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From IR thermal images to heat source assessments

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CNRS Summer School

*“Identification Procedures using Full-Field Measurements
Applications in Mechanics of Materials and Structures”*

May 21th – May 25th 2013 – Montpellier (France)



From IR thermal images to heat source assessments

Part 1

Measurements of temperature fields



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What are the necessary investments?

Part 1

- 1 - Thermal sciences and heat diffusion..... 9 slides
- 2 - Thermal sensors..... 3 slides
- 3 - Quantitative Infrared thermography 3 slides

Part 2

- 4 - Theoretical framework (CM + TIP)11 slides
- 5 - Image processing and heat source assessment11 slides
- 6 - Illustrative examples 6 slides

Part 3

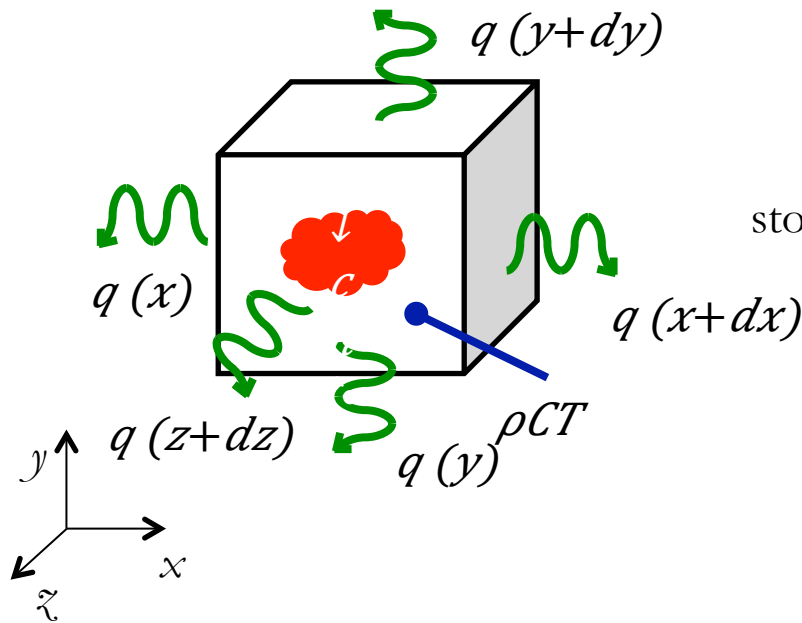
- 7 - Tutorial session

Notion of temperature

temperature T :

- intensive physical quantity objectively characterizing the subjective sensation of “coldness” or “hotness” in contact of a body
- several definitions:
 - “macroscopic”: following the 2nd principle of Thermodynamics (see IHS-1)
 - ☒ non-negative scalar such as: “ $s \geq \delta Q/T$ ”
 - “thermo-statistics”: increasing function of the kinetic energy of the system
 - ...

Heat equation



volume heat source : $w \downarrow ch \uparrow \bullet$

stored/released heat:
 $\rho C T$

exchanged heat:
 $\text{div}(q)$

hyp.: conduction follows Fourier's law

$$q = -k \text{ grad}(T)$$

\boxtimes heat diffusion equation (see IHD -1):
 $\rho C T - k \text{ grad}(T) = w \downarrow ch \uparrow \bullet$

regularizing effect of heat diffusion \boxtimes

inverse estimation of the heat sources from the temperature : **very instable !**

cf. IHS-PS1 and the (old) following example ...

Example of heat diffusion

1990, 20 years ago !!

Agema 880 camera,
digitized video signal
2 Hz

IBM 80286

Dos 4.1 , HD 60 Mo
(NETD : 200 mK)

temperatures maps :

1 « hot spot »

$$q = 3.5 \text{ } ^\circ\text{C}$$

heat sources map :

2 wires heated via Joule effect

$$\text{power} : 3 \cdot 10^{-2} \text{ W}$$

screen capture, Turbo Pascal programming

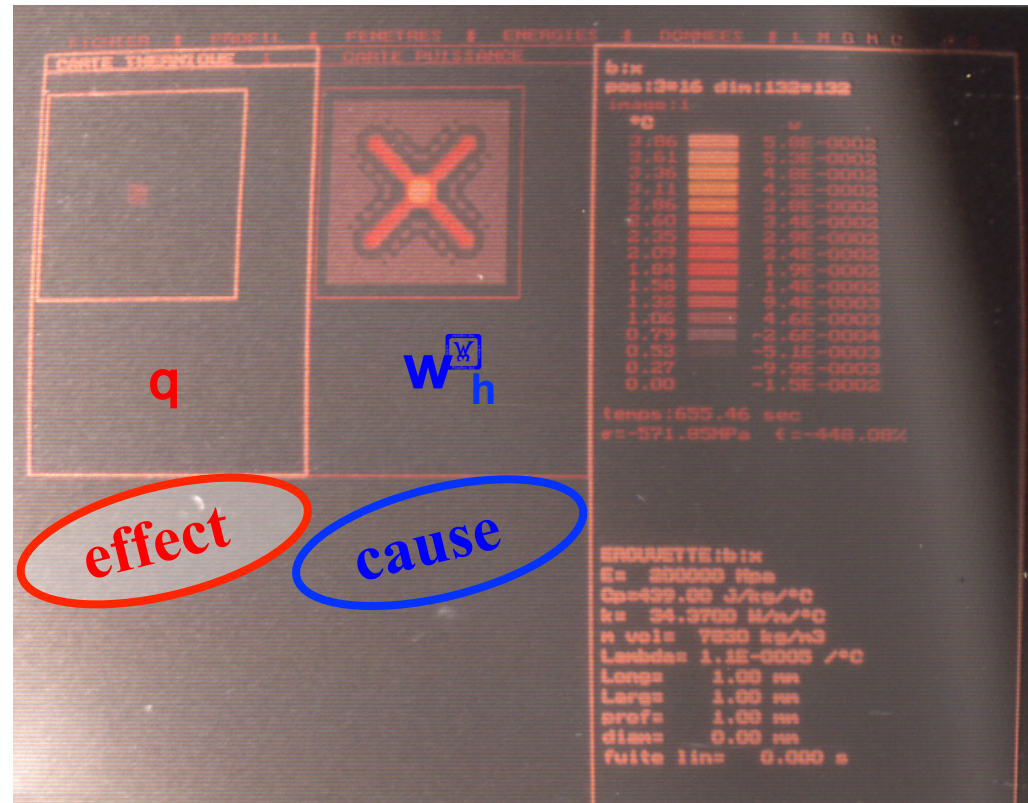
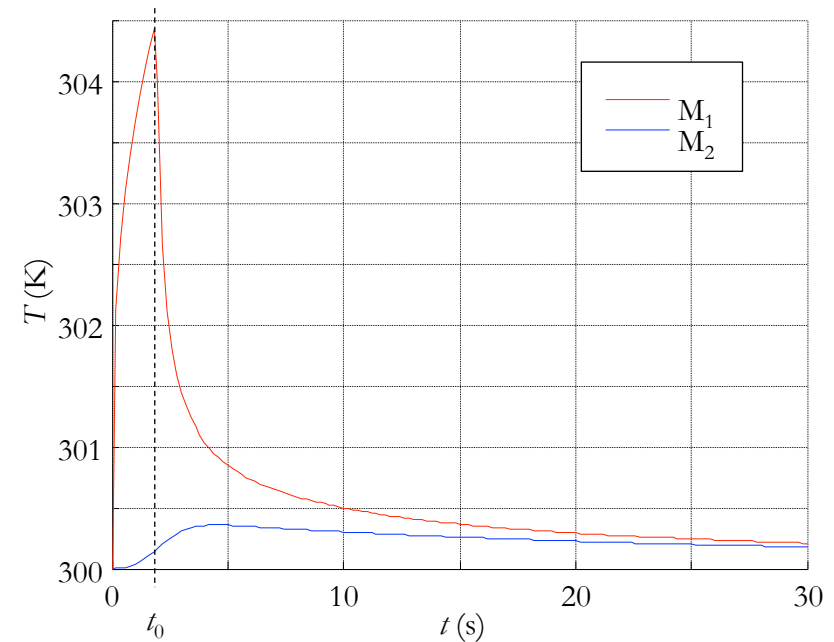
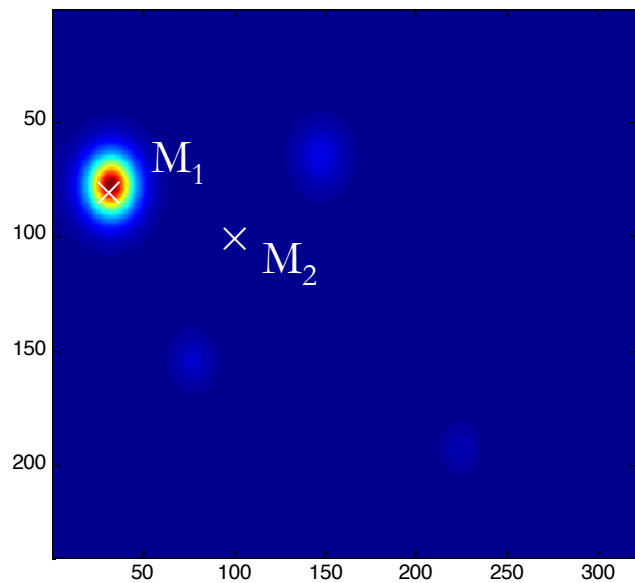


