Eurotherm Seminar 94Advanced Spring School:
Thermal Measurements & Inverse Techniques 5th edition
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L5-B: Measurements without contact in heat transfer: principles, implementation and pitfalls

Jean-Claude Krapez
ONERA   DOTA/MVA
13300 Salon de Provence

Outline

Temperature measurement by sensing the thermal emissive power

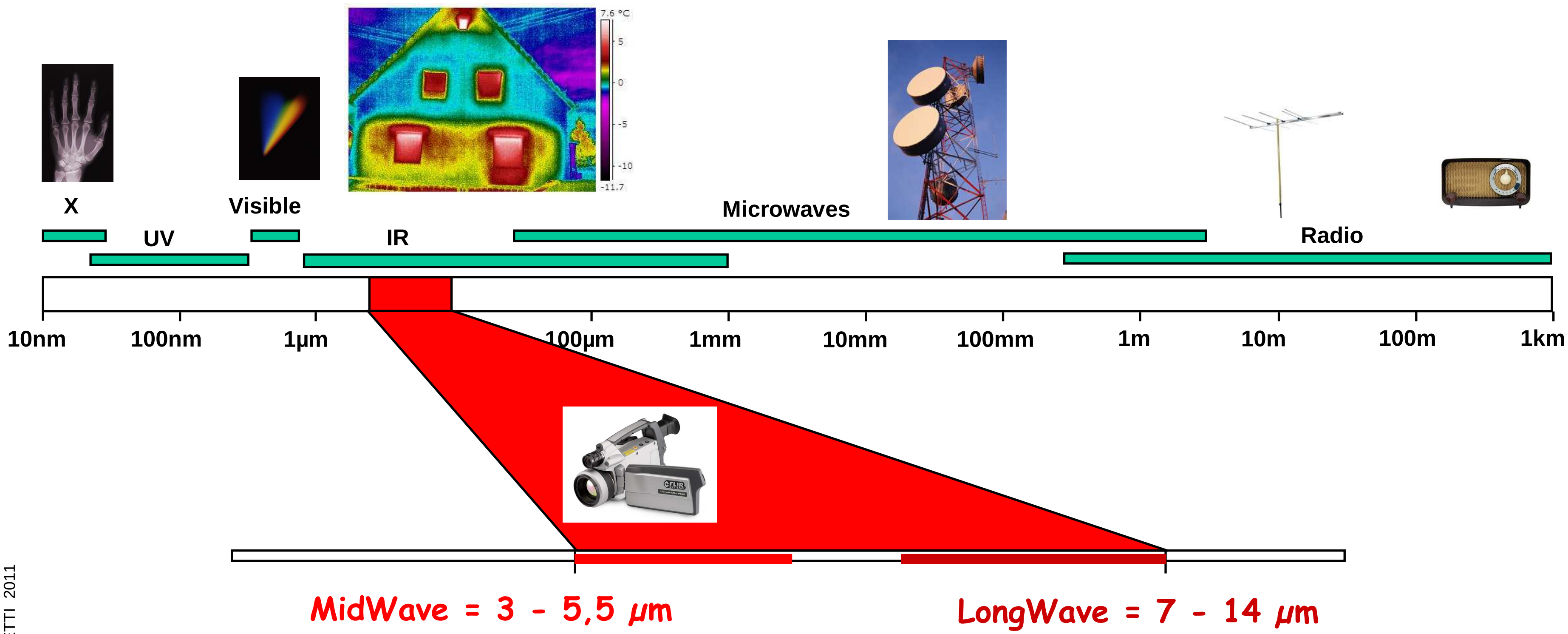
- Basics : Planck's law, Wien's law and s.o.
- Emissivity-Temperature Separation problem (ETS)
  - Pyrometry
    - single-color, bispectral pyrometry
    - multispectral pyrometry
  - ETS in airborne/satellite remote sensing
    - atmosphere compensation
    - Spectral-Smoothness method
    - Multi-temperature method
- Conclusion

Thermal radiation

Matter emits EM radiation

Intensity increases with temperature

→ Monitoring of emitted radiation offers a mean for temperature measurement



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