ECOLE DES MINES D'ALBI
CARMAUX

PROJETO DE COOPERAÇÃO SUL-AMERICANA EM IDENTIFICAÇÃO DE PROPRIEDADES FÍSICAS EM TRANSFERÊNCIA DE CALOR E MASSA
Programa CNPq/PROSUL

MINI-CURSO
IDENTIFICAÇÃO DE PROPRIEDADES FÍSICAS

Infrared thermography for thermal characterization

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ECOLE DES MINES D'ALBI
C A R M A U X

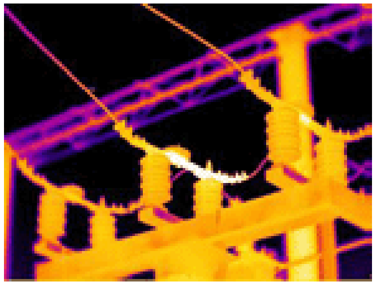
RAPSODEE UMR 2392 CNRS
=
Chemical Engineering Laboratory
for Finely Divided Solids,
Energy & Environment

- South West of France
- Ministère de l'Economie, des Finances, et de l'Industrie
- Civil Engineers *(Major in Chemical Engineering)*

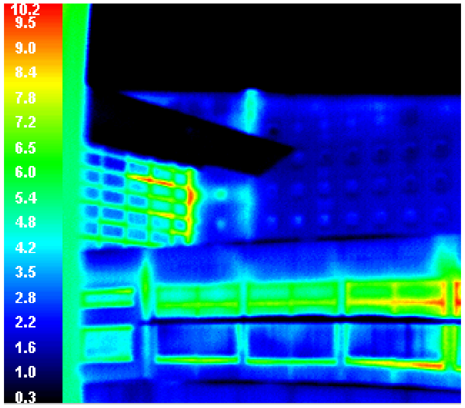
IR Imaging Systems : a widespread technic !!!