PHOTO VISION
 NOV. 1990

Example of heat diffusion

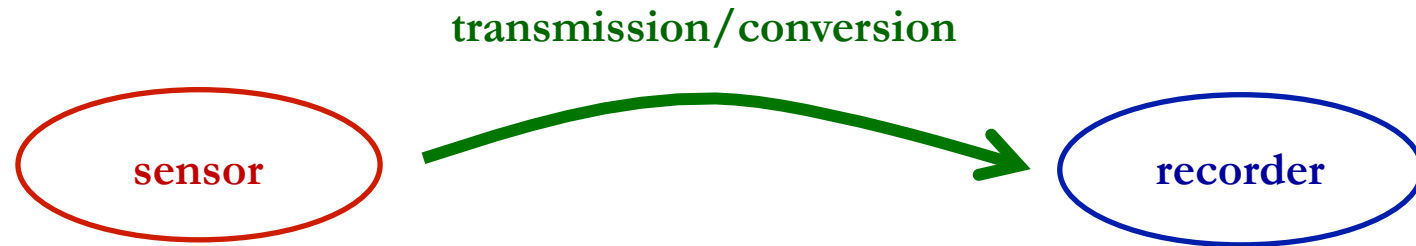
- steel plate : 4 spots :
active before t_0 , then deactivated



- temperature variations can be observed (somewhere) ...
... while no heat sources are active !
- no temperature variations can be observed ...
... while heat sources are active (somewhere else) !

Measurement of temperatures

measurement chain:



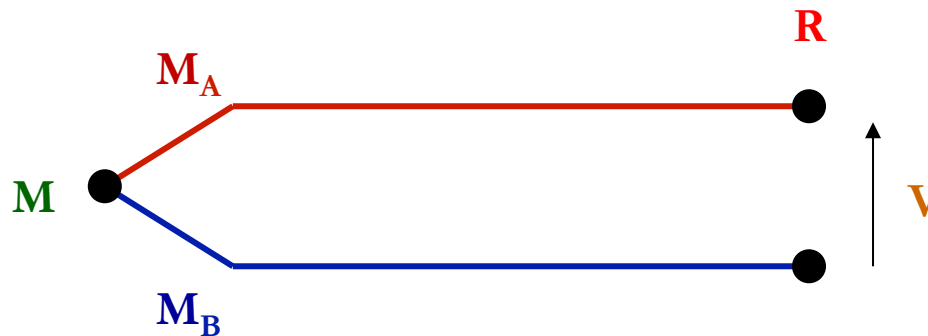
common types of sensors:

- thermo-mechanic effect: dilatation of a gas/liquid/solid
- thermo-electric effect: thermocouples
- radiation: pyrometers, bolometers, (*cf.* IR cameras)
- electric resistance: thermistances
- ...

Principle

thermocouples are made of two different metals M_A and M_B , connected by two junctions:

- a reference “cold” junction **R**
- a measuring “hot” junction **M**



 voltage difference (**V**) generation through the thermo-electric Thomson effect

Characteristics

- ≠ applications \square ≠types of thermocouples:
K, T, J, N, E, R, S, B, G, C, D
- most common thermocouples:
 - type K:** NiCr (Chromel) / NiAl (Alumel).
 - operating temperature T_{ext} \square [90K, 1000K]
 - accuracy: \square 1.5K (Class 1), \square 2.5K (for Class 2)
- necessity to protect the thermocouples:
 - \square electrical insulation/thermal protection
 - PTFE: T_{ext} \square [200K, 520K]
 - silk glass: $T_{\text{ext}} < 720\text{K}$, ...

Choice criteria

Advantages:

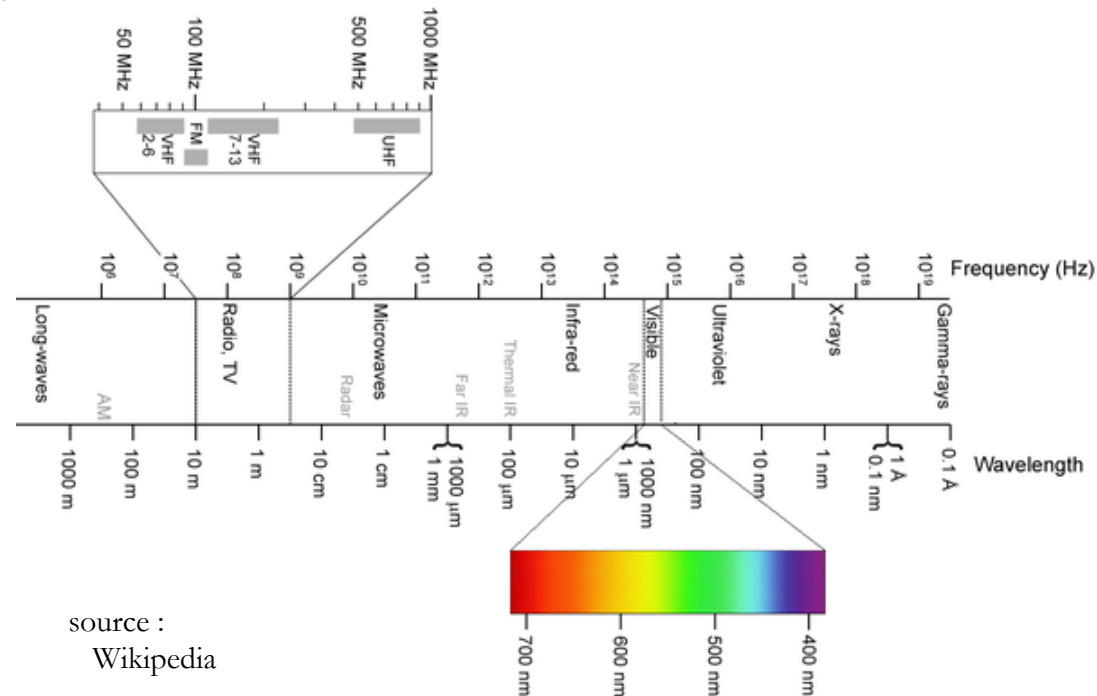
- low cost (a few € to a few hundred €).
- good accuracy: $\pm 1.5\text{K}$ (Class 1), $\pm 2.5\text{K}$ (Class 2)
- good response time (depending on the thermocouple τ):
time constant $t_{63\%}$ τ [0.05 s, 5s], even 0.007s (τ τ 0.25mm)
- wide range of temperature (depending on the type)

Drawbacks:

- contact measurement
- punctual measurement τ fields?
... collections of sensors !

