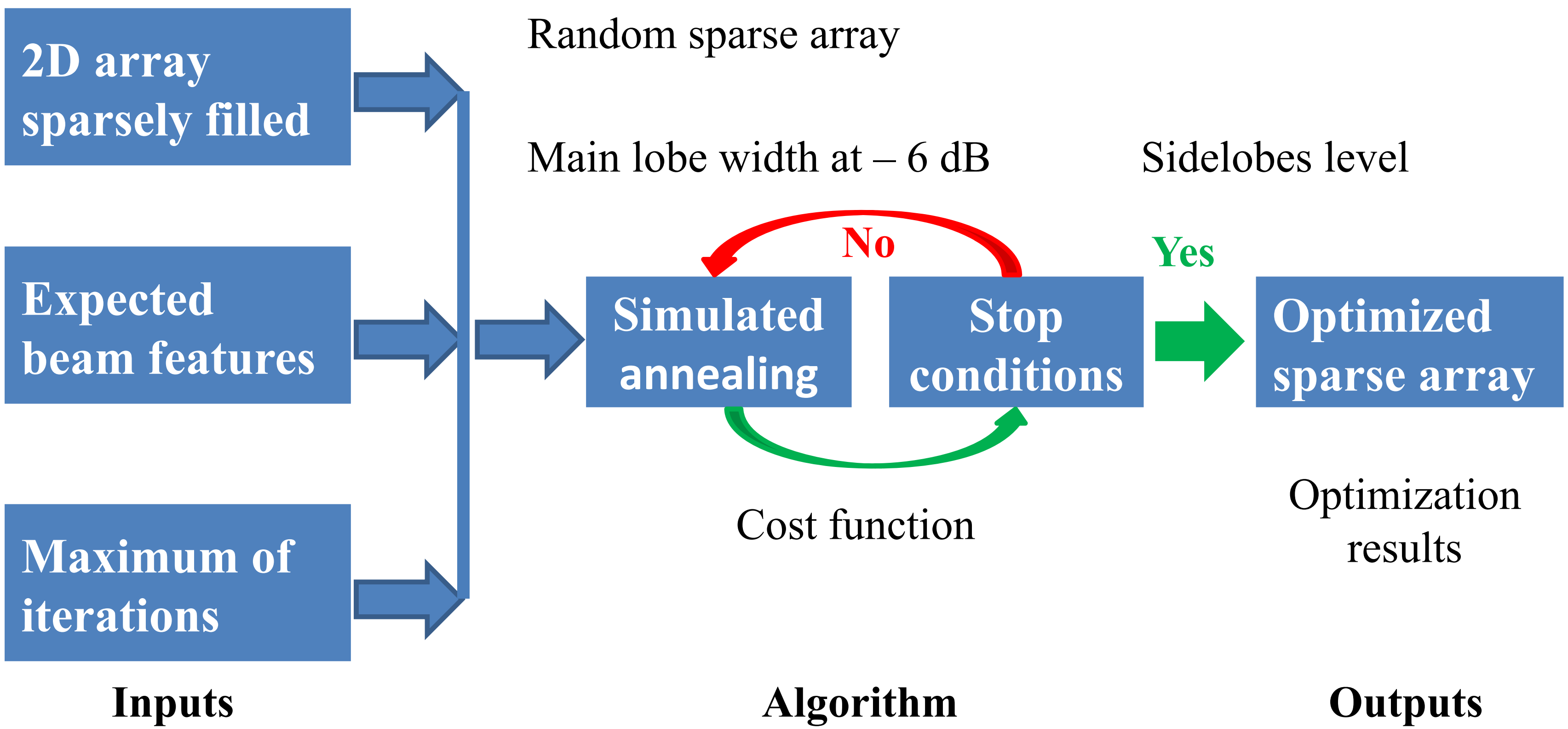
Grating lobes
- 36 dB/ -17 dB
- 27 dB/ -17 dB

Random sparse array



Optimization

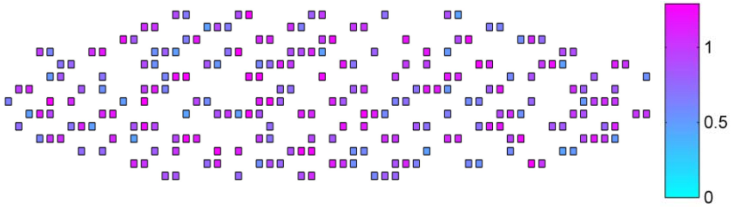
- **Active number elements**
- **Main lobe width**
- **Level of sidelobes**
- **Energy loss**



Optimization

Optimization → Element number minimization

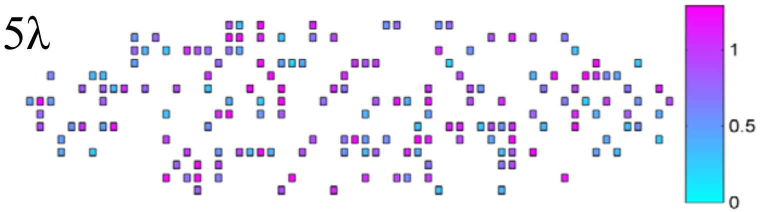
Trucco's method



235 elements

w= 0.5λ

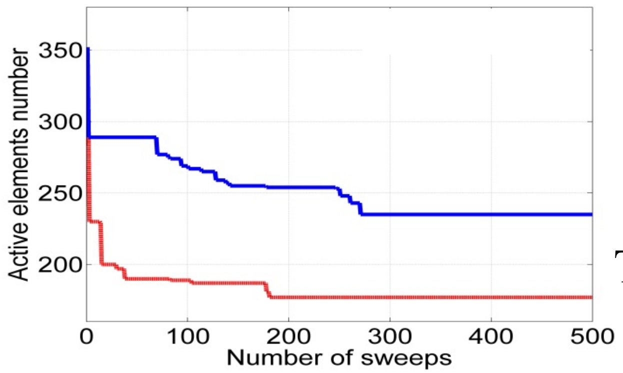
Diarra's method



177 elements

— Trucco method

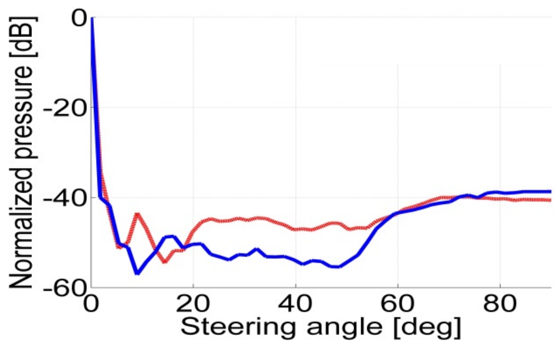
··· Diarra method



Less active elements

Reduction of 25%

The same beam feature



- The new version gives at least the same properties as the reference

- Used in the rest of the study

Motivation and objectives

- Remove the regular grid in element positioning
  - → Reduce the grating lobes
  - → Favor the use wide elements to
    - ➢ Maximize the array sensitivity (energy)
    - ➢ Reduce the element number for a given footprint

Two strategies are proposed

- Constant element size and random pitch **Non-grid array**
- Random element size and pitch

