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Aberration correction in transcranial ultrasonic imaging using CT data and simulation-based focusing algorithms

Sylvain Chatillon¹, Arthur Waguet¹, Vincent Brulon², Ekaterina Iakovleva¹,
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(2) BIOMAPS, Université Paris-Saclay, CNRS, INSERM, CEA



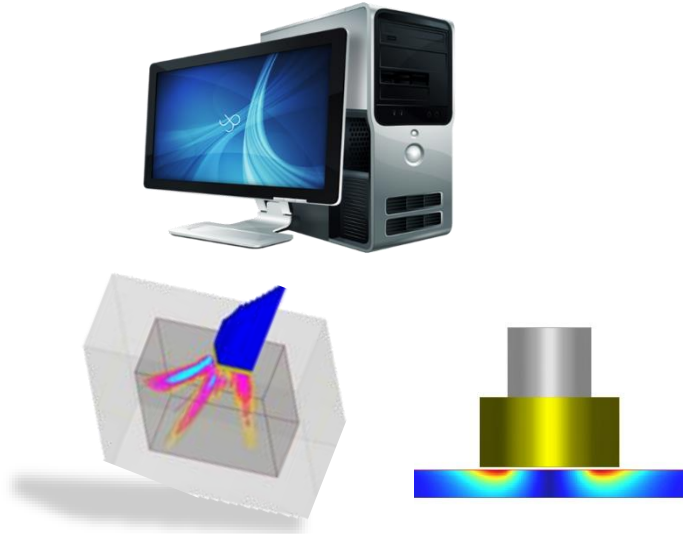
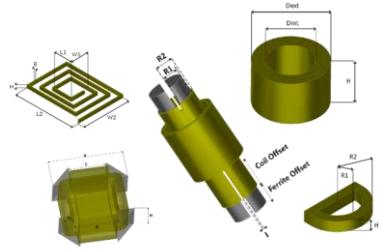
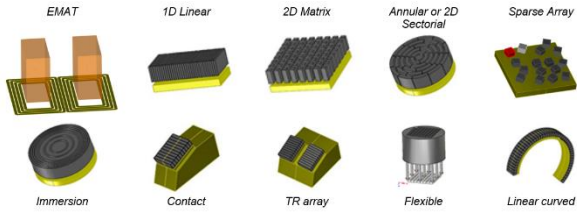
- **Context and objectives of the ATTRACT EchoBrain projet**
- **Presentation of the CIVA platform**
 - Principles of Dynamic Ray Tracing (DRT) model
 - Application to pressure field and delay law computation in complex structures
- **Simulation based Transcranial imaging**
 - Full matrix capture
 - Total Focusing Imaging
 - Description of the set-up
 - Experimental results on several targets
- **Conclusion and perspectives**

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- In France, every year 130,000 people suffer from stroke
- Essential to distinguish as soon as possible its origin since
 - time is a key factor to protect brain
 - since ischemia and hemorrhages require radically different treatments.
- X-rays and MRI brain imaging are diagnosis techniques currently used
 - not easily applicable in the emergency field.
 - access for patient monitoring can be very complicated.
- Ultrasonography is a more flexible and less expensive modality
 - Emergency diagnosis : brought into the vehicle carrying the patient.
 - Continuous monitoring in intensive care units
- Beyond early or continuous diagnosis, improvement of US brain imaging could be of great interest for neuroscience.

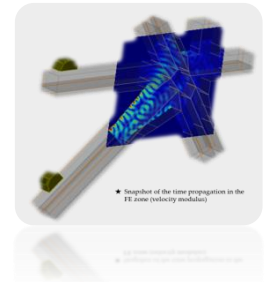
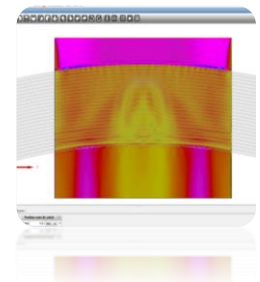
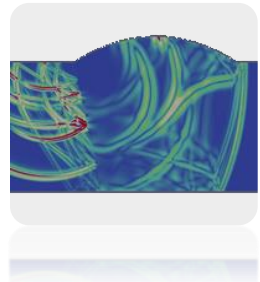
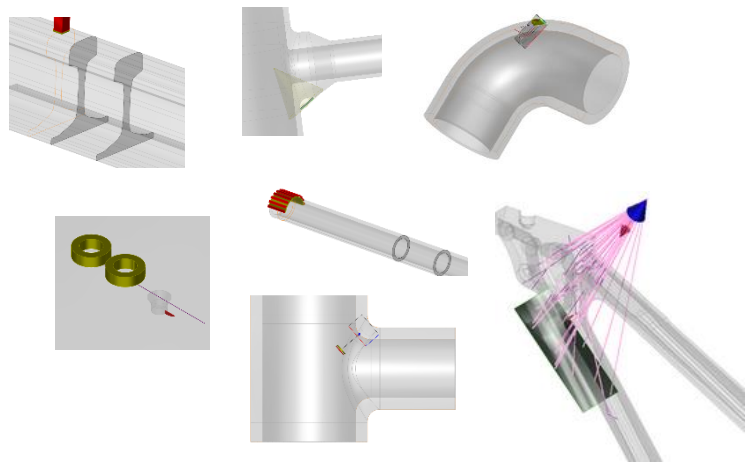
- Aims : create a breakthrough in the field of brain imaging
 - Improve brain images quality by counteracting ultrasonic wavefront aberration due to human skull
 - significantly improve the understanding of brain pathologies, brain trauma and physician diagnosis.
- Means : Adapt the simulation-based imaging tools developed by CEA-LIST for Non-Destructive Testing (NDT) applications
 - Programmable ultrafast ultrasound device Aixplorer™ (Supersonic Imagine, Aix en provence, France)
 - Full Matrix Capture (FMC) acquisitions
 - Total Focusing Method (TFM) imaging
 - CIVA simulations tools to calculate field propagation through the skull
 - Skull geometry provided by a previously acquired 3D CT scan of the patient.