Electromagnetic radiations

any body at a temperature $> 0 \text{ K}$ emits a thermal radiation

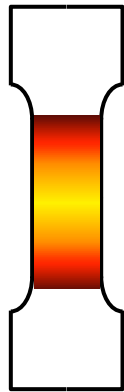


- the infrared radiation occupies only one part of the thermal radiation spectrum (IR-visible-UV : cooler \boxed{W} warmer)
- the spectral band covered by the infra-red thermography is narrower: $[2\mu\text{m}, 15 \mu\text{m}]$

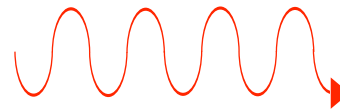
Principles of IR radiometry

Motives : surface temperature measurements
 (... for heat sources identification, see IHS-1)

radiating target



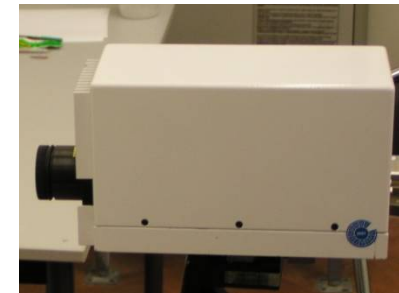
atmosphere



I.R. radiation

IR detector

(single, linear, matrix sensor)



$D_1=3-5 \mu\text{m}$, $4-8 \mu\text{m}$, $8-12 \mu\text{m}$, ...

Medium : pyrometer, IR focal plane array camera

detector : produces an electrical signal (V) related to the radiated power (W)

exitance : overall flux emitted by the target per unit surface ($\text{W}\cdot\text{m}^{-2}$)

... for a given bandwidth

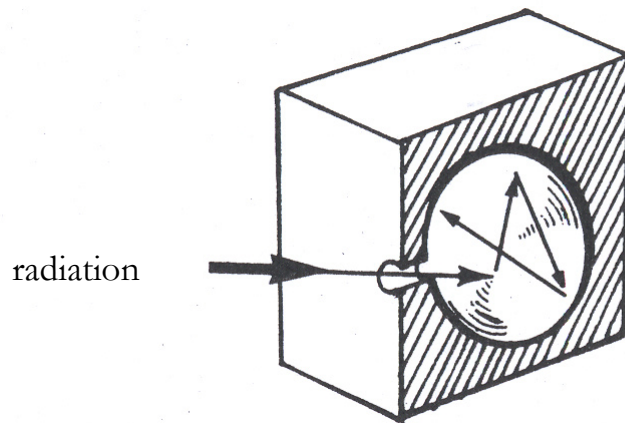
$$R = \int_{\Delta\lambda} \frac{\partial R(\lambda, T)}{\partial \lambda} d\lambda$$

spectral exitance
varies with T !

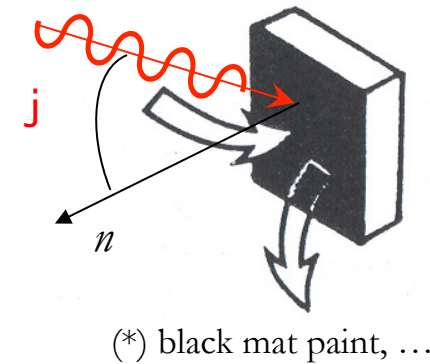
A simple common situation ...

- **target = « black body »** : able to absorb every incident radiation, $\tau_j = 1$, $\tau = 1$, $\tau = 1$,
(*i.e.* no reflexion, no transmission: see slide 14)

almost totally
closed cavity



« perfectly » absorbing
coating (*)



[G. Gausorgues, Infrared Thermography, 94]

- **atmosphere = small distance, dry air** (transparent to IR radiations)
 - $\tau = 1$ perfect transmission
(*i.e.* every radiation emitted by the target is received on the detector)

Radiation laws

for a black body ...

- Planck's law

$$\frac{\partial R_{cn}(\lambda, T)}{\partial \lambda} = \frac{2\pi hc^2 \lambda^{-5}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

R : exitance, $W.m^{-2}$

h : Planck, $6,66.10^{34}$ J.s

k : Boltzmann, $1,38.10^{23}$ J.K⁻¹

c : light celerity, 3.10^8 m.s⁻¹

T : temperature, K

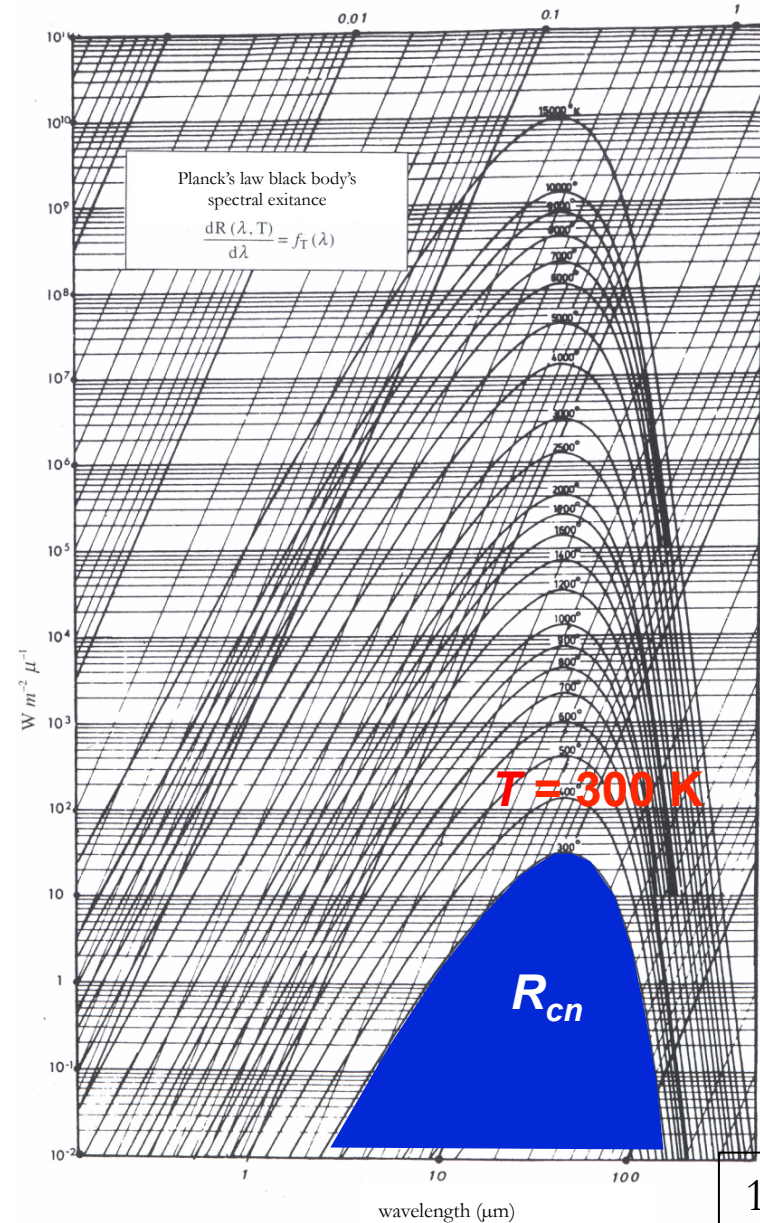
- Stefan-Boltzmann's law

$$R_{cn} = \sigma_s T^4$$

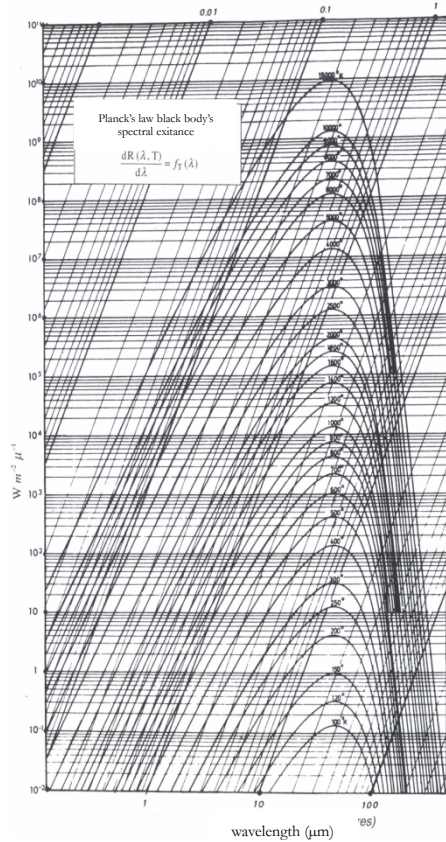
σ_s : Stephan's constant

$$\sigma_s = \frac{2\pi^5 k^4}{15c^2 h^3} = 5,67 10^{-8} W.m^{-2}.K^{-4}$$

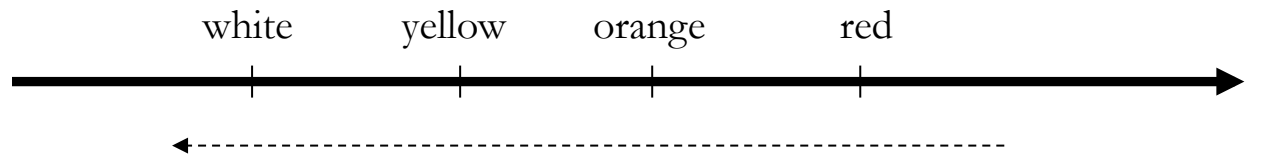
[G. Gaussorgues]



