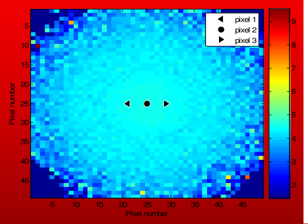
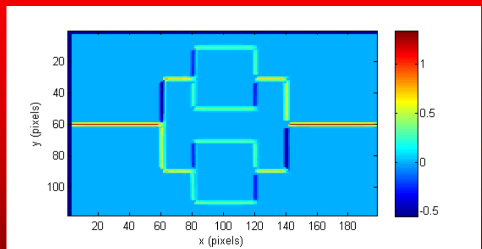
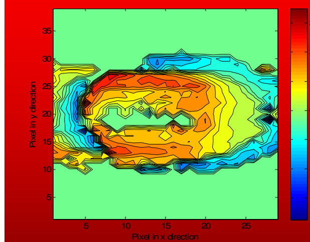
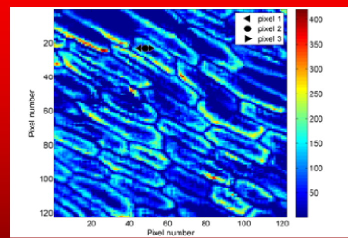
Multispectral « THz » imaging for heat and mass transfer studies in multiphysics problems





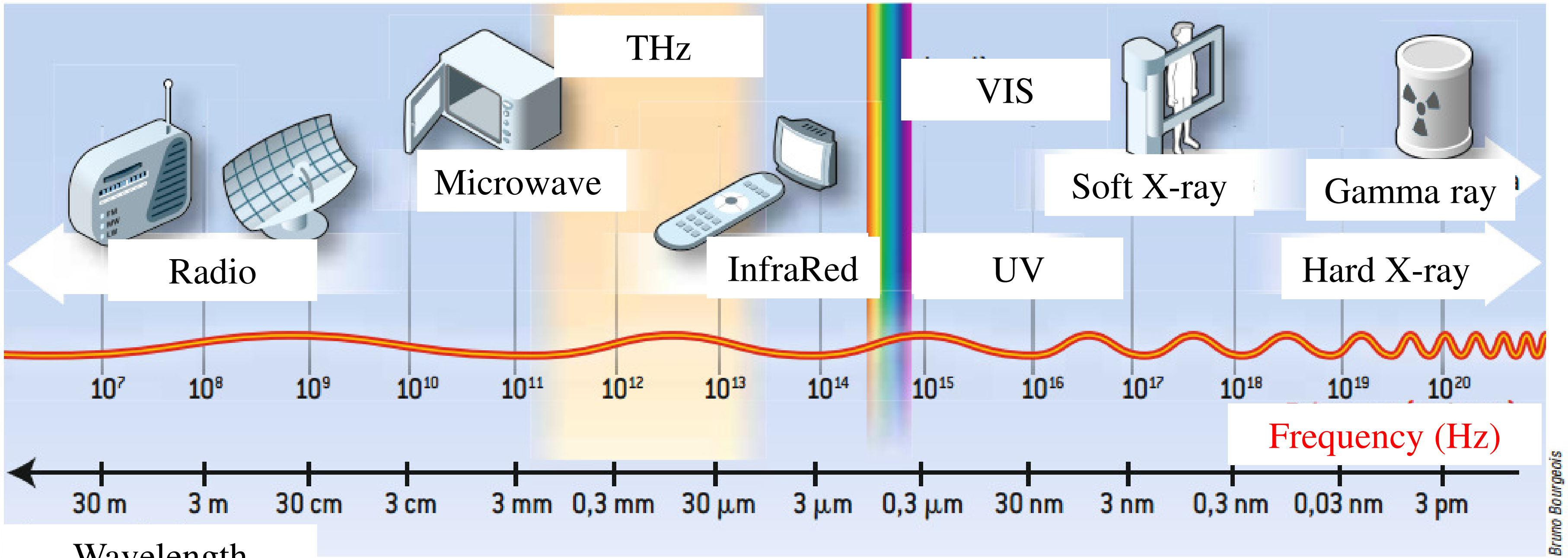


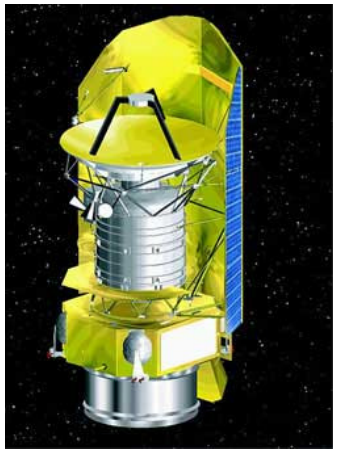


C. Pradere, A. Sommier and J.C. Batsale

What is the range of THz wavelength

THz is defined from 0.3 to 3 THz as sub-millimeter radiation





But from a "Range" point of view ???

And from "Herschel" point of view ???

Could we speak about "IR radiation" ???

Herschel Space Observatory

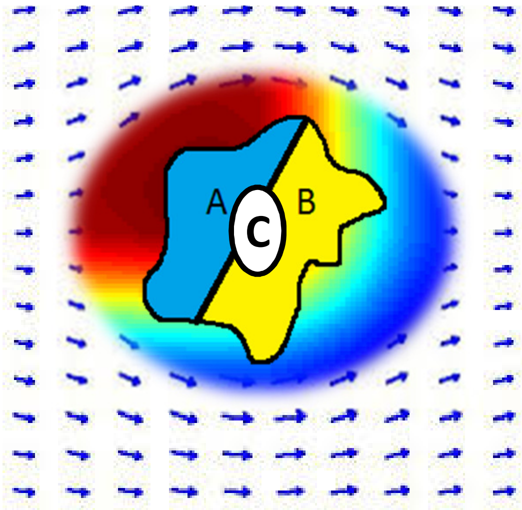
Sir William Herschel

Multiphysics and multiscale problem

<<REACTION-DIFFUSION>> problems

Energy conversion → Chemical reaction, biological system, phase change

Heat and mass transfer with hydrodynamic



transport

Multi constituent (C_i)

Mass transfer (C)

Source (Joule /mol)

Heat transfer (T)

EQUATIONS of DIFFUSION

$$\frac{\partial}{\partial t} = D\frac{\partial^2}{\partial x^2}$$

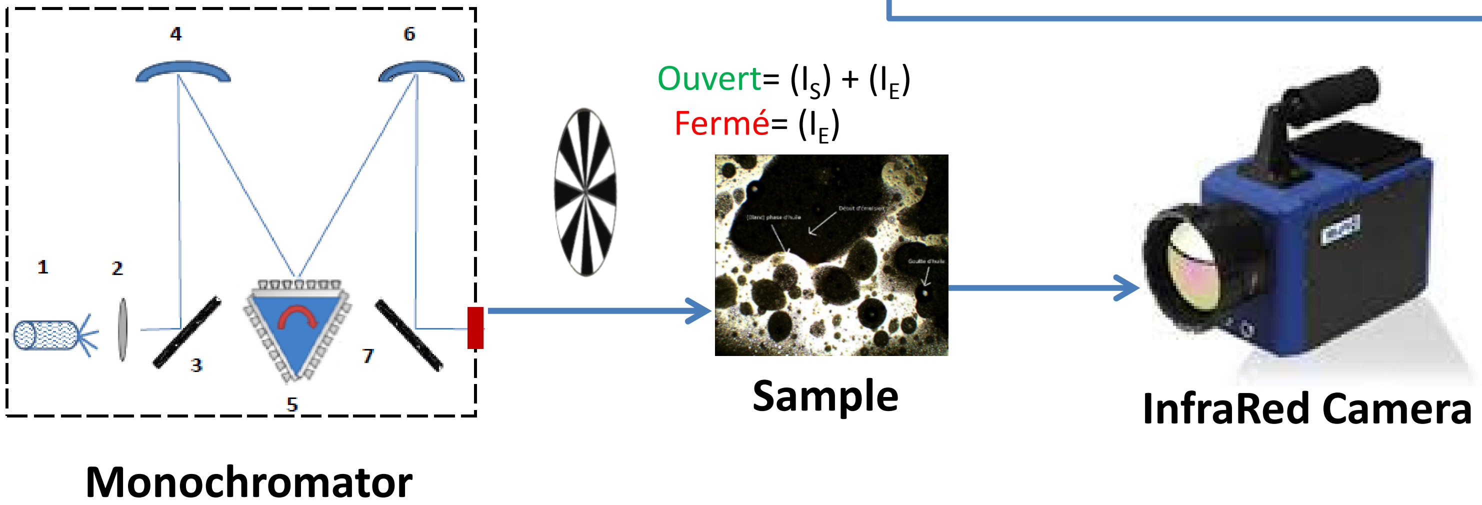
SCIENTIFIC GOALS : Understanding such phenomenon

Design of multiscale thermal characterization from global to local approaches
From contact to non contact calorimetry
(heat fluxes and temperatures measurements)