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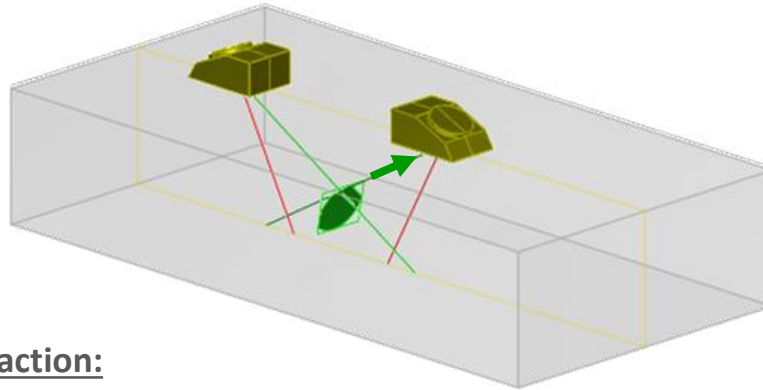
NDT simulation

Multi-techniques, NDT Oriented Environment, Modeling using fast Semi Analytical Models or Hybrid FEM strategy, Parallelization, metamodeling and statistical tools



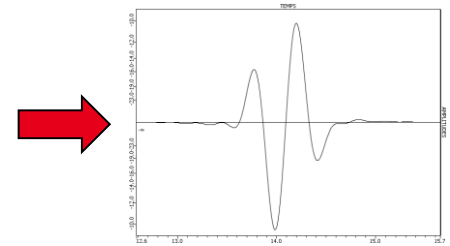
1. Emission and propagation:

Computation of the incident field on the defect : ray-based model



3. Reception of echoes:

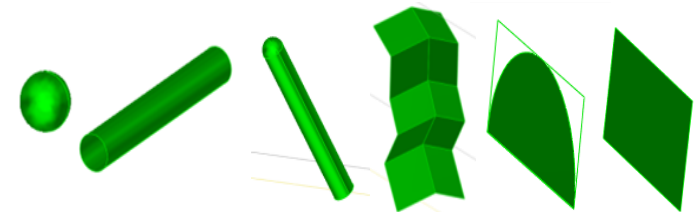
Received signal synthesis using Auld reciprocity principle



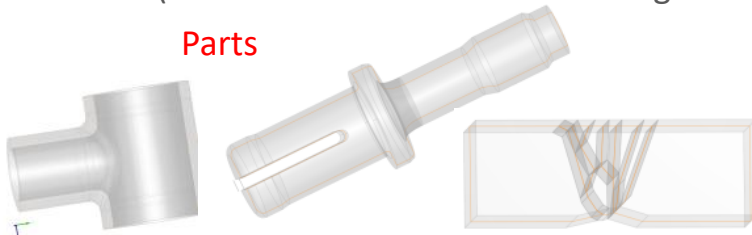
2. Beam defect interaction:

The scattering of the wave is modeled by applying suitable asymptotic solutions (Kirchhoff, GTD, SOV, ...) according to the defect and inspection