Remarks on Planck's law

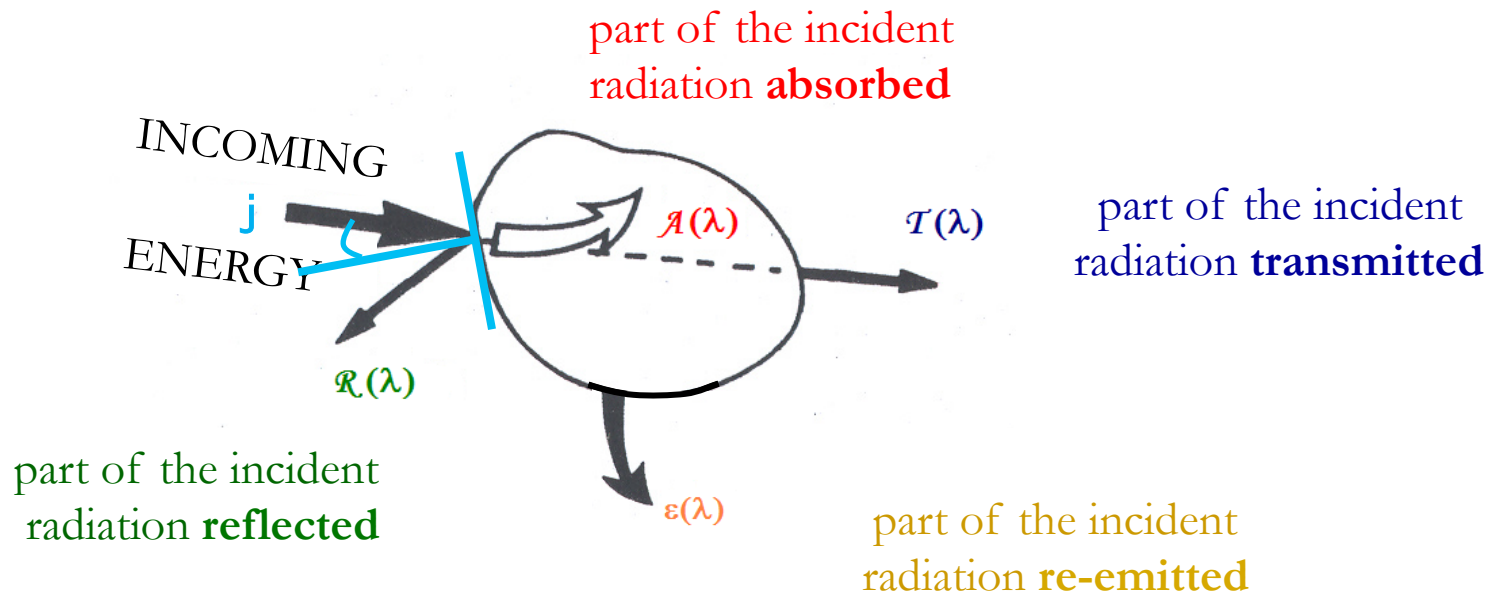


- the emission spectrum of a black body is continuous
- if $T < 2300\text{K}$, the totality of emitted energy is in the infrared spectrum
- at fixed λ , the exitance increases if T increases
- when T increases the maximum of energy moves to the weak wavelength (*cf.* Wien's law)
 this displacement explains the change of color during the heating of a body.



displacement of $\max(R)$ when T increases

Target and environment



\mathcal{A} , \mathcal{R} and \mathcal{T} depend on l , but also on j , T , surface roughness, ...

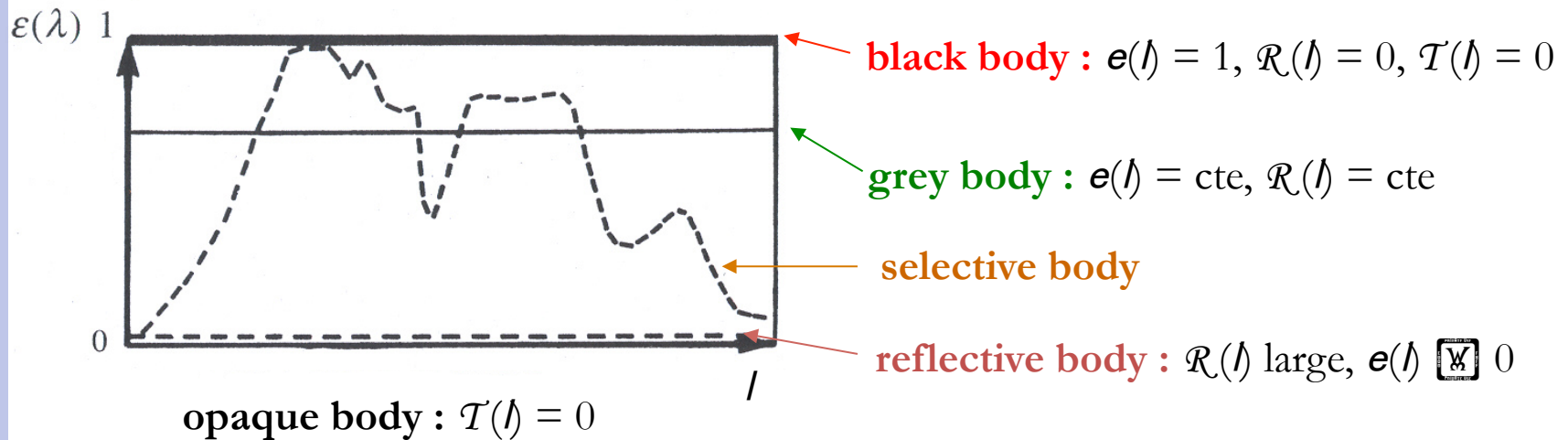
- energy conservation:

$$\mathcal{A}(l) + \mathcal{R}(l) + \mathcal{T}(l) = 1$$

- « thermal » equilibrium:

$$\mathcal{A}(l) = \epsilon(l) \rightarrow \text{emissivity}$$

Classification of several bodies



(reflection and absorption are surface phenomena
occur within a limited, less than $1\mu\text{m}$, depth under the surface)

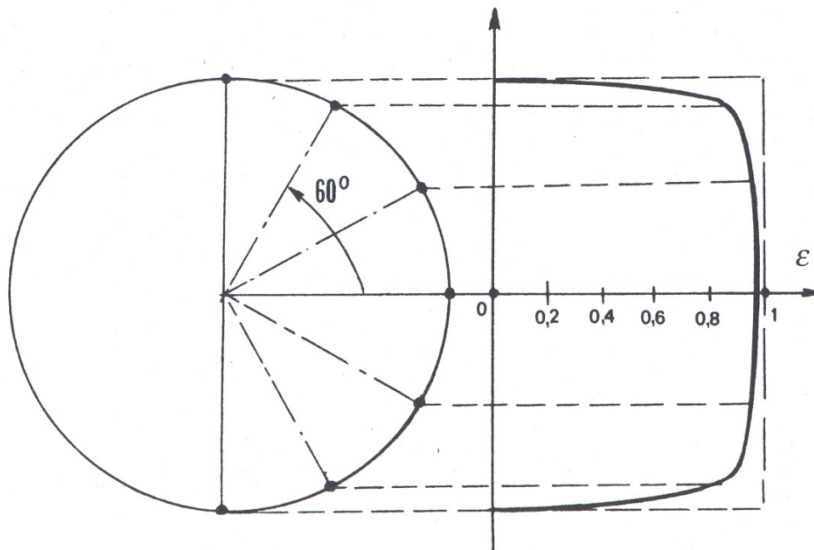
N.B.:

- no other surface can emit more energy than a blackbody, for given (T, λ)
- the emission of a blackbody is isotropic

$$\frac{\partial R}{\partial \lambda}(\lambda, \varphi, T) = \epsilon(\lambda, \varphi) \frac{\partial R_{cn}}{\partial \lambda}(\lambda, T)$$

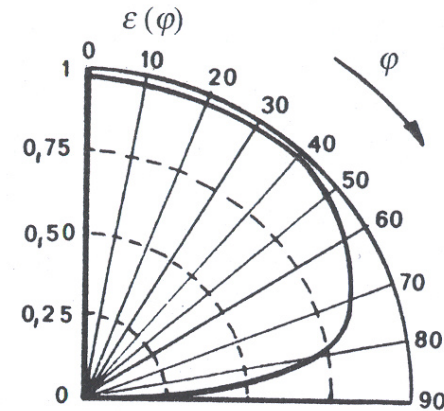
$$R_{\Delta\lambda}(T, \varphi) = \int_{\Delta\lambda} \epsilon(\lambda, \varphi) \frac{\partial R_{cn}}{\partial \lambda}(\lambda, T) d\lambda$$

Radiations' incidence angle



dielectric sphere
emissivity

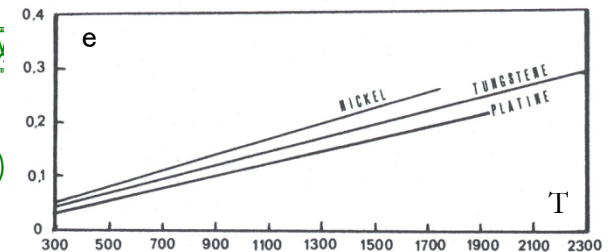
e : emissivity



j : observation angle

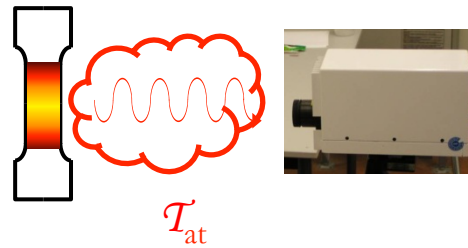
water emissivity for $l=10 \mu\text{m}$

- up to $j = 45-50$ degrees, lambertian bodies ... ☒☒/☒☒ ☒
- small risks : flat samples ☒ optical axis of the camera
- + grey body with a large emissivity (paint, ...)
- + small temperature variations



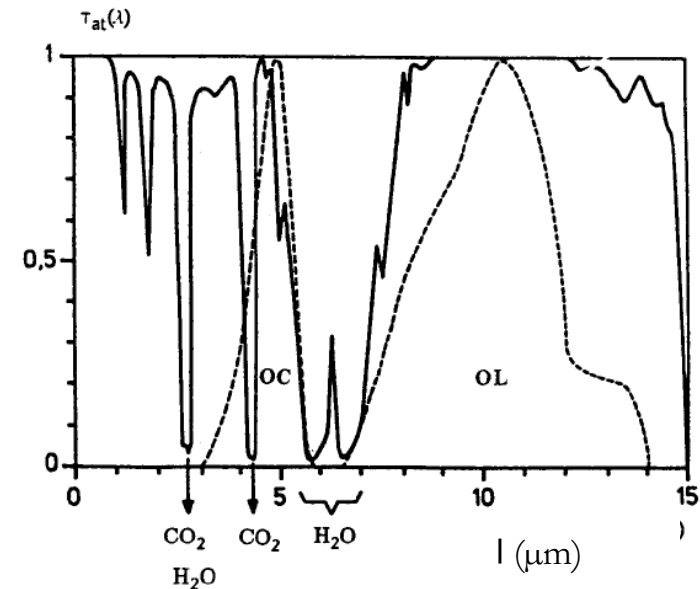
$$R_{\Delta\lambda}(T) \approx \varepsilon R_{cn_{\Delta\lambda}}(T)$$

Atmospheric transmittance (I)



\mathcal{T}_{at} : atmospheric transmittance
for the standard atmosphere
(thickness of 30 m)

(source: Pajani D. ADD Ed.)

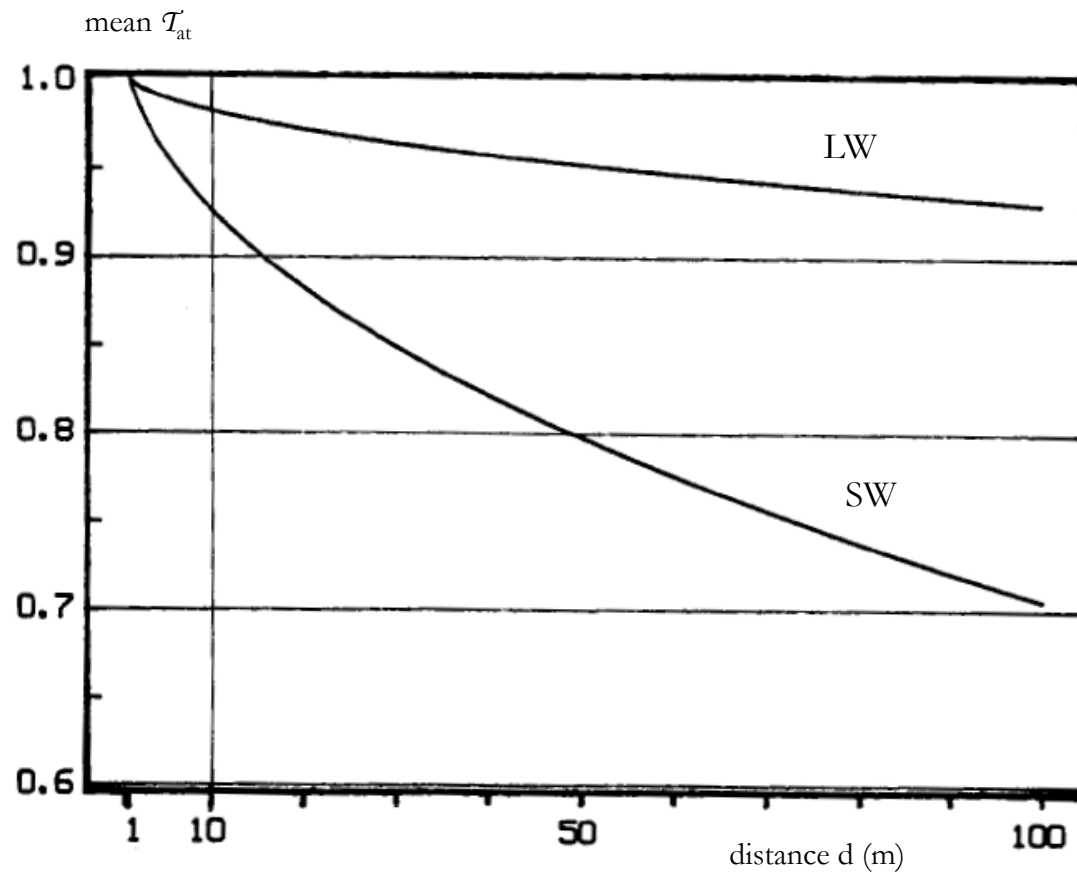


- ☒ **forbidden wavelength bands** (in μm):
 - [2.5,2.8] **absorption** of radiation by **CO₂** and **H₂O**
 - [4.2,4.4] **absorption** of radiation by **CO₂**
 - [5.5,7.3] **absorption** of radiation by **H₂O**

- ☒ **two common bands** used for infrared detectors:
 - SW:** Short Wave [3 μm , 5 μm]
 - LW:** Long Wave [8 μm , 12 μm]

Atmospheric transmittance (II)

Atmospheric transmittance for the standard atmosphere (30 ppm of CO₂ and 50% of humidity)
(source: Pajani D. ADD Ed.)



