Numerical study of sapflow measurement in woody stems combining microwave heat pulse and thermal imaging

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Outline

Context

Climate change induces multiple stress in plants :

- hotter and drier conditions,
- water salinity,
- drought stress,
- climate variability (extreme weather => water availability)

Combination with increase of population and food demand...

$\Rightarrow$ **Urgent needs :**

- understand the water use of plants (= plant transpiration)
- increase water and crop efficiency

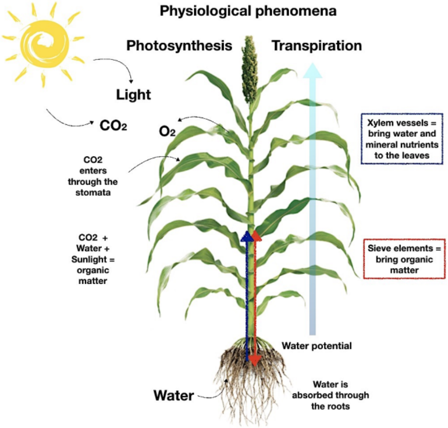
What is sap flow ?

- movement of water in roots (= xylemian sap flow)
- distribution of nutrients (= phloemian sap flow)

Sap flow measurement :

- indicator of plant water status
- water use of plant

⇒ **Key for irrigation decision**
⇒ **Sap flow measurement is challenging**



R. Sidiboulenouar, PhD (2018).

Sap flow measurement methods

1) Thermal dissipation methods continuous[1] or transient[2]

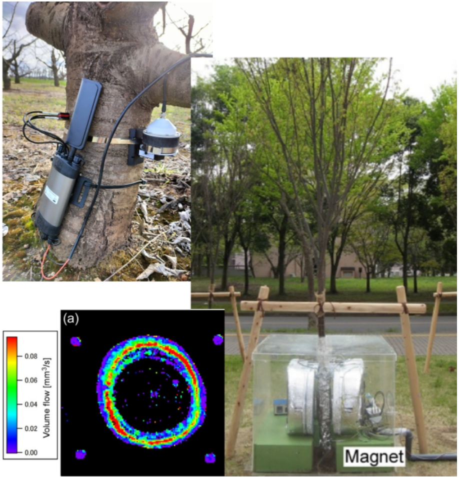
- Needles inserted in the trunk
- Invasive
- Biases : water content ? 0-flow ?

[1] *A. Granier, Ann. Sci. For. 42 (2), 193–200, (1985).*
[2] *F.C. Do, Tree Physiol. 31, 369–380, (2011).*

2) NMRI

- Non-invasive
- Image of sap flow in Xylemian vessels
- Tool for academic research [3]

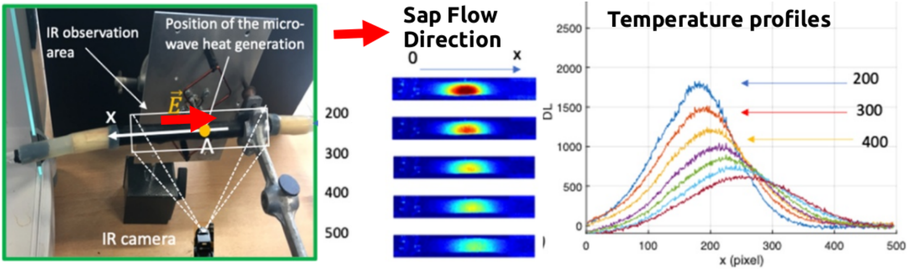
[3] *A. Nagata et al., Journal of Magnetic Resonance, vol. 265, (2016).*



TIMFLOW measurement method

TIMFLOW : Combination of microwave heat pulse and infrared thermography imaging.

- Short trunk $\Rightarrow$ imposed water flow direction
- Near field µwave antenna (@ $2.45 GHz$)
- Infrared (IR) thermography observation
- Image processing



H. Louche et al.,, Agricultural and Forest Meteorology, Vol. 347, (2024).

Measurements on a large root of Faidherbia Albida in an agroforestry crop *(M. Faye, PhD)*