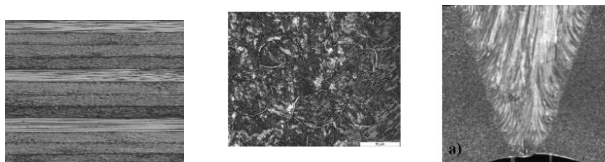
defects



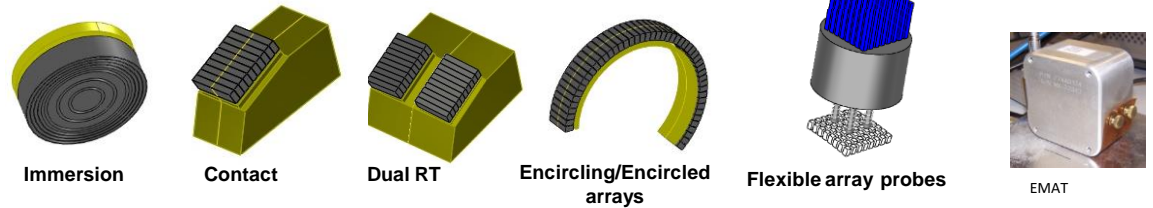
Parts



Materials

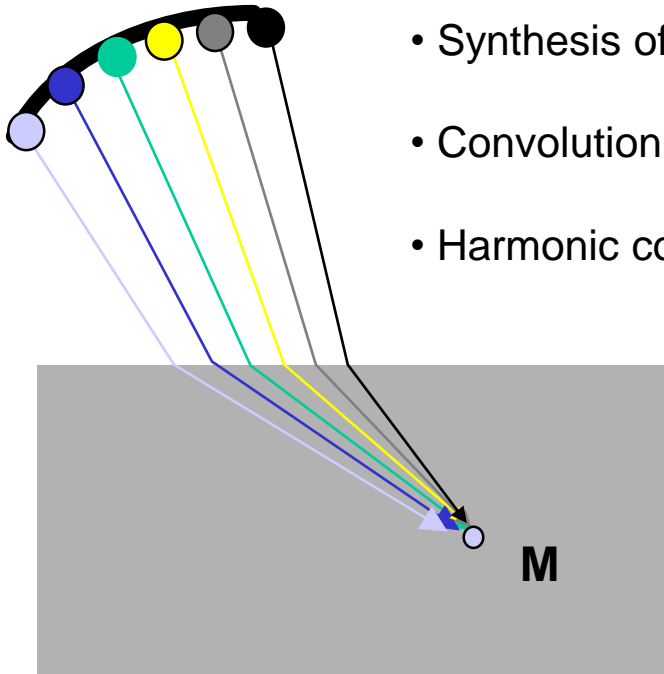


Probes

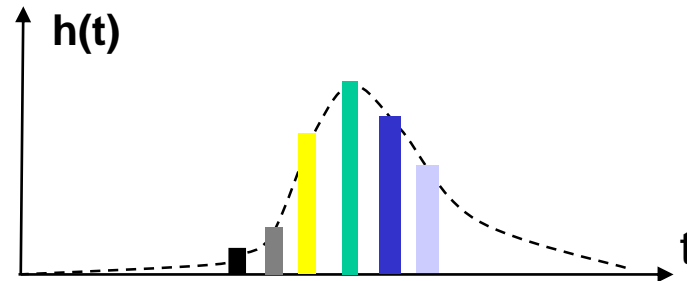


Continuous validation, optimization and enrichments of this general approach in order to address new (complex) cases

- Computation of the contribution of each source point using the pencil method taking into account the geometry and the material properties
 - Time of flight
 - Amplitude
 - Wave polarization

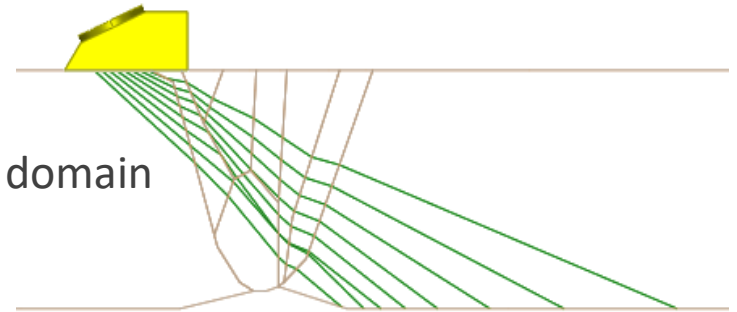
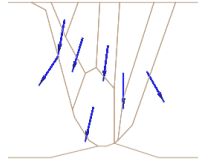


- Synthesis of the impulse response
- Convolution by any wave form $u(M, t) = h(M, t) \otimes v(t)$
- Harmonic computation at any frequency



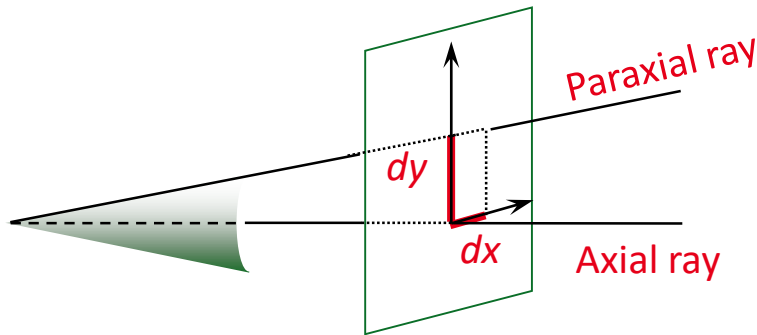
Ray-paths and travel time

Rays travel in straight line inside each homogeneous domain



Ray amplitude

Computation of the ray amplitude through matrix products expressing the evolution of a paraxial ray describing a ray tube or « pencil ».



$$\Psi = \begin{pmatrix} dx \\ dy \\ ds_x \\ ds_y \end{pmatrix}$$

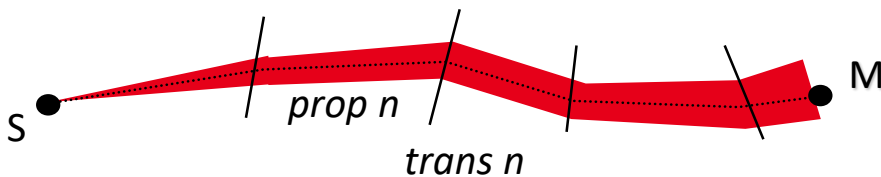
[Gengembre & Lhémery, *Ultrasonics* **38** (2000)]

Position of paraxial ray relative to the axial ray

Slowness of paraxial ray relative to the axial ray

$$\psi_2 = \tilde{\mathbf{L}} \psi_1 = \begin{bmatrix} \tilde{\mathbf{A}} & \tilde{\mathbf{B}} \\ \tilde{\mathbf{C}} & \tilde{\mathbf{D}} \end{bmatrix} \psi_1$$

$$Y_M = L_{prop1} \cdot L_{trans1} \cdot L_{prop2} \cdot L_{trans2} \cdot L_{prop3} \cdot L_{trans3} \dots Y_S$$



$$DF^{-2} = s^2 \det \tilde{\mathbf{B}}$$

↑ Divergence factor
 ↑ Slowness at source point

Pressure field calculation through the skull bone

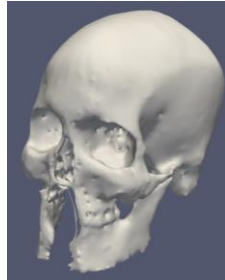
skull:

homogeneous and isotropic
elastic media

$$\rho = 1908 \text{ kg/m}^3,$$

$$c_L = 3183 \text{ m/s},$$

$$c_T = 1600 \text{ m/s}$$



Probe :

