

Imagerie par tomographie acoustique et ultrasonore du matériaux bois

(Retour d'expérience 2003-2025)

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Journée Contrôle et Evaluation Non Destructive du bois

21 octobre 2025 (IUT de Tarbes)

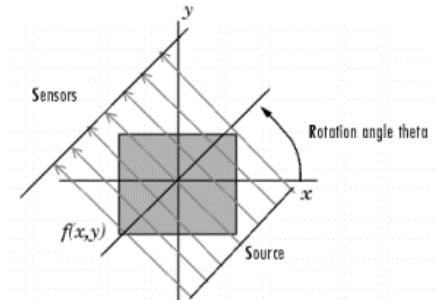
Tomographie - Définition



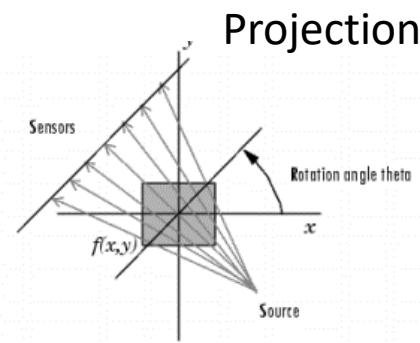
Tomographie - Définition

- Cartographie 2D ou 3D d'une caractéristique intrinsèque de la matière. ex : densité(humidité) pour les RX
- Reconstruction obtenue à partir de projections (série de mesures d'une propriété, ex : temps de propagation \Rightarrow la lenteur)

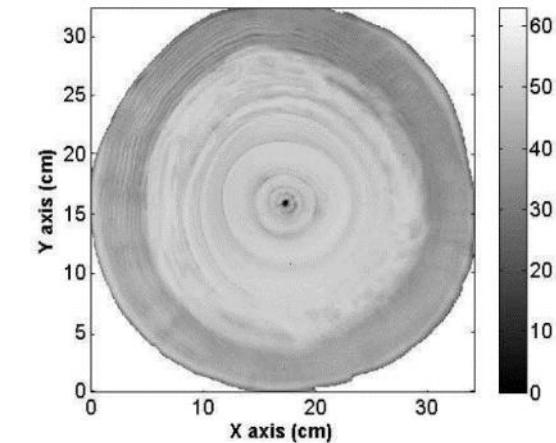
En transmission



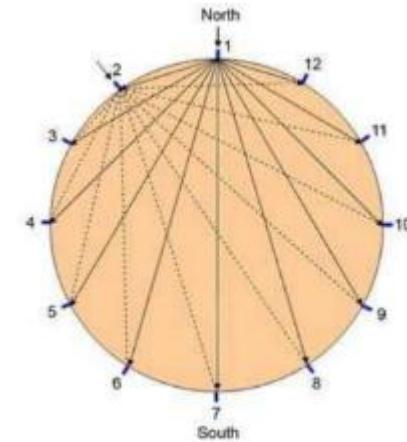
Parallel beam



Fan beam



Peuplier (RX, atténuation. 2010)



(Wang et al. 2007)

Tomographie - Définition



(2014)



Tomographie RX (2025)



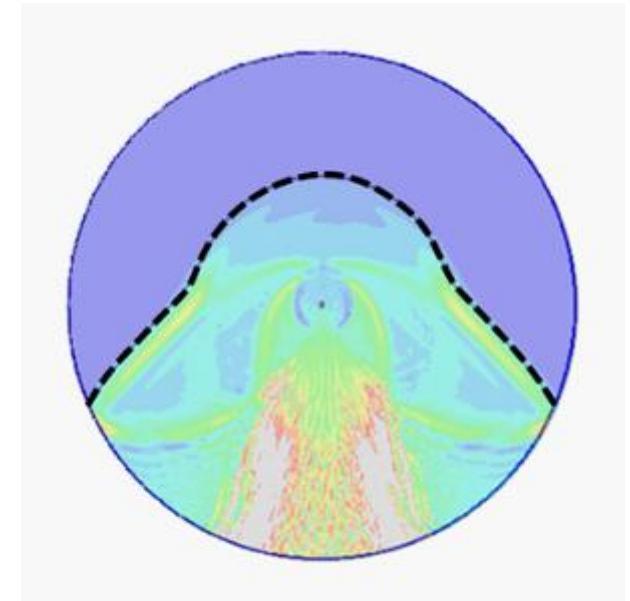
Tomographie acoustique (2025)

Tomographie - Définition

- Cette propriété doit être sommable le long du trajet de propagation (qui peut ne pas être une ligne droite, isotrope vs orthotrope)

$$P = \frac{t}{d} = \frac{\sum_{i=1}^N t_i}{Nd_i} = \frac{1}{N} \sum_{i=1}^N \frac{t_i}{d_i} = \frac{1}{N} \sum_{i=1}^N P_i$$

Acoustique et ultrasons (ondes mécaniques) : propriété = lenteur
Caractéristique intrinsèque : C / ρ