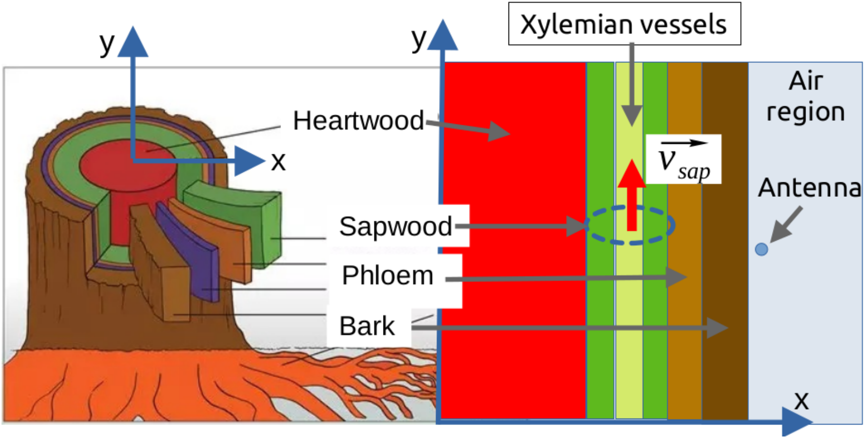
Comparison of TIMFLOW method with thermal transient dissipation method ⇒ raises questions :

- discrepancies between thermal dissipation and TIMFLOW methods...
- limitation of the TIMFLOW method ?

⇒ **investigation using finite element simulation !**

2D simulation : a) geometry description

Trunk (or root) is modelled in a 2D transverse plane in cartesian coordinate



Electromagnetic model : from Maxwell's equations to Helmholtz equation (harmonic regime) :

$$\nabla \wedge \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{B} = \mu_0 \vec{H}$$
$$\nabla \wedge \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad \vec{D} = \epsilon_0 \overline{\epsilon_r} \vec{E} \qquad \Rightarrow \vec{\nabla}^2 \vec{E} + k^2 \vec{E} = 0$$
$$\vec{J} = \sigma \vec{E}$$

https ://doc.freefem.org/tutorials/complexNumbers.html
https ://doc.freefem.org/tutorials/wifiPropagation.html

Variational form $\Rightarrow \iint_\omega \vec{\nabla} \vec{E} \vec{\nabla} \vec{v} - \iint_\omega k^2 \vec{E} \vec{v} = 0$
$+$ Boundary conditions of Dirichlet type.

Dielectric permittivity in plant organs as a function of WC (Water Content) :
https ://onlinelibrary.wiley.com/doi/10.1002/cjce.21826

$$k^2 = -\omega^2 \epsilon_0 \overline{\epsilon_r} \mu_0 + j\omega\sigma\mu_0$$
$$\overline{\epsilon_r} \approx 2 + 12 \times WC - j6 \times WC$$
$$\sigma \approx 0$$

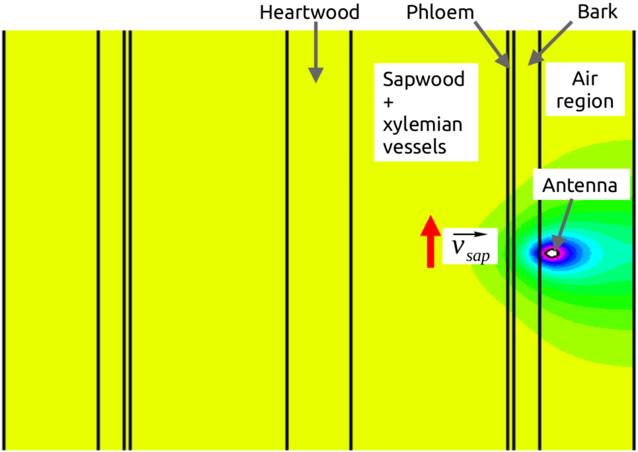
Heat dissipation : Specific Absorption Rate (SAR) :

$$SAR = \iiint_{Wood} \sigma \frac{\|\vec{E}\|^2}{2} dv + \iiint_{Wood} \Im(\overline{\epsilon_r}) \frac{\|\vec{E}\|^2}{2} dv$$

Physical parameters table (70mm diameter root)

Tree organ	thickness (mm)	density	WC (%)
Heartwood	5	0.3	50
Xylemian vessels	25	0.506	105
Phloem	1	0.4	150
Bark	4	0.3	50