Multispectral imagery

Aircraft signature

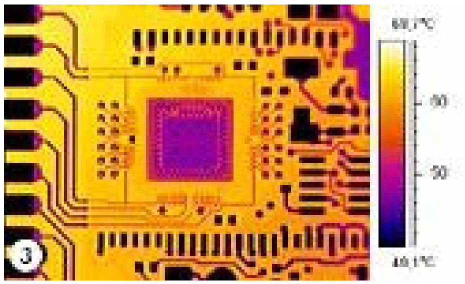


Electrical control

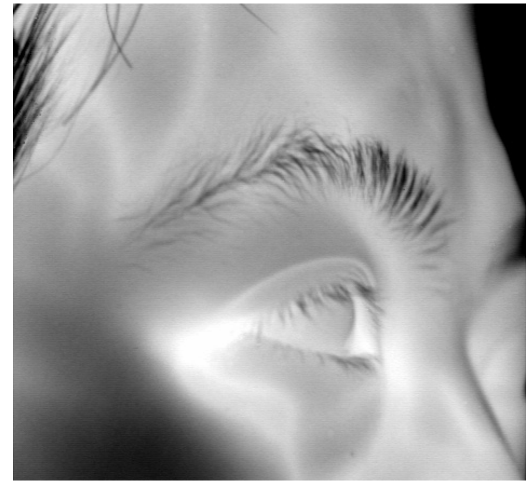


Building inspection

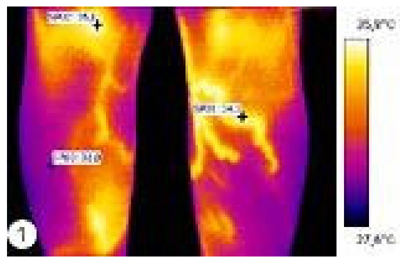
Security control



Microcomponent analysis

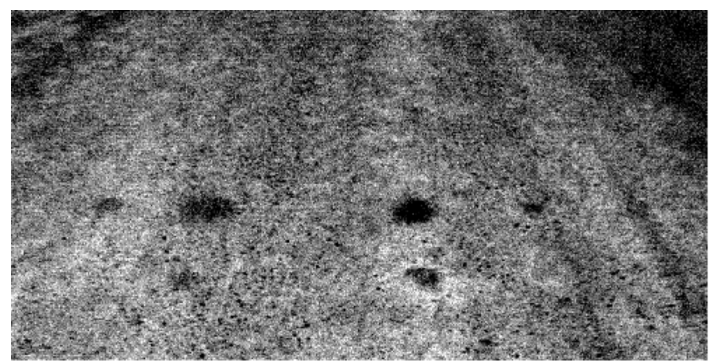


Skin & Fever