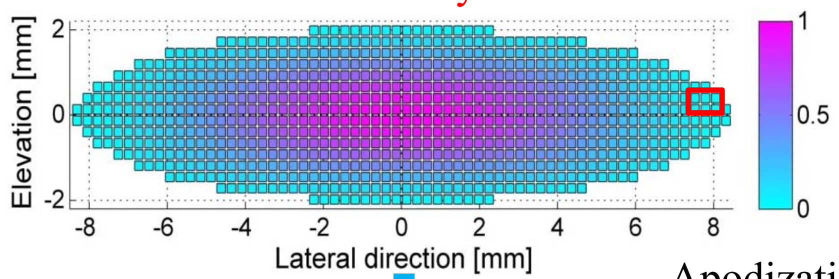
Variable-size array

Non-grid array

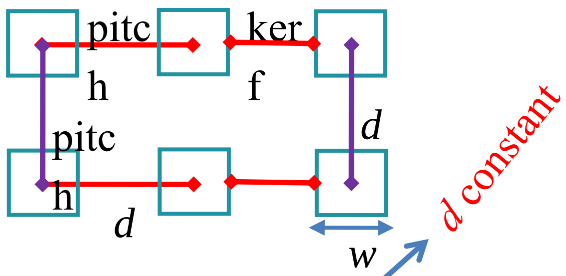
Constant element size - random pitch

Diarra, *IEEE IUS*, 2012

Dense array



Zoomed picture

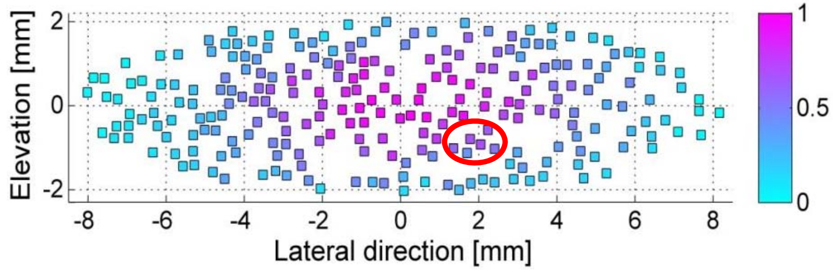


Remove periodicity

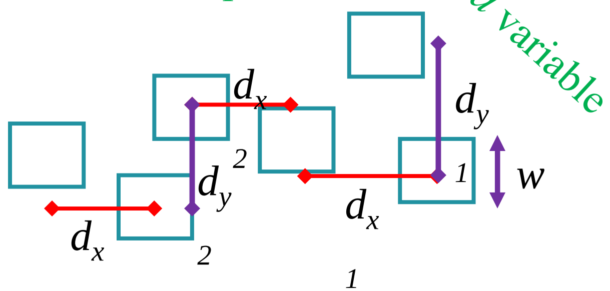
Apodization Hanning

Pitch = $d\,(d_x, d_y)$

Non-grid 2D array



Zoomed picture



No periodicity ⇨ no grating lobes

No constraints on the pitch ~~Pitch < λ/2~~

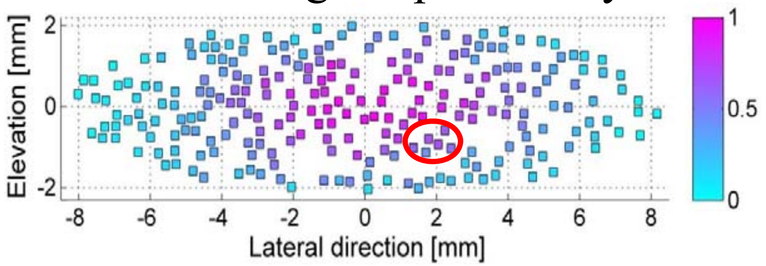
Random element size - random pitch

- Increase the randomness in element positioning

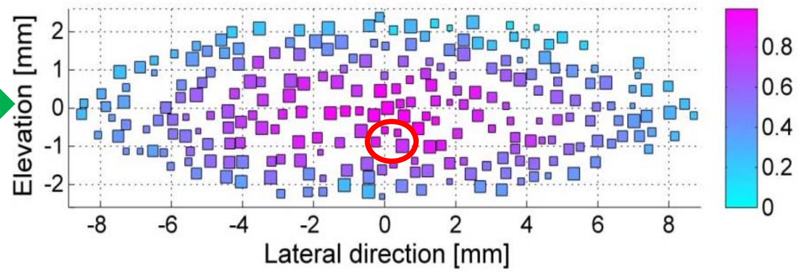
Diarra, *IEEE IUS*, 2013

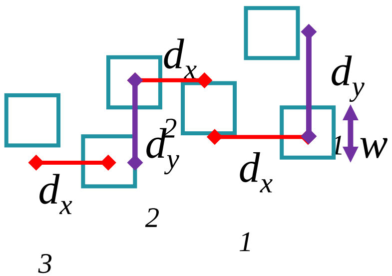
- Considerable reduction of the grating lobes