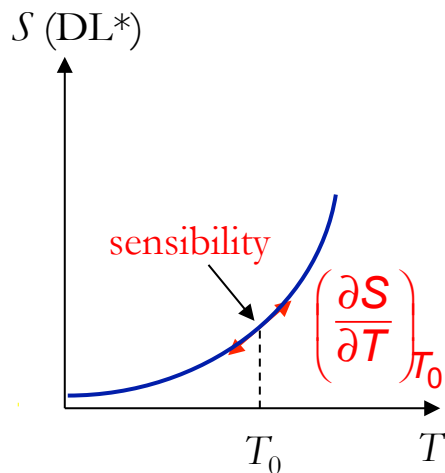
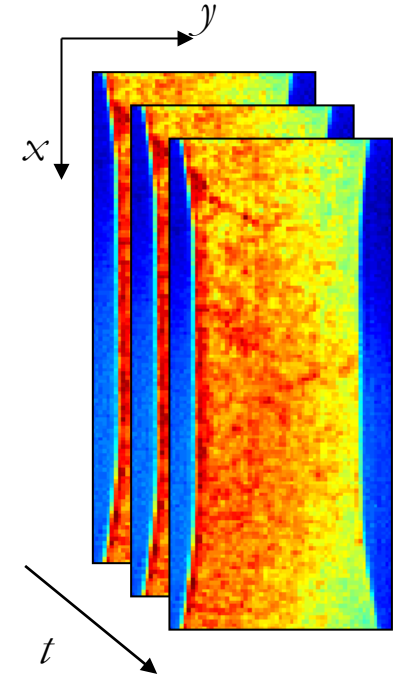
Measurement by IR radiometry

- advantages:
 - no contact
 - response time ($\approx 1 \mu\text{s}$)
 - temperature fields (lines, arrays) at each recorded time
 - good accuracy: $\approx 2\text{K}$ or 2%
 - good spatial resolution ($\approx 10 \mu\text{m}$)
- drawbacks:
 - cost: from 5k€ to 100k€ ...
 - calibration
- many products with many technologies:
 - thermo-detectors: bolometers, ...
 - photo-detectors: semi-conductors (In-Sb, ...)
- difference between **imagery** and **measure**

IR camera description



- image : 320 \times 240 pixels
- coding : 14 bits
- frame rate : 250 im./s
- spatial resolution : « \pm » 100 μm /pix.
- NETD : 20 mK at room temp.



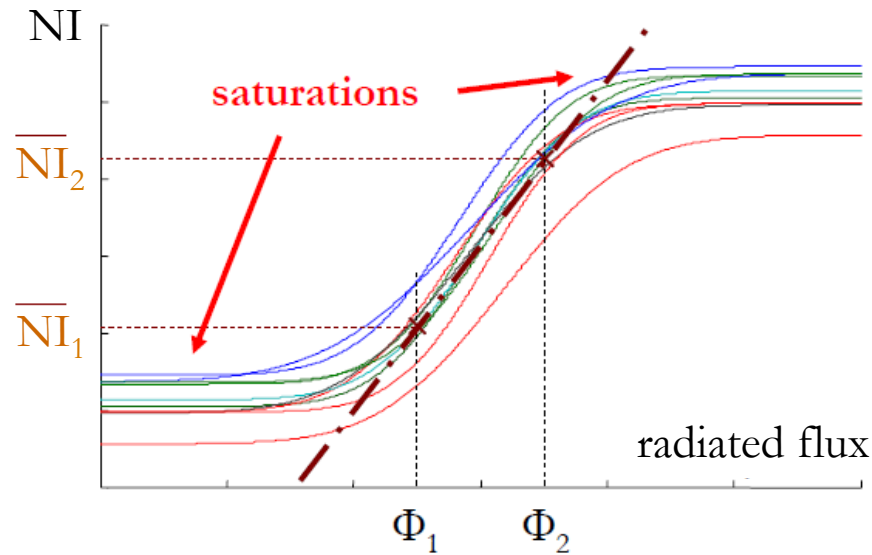
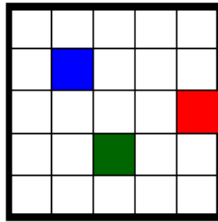
(*) DL: digital level

NETD : (noise equivalent temperature difference)
 temperature difference equivalent to the noise root mean square
 value measured on the thermo-signal

$$\text{NETD}(T_0) = \frac{\text{std}(S)}{\left(\frac{\partial S}{\partial T}\right)_{T_0}}$$

IR camera calibration (I) : NUC

manufacturer procedure



- 2 uniform thermal scenes (F_1 and F_2)
white paper sheet (F_1) + hand (F_2) ...
- DF 5 50 % of the sensors' range (linear part)
- NUC and BPR operations

- determination of **one set** of calibration parameters (a_k):

$$T = \sum_{k=0}^{\infty} \frac{1}{k!} \frac{d^k}{dL^k} a_k DL$$

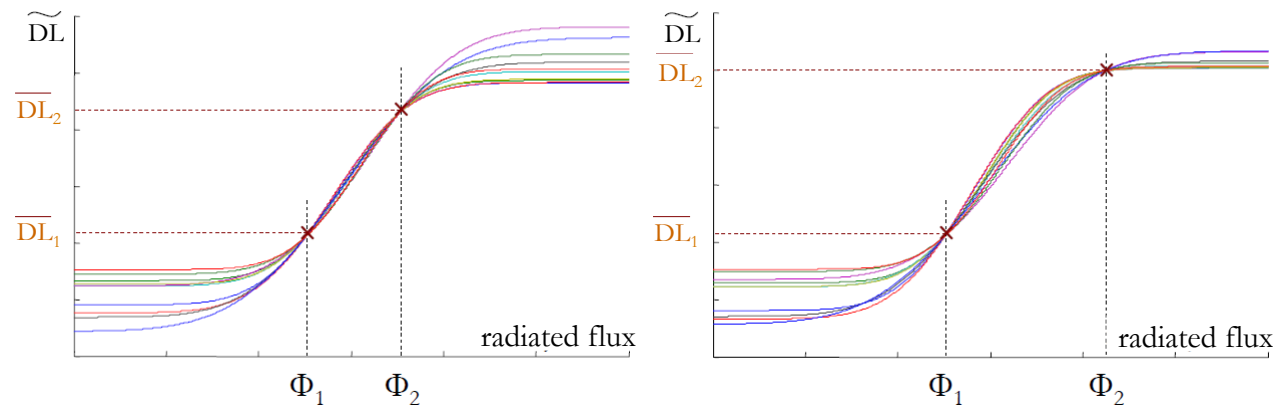
principle of NUC :

find the gains (a_{ij}) and the offset (b_{ij}) of each pixel in order to bring the linear part of the responses on the same curve :

$$\widetilde{DL} = \alpha_{ij} DL + \beta_{ij}$$

IR camera calibration (II) : NUC

limits of the NUC

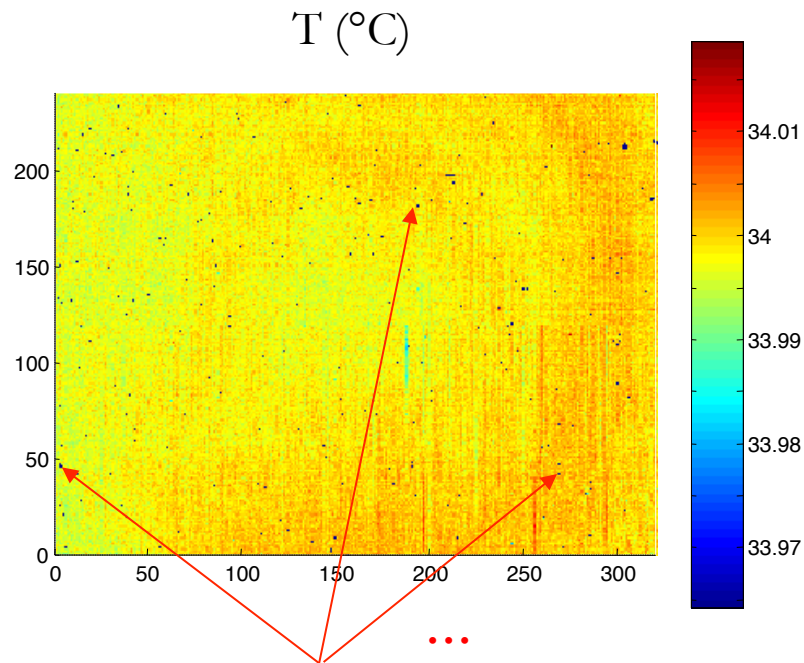


- hypothesis of the linear response of the sensor
- non intrinsic definition of (a_{ij}) and (b_{ij})