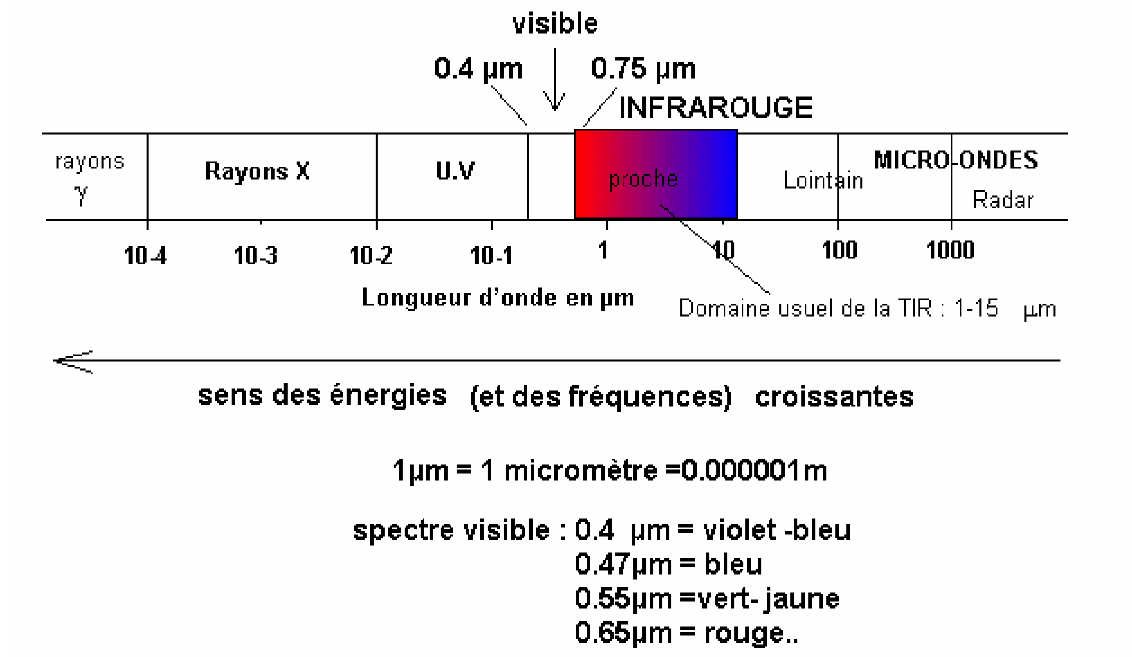
Vascular

Art restoration

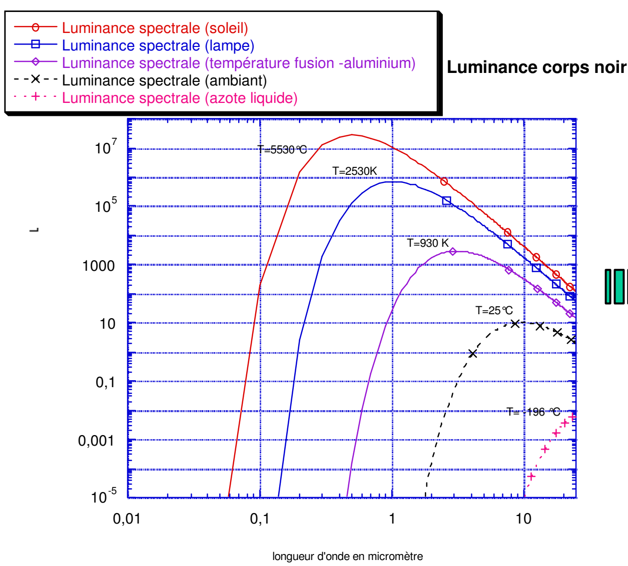


Underground Landmines Detection from Thermal Imaging

Thermal Radiation



Black body spectral radiance

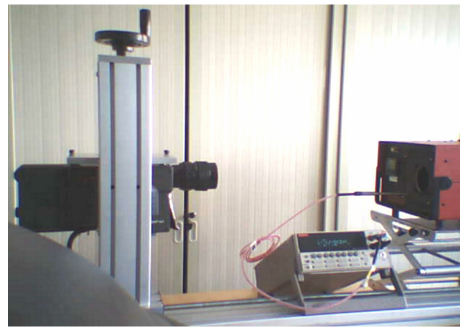


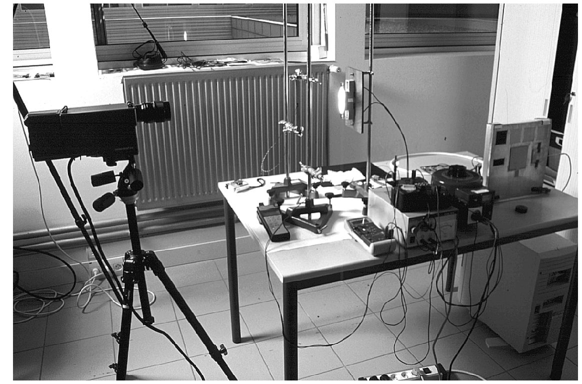
Infrared thermography : usually 1 – 15 µm