Non-grid sparse array



Variable-size array





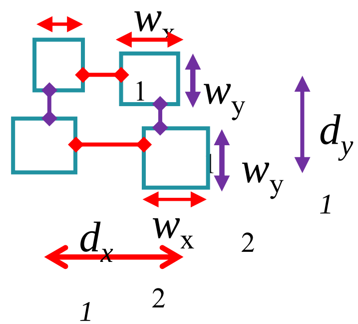
w = constant

d = varying

w = varying

d = varying

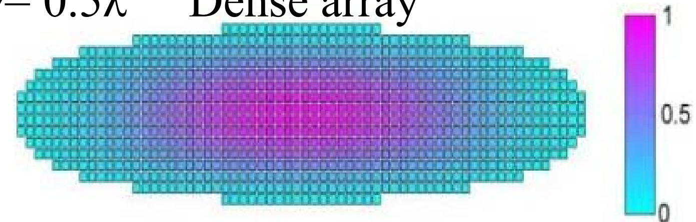
$w_1 \neq w_2 \neq \ldots \neq w_n$



Optimized non-grid array

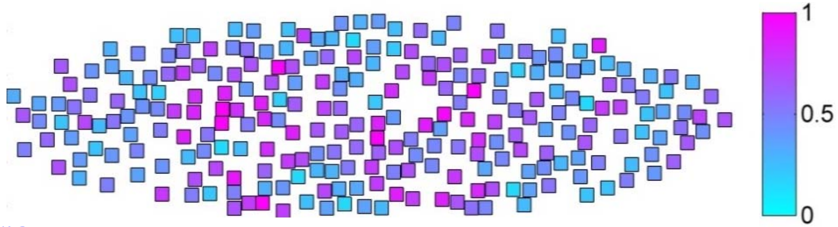
Optimization → **Element number = 256**

w= 0.5λ Dense array



828 elements

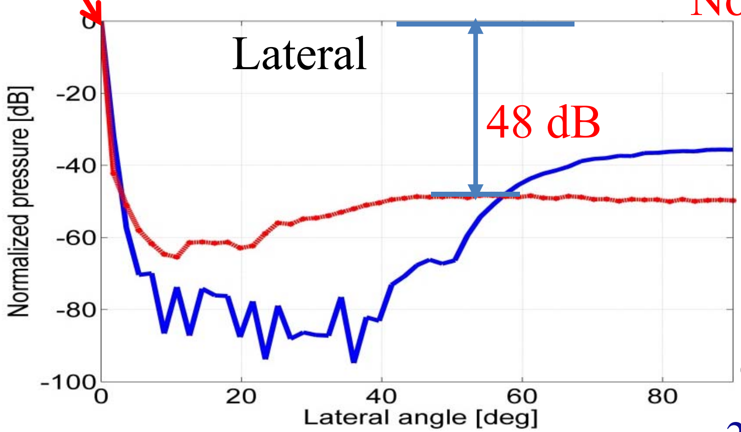
w= 0.7λ Optimized non-grid array



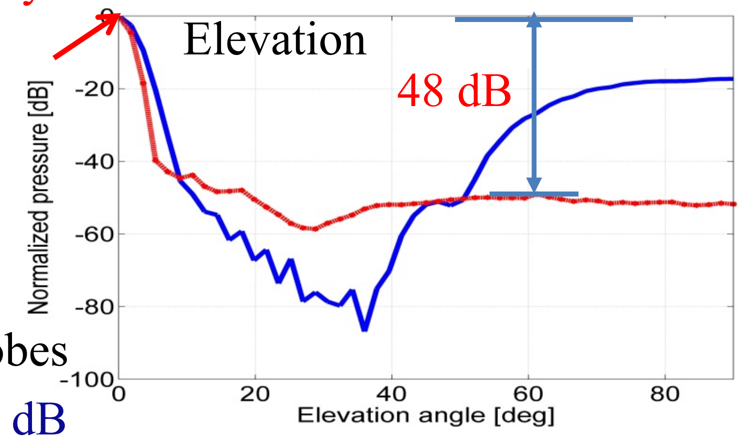
256 elements

— Dense array
··· Non-grid array

0 dB



0 dB



Energy loss = 0 dB

Grating lobes

- 36 dB/ -17 dB

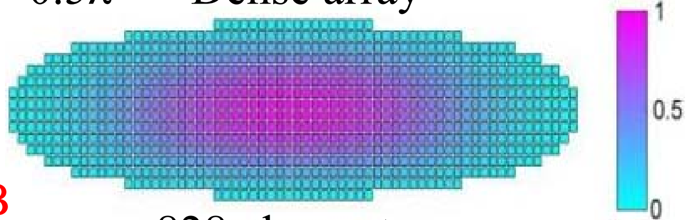
- 48 dB/ -48 dB

Element number reduction of 69%

Optimized variable-size array

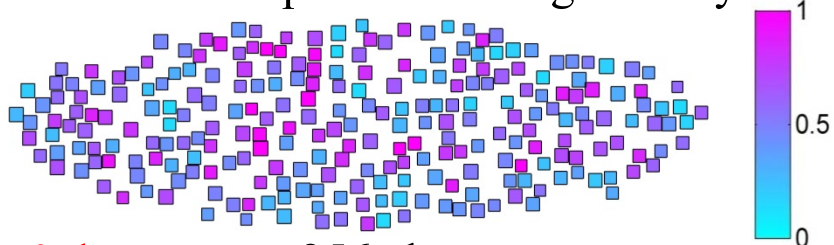
Optimization → Element number = 256

w= 0.5λ   Dense array

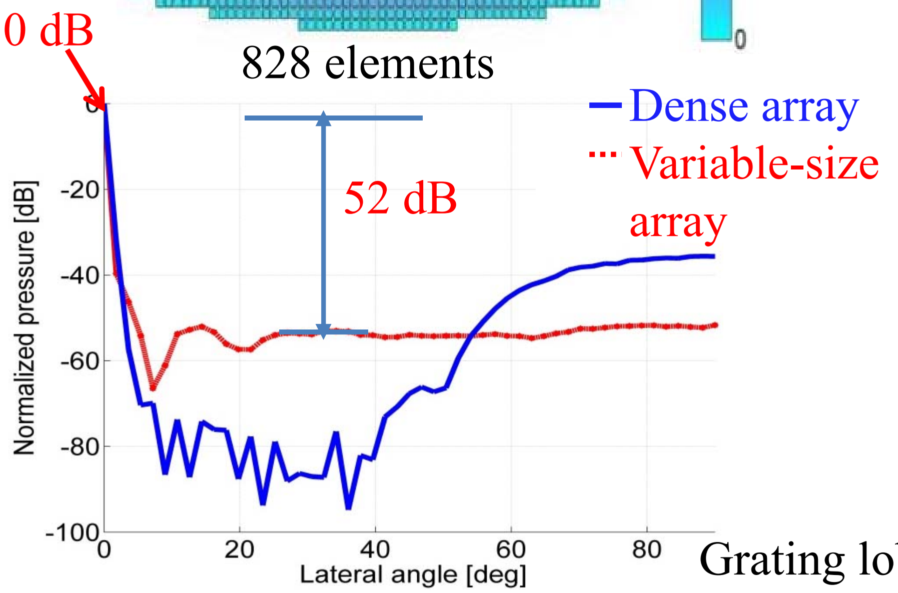


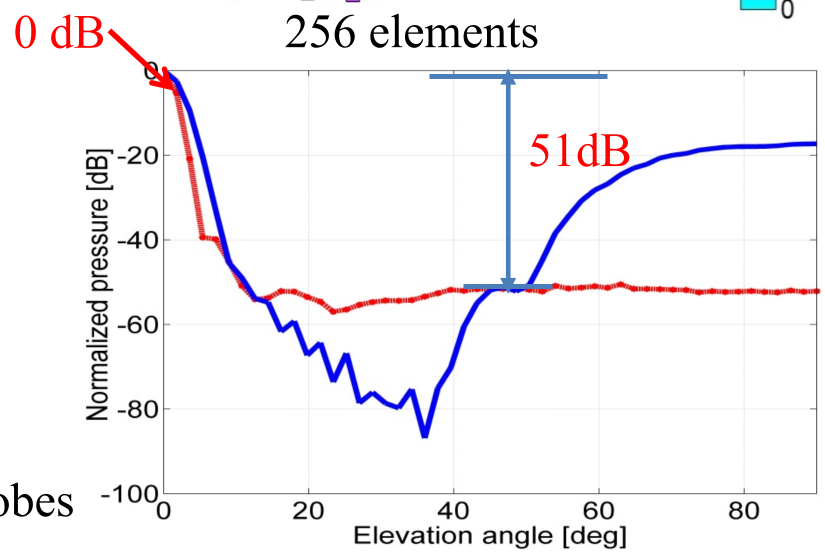
828 elements

w= 0.6- 0.8λ   Optimized non-grid array



256 elements





Grating lobes

- 36/ -17 dB
- 52/ -51 dB

Energy loss = 0 dB

Element number reduction of 69%

Summary of the results

	Dense array	Standard sparse array	Non-grid array	Variable-size array
Number of elements	828	256	256	256
Element size	λ/2	5λ/10	7λ/10	6λ/10- 8λ/10
Lateral / Elevation main lobe width at −6 dB (degree)	0.7 / 6	0.6 / 4.6	0.6/ 3.7	0.6/ 3.8
Lateral/ Elevation grating-lobe level (dB)	−35.6/−17.3	−39 / −20	−48/ −48	−52/ −51
Energy (dB)	0	−13	0	0
Active surface (mm²)	49.5	12.4	26	25

Legend
Best array
Worst array

Conclusion/discussion

- **For fixed beam properties**
  - The non-grid array provides a reduction of about **20%** (177→ 142) compared to the sparse array
  - Grating lobes are reduced of **6 dB** (39 dB→45 dB) and **21 dB** (19 dB→40 dB) in lateral and elevation directions
  - The energy loss is only **8 dB** against **15 dB** in sparse array
- **For the element number fixed to 256**
  - The grating lobes reduction is **9 dB** and **31 dB** in lateral and elevation directions
  - The energy loss is negligible against **13 dB** in sparse array

Outline

- Medical context
- 2D US probe for 3D imaging
- Needle detection and tracking
- Future work