(Espinosa, 2019)

Première expérience (2005)

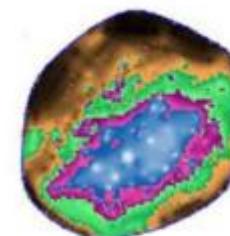
- Idée de la tomographie date de 1914
- Transformée de Radon en 1917



D. J. Readman

(Source Wikipedia)

- Nombreuses publications pour les arbres sur pied (tomographie acoustique)



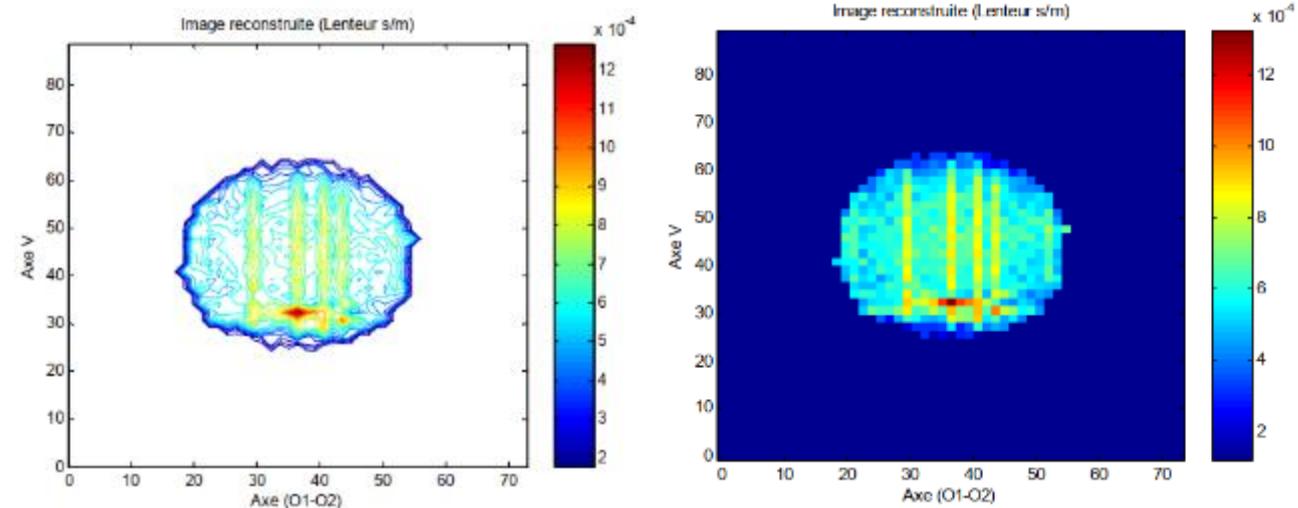
(c) Upper section (200-cm elevation)

(Wang, 2007)

Figure 2. Comparison of acoustic tomograms with photographs of corresponding cross sections for red oak tree #307.

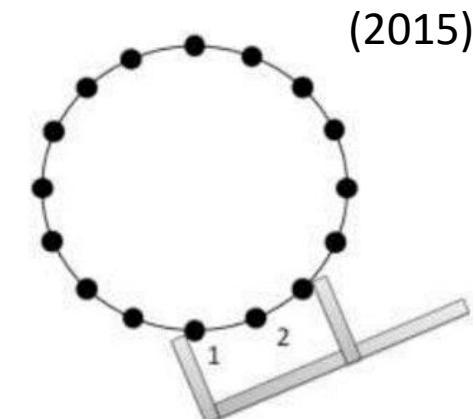
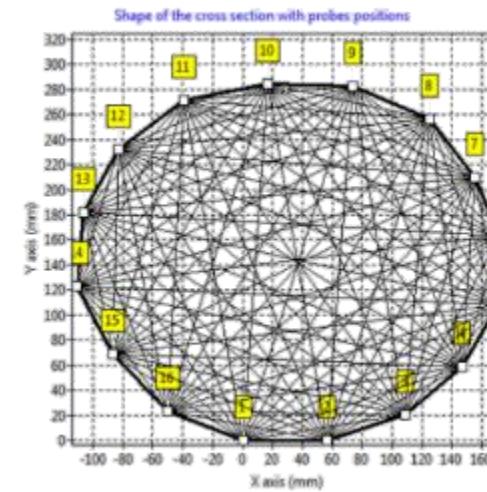
Première expérience (2005)

- Panneau de MDF (19mm)
- Perçages : 1xØ100mm, 2xØ50mm (distance 50mm), 2xØ30mm (distance 30mm)
- Marteau force – Accéléromètre
- 32 positions, 992 essais...
- Inversion algébrique par Ridge, PCR, PLS, Rétroprojection filtrée (Shepp-Logan)