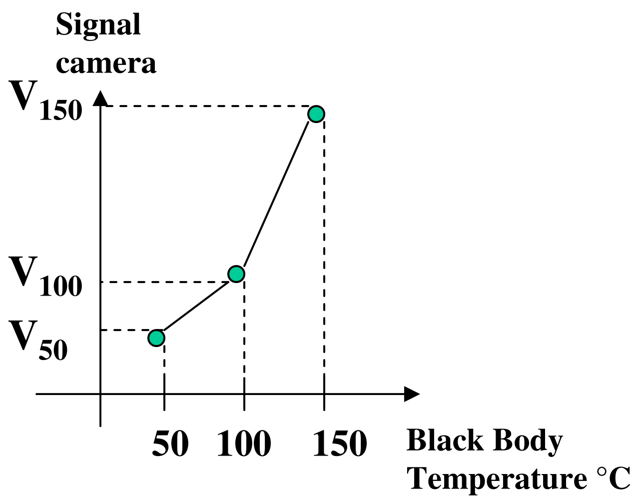
Energy ➔ Signal / Noise

Sensitivity ➔ Resolution

Calibration : Black body





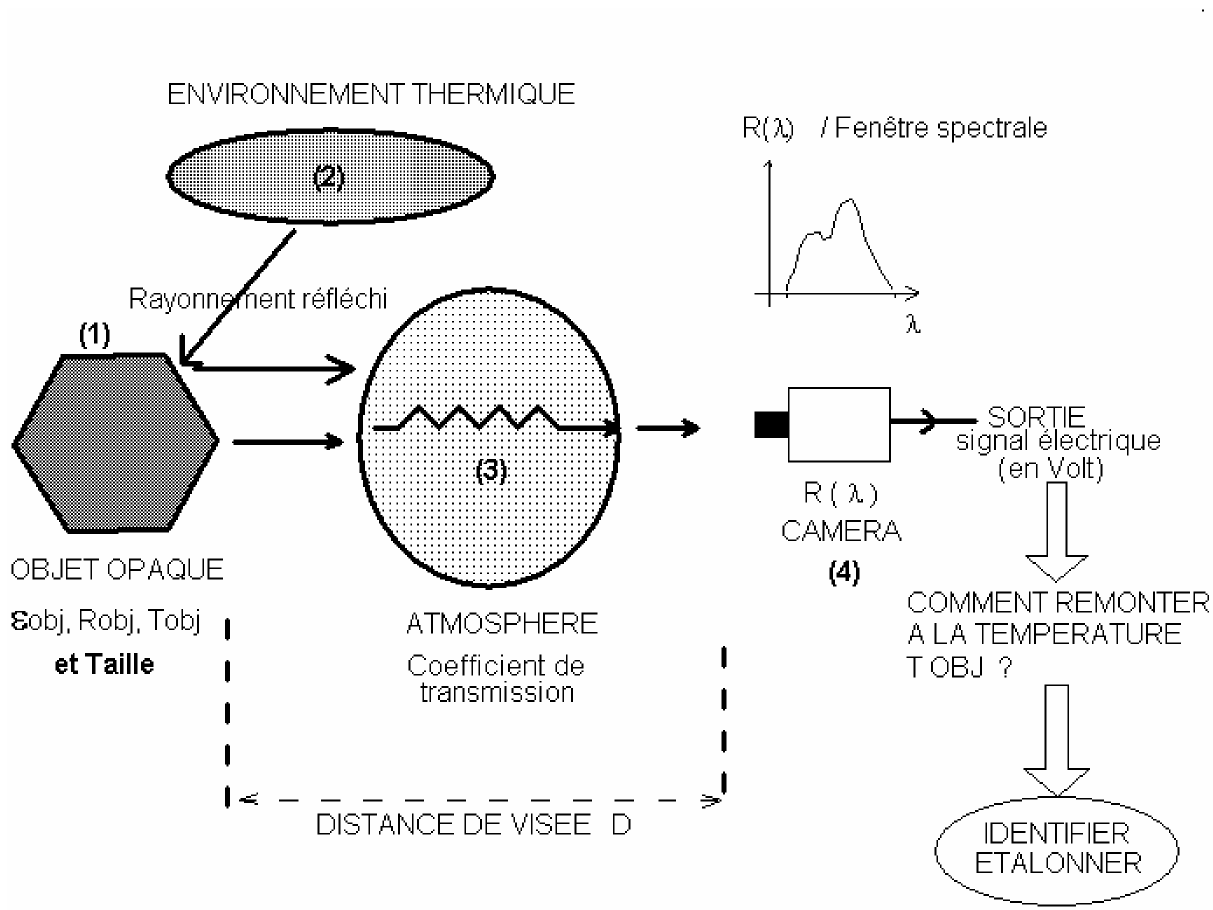


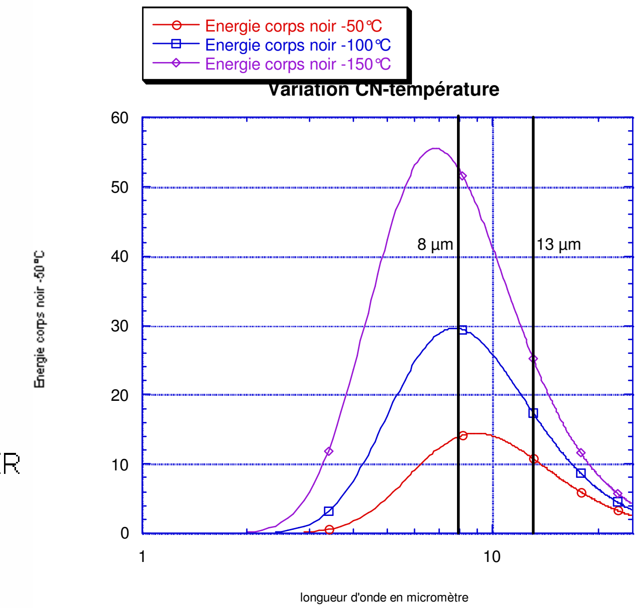
After calibration, the optical properties are necessary in order to measure the surface temperature of the sample :