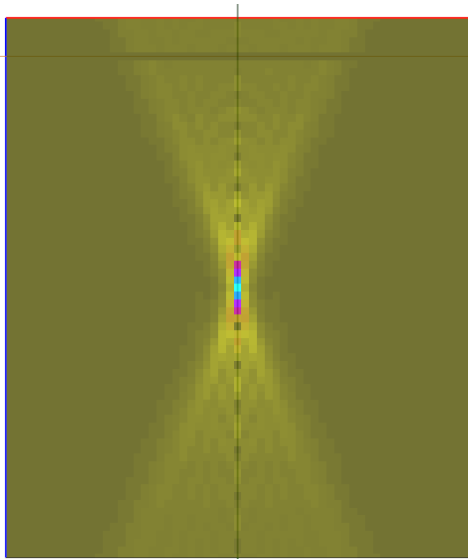
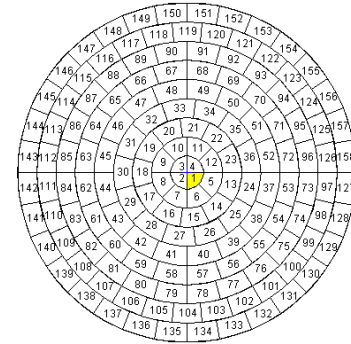
$$\Phi : 160 \text{ mm}$$

Curvature : 180 mm

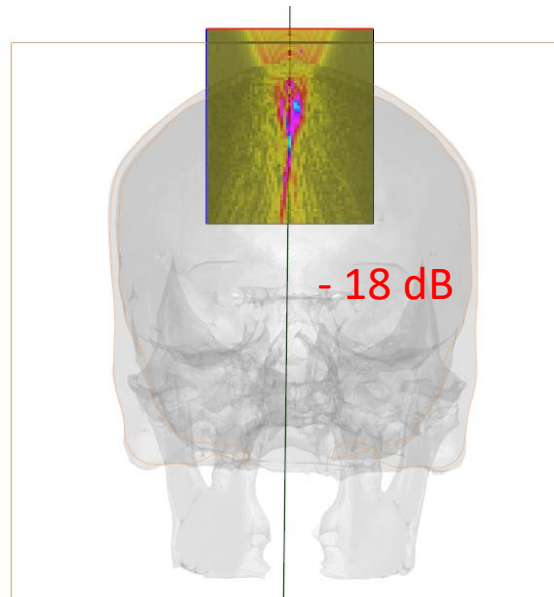
Annular and sectoral cutting

109 elements

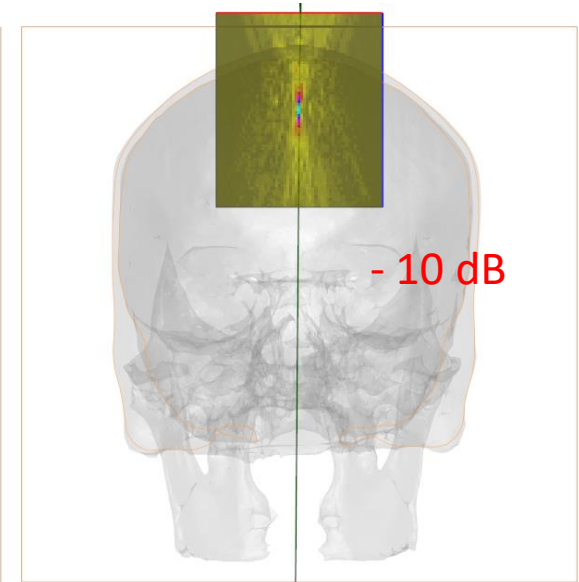
3 MHz



Pressure field in water
(no phase law)



Pressure field through the skull
(no phase law)



Pressure field through the skull
(adapted phase law)

Experimental validation in progress

APPLICATION TO TRANSCRANIAL PROPAGATION

Pressure field calculation through the skull bone

skull:

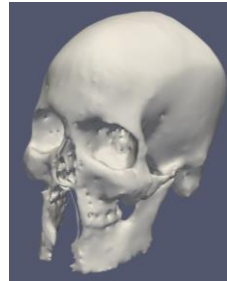
homogeneous and isotropic

elastic media

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$c_L = 3183 \text{ m/s}$,

$c_T = 1600 \text{ m/s}$



Probe :

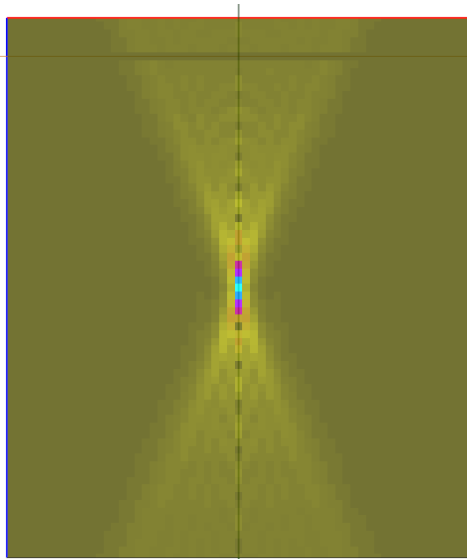
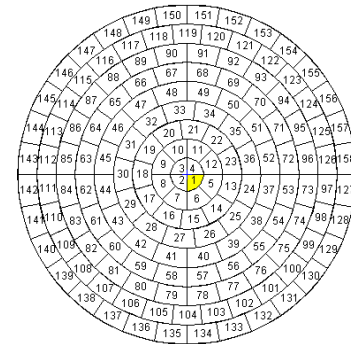
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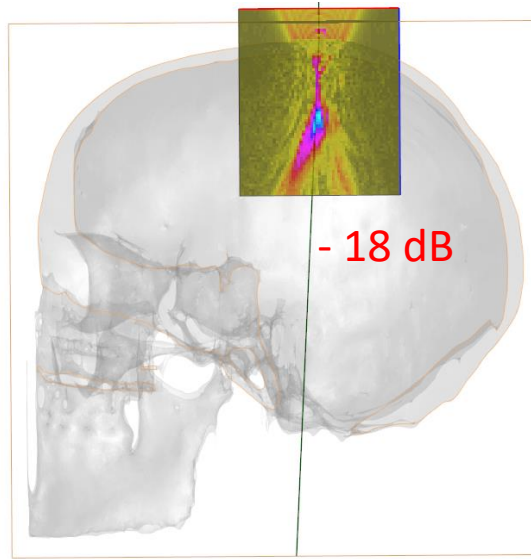
Annular and sectoral cutting