IR camera calibration (III) : BPR

principle of BPR :

- (i) detection of « dead » or « abnormal » pixels
- (ii) possible replacement of the « defective » pixels temperature

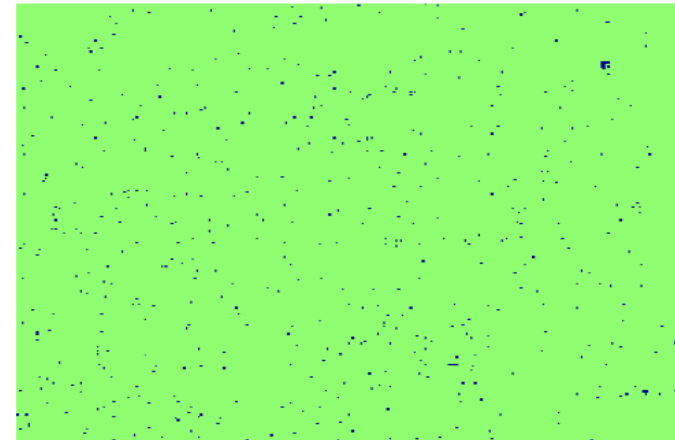


pixels whose response is
« very » different from the others

 **defective pixels**

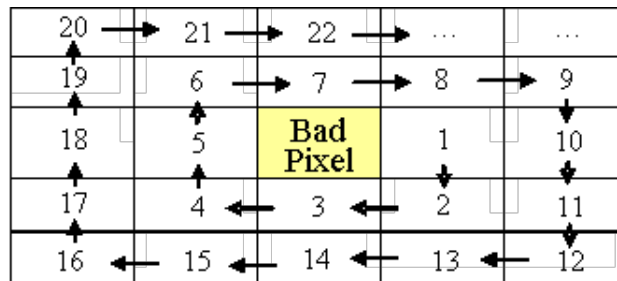
(i) search algorithm (3 criteria) :

- in « gain » :
 $(i,j) : |\alpha_{ij} - 1| > a$
- in « offset » :
 $(i,j) : |\beta_{ij}| > b \cdot 2^{\uparrow dyn}$
- in « noise » :
 $(i,j) : \text{rms}(T_{ij}) > T_{ij} + c \cdot \text{std}(T_{ij})$




IR camera calibration (IV) : BPR

(ii) different replacement algorithms



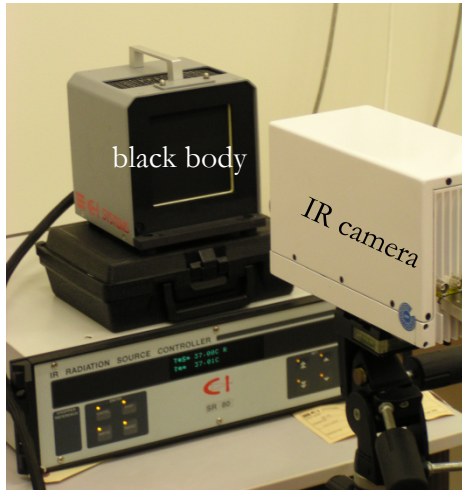
21	13	9	14	22
20	5	1	6	15
12	4	0	2	10
19	8	3	7	16
24	18	11	17	23

drawbacks of the BPR :

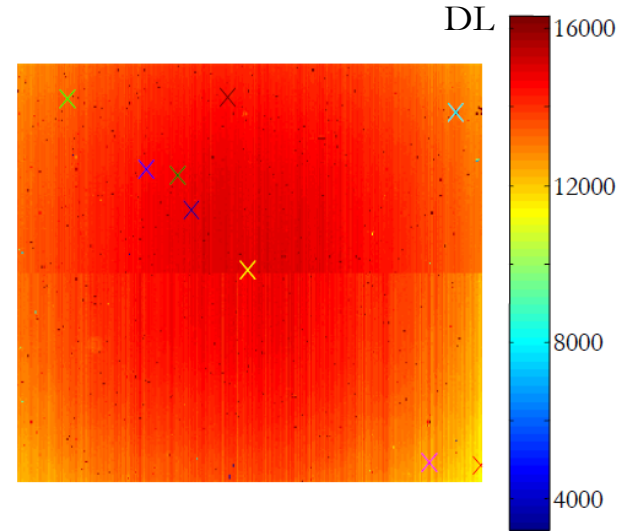
- introduction of **correlations** between neighboring pixels
-  errors in the estimation of gradients
- « **clusters** »

IR camera calibration (V)

laboratory procedure :
pixel by pixel calibration

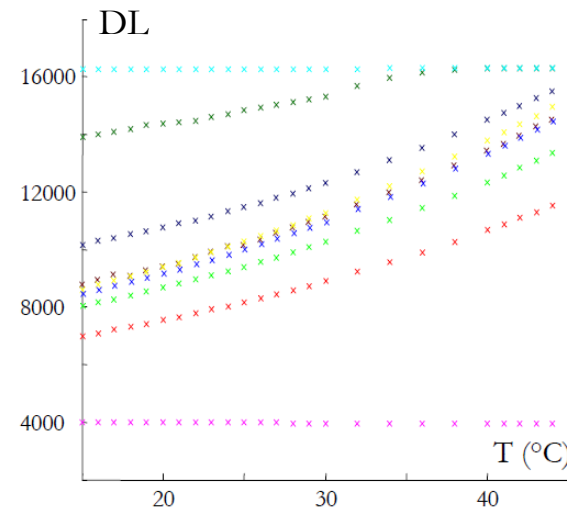


« **dead** » pixels
« **abnormal** » pixels
« **saturated** » pixels

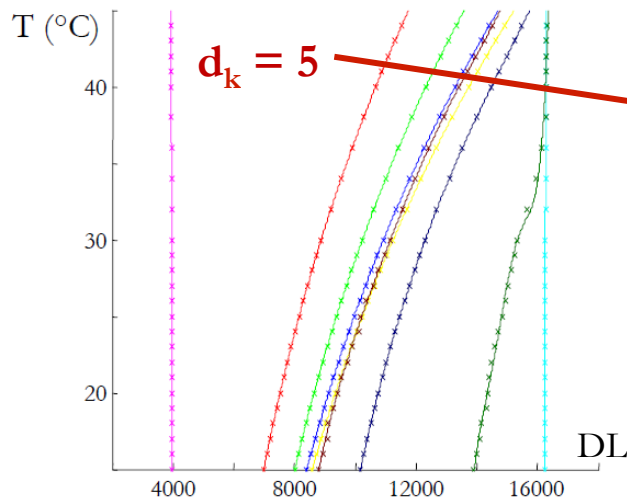


extended plane **black body** :

- $\epsilon(\lambda) \approx 0.98$
- $T(x,y) = T_0$ ($\pm 0.02^\circ\text{C}$ uniformity
 0.008°C precision)