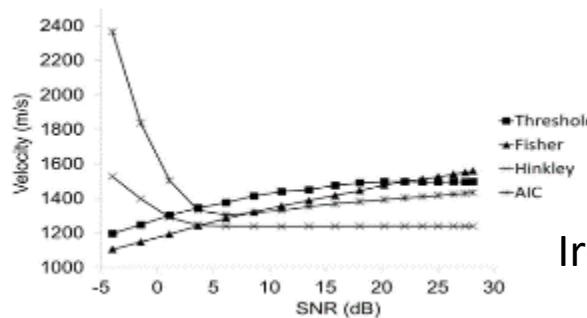
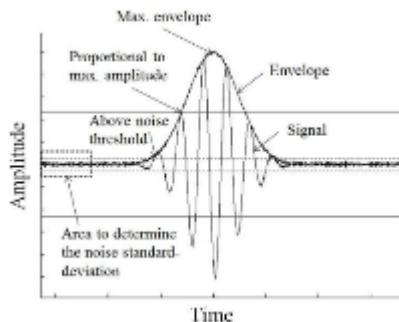
Points clefs de la reconstruction

- Nombre des sondes
- Repérage des sondes
- Détermination du TOF
- Fréquence des capteurs et couplage
- Modèle physique (2D, 3D) et hypothèses
- Méthode d'inversion

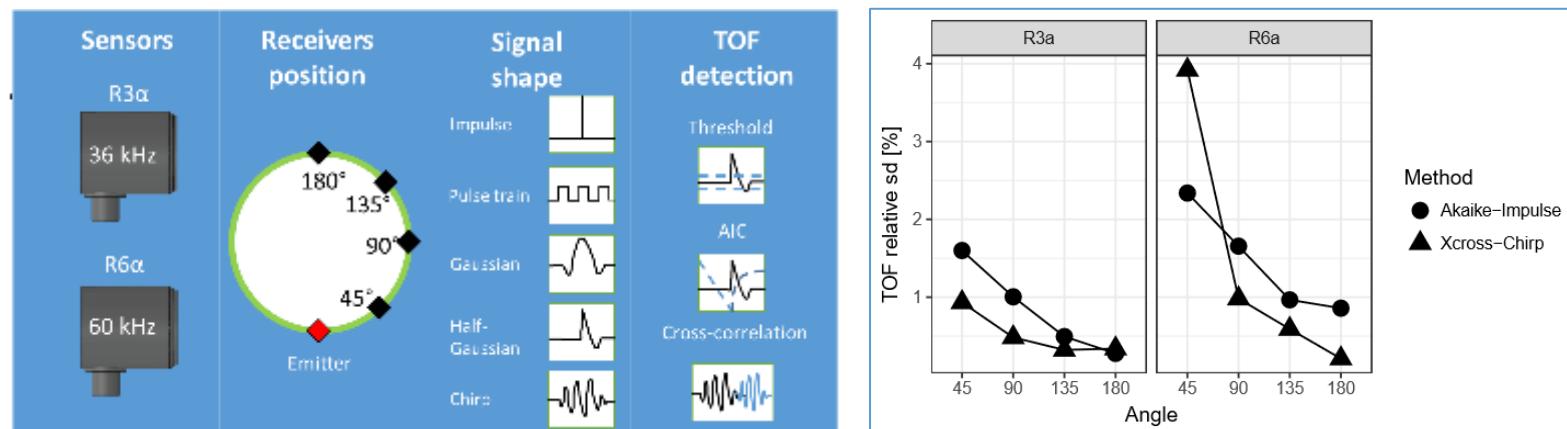


Détermination du TOF (fréq. capteur)

- Longueur d'onde : acoustique ~30 cm, ultrasons (60 kHz) ~2.5cm
- TOF : temps de propagation



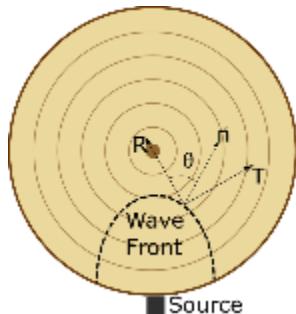
Iroko (Arciniegas, 2014)



(Espinosa, 2019)

Modèle physique 2D et hypothèses

- Equation de Christoffel (2D)



$$V = \sqrt{\frac{\Gamma_{11} + \Gamma_{22} + \sqrt{(\Gamma_{22} - \Gamma_{11})^2 + 4 \cdot \Gamma_{12}^2}}{2\rho}}$$

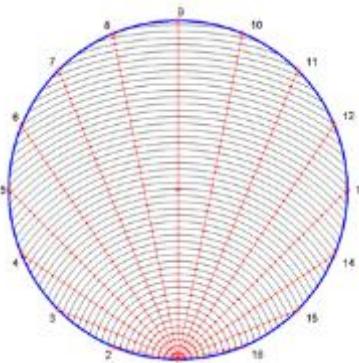
$$\left\{ \begin{array}{l} \Gamma_{11} = C_{11} \cos^2 \theta + C_{66} \sin^2 \theta \\ \Gamma_{22} = C_{66} \cos^2 \theta + C_{22} \sin^2 \theta \\ \Gamma_{12} = (C_{12} + C_{66}) \cos \theta \sin \theta \end{array} \right.$$