109 elements

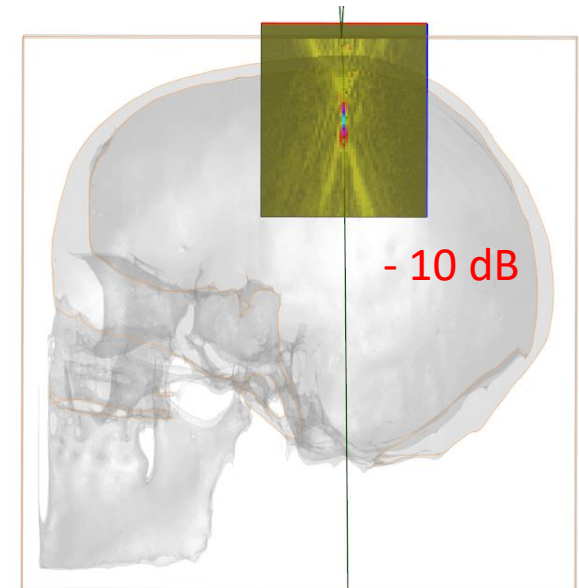
3 MHz



Pressure field in water
(no phase law)



Pressure field through the skull
(no phase law)



Pressure field through the skull
(adapted phase law)

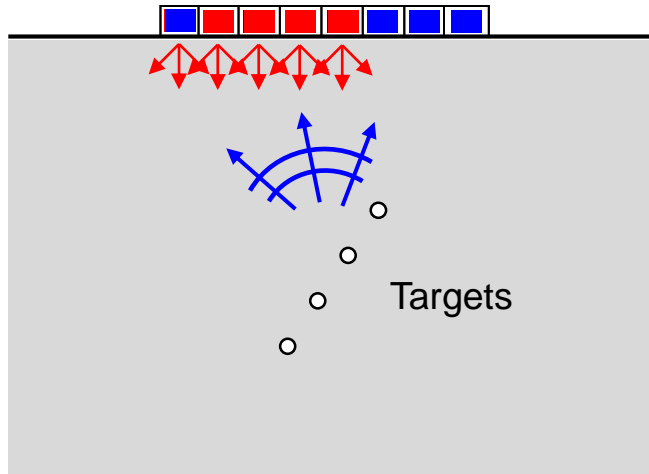
Experimental validation in progress

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PRINCIPLE OF FULL MATRIX CAPTURE (FMC) ACQUISITION

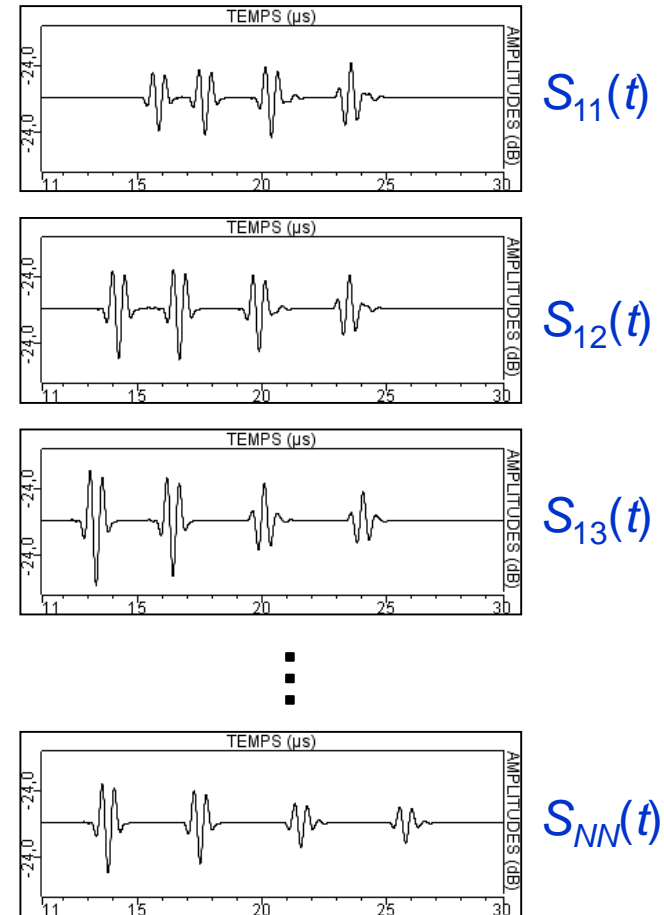
- N successive shots (N : nb of elements)
- One shot: 1 transmitting element
All elements receiving

- Transmit
- Receive



Acquisition

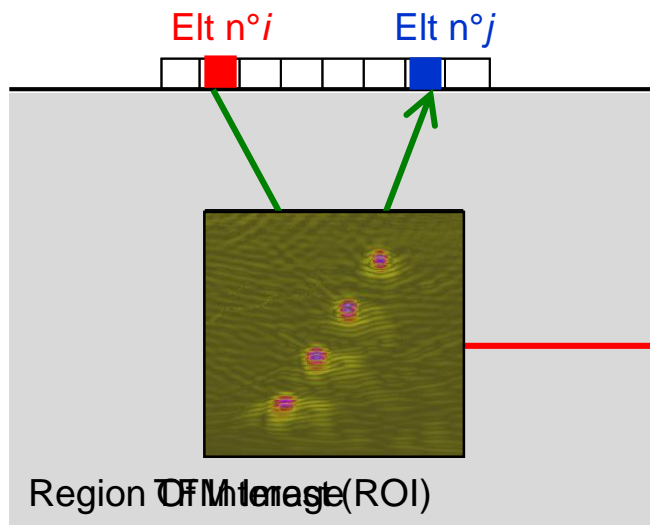
N elements $\rightarrow N \times N$
elementary signals $S_{ij}(t)$