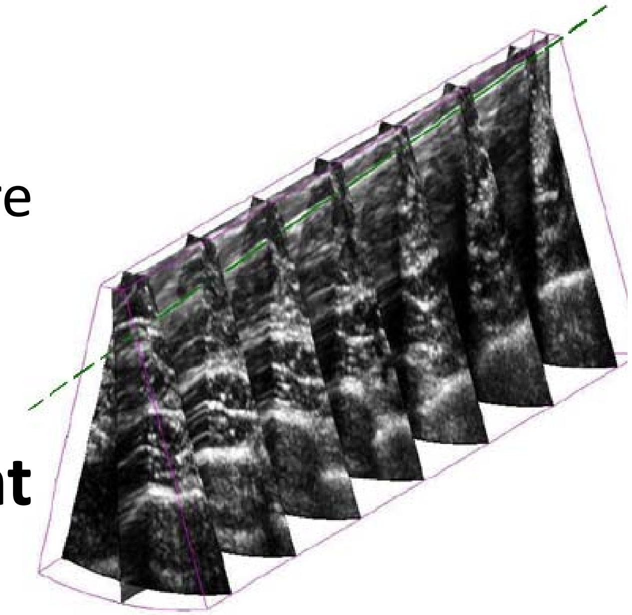
- **Méthodes existantes**
  - Analyse en composantes principales
  - Projections

- **Nos travaux: ROI-RK method**
  - RANSAC
  - Line filtering
  - Region of interest (ROI)
  - Kalman filter
  - Logiciels développés

- **Conclusions perspectives**

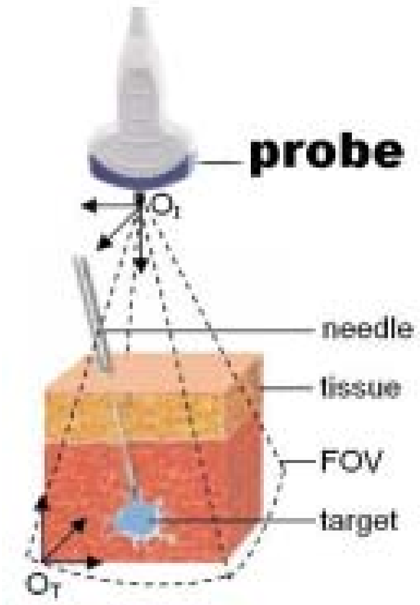
Hypothèses

- **Objet de géométrie linéaire**
  - Aiguille de biopsie (1-3 mm) OK
  - Électrode + fine (200 µm) ➔ faible courbure acceptée



- **Objet + échogène que tissu environnant**
  - Autres structures fortement echogènes
  - Aiguille non visible suivant l’angle d’insonnification

Introduction



a. 3D probe , tissue and needle

b. 3D volume

c. The plane containing the needle

3D volume from simulated data

ROI-RK method

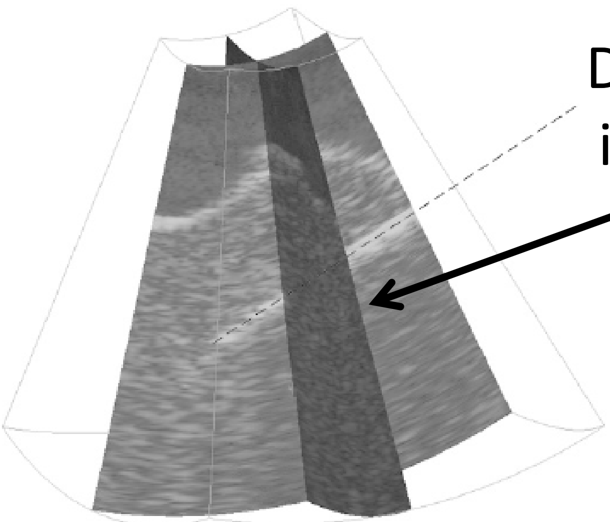
- **RANSAC algorithm**
  - Step 1: Thresholding – Reducing the number of voxels
  - Step 2: Axis localization – Using RANSAC algorithm to estimate an approximate position of the needle
  - Step 3: Local optimization – Finding a more accurate solution
  - Step 4: Tip localization – Indentifying the tip position of the tool along the tool axis

RANSAC : seuillage

- **Hypothèse : voxels aiguille de grande intensité**
- **On les sépare en deux classes**

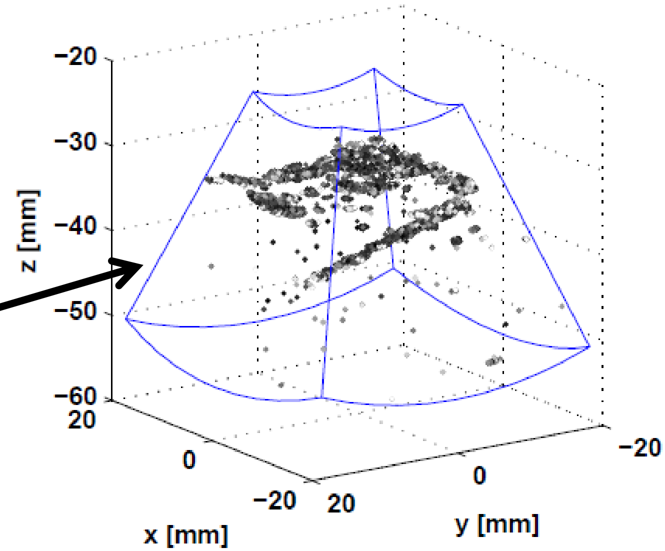
$$\mathcal{X}_t = \{\mathrm{x} \in \mathcal{X} : I(\mathrm{x}) \geq T_I\}$$
$$\mathcal{X}_b = \mathcal{X} \setminus \mathcal{X}_t,$$