Orthotropic

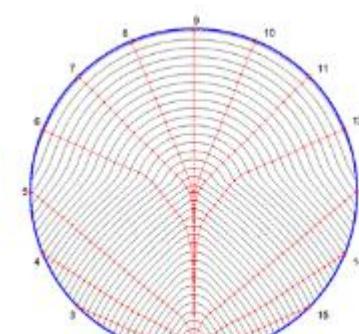
$$S = C^{-1} = \begin{pmatrix} \frac{1}{E_R} & -\frac{v_{TR}}{E_T} & 0 \\ -\frac{v_{RT}}{E_R} & \frac{1}{E_T} & 0 \\ 0 & 0 & \frac{1}{G_{RT}} \end{pmatrix}$$

(Arciniegas, 2014) (Espinosa, 2019)

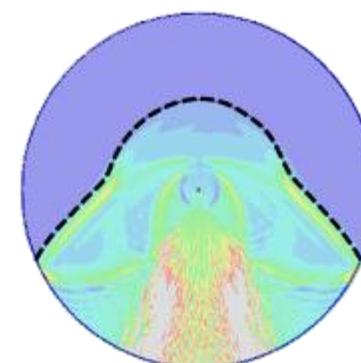
- Propagation : méthode du ray-tracing



Isotrope



Orthotropic à géométrie cylindrique

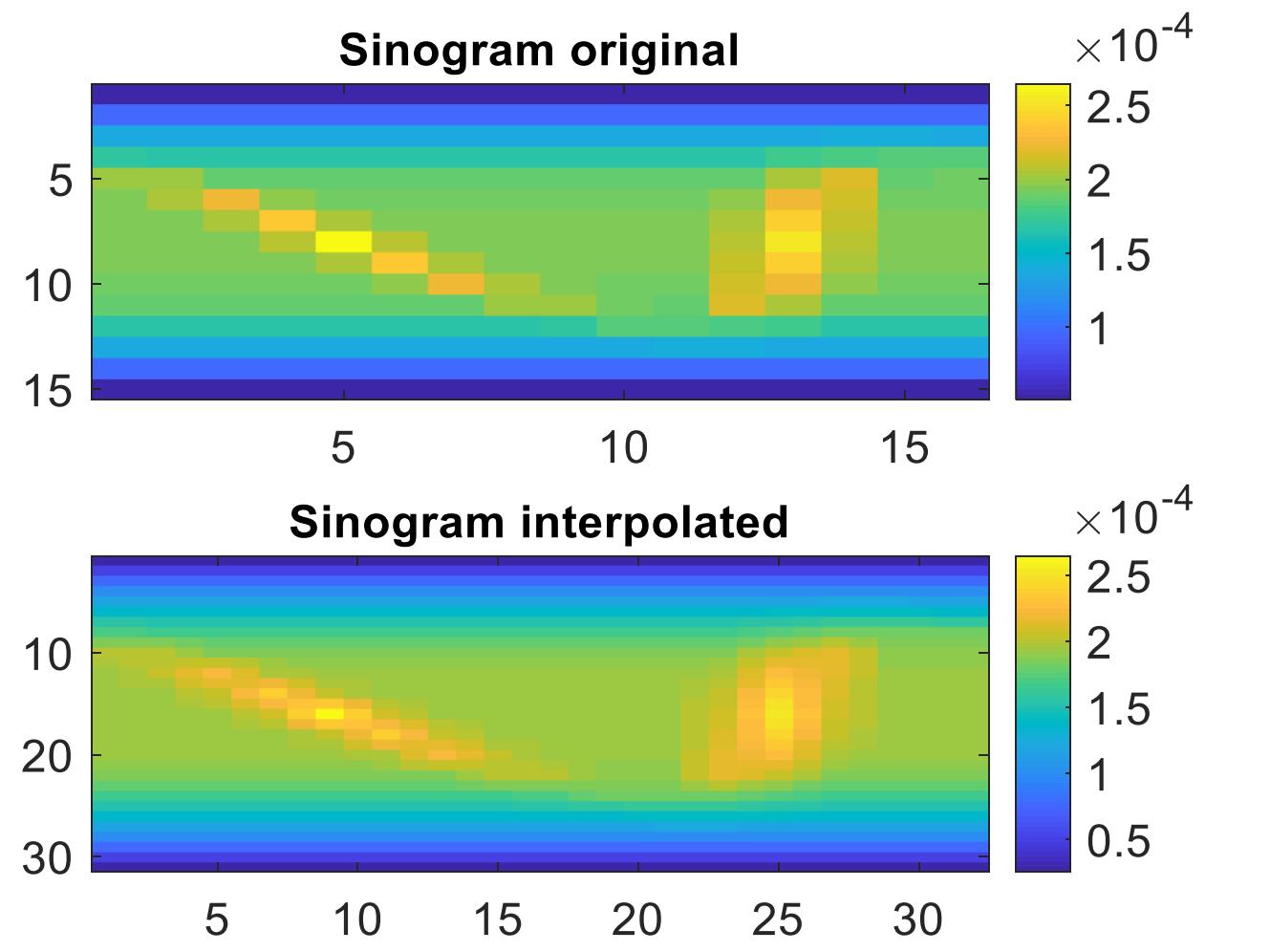
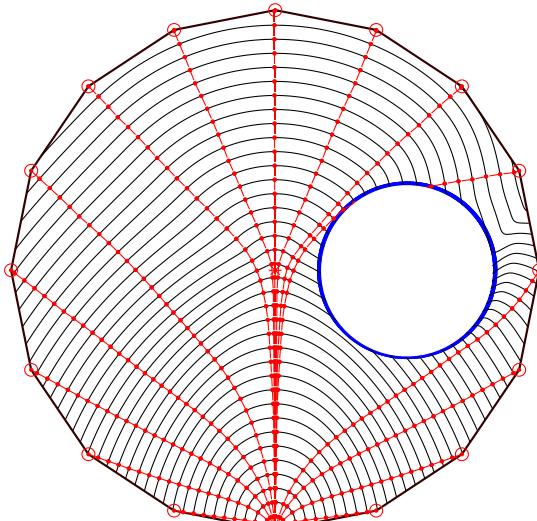