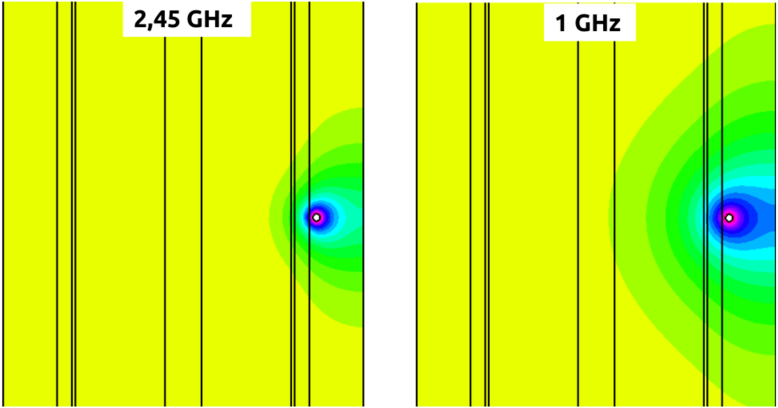
E field distribution @ 2.45 GHz ($\overline{\epsilon_r} = 2 + 6 \times WC + 2i \times WC$)



Penetration of E field is shielded by high WC organs...

2D simulation : c) Results

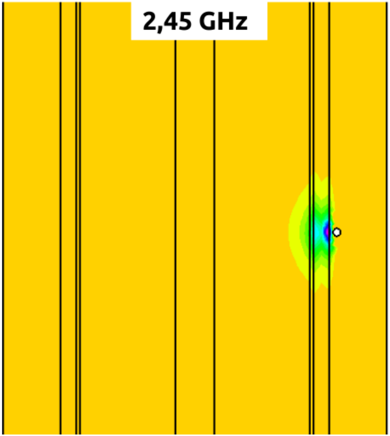
Effect of micro-wave frequency on electric field penetration in tissues : :

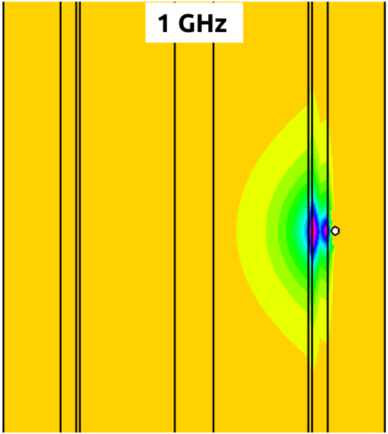


⇒ Lower frequency improves the penetration of E field

2D simulation : c) Results

SAR distribution : heat dissipation in the wood tissues @ $2.45GHz$ and $1GHz$:





@2.45GHz SAR is mainly deposited on bark, phloem and to a lesser extent in xylemian tissues

SAR distribution : input of the thermal model.

Sap flow is modelled through a transport term (v_{SAP}) in heat equation :

$\rho C_p(\frac{\partial T}{\partial t} + \vec{v}_{SAP}\vec{\nabla} T) - \lambda \vec{\nabla}^2 T - SAR(x, y, t) = 0$

In xylemian tissues, sap flow is oriented along y axis :

$\vec{v}_{SAP}\vec{\nabla} T \Rightarrow v_{SAP} \times (\frac{\partial T}{\partial y})$

In phloem, sap flow is opposite : $\vec{v}_{SAP-Phloem}\vec{\nabla} T \Rightarrow -v_{SAP-Phloem} \times (\frac{\partial T}{\partial y})$

Variational form :

$\iint_\omega \rho C_p(\frac{\partial T}{\partial t} + v_{SAP} \times \frac{\partial T}{\partial y}) \times v + \iint_\omega \lambda \nabla T \nabla v - \iint_\omega SAR \times v = 0$

$+$ Boundary condition (convection on bark) :

$-\lambda \frac{\partial T}{\partial x} \times v = k(T - T_{amb}) \times v$

(h : convection coefficient, T_{amb} : ambient temperature)

Iterative resolution : $\frac{\partial T}{\partial t} \Rightarrow (T^{j+1} - T^j)/dt$