- **TI**
  - un apprentissage
  - sinon 5% des pixels de + haute intensité



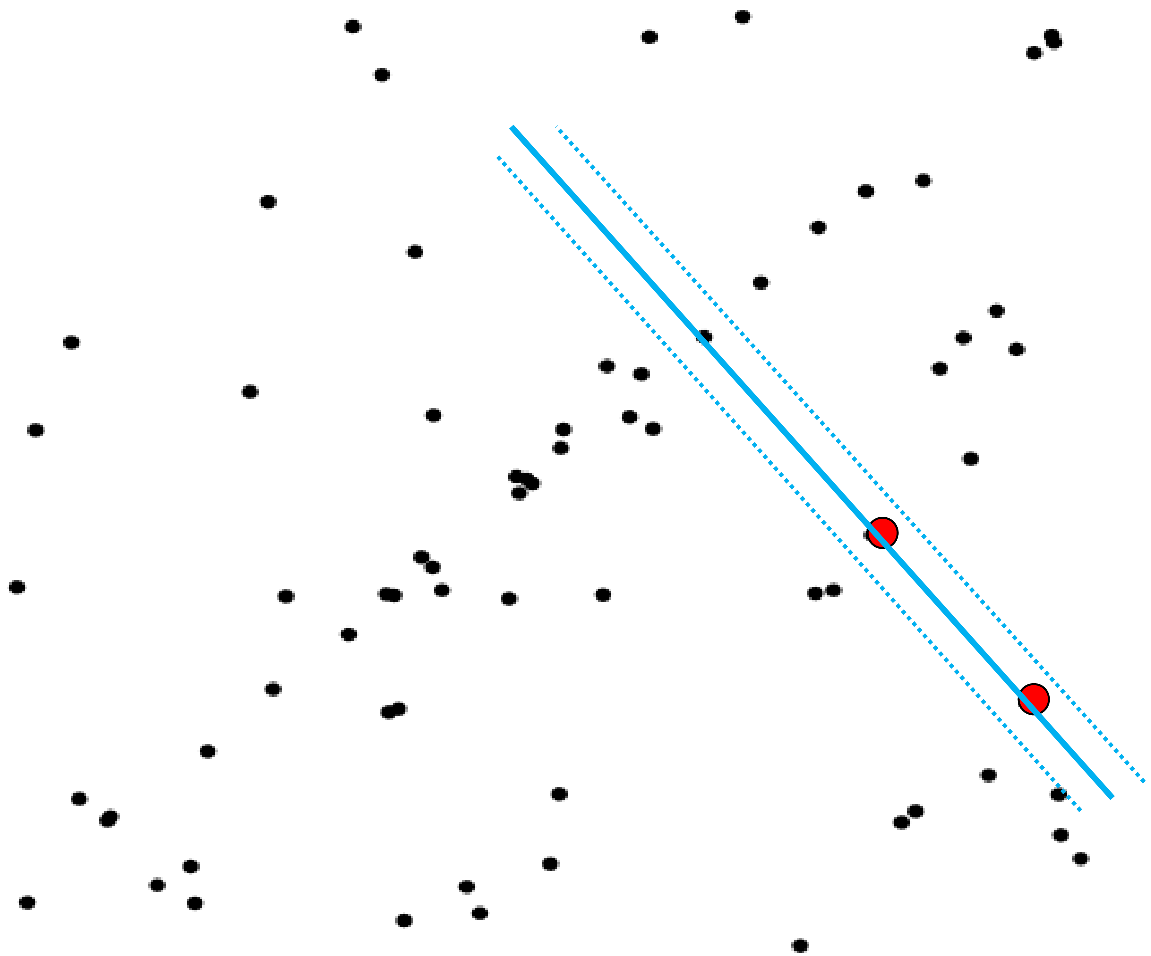
Données initiales

Données seuillées

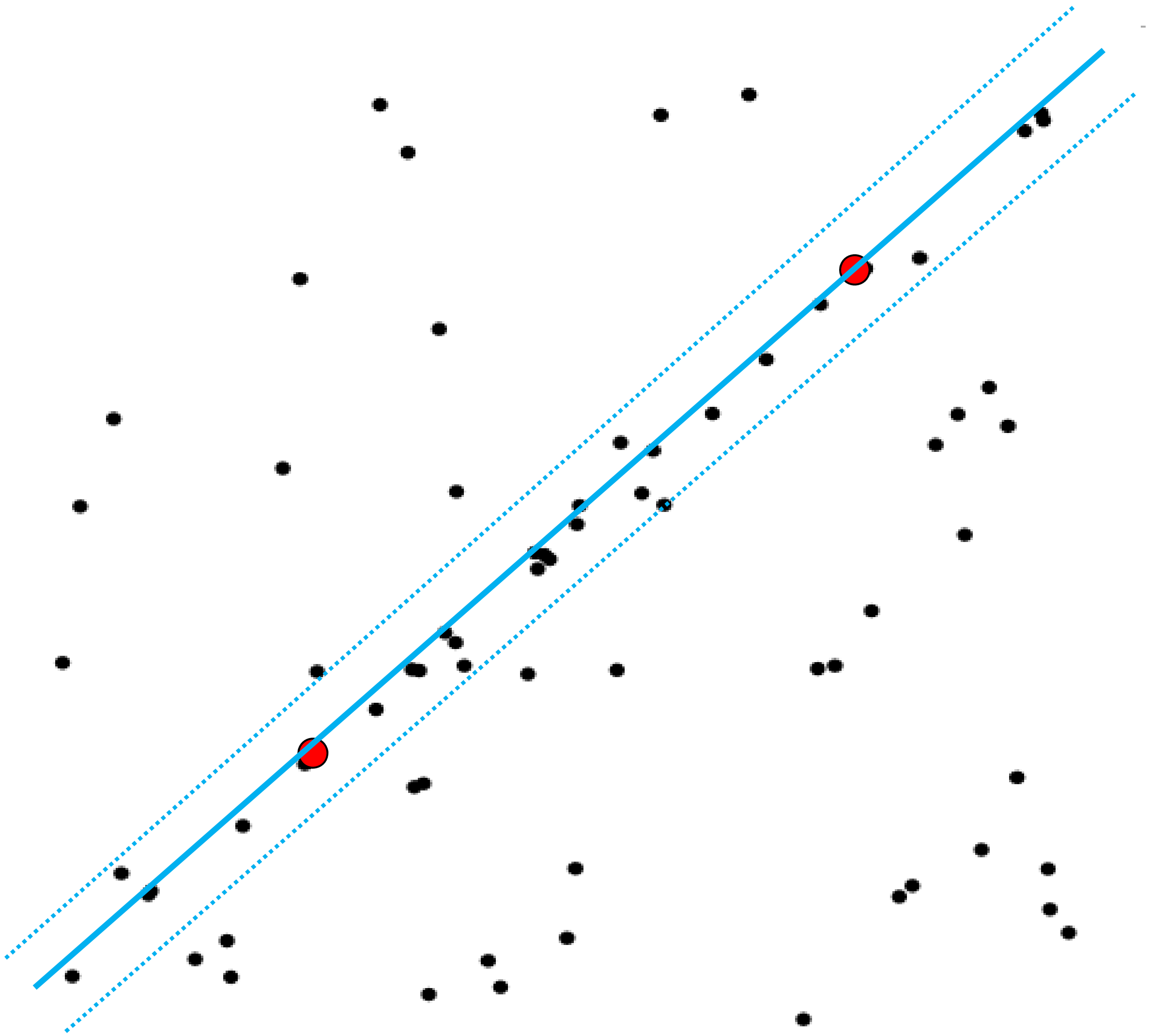


☹ Présence de faux positifs dans le tissu environnant.