Validation FEM

(Espinosa, 2019)

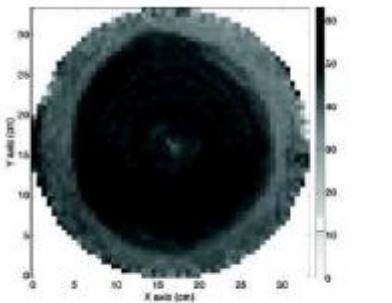
Méthode d'inversion

- Interpolation du sinogramme

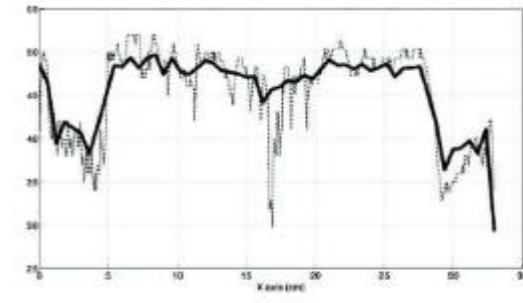
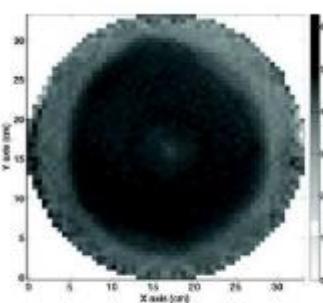
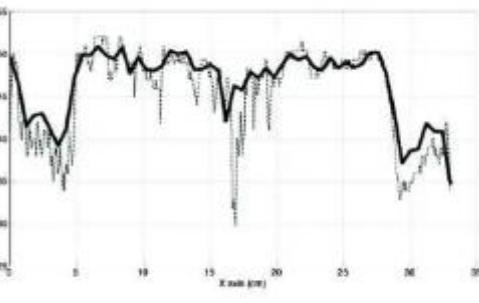


Méthode d'inversion

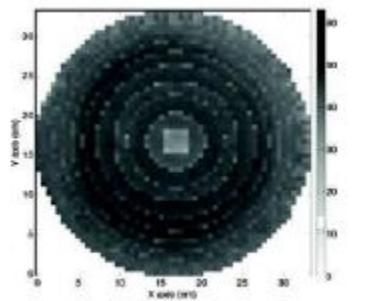
- Transformation de Radon (rétrorprojection), SIRT, Layer stripping, PLS... Ridge, PCR, gradient biconjugué, ART...



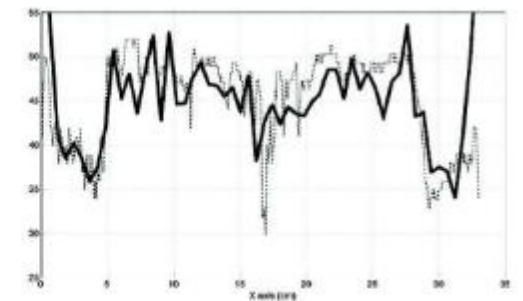
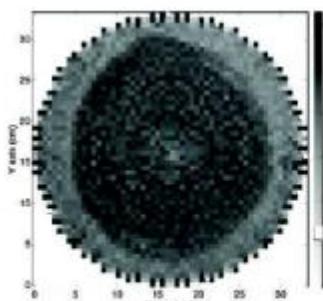
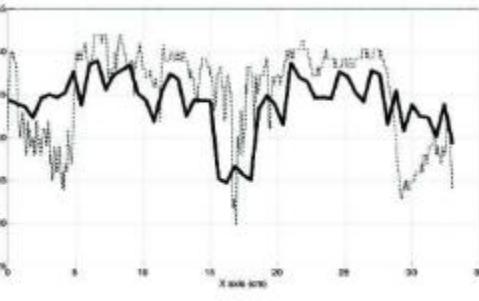
A FBP