PRINCIPLE OF TOTAL FOCUSING METHOD (TFM) IMAGING

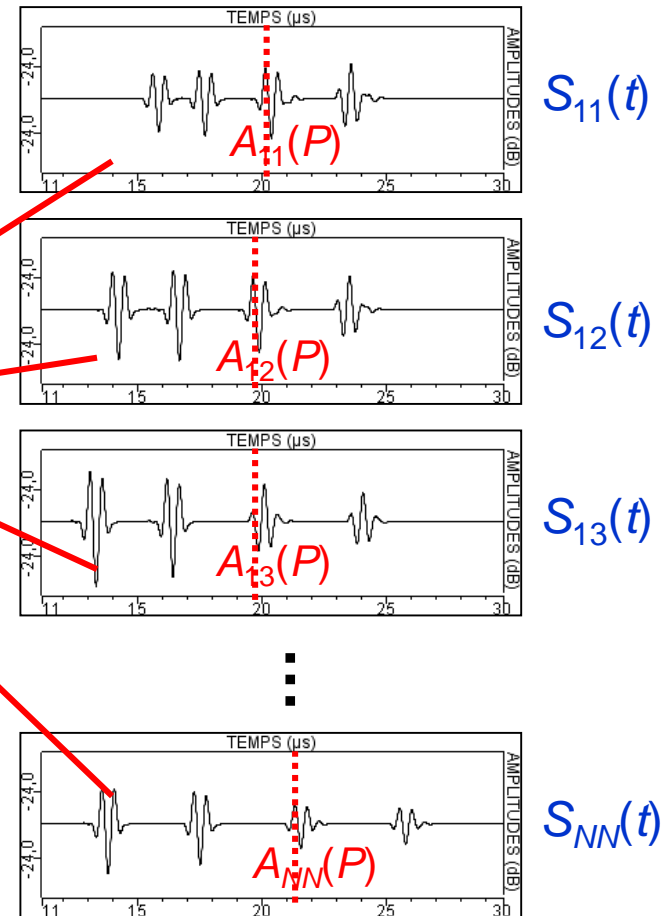
Post-processing

A posteriori synthetic focusing by coherent summation of all the received $S_{ij}(t)$ signals for all points P of the region of interest



Acquisition

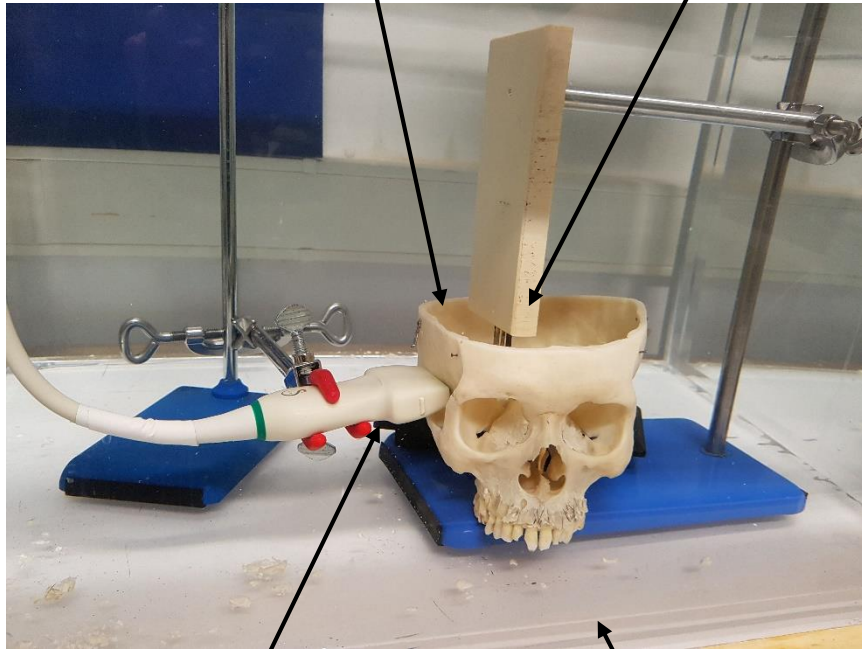
N elements $\rightarrow N \times N$ elementary signals $S_{ij}(t)$



transcranial ultrasound imaging

Human skull

Targets

Linear array probe
(SL10-2, Supersonic
Imagine)

Water tank

Acquisition

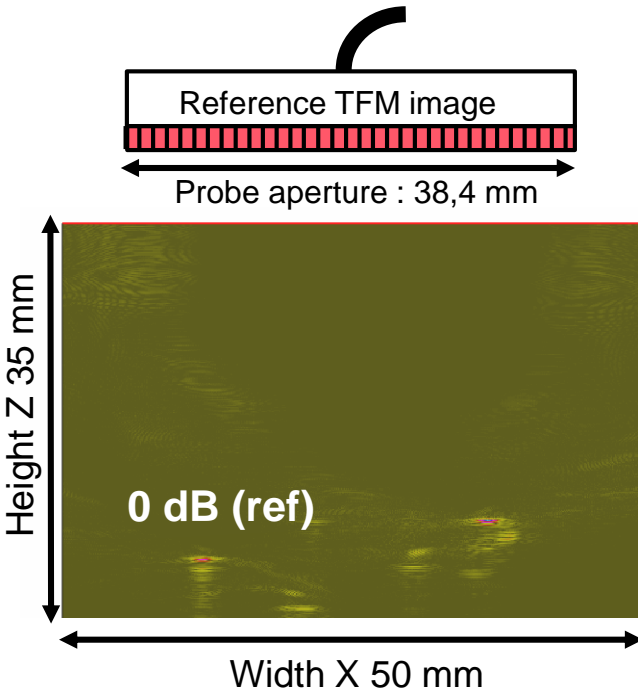


- FMC using an Ultrafast Ultrasound device, AixplorerTM,
- Fusion navigation module to locate the probe according to the skull