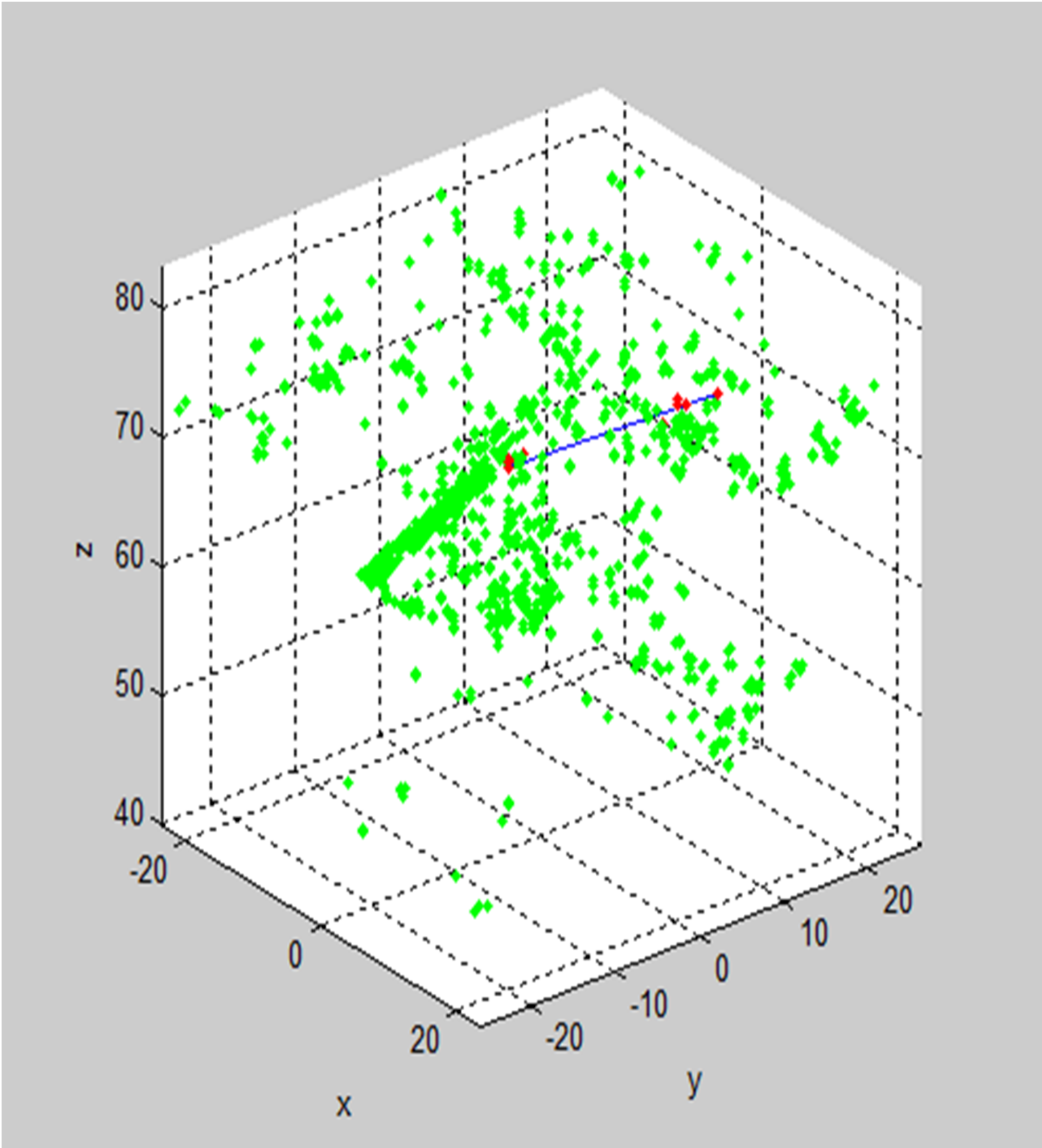
RANSAC - RANdom SAmple Consensus



RANSAC - RANdom SAmple Consensus



Ransac



ROI-RK method

ROI definition

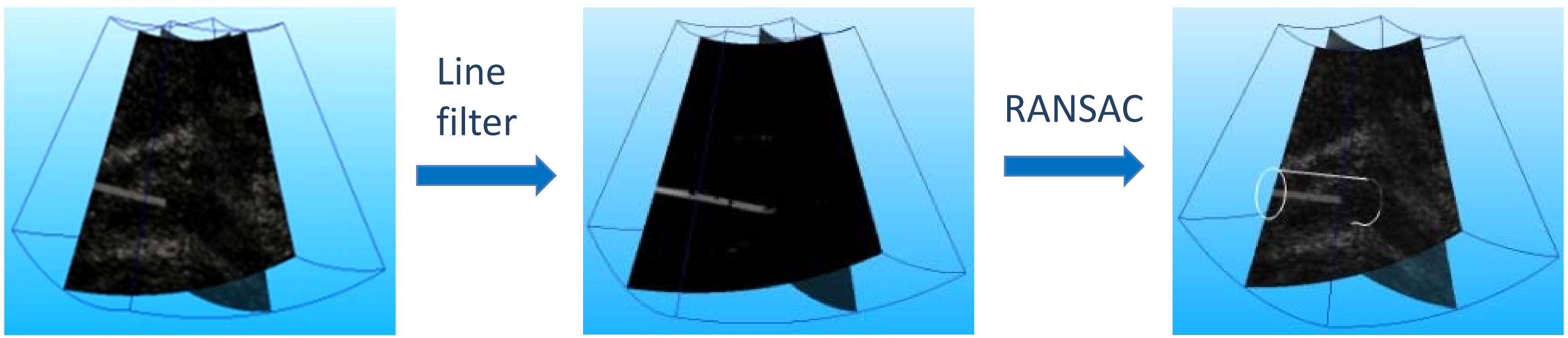
- The ROI is a cylinder liked region chosen around the needle position

$$\chi_{roi} = \{\mathbf{x} \in \chi_n \mid d(\mathbf{x}, l(t;\mathbf{A})) \leq R_{ROI}\}$$

R_{ROI} -- Radius of ROI, $d(\mathbf{x}, l(t;\mathbf{A}))$ --Distance from voxel to the estimate axis

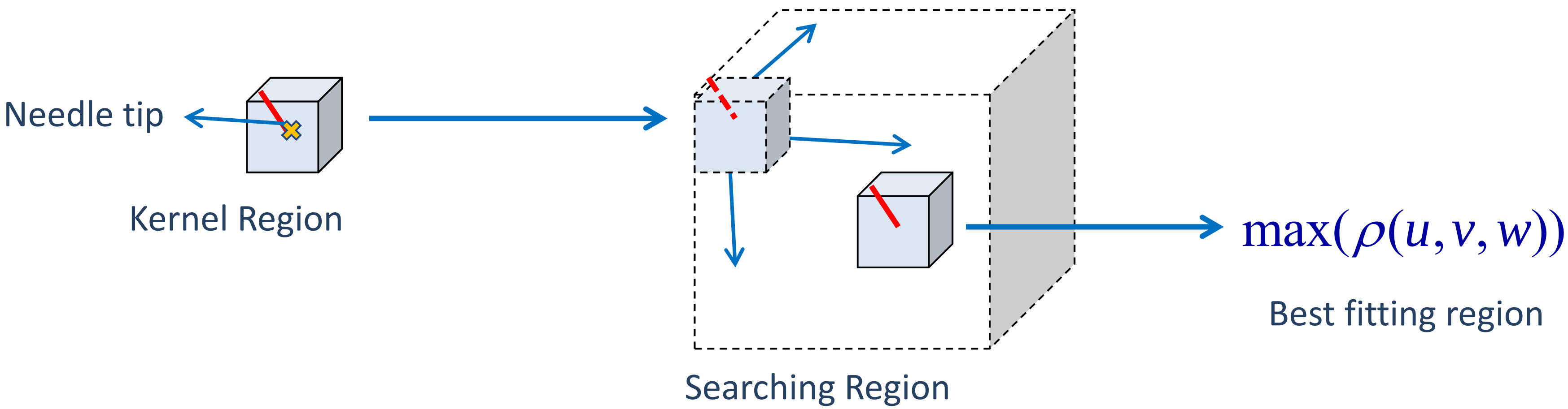
Automatically initialize ROI

- A 3D line filter [Frangi et al] is used to enhance the contrast in the 3D US volume



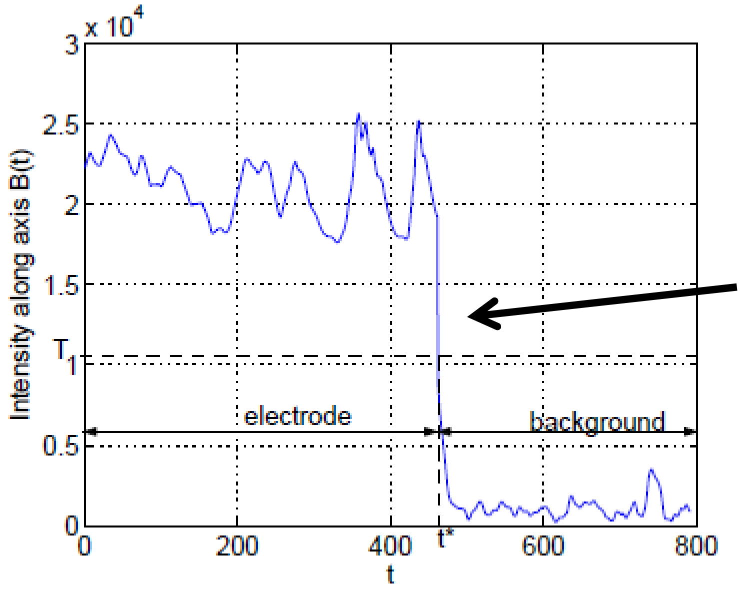
- **Motion estimation**
  - Speckle tracking (3D)
  - Normalized cross correlation

$$\rho(u,v,w)=\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{p}[\mathbf{X}_0(i,j,k)-\bar{\mathbf{X}}_0][\mathbf{X}_1(i+u,j+v,k+w)-\bar{\mathbf{X}}_1]}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{p}[\mathbf{X}_0(i,j,k)-\bar{\mathbf{X}}_0]^2\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{p}[\mathbf{X}_1(i+u,j+v,k+w)-\bar{\mathbf{X}}_1]^2}}$$