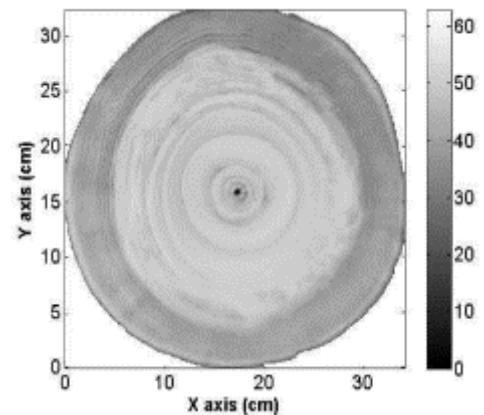
B SIRT



C LS



D PLS



Fantôme numérique

Reconstruction algébrique
 $\vec{Y} = [X]\vec{\beta}$

(Arciniegas, 2014)

Méthode d'inversion algébrique

- Formulation algébrique adaptée l'orthotropie du bois (géométrie cylindrique)

Pour un trajet, le TOF s'écrit :

$$t_m = \sum_{k \text{ along } m} l_{mk} \alpha_k$$

Exprimé sous forme matricielle :

$$\begin{bmatrix} 1 & 0 & \dots & 1 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_N \end{bmatrix} = \begin{bmatrix} D_1 A_1 \\ D_2 A_2 \\ \vdots \\ D_m A_m \end{bmatrix}$$

Pour chaque pixel, fonction de lenteur (équation de Christoffel linéarisée)

$$\alpha_k = \beta_{5,k} \theta_{k,m}^5 + \beta_{4,k} \theta_{k,m}^4 + \beta_{3,k} \theta_{k,m}^3 + \beta_{2,k} \theta_{k,m}^2 + \beta_{1,k} \theta_{k,m}^1 + \beta_{0,k} \theta_{k,m}^0$$



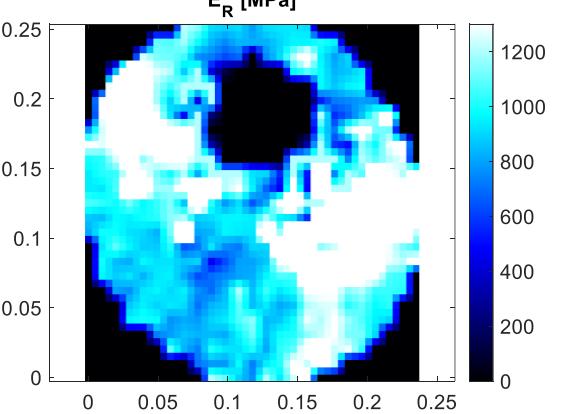
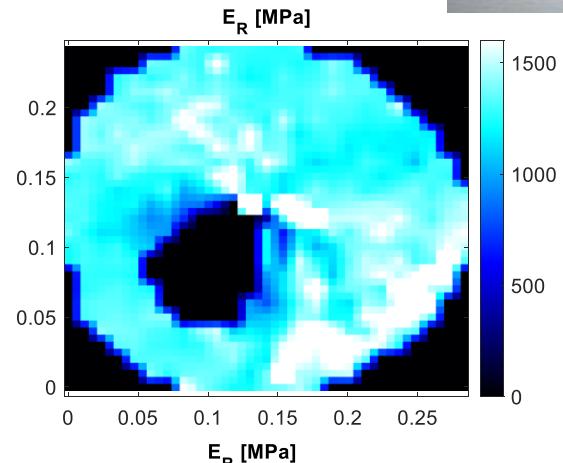
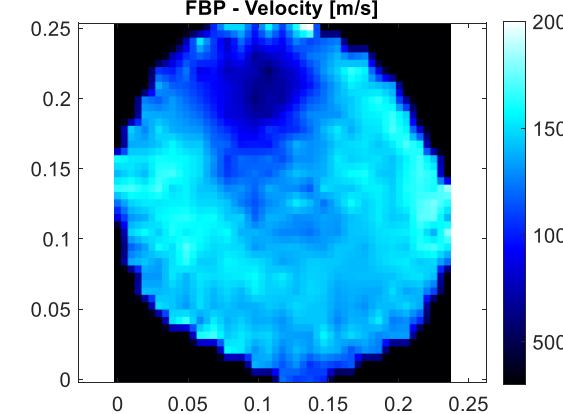
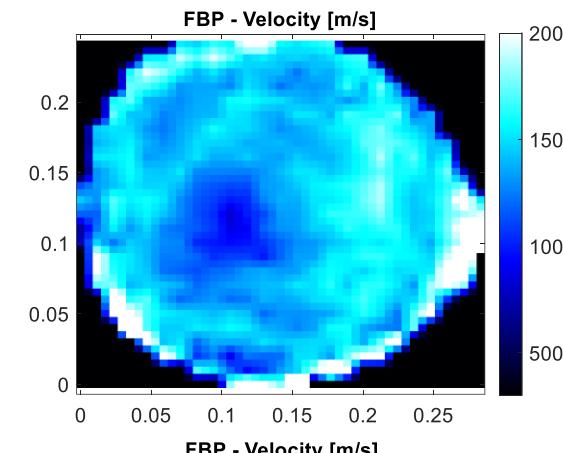
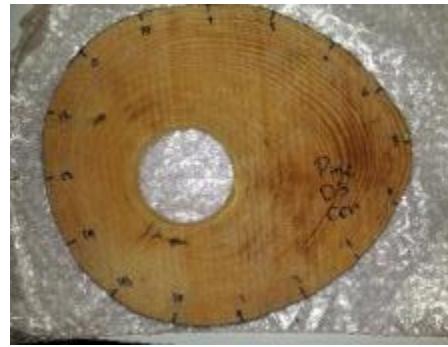
$$\begin{bmatrix} \theta_{1,1}^5 & \dots & \theta_{1,1}^0 & 0 & \dots & 0 & \dots & \theta_{N,1}^5 & \dots & \theta_{N,1}^0 \\ 0 & \dots & 0 & \theta_{2,2}^5 & \dots & \theta_{2,2}^0 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ \theta_{1,M}^5 & \dots & \theta_{1,M}^0 & 0 & \dots & 0 & \dots & \theta_{N,M}^5 & \dots & \theta_{N,M}^0 \end{bmatrix} \begin{bmatrix} \beta_{5,1} \\ \vdots \\ \beta_{0,1} \\ \beta_{5,2} \\ \vdots \\ \beta_{0,2} \\ \vdots \\ \beta_{5,N} \\ \vdots \\ \beta_{0,N} \end{bmatrix} = \begin{bmatrix} D_1 A_1 \\ D_2 A_2 \\ \vdots \\ D_m A_m \end{bmatrix}$$