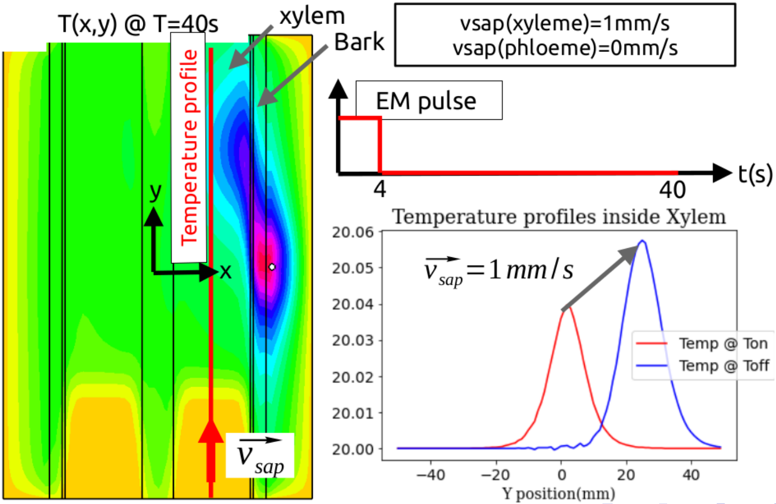
2D simulation : d) Thermal and transport modelling

Thermophysic models of plants *A. Penarier et al., JNM conference, Antibes (France), june 2024*

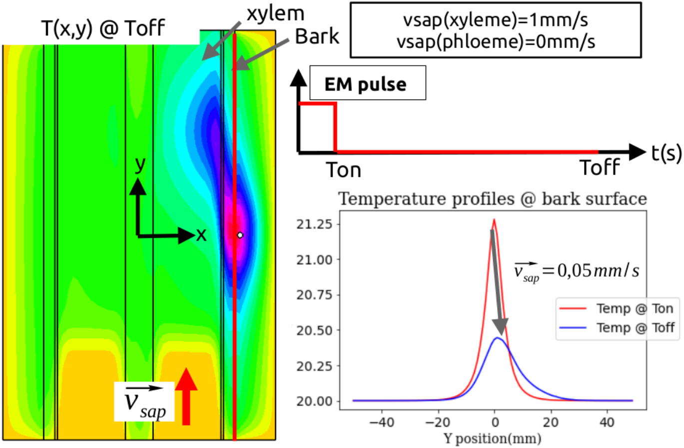
$$\rho = \rho_{anhydre}(1 + WC)$$
$$C_P = \frac{Cp_{anhydre} + WC Cp_{water}}{1 + WC}$$
$$\lambda = \frac{\lambda_{anhydre} + WC\lambda_{eau}}{1 + WC}$$

Thermophysic parameters by region using WC values of each tissue (cf. table parameters)

EM source is ON during $T_{ON} = 4s$ and OFF until $T_{OFF} = 40s$.
Temperature profile is observed at the end of the pulse sequence



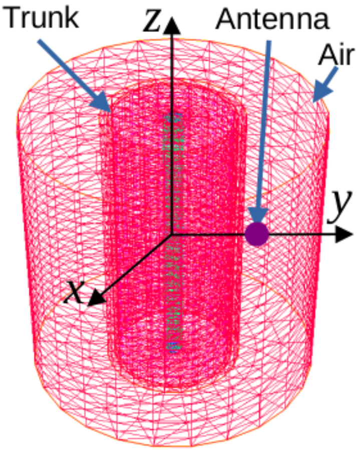
Temperature profile on bark surface

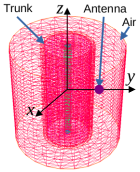


⇒ **Heatwave is slow down by the thermal diffusivity of bark**

⇒ Is 2D simulation representative ? ⇒ 3D simulation

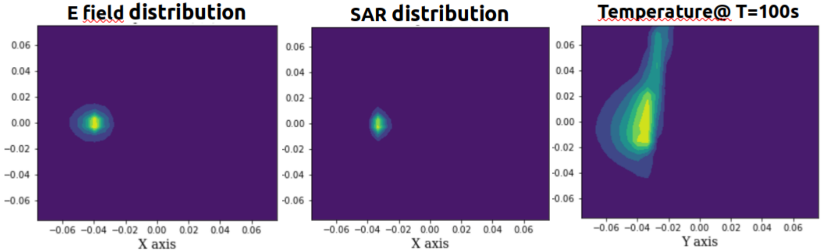
Meshed geometry in 3D :





Meshed geometry in 3D

⇒ Visualisation in 2D (y-z plane)



Qualitative results are consistent with 2D simulation

Quantitative analysis : work in progress.

Conclusion and perspectives

- Freefem investigation : help for measurement interpretation
- FEM study opens method improvement
- Simulation 3D : methodology to mesh of composite volume is not trivial (volumic mesh => generation of surface mesh => volumic mesh construction using tetgen)
- Perspective : implement a distribution of xylemian vessels

Question : how to share a script with freefem community ?

Thanks to FreeFEM team

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