Experimental set-up of TREFLE

General description

Chemical and thermal analysis ⟷ **High spatial and temporal resolution**



Spectral resolution
dλ = 0.3 nm

Spatial resolution 4 µm to 3 mm
Frequency rate 1 to 1000 Hz

Broadband sensor from 1 µm to 14 mm
With IR to THz camera

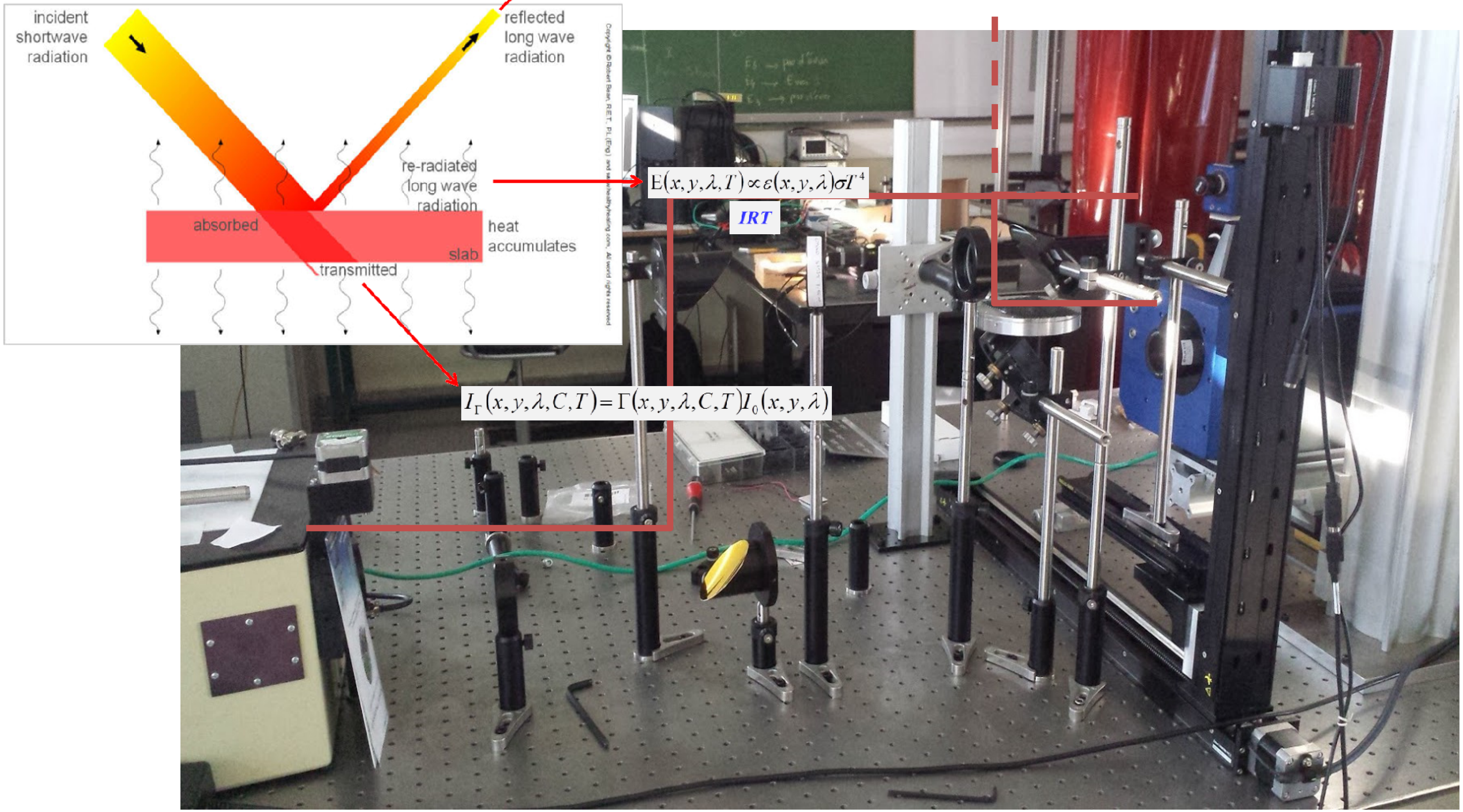
M. Romano et.al., Infrared Physics Technology Journal 2015

Multispectral set-up of C and T fields

Photography of the system

$I_0(x,y,\lambda)$

$I_R(x,y,\lambda,C,T)=R(x,y,\lambda,T)I_0(x,y,\lambda)$

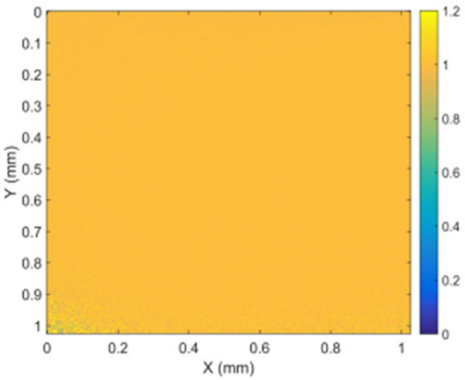


$\mathrm{E}(x,y,\lambda,T)\propto\varepsilon(x,y,\lambda)\sigma T^4$

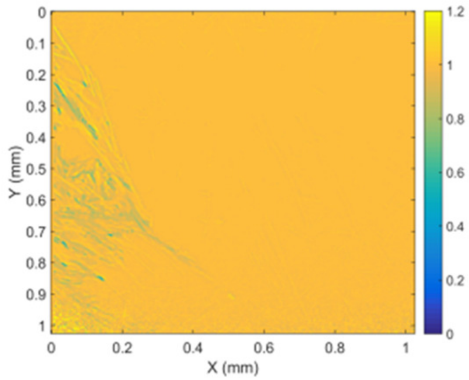
$I_\Gamma(x,y,\lambda,C,T)=\Gamma(x,y,\lambda,C,T)I_0(x,y,\lambda)$

Frame rate 200 images/s

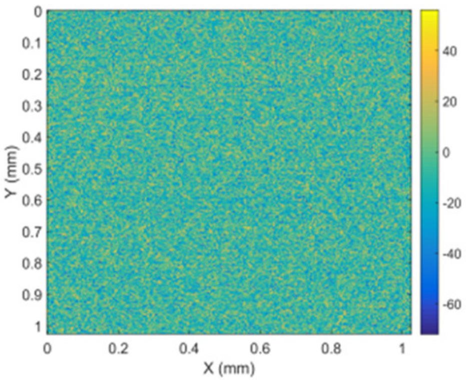
東京工業大学 Tokyo Institute of Technology

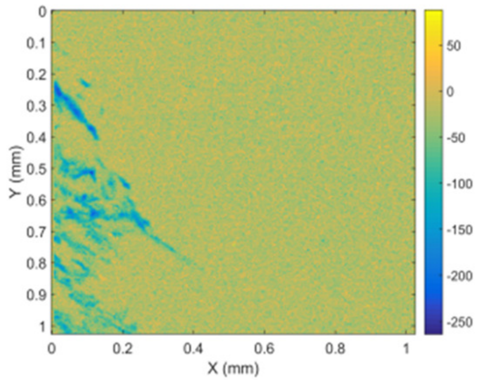


t = 0 s

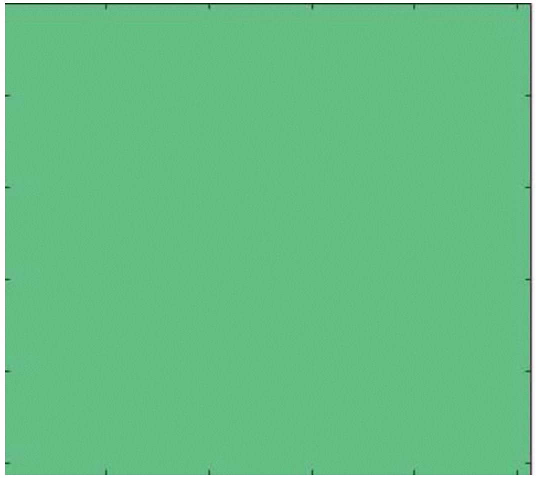


t = 5 ms





Concentrations



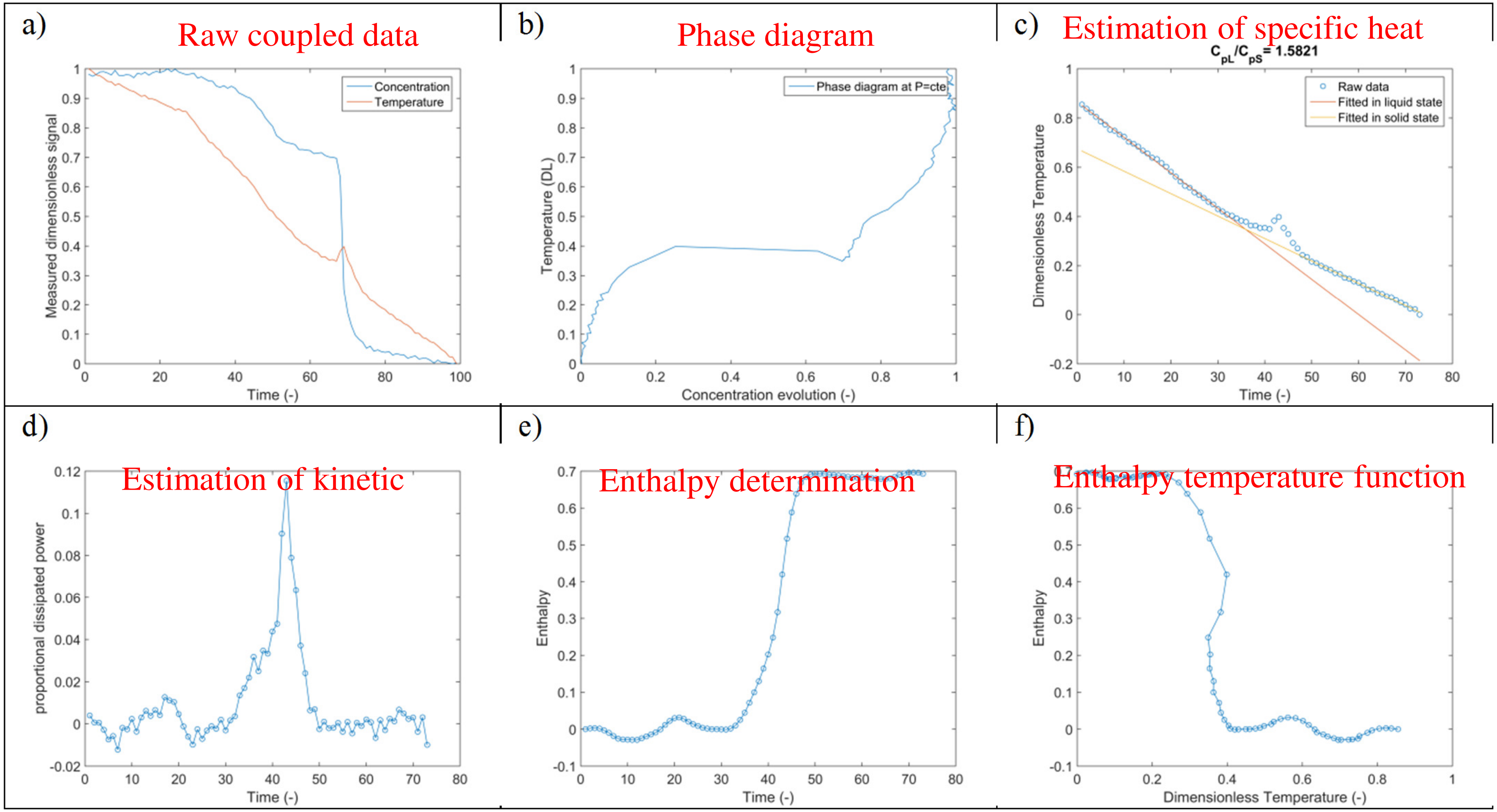
Temperatures

Non contact calorimetry

Estimation of phase diagram, specific heat, enthalpy temperature function……

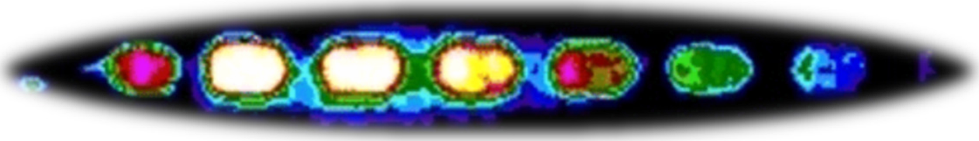
Simultaneaous measurement of C and T during phase change