Emissivity

$$\boxed{\varepsilon = \frac{E_{objet}(T)}{E_{Corps\ noir}(T)}}$$

Infrared measurement : typical situation





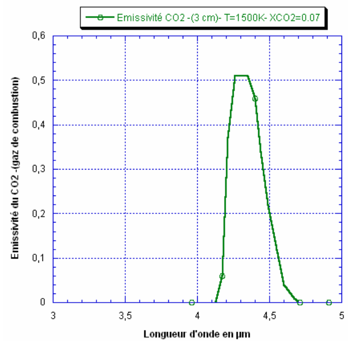
Atmospheric transmission

3-5 µm **8 - 12 µm** ← Outdoor measurments

Spectral Range of measurements

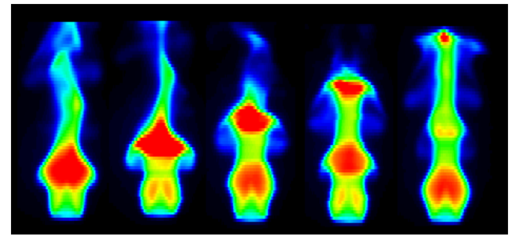
Combustion

Methane - Air



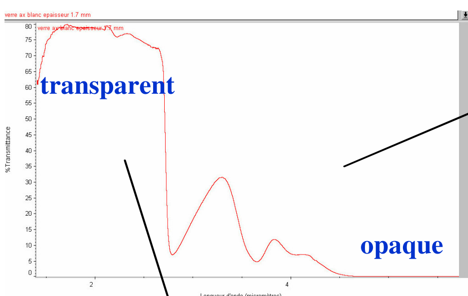
CO_2 spectral emissivity

3-5 µm



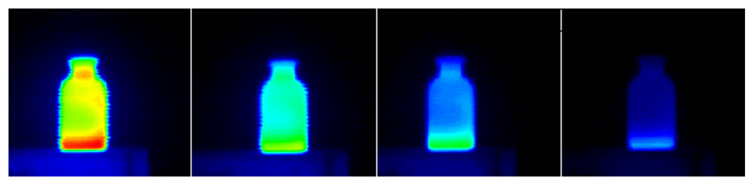
Flame instability

Glass bottle process

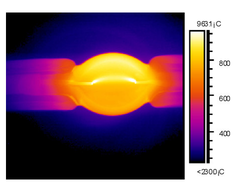


« Spectre » de transmission IR du verre

8 - 12 µm



Bottle Cooling / Surface Temperature



Infrared thermography

Qualitative

Quantitative — *Absolute temperature measurements*

Relative temperature evolution

Passive thermography

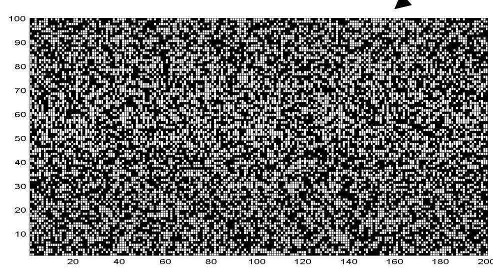
Active thermography testing

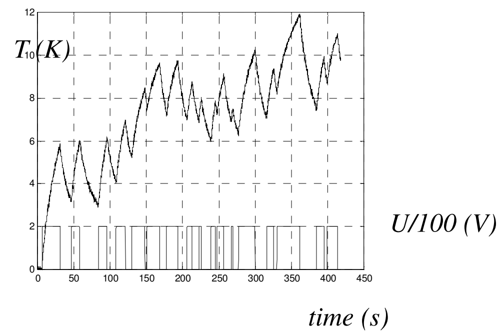
Pulsed Thermography → **Flash methods**

Step heating Thermography → **Coating thickness**

Lock-in Thermography → Periodic

Random Heating





Detector main characteristics

Responsivity

$$R(x, y, \lambda, f) = \frac{\partial V}{\partial F} \qquad V.W^{-1}$$

incident optical flow

Noise Equivalent Temperature Difference (NETD)

Change of temperature

Black Body

IR Camera

Change of Signal-to-noise ratio = 1

Thermal sensitivity depends strongly on Temperature !!!