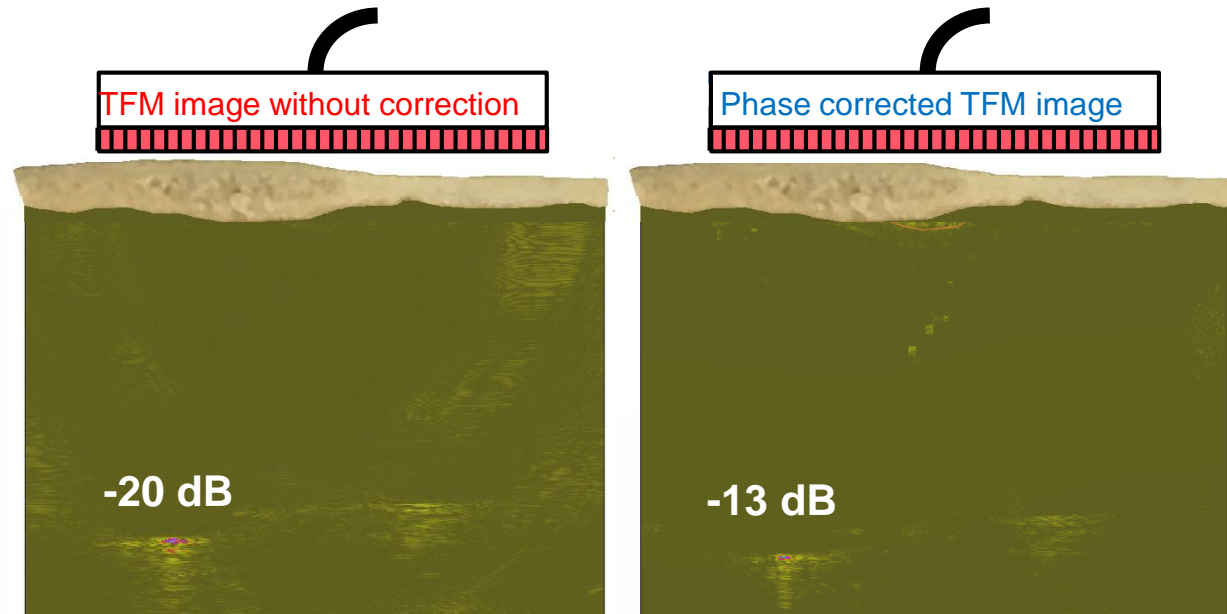
Reconstruction

- TFM imaging
- Time of flight computed by CIVA
- 3D CAD file of the skull from CT
- Skull considered as homogeneous and isotropic
- optimization loop on speed

Acquisition without skull

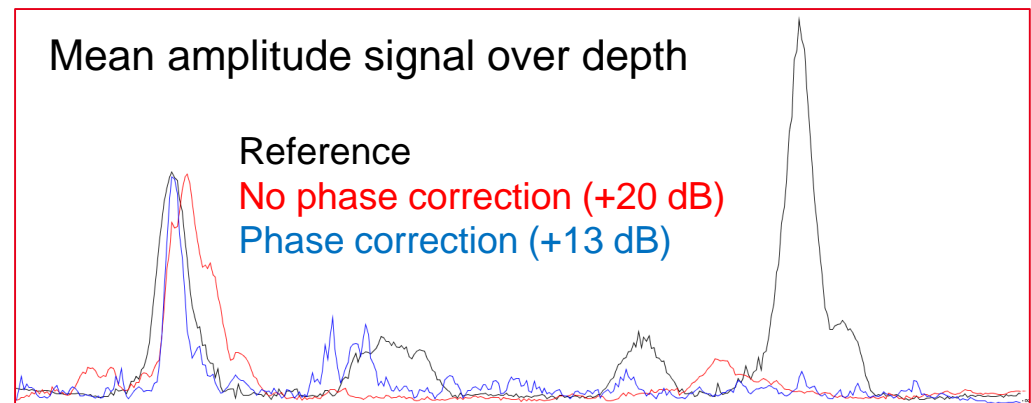


Acquisition with the human skull



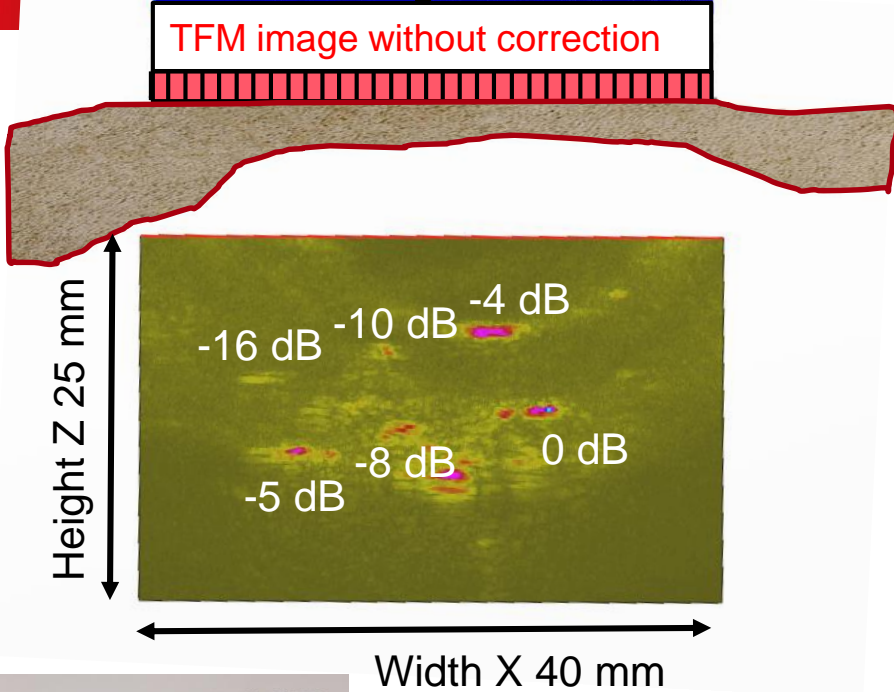
Phase correction enable improvement of

- Sensitivity (+ 7 dB)
- Lateral positioning (0,6 mm)
- Resolution (factor 2,5)