Frame rate 200 images/s



Application to diffusion, transport and source problem

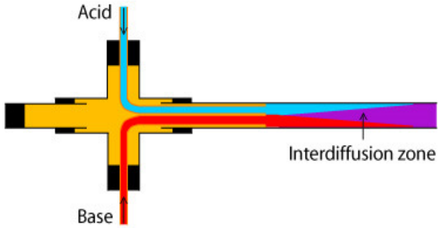
Example of microfluidic systems



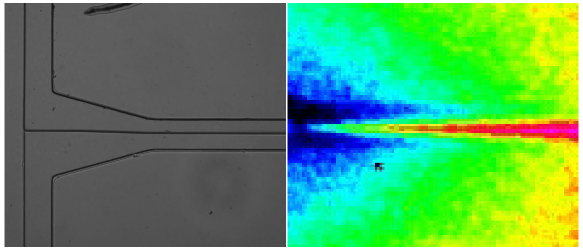
General contexte of the research

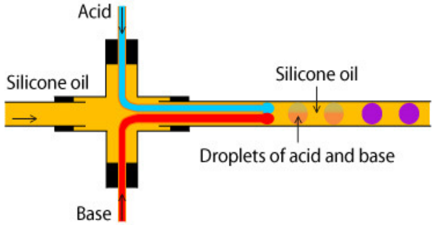
Goals: Determination of kinetic and enthalpy of chemical reaction or phase change in millifluidic droplet flow and the heat transfer mechanisms

❶ Applications : Chemical reaction or phase change in co-flow or droplet flow

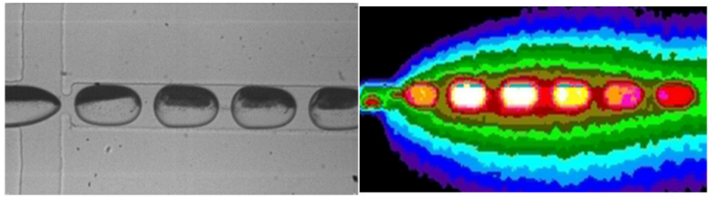


Laminar flow (low Reynolds number)
Mixing by species diffusion
Steady state (x = vt)





Mixing is faster
1 droplet = 1 microreactor

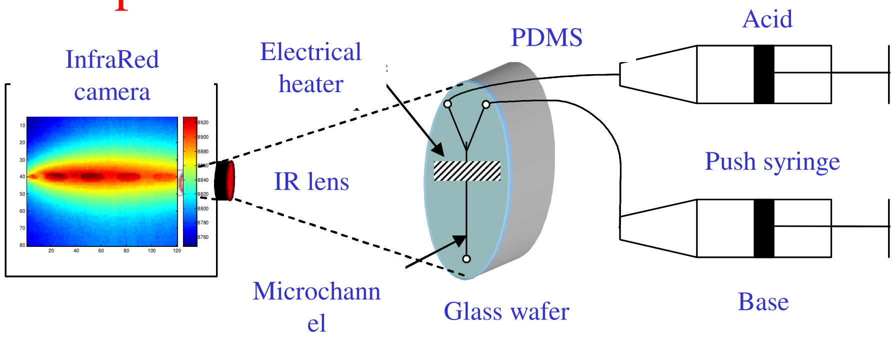


Tools : ***Temperature fields measurements at microscales*** (InfraRed camera), ***analytic and numerical modelisation*** (quadripole, finite difference…) and ***inverse methods*** (nodal: OLS, TLS and modal: SVD approaches)

Method for chemical reaction estimation

Measurement of chemical Acid (HCl)-base (NaOH), C = 0.25 M:

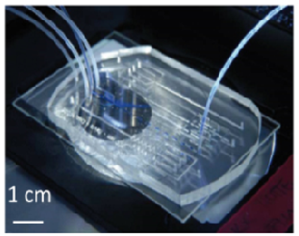
Principal



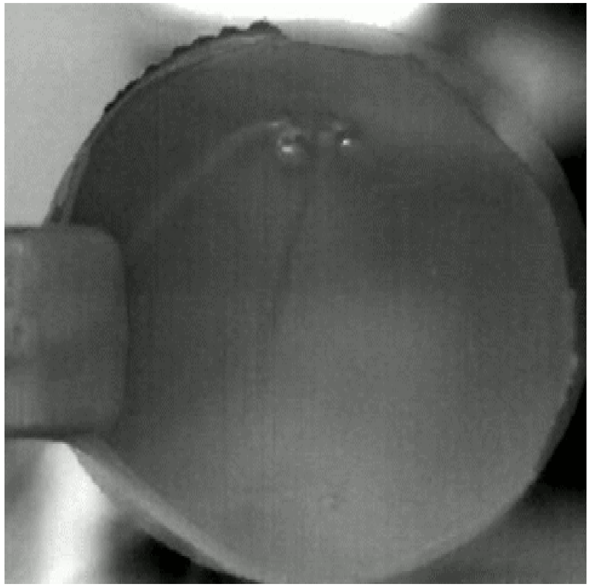
Thermal modelization

$$\frac{V(x,y)}{a}\frac{\partial T}{\partial x} = \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \phi(x,y)$$

$$\phi_{i,j} = \Delta\left(T^c_{i,j}\right) - Pe_{i,j}\,\delta\left(T^c_{i,j}\right)$$



Results



Températures T^c, à Q = 1000 µl/h

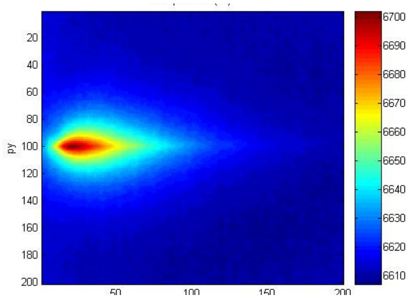
2 parameters estimation
Peclet number
Thermal calibration

Thermal analysis in coflow by IRT

Heat source and hydrodynamic analysis

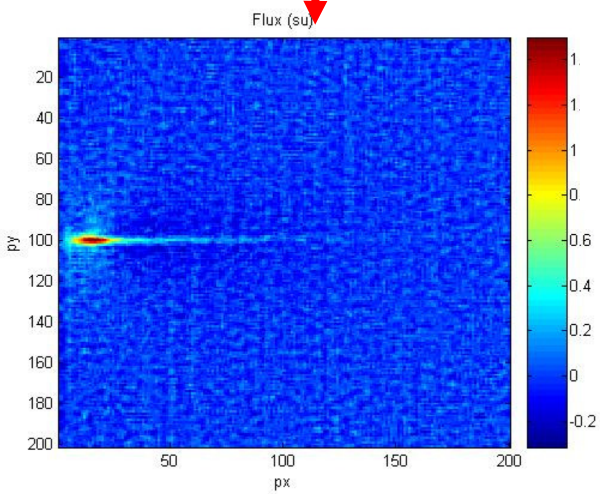
Acide (HCl)-base (NaOH), C = 0.25 M

Temperature measurement

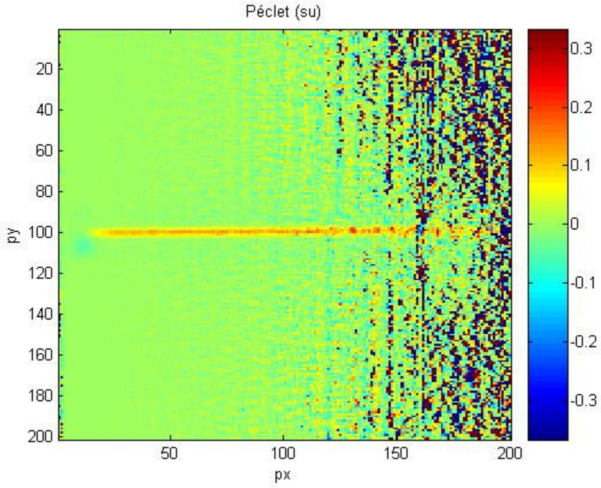


Température T^c, à Q = 1000 µl/h

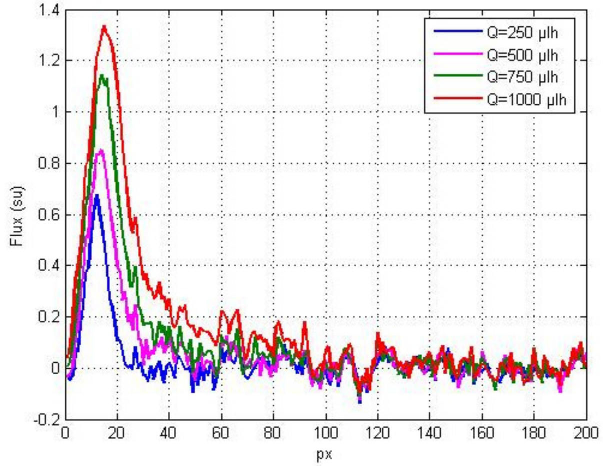
$$\phi_{i,j} = \Delta\left(T^c_{i,j}\right) - Pe_{i,j}\,\delta\left(T^c_{i,j}\right)$$