T

^

Detector main characteristics

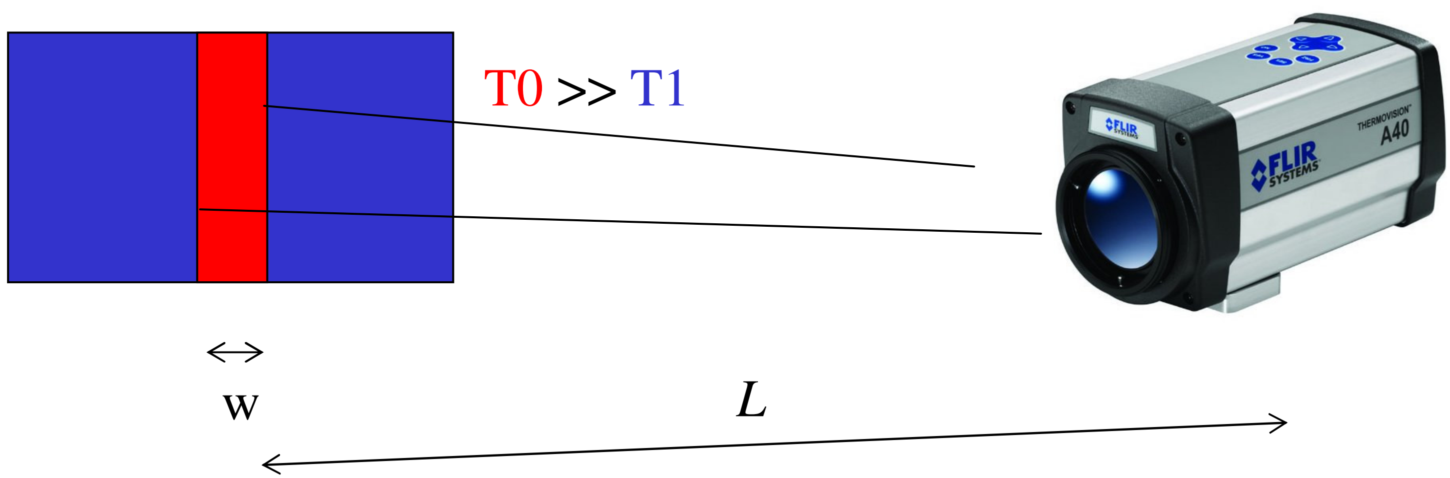
Spatial resolution

Line spread function (LSF)

*Recorded image = LSF * original image*

Slit response function(SRF)

$m = \max(R(w)/\max(R(w \rightarrow))$ as a function of w/L



Detector main characteristics

Example SRF

IR Camera with

12° Aperture lens
105 px / line
L = 1000 mm

Field of view 210x210 mm

Spatial resolution at m %

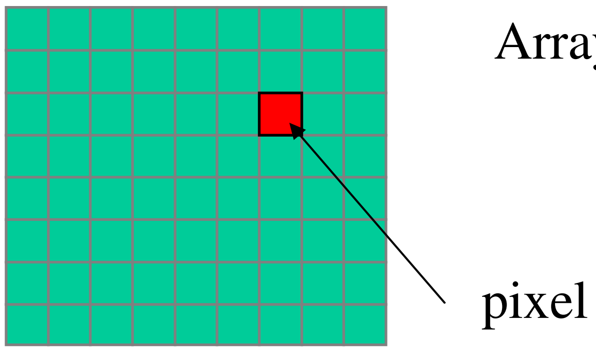
If SRF curve gives 6 mrad at m = 100 % ⇒ **6 mm**

If you want m = 50 % and SRF→ 2 mrad ⇒ **2 mm**

Apparent resolution = 210 mm / 105 px → 2 mm / px

Detector main characteristics

Focal Plane Array : matrix of sensors



Array of detectors

Commonly : 320 x 256 30 x 30 µm

Thermal detectors = heated by incident radiation ➔

microbolometric Measurement of electrical conductivity variations

« cheap » ; « slow » ; « noisy » ; « uncooled »

Photonic detectors ➔quantum = photon interactions ➔ photoelectric

CMT InSb

« fast » ; « cooled » ; « spectral range »

- **Sensor : InSb, InGaAs, MCT, microbolometric…**
- **Focal plane Array: 640x512 pixels or 320x256 pixels**
- **Typical : 150 – 400 Hz !!!**
- **thermal sensibility 30 °C: < 20 mK InSb, MCT**

  < 85 mK μbolometric
- **Spectral Sens. : 1 - 5 µm or 3 - 5 µm (InSb), 8 - 12 µm**
- **Integration time: about 10 µs**
- **One pixel Sensor = 30 µm**