- Optimisation sur les trajets de projection et la méthode SIRT

(Espinosa, 2019)

Résultats

- Essence : Pin, \varnothing : 24 cm, épaisseur : 3 cm, Défaut \varnothing 7.6 cm
- 16 sondes, interpolation du sinogramme



(Espinosa, 2019)

Conclusions - Ce qui a été accompli

- Redondance d'information (nb. de sondes)
- Repérage des capteurs
- Méthode optimale TOF : excitation Chirp et inter-corrélation
- Fréquence des capteurs ~ 60 kHz (ultrasons basse freq.)
- Modèle physique 2D : Equation de Christoffel pour un solide orthotrope à géométrie cylindrique
- Méthode d'inversion : SIRT avec le modèle L. Espinosa (2020)
- Interpolation du sinogramme

Perspectives

- Améliorer le couplage capteur - tronc
- Reconstruction en 3D (modèle physique et méthode, vraie 3D)
- Caractéristique intrinsèque finale E , G / ρ (découplage de la densité)
- Temps d'une expérience ~ 1 heure (placement, repérage, essais)
- Problème du coût d'un tel type d'expérience



(2025)

(2025)

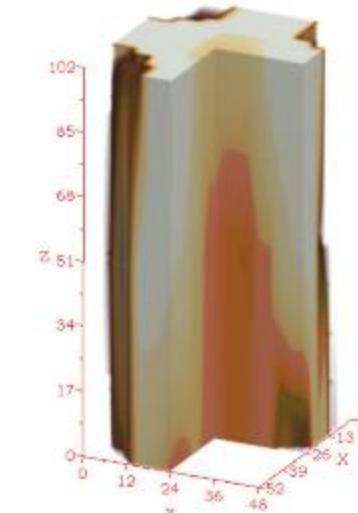


Fig. 1. 3D reconstructed image of internal structure of a wood with an important area of decay [7]

Interpolation d'images 2D
(Bucur, 2005)

Grand merci à l'ensemble de mes collègues et étudiants !

- Philippe Lasaygues du CNRS – LMA
- Debieu E., Lefebvre J.P., Dikrallah A., Kabouchi B., Hakam A., Baillères H., Famiri A., Ziani M., Saadat-Nia M. A., Gallet P., Enayati A. A., Pourtahmasi K., Honarvar F., El Mouridi M., Laurent T., Arnould O., Gril J., Arciniegas A., Prieto F., Espinosa L., Cortes Y., Bacca J.

Voir la liste des publications en annexe

C'est la fin de l'exposé...