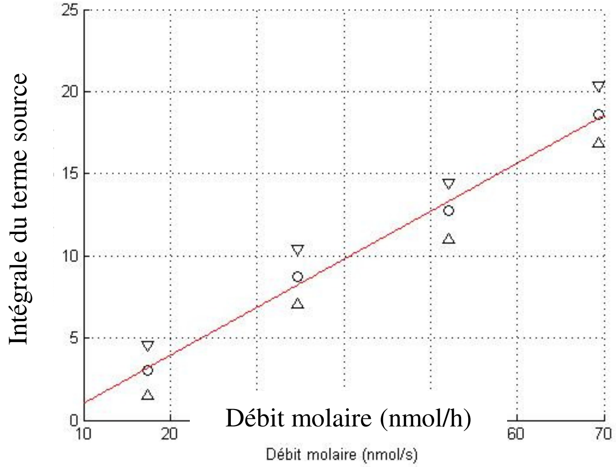


Cartographie de terme source à Q = 1000 µl/h



Estimated source





Intégrale du terme source (selon x) à différents débits

Kinetic and enthalpy by non contact calorimetry

Global approach: application on chemical reaction

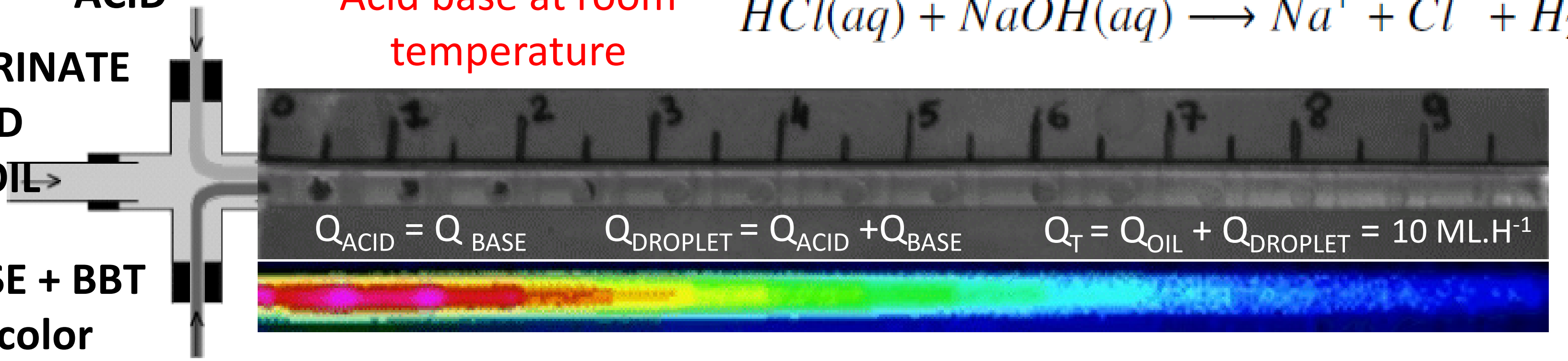
ACID

FLUORINATED OIL

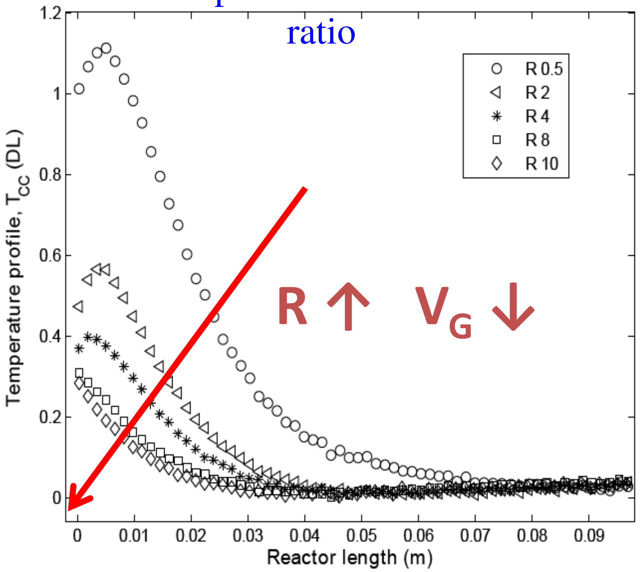
BASE + BBT (color indicator)

Acid base at room temperature

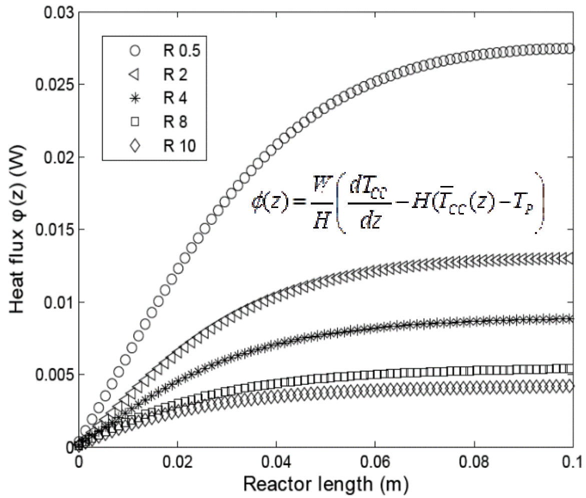
$$HCl(aq) + NaOH(aq) \longrightarrow Na^{+} + Cl^{-} + H_2O$$



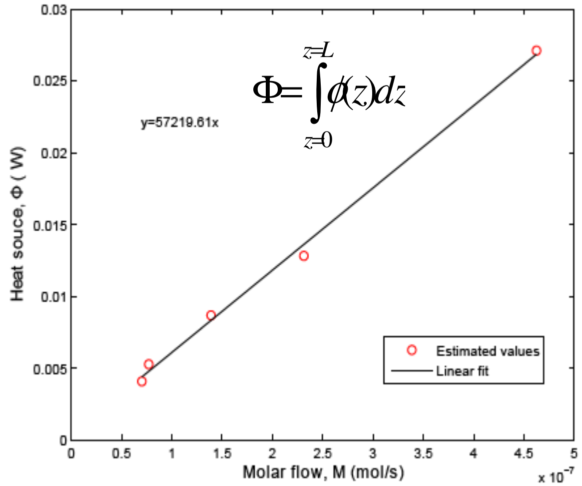
Measured temperature as function of the R ratio



Estimated kinetic



Estimated enthalpy



Kinetic estimation and Enthalpy measured = 57 ± 2.4 kJ/mol,
Reported valued on literature = 56 KJ/mol

Application to diffusion problem in mass transfer

Example of drying process

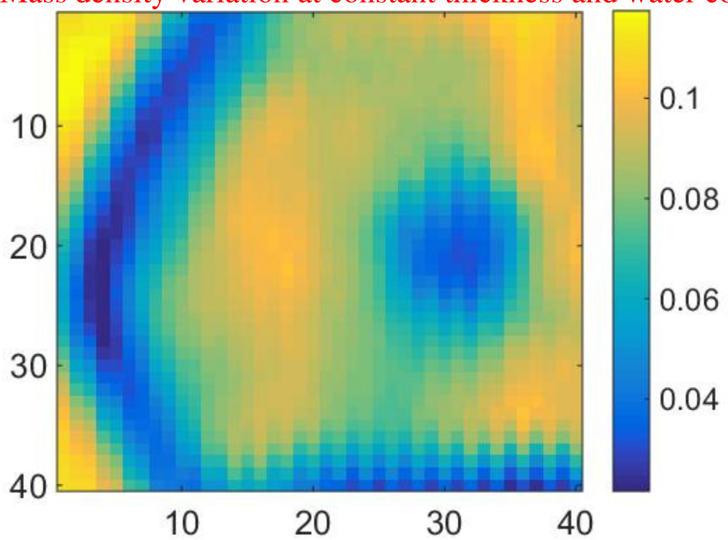
Classical law of absorption

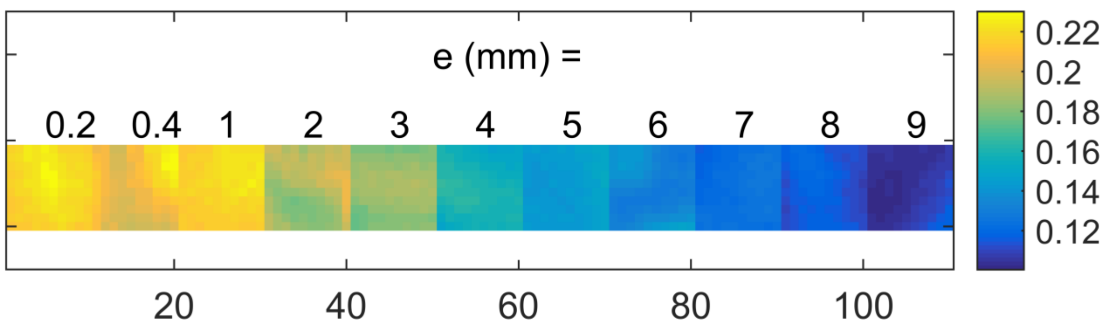
THz attenuation coefficient is based on Beer-lambert law

$$\frac{A(x,y,\lambda)}{l_s} = \mu_s(x,y,\lambda) + \mu_w(x,y,\lambda)\frac{\rho_s(x,y,\lambda)}{\rho_w(x,y,\lambda)}W(x,y,\lambda)$$

$A(x,y,\lambda)$ is the absorbance,
$\mu_s(x,y,\lambda)$ *and* $\mu_w(x,y,\lambda)$ are the absorption coefficient of solid and water,
$\rho_s(x,y,\lambda)$ and $\rho_w(x,y,\lambda)$ are the density of solid and water,
$W(x,y,\lambda)$ is the local water content

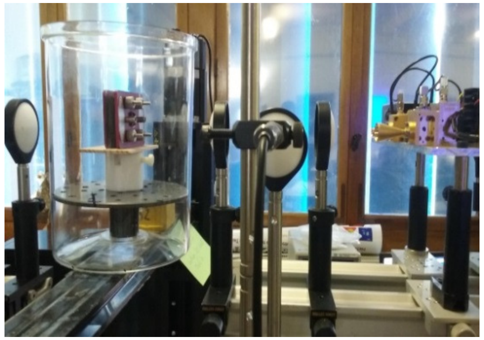
Mass density variation at constant thickness and water content on apple slice