IR camera calibration (VI)



calibration relation :

$$T_{ij} = \sum_{k=0}^{d_k} d_{lk} \cdot a_{lijk} \cdot DL_{ij}^k$$

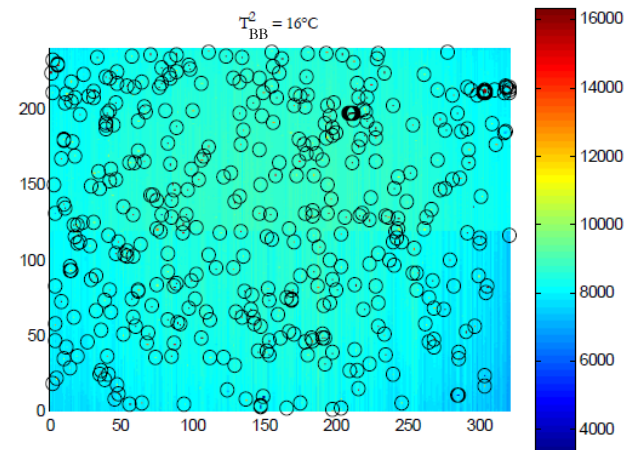
$\sum_{k=0}^{d_k} (d_k + 1) \cdot n_i \cdot n_j$ coefficients

$\sum_{k=0}^{d_k} 1\,600\,000$ for a (320×240) image

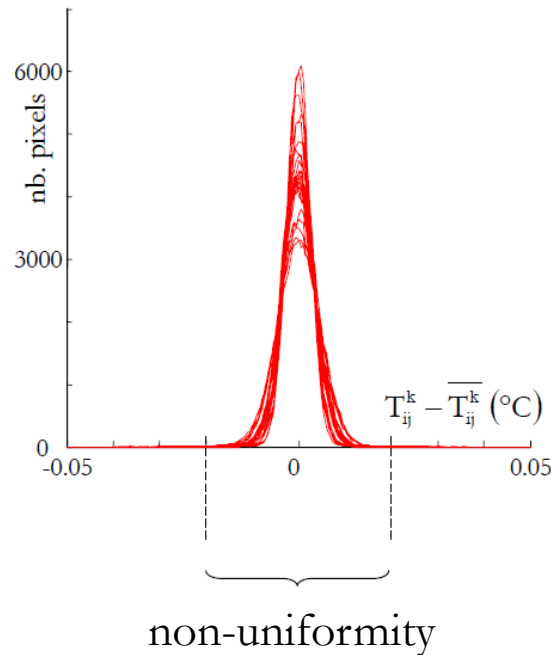
« defective » pixels determination :

$$(i,j) : \exists k, |T_{ij}^k - T_{BB}^k| > \epsilon_{dead} \quad 0.04 \text{ } ^\circ\text{C}$$

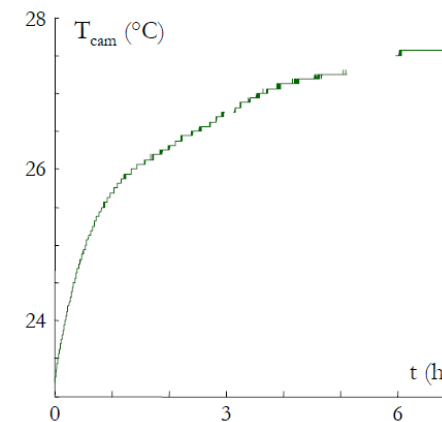
- 539 « bad » pixels $\sum_{k=0}^{d_k} 0.07\%$
- $\sum_{k=0}^{d_k}$ homogeneous distribution
- a few « clusters »



IR camera calibration (VII)



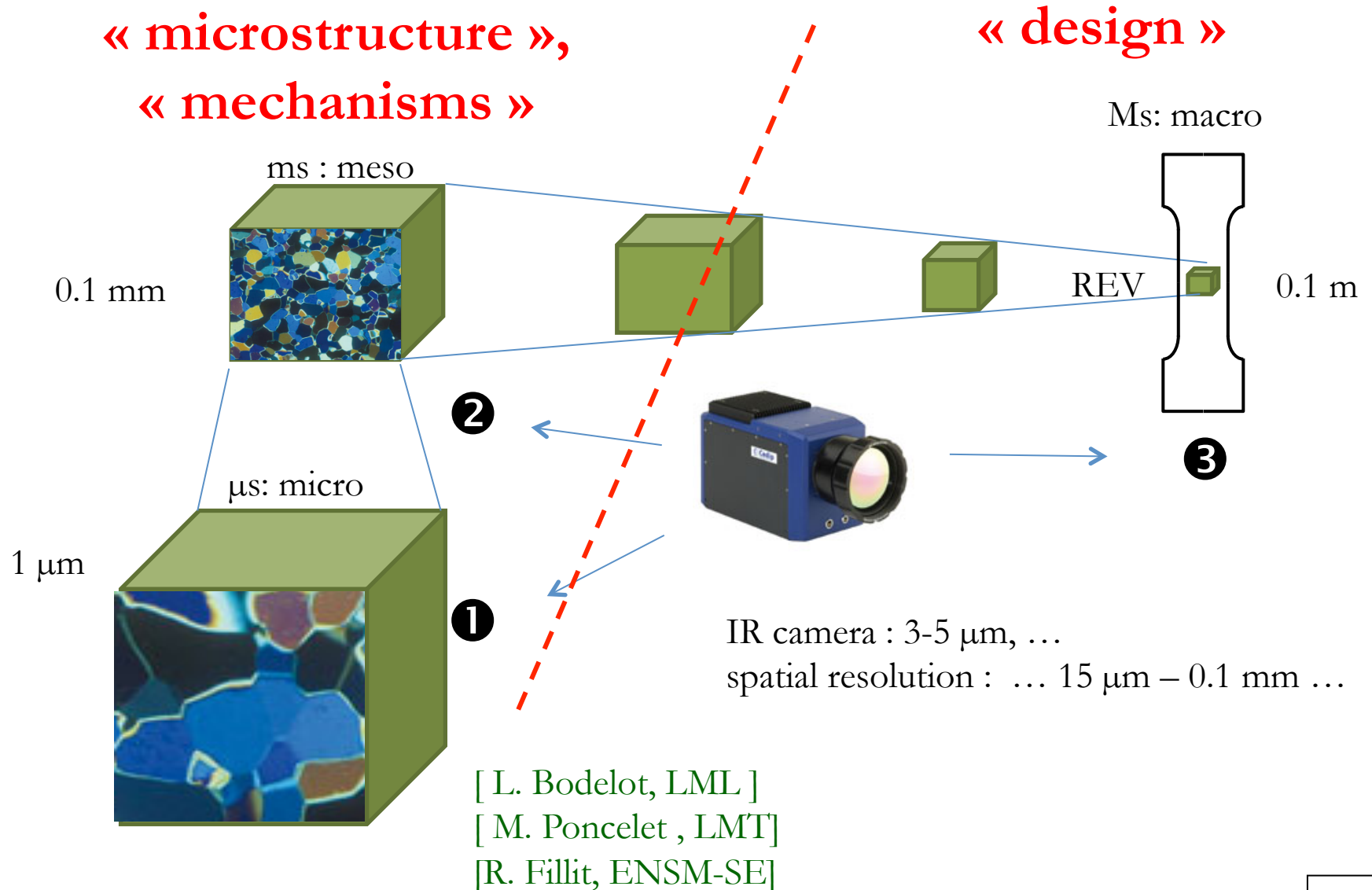
- **precision** of the black body
- **non-uniformity** $< 0.02^\circ\text{C}$



limits of the « laboratory » procedure :

- requires 1 extended **black body** (30 k€)
- **thermal stability** of the camera in its environment (4-5 h)
- 1 calibration per **shooting condition** (integration time, image size, lens, focus, ...)

Scales in Infrared Thermography



Temperature fields for IHS

- « dense » temperature fields on the boundaries
 - multiple punctual sensors (thermocouples, optical fibres pyrometers, ...)
 - IR cameras
- high temporal resolution:
 - ultra-fast imaging devices (1 MHz frame rate, scanning devices)
- emissivity determination:
 - multi-spectral thermography, ...
- multiple physics:
 - simultaneous knowledge of other state variables (strain, phase proportion, ...)
- IR tomography?
 - identification of heat sources: see IHS-1