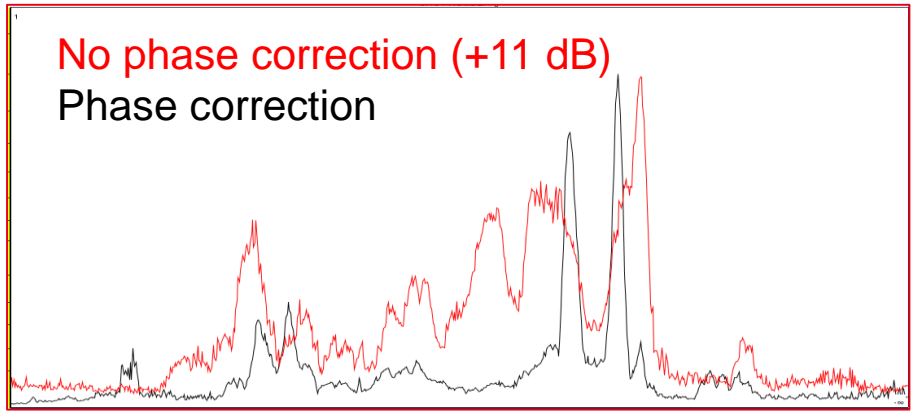
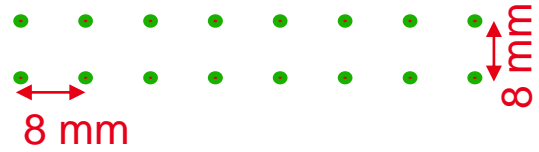
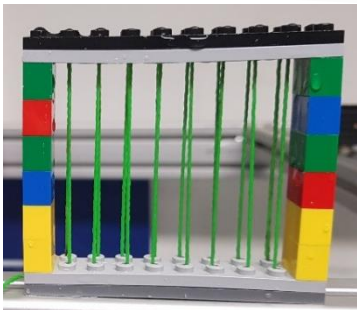
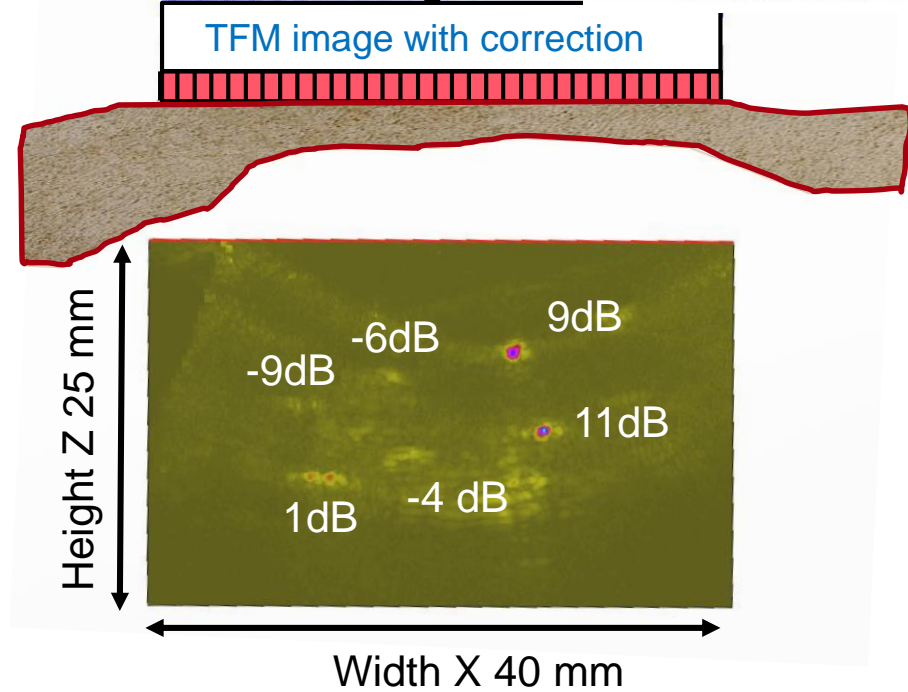


EXPERIMENTAL RESULTS ON NYLON THREADS

TFM image without correction



TFM image with correction



Phase correction enable improvement of

- Sensitivity (+ 11 dB)
- Lateral positioning (2 mm)
- Resolution (factor 2,5)

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- **Aim** : the improvement of transcranial ultrasonic brain imaging
- **Mean**
 - FMC acquisition with fast ultrasonic device and fusion navigation module
 - CIVA Model based TFM imaging with 3D CAD file for skull description (CT)
 - Simplified description (homogeneous and isotropic) of skull properties
- **Results**
 - Significant improvements in terms of sensitivity, resolution and positioning
 - Proof of concept: homogeneous description enables use of fast DRT model
- **Perspectives**
 - Specialization and optimization of the DRT model for very fast imaging
 - At long term, autonomous imaging system, free from morphological CT or MRI.
 - Virtually, all brain diseases could benefit from this improvement. The societal impact could therefore be significant

Thank you for your attention

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