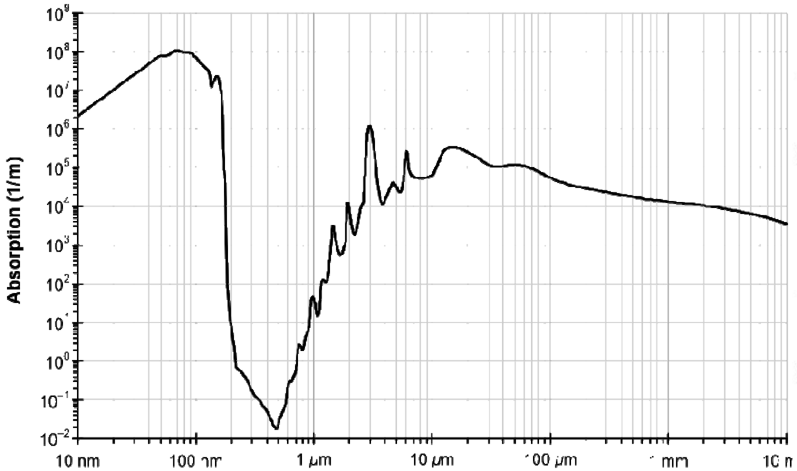


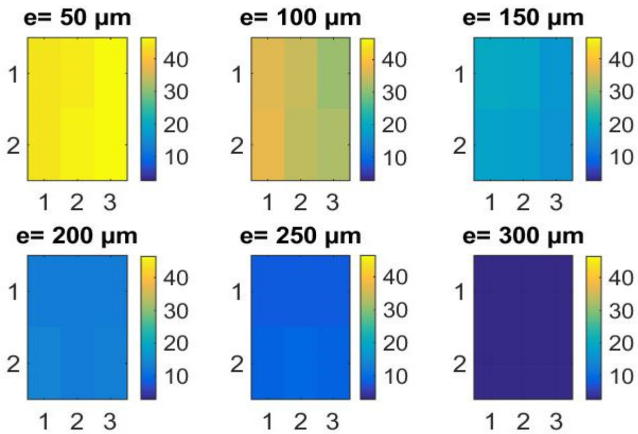


THz attenuation coefficient as function of thickness
On blotting paper

Validation on pure water on « THz » wave

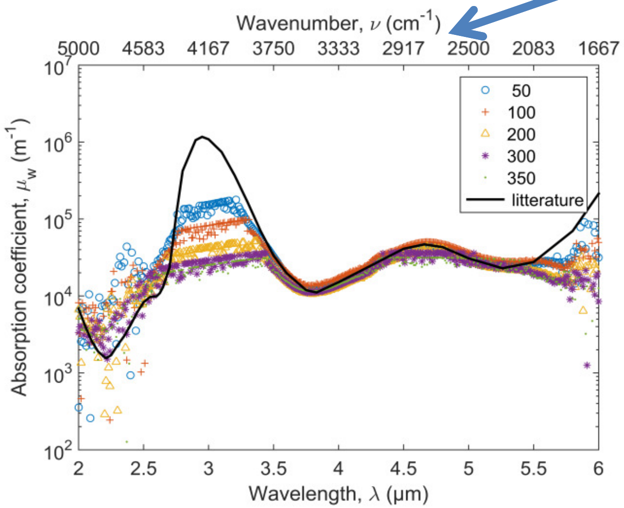


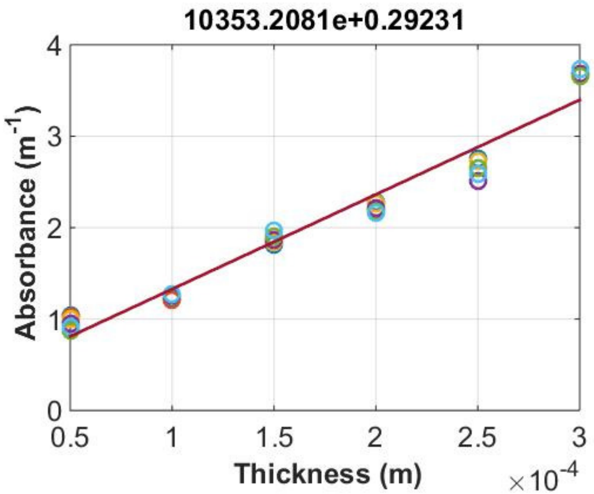




Up to 400 µm of water in mm waves

Up to 10 cm in µm one

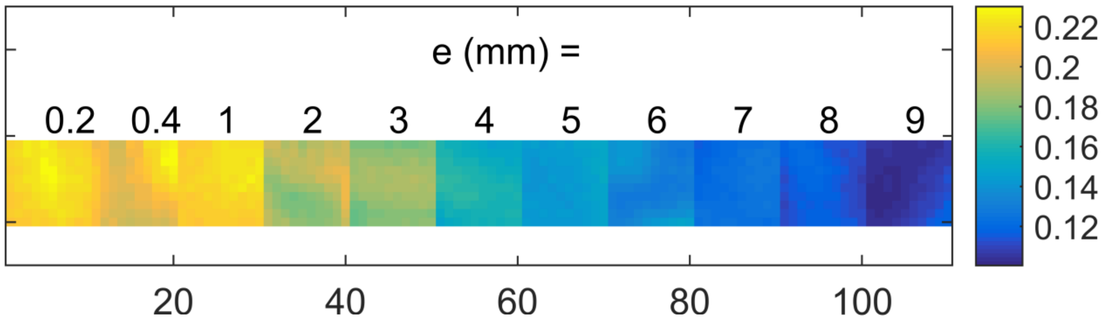


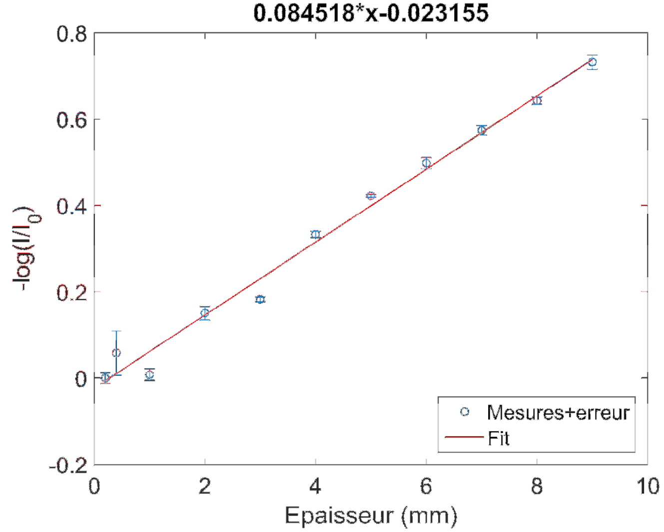


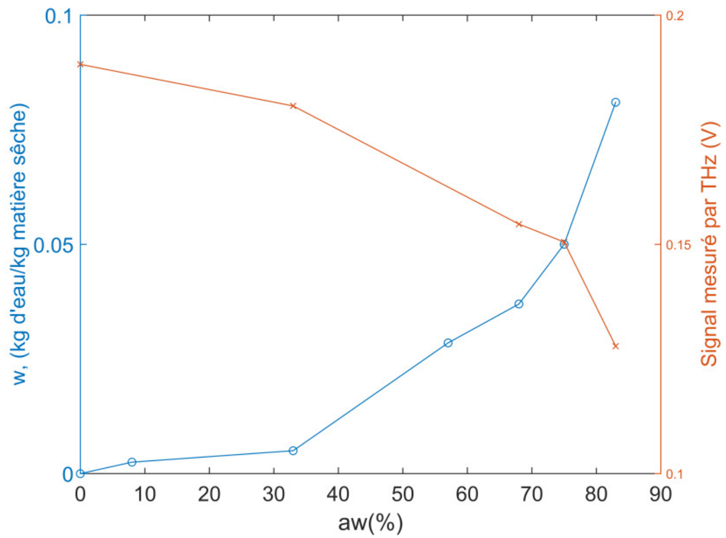
Application on wetting and dry process

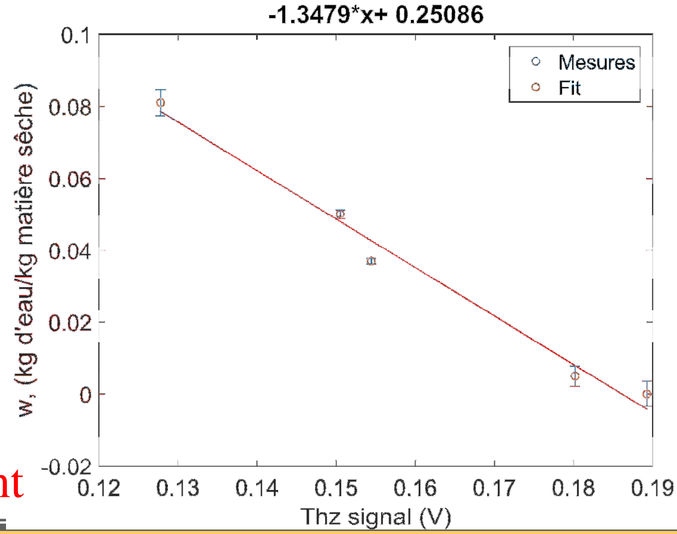
Calibration of water content validity on blotting paper