Linear least squares
Maximum likelihood Estimator

$$\mathbf{T} = \mathbf{X\beta}$$

<u>Hypothesis :</u>

- zero mean and additive errors

- β constant and unknown before the estimation and X_{ij} known without error

- constant variance (σ known) and uncorrelated errors

$$S = (\mathbf{Y} - \mathbf{X\beta})^t . (\mathbf{Y} - \mathbf{X\beta})$$

Estimator $\hat{\boldsymbol{\beta}} = (\mathbf{X}^t \mathbf{X})^{-1} . \mathbf{X}^t \mathbf{Y}$

Estimation error $cov(\mathbf{e}_{\boldsymbol{\beta}}) = (\mathbf{X}^t \mathbf{X})^{-1} . \sigma^2$

Example : Non-Stationary Signal -Estimation of one parameter

$$\begin{bmatrix} T_1 \\ T_2 \\ : \\ : \\ T_N \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ : \\ : \\ f_N \end{bmatrix} \beta$$

$$\hat{\beta} = \frac{\sum_{i=1}^{N} f_i \hat{T}_i}{\sum_{i=1}^{N} f_i^{\,2}}$$

$$\sigma_\beta^{\ 2} = \frac{\sigma^2}{\sum_{i=1}^{N} f_i^{\,2}}$$

$$\left\| f(t) \right\| = \sqrt{\int_0^{t_{\max}} f^{\,2}(t)\,dt}$$

$$\sigma_\beta^{\ 2} = \frac{t_{\max}\sigma^2}{N\left\| f \right\|^2}$$

-If N small, T_i must be chosen as f is maximum

- T_i regularly spaced, N must be chosen <u>as great as possible!</u>

Estimation of several parameters

(*f* and *g* assumed to be orthogonal)

$$\begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_N \end{bmatrix} = \underbrace{\begin{bmatrix} f_1 & g_1 \\ f_2 & g_2 \\ \vdots & \vdots \\ f_N & g_N \end{bmatrix}}_{\boldsymbol{X}} \cdot \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix}$$

$$\hat{\beta}_1 = \frac{\left(\boldsymbol{f}^t \cdot \hat{\boldsymbol{T}}\right)}{\left(\boldsymbol{f}^t \cdot \boldsymbol{f}\right)} \qquad \hat{\beta}_2 = \frac{\left(\boldsymbol{g}^t \cdot \hat{\boldsymbol{T}}\right)}{\left(\boldsymbol{g}^t \cdot \boldsymbol{g}\right)}$$

$$\operatorname{cov}\left(\hat{\boldsymbol{B}}\right) = \sigma^2 \begin{pmatrix} \left(\boldsymbol{f}^t \boldsymbol{f}\right)^{-1} & 0 \\ 0 & \left(\boldsymbol{g}^t \boldsymbol{g}\right)^{-1} \end{pmatrix}$$

$$\operatorname{cov}\left(\hat{\boldsymbol{B}}\right) \approx \sigma^2 \left(\frac{N}{t_{\max}}\right)^{-1} \begin{pmatrix} \|f\|^{-2} & 0 \\ 0 & \|g\|^{-2} \end{pmatrix} \qquad \operatorname{cond}\left(\operatorname{cov}\left(\hat{\boldsymbol{B}}\right)\right) \approx \frac{\|f\|^2}{\|g\|^2}$$

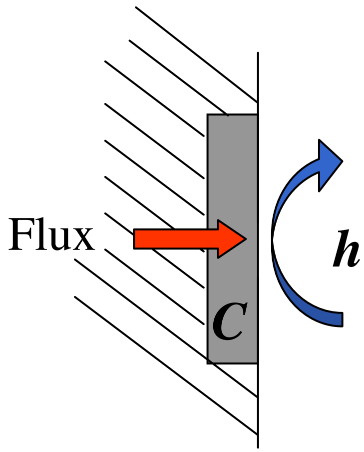
- T_i regularly spaced, N must be chosen <u>as great as possible!</u>

-The conditioning number is <u>non-dependant on N</u> !

Imaging Systems with « matrix » of sensors

Convective coefficients mapping

Thermal characterization of cyclist casque



$$C\frac{dT}{dt} = \varphi(t) - hT$$

Characteristic frequencies are estimated : $\frac{h}{C}$