- Parcours des données le long de l'axe
- Recherche d'un gap important

Intensités le long de l'axe



Gap indiquant la position de la pointe

Results

- **Inhomogeneous background**
  - simulated from real tissue
- **simulated needle**
  - Position of needle

    $\alpha = 0^\circ, 30^\circ, 60^\circ, 90^\circ$

    $\beta = 107^\circ$
  - Velocity of insertion

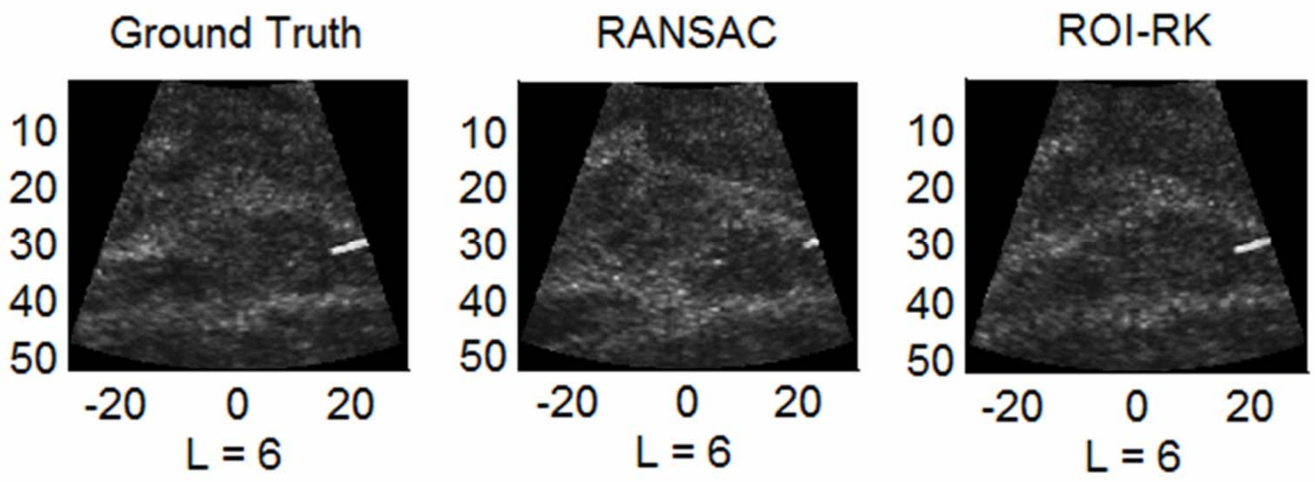
    $v_{tip} = 1mm / s$
  - Intensity from real distribution

- **Useful parameters in one volume**

Name of parameter	Value
Size of the phantom [mm^3]	50*50*50
Length of needle [mm]	6 ~ 25
Radius of needle [mm]	0.5
Number of planes / volume	55
Number of beams / plane	64
Number of samples / beam	160
Number of trials	20

Table I Simulation parameters of one volume

Results



The tool planes found by the two method compared with ground truth (α = 90°, the needle is perpendicular with the scan plane).

Future work

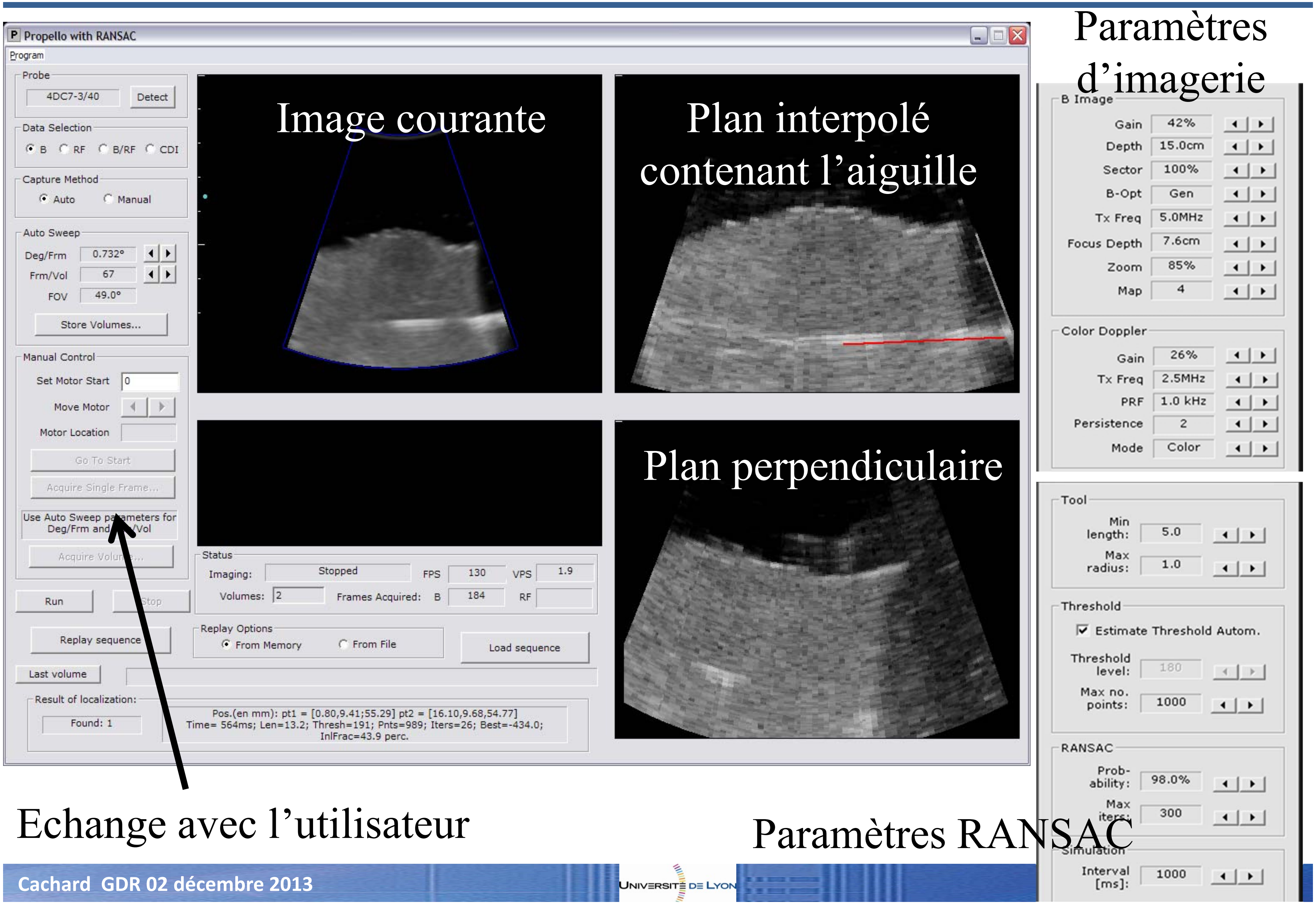
- **Visible diameter is far bigger than real diameter in real US image**
  - Pre-processing: deconvolution
- **Accurate motion estimation method**
  - Mean shift algorithm
- **Clinical software**
  - Manual interaction