THz attenuation coefficient as function of thickness on blotting paper



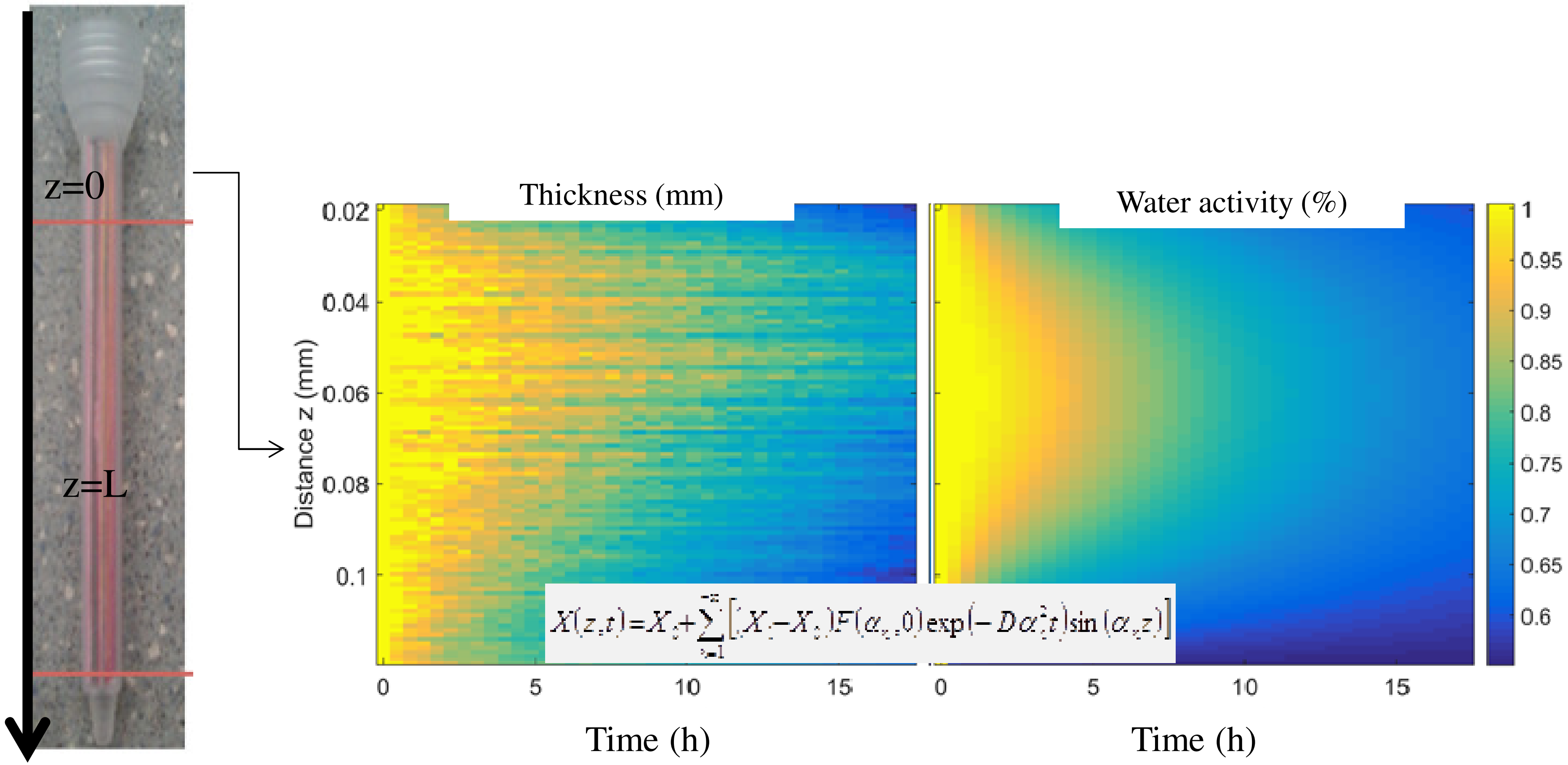




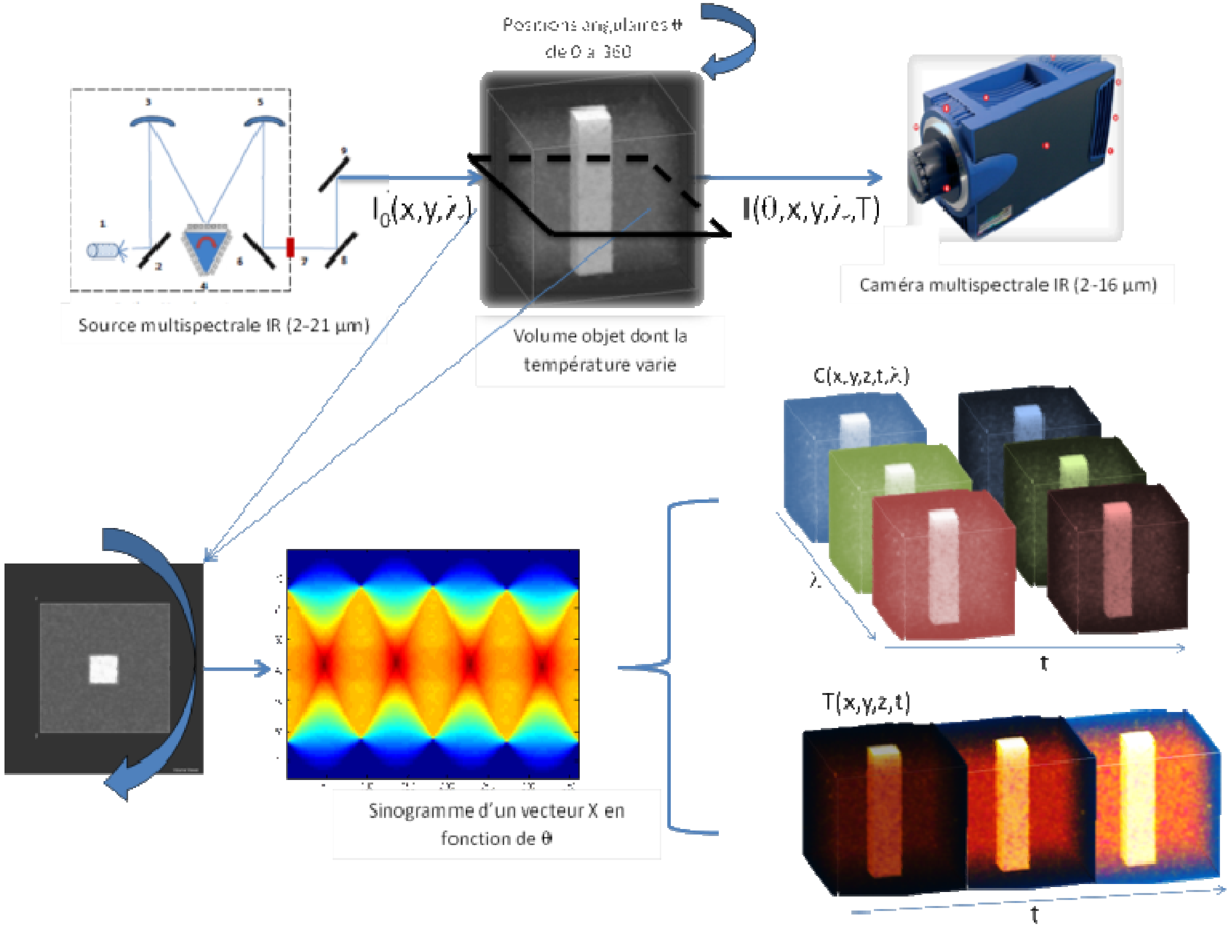


CONTACTLESS volumic water content measurement

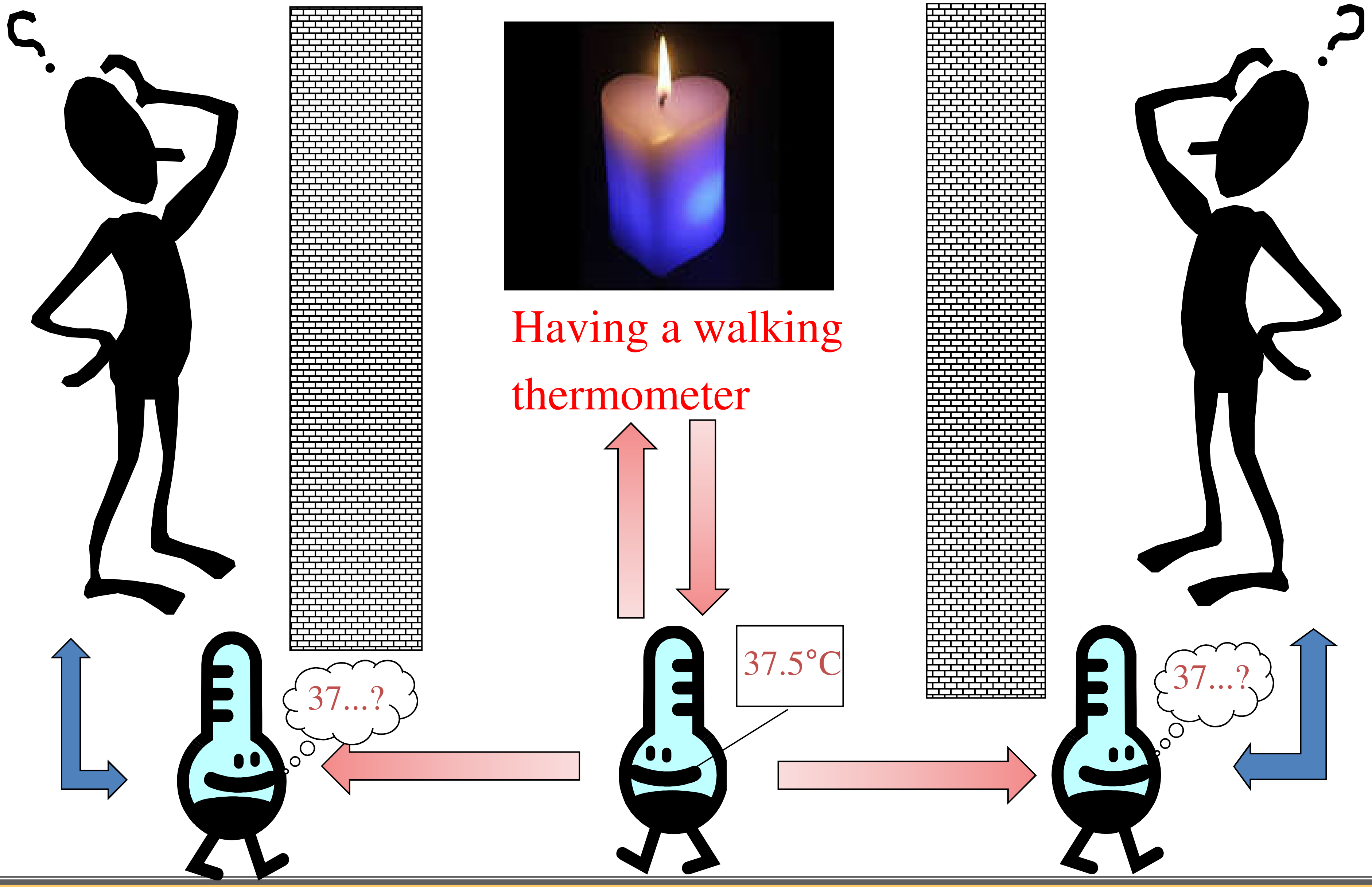
Application on dynamic mass transfer diffusion problem