Vidéo (2011)

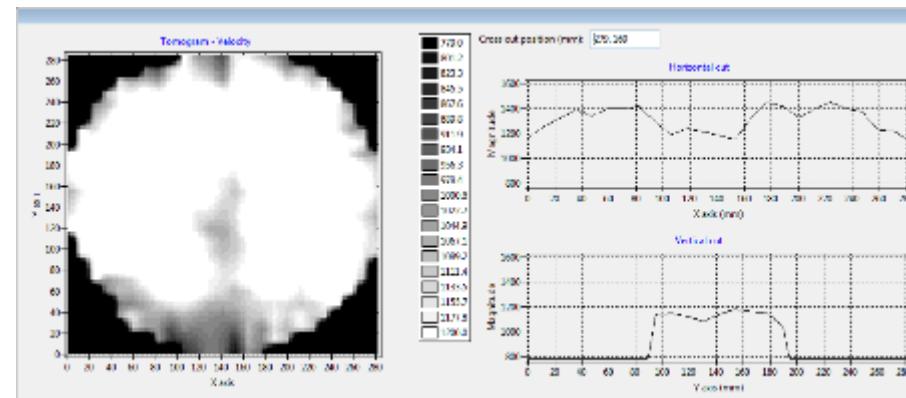
50 kHz, train onde carré (5MHz, 16bits)
630 acquisitions ~ 45mins



(2015)



Guyane, Mangroves (2014)



Merci pour votre attention !

Liste des publications (2008-2015)

- Loïc Brancheriau, Philippe Lasaygues, Eric Debieu, Jean Pierre Lefebvre (2008) " *Ultrasonic tomography of green wood using a non-parametric imaging algorithm with reflected waves* ", Annals of Forest Science, Vol. 65, N°7, pp. 712-718.
- Dikrallah A., Kabouchi B., Hakam A., Brancheriau L., Baillères H., Famiri A., Ziani M. (2010) "Study of acoustic wave propagation through the cross section of green wood", C. R. Mecanique, Vol. 338, N°2, p.107-112.
- Saadat-Nia, M. A., Brancheriau, L., Gallet, P., Enayati, A. A., Pourtahmasi, K., and Honarvar, F. (2011). "Ultrasonic wave parameter changes during propagation through poplar and spruce reaction wood", BioRes. 6(2): 1172-1185.
- M. El Mouridi, T. Laurent, L. Brancheriau, O. Arnould, A. Famiri, A. Hakam, J. Gril (2011) "Searching for material symmetries in the burr wood of thuja by a direct contact ultrasonic method on spherical samples", Maderas 13(3): 285-296.
- Arciniegas A., Brancheriau L., Gallet P., Lasaygues P. (2014) "Travel-time ultrasonic computed tomography applied to quantitative 2-D imaging of standing trees: a comparative numerical modeling study", Acta Acustica, 100(6): 1013-1023.
- Arciniegas A., Prieto F., Brancheriau L., Lasaygues P. (2014) "Acoustic and ultrasonic tomography of standing trees: Literature review and signal processing open problems", Trees - Structure and Function, 28(6): 1559–1567.
- Arciniegas A., Brancheriau L., Lasaygues P. (2015) "Tomography in standing trees: revisiting the determination of acoustic wave velocity", Annals of Forest Science, 72(6): 685-691.

Liste des publications (2017-2020)

- Espinosa L., Arciniegas A., Cortes Y., Prieto F., Brancherieu L. (2017) "Automatic segmentation of acoustic tomography images for the measurement of wood decay", *Wood Science and Technology*, 51(1):69-84.
- Espinosa L., Brancherieu L., Prieto F., Lasaygues P. (2018) "Sensitivity of ultrasonic wave velocity estimation using the Christoffel equation for wood non-destructive characterization", *BioResources*, 13(1):918-928.
- Espinosa L., Bacca J., Lasaygues P., Prieto F., Brancherieu L. (2018) "Accuracy on the time-of-flight estimation for ultrasonic waves applied to non-destructive evaluation of standing trees: a comparative experimental study", *Acta Acustica*, 104(3):429-439.
- Lasaygues P., Prieto F., Brancherieu L., Espinosa L., Arciniegas A. (2018) "Accuracy of coded excitation methods for measuring the time of flight. Application to ultrasonic characterization of wood samples", *Ultrasonics*, 89:178-186.
- Espinosa L., Prieto F., Brancherieu L., Lasaygues P. (2019) "Effect of wood anisotropy in ultrasonic wave propagation: a ray-tracing approach", *Ultrasonics*, 91:242-251.
- Espinosa L., Prieto F., Brancherieu L., Lasaygues P. (2020) "Quantitative parametric imaging by ultrasound computed tomography of trees under anisotropic conditions: Numerical case study". *Ultrasonics*, 102(UNSP 106060).
- Espinosa L., Brancherieu L., Cortes Y., Prieto F., Lasaygues P. (2020) "Ultrasound computed tomography on standing trees: accounting for wood anisotropy permits a more accurate detection of defects". *Annals of Forest Science*, 77(3):77-68.