Logiciels associés: embarqué sur échographe

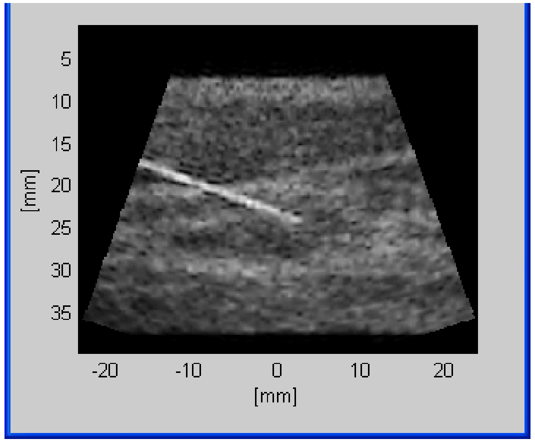
- **Echographe Ultrasonix**
  - SDK Porta et Propello
  - sonde à balayage mécanique
- **Interface temps réel en ligne**
  - $\cong$1 volume:s
  - acquisition
  - traitement
- **Affichage**
  - image courante acquise
  - plan incident de l'aiguille
  - plan perpendiculaire
- **Possibilité de fonctionner sans échographe**
  - données préalablement acquises

Logiciels associés: embarqué sur échographe

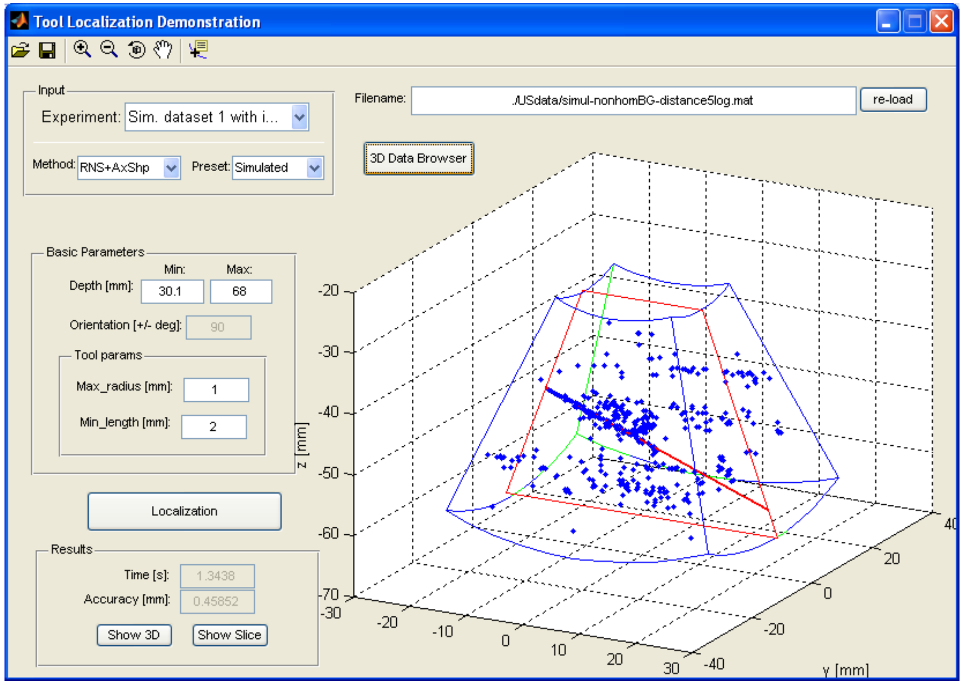
Creatis

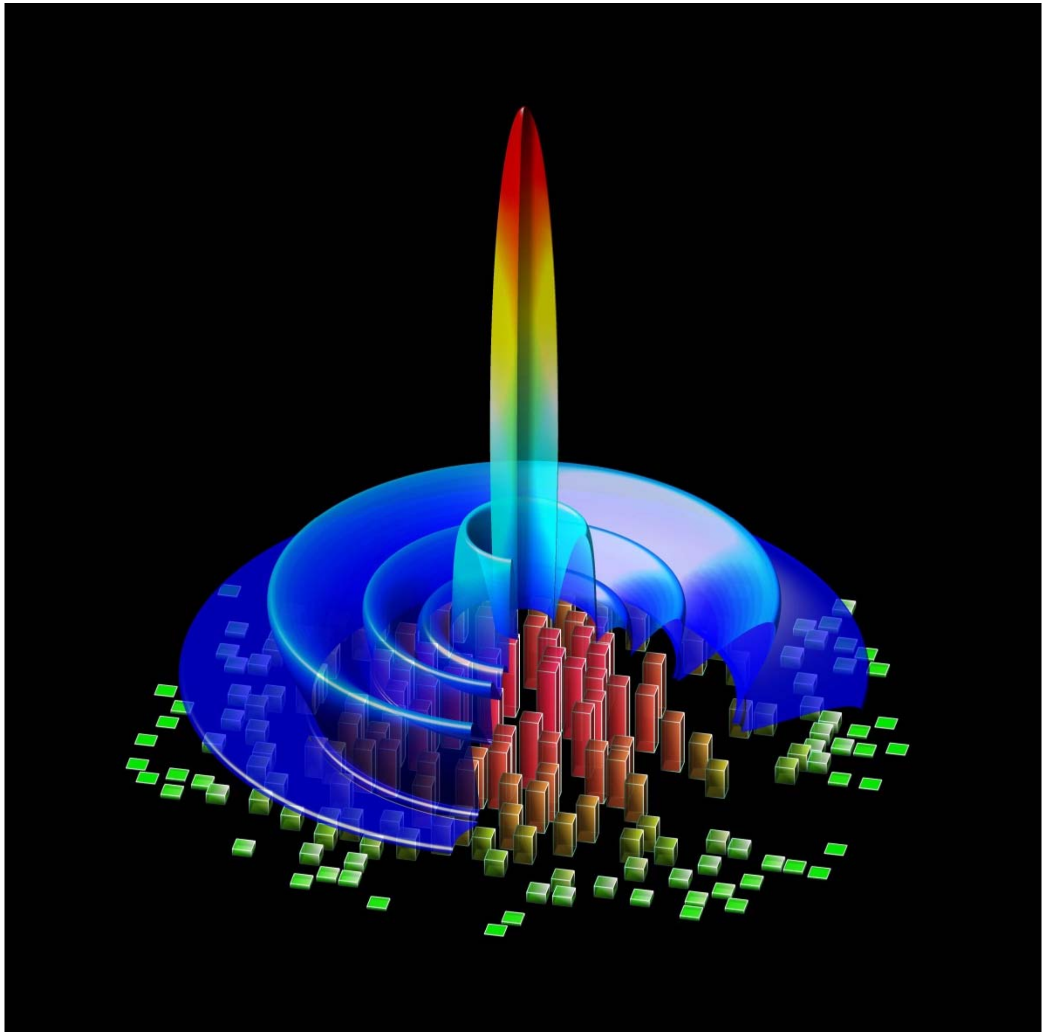


Logiciels associés: Matlab



- **Chargement de différents types de données**
  - Simulations, fantôme, biopsie
- **Réglage de paramètres simples**
  - ROI traitée, diamètre aiguille
- **Lance le traitement**
  - Affiche résultat
  - Temps de calcul
  - Précision





Démonstration Matlab