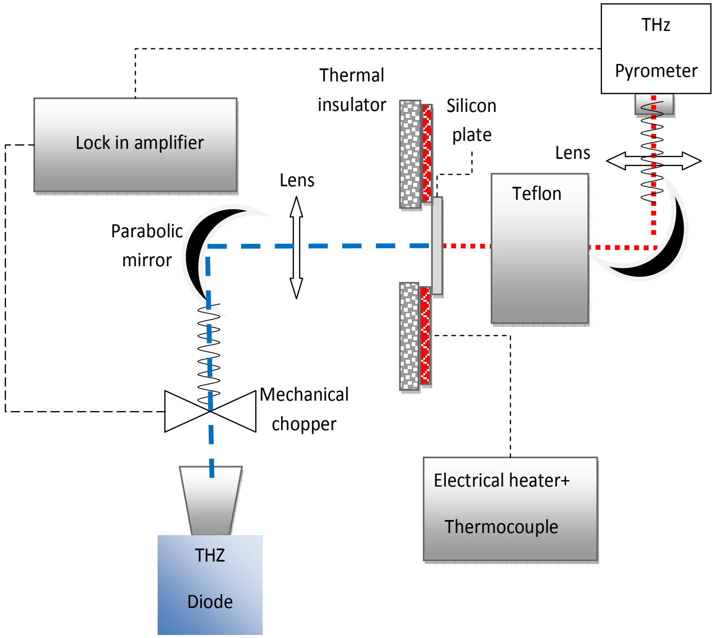
From broadband THz camera



To 3D thermal imaging tomography

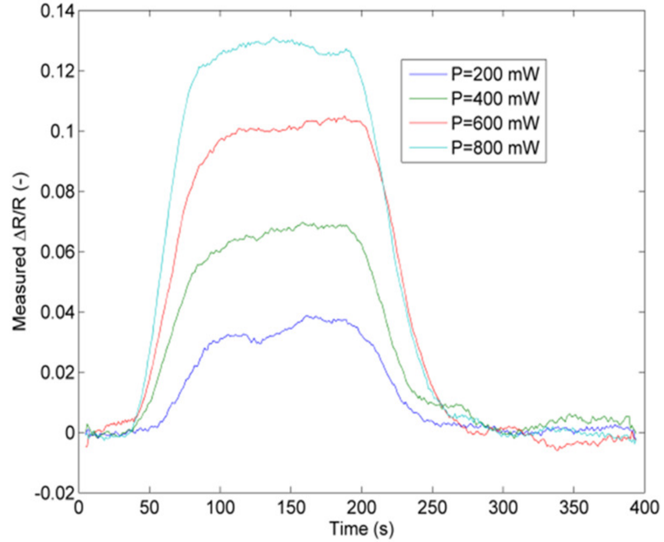

Having a walking thermometer
37...?
37.5°C
37...?

1Dt temperature measurements and calibration

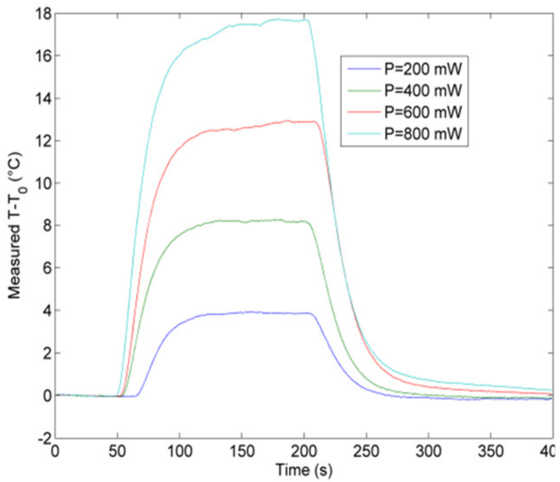


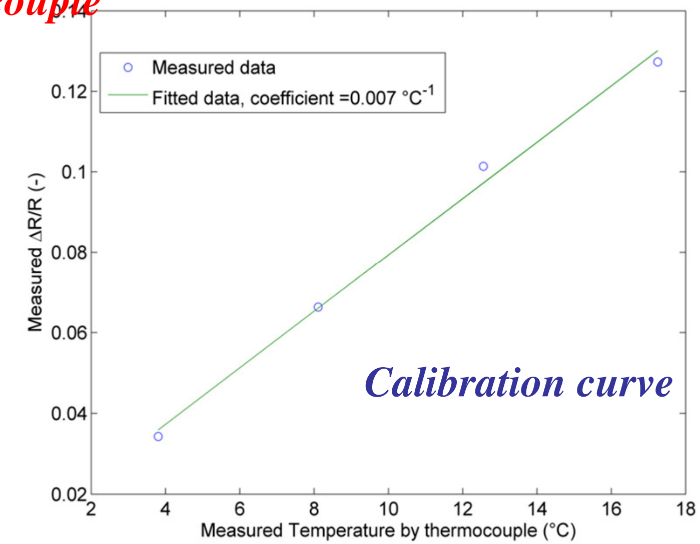
$$\frac{\Gamma(T)-\Gamma(T_0)}{\Gamma(T_0)} = \tau(T-T_0)$$

Temperature measured by our method



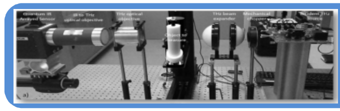
Temperature measured by thermocouple

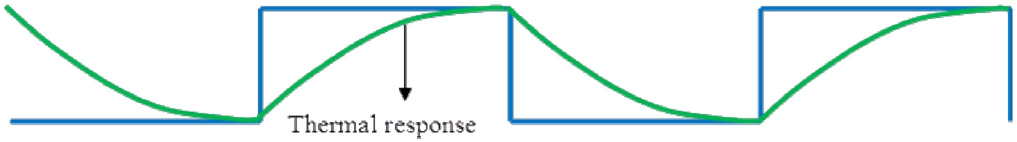




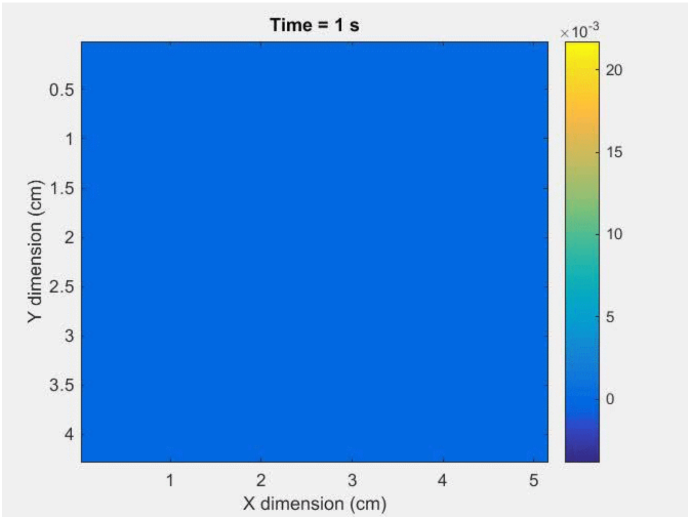
Very good linearity beetween measured temperature with TC and THz
VERY GOOD sensitivity 100 mK

Experimental procedure

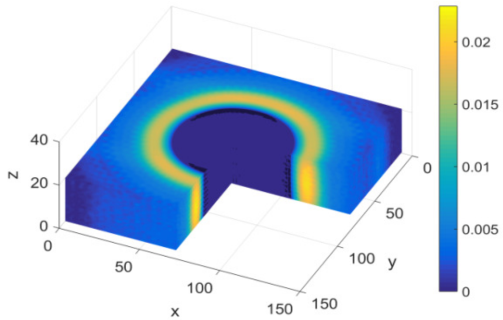




Angular position

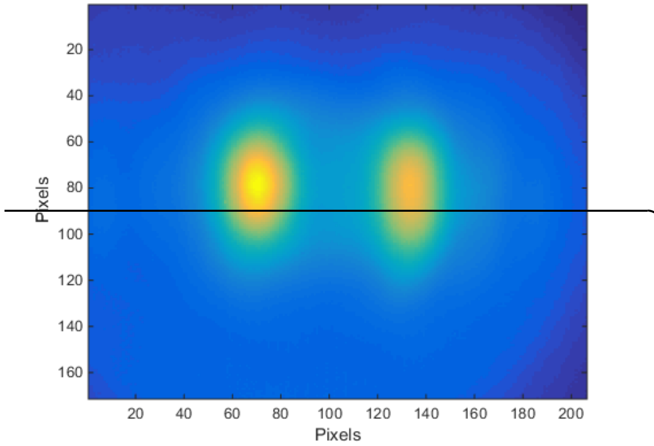


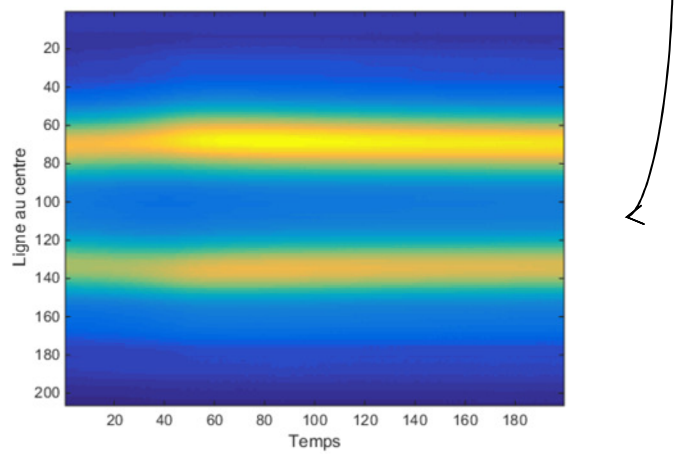
Measured images as function of time



3D reconstruction after radon transform

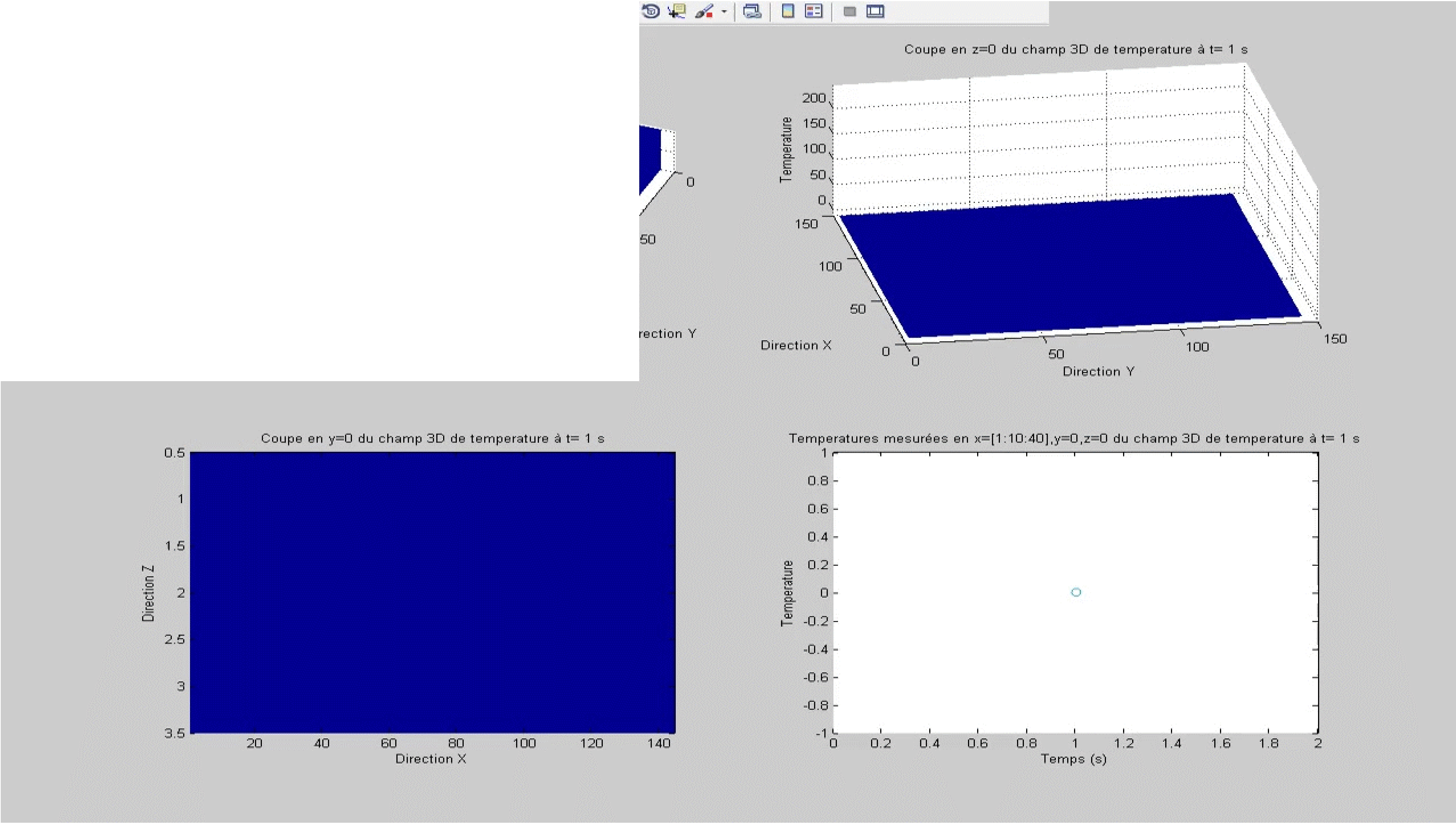
Image at room temperature





Line as function of time

First results of transient temperature tomography



Conclusion

Thz imaging and tomography

Development of a broadband multispectral camera

No obstacle to measure T and C variations inside materials

First temperature images on homogeneous media

Improvements

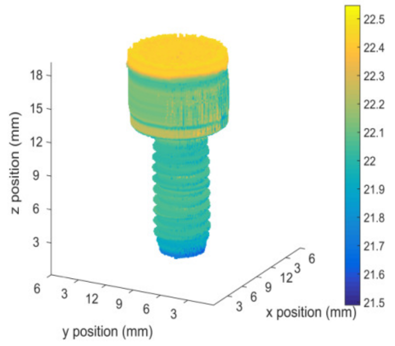
Analysis of error sources (optics, environment…)

Extension to liquids or gas

Applications

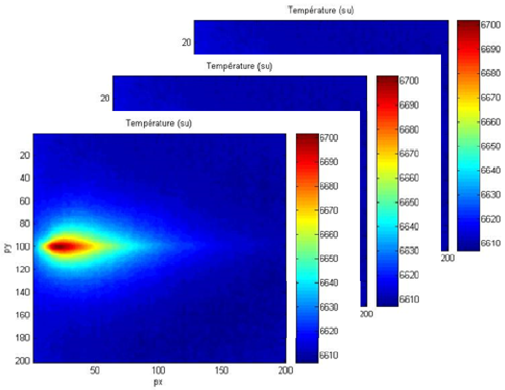
Dynamic study of Drying and wetting process in wood

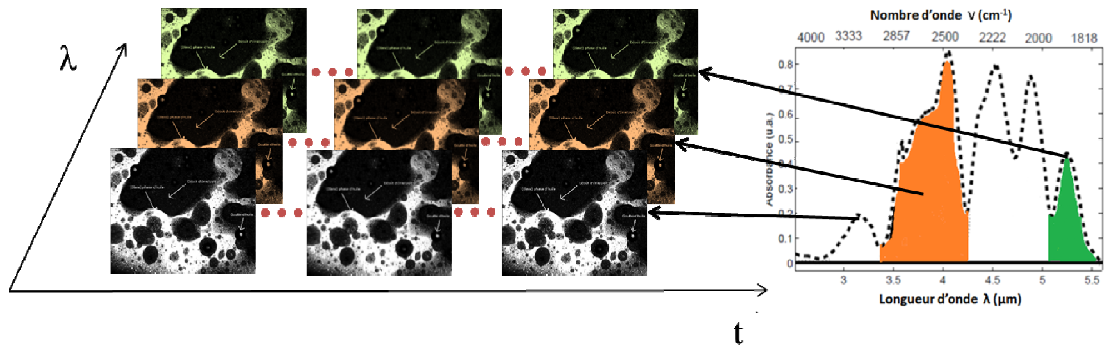
Tools for 3D characterization of materials



Perspectives: Thz multispectral tomography

Experimentation joint the numeric (big data and multiphysics)



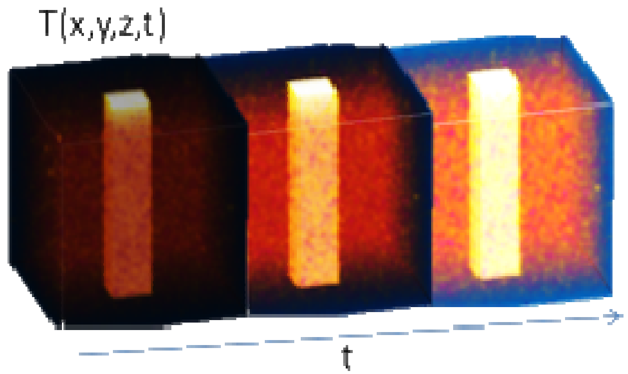


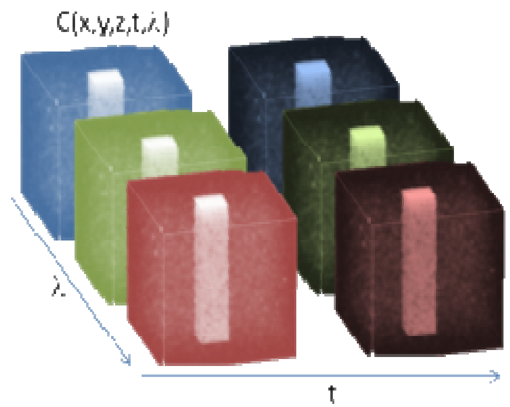
Transient Thermal (65 Mo) **3D**

Transient Spectroscopy (26 Go)

Transient Thermal Tomography (16 Go) **4D**

Transient Spectral Tomography (6 To) **5D**

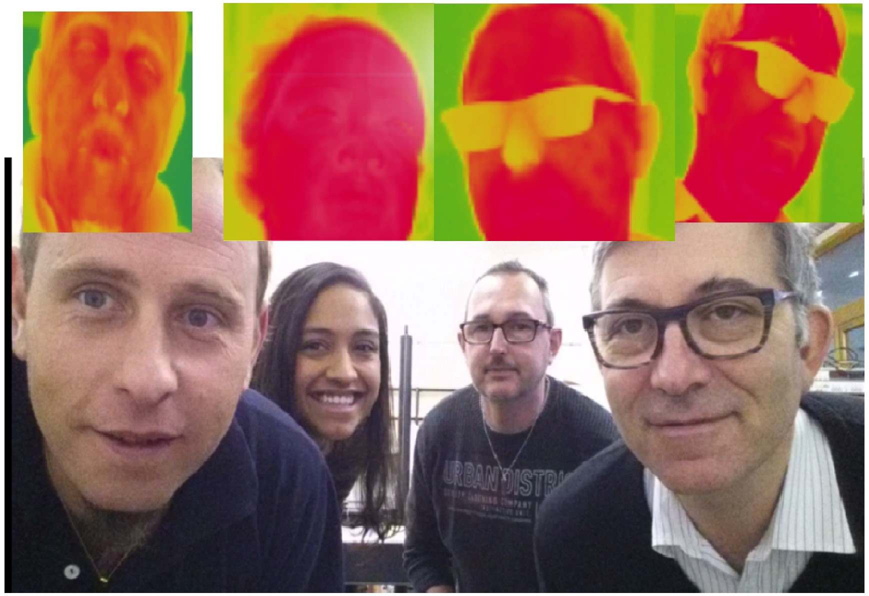




Thank you for your attention

The team

C. Pradere M. Romano A. Sommier J.C. Batsale



Pitch of our team

WEBSITE

http://cirts.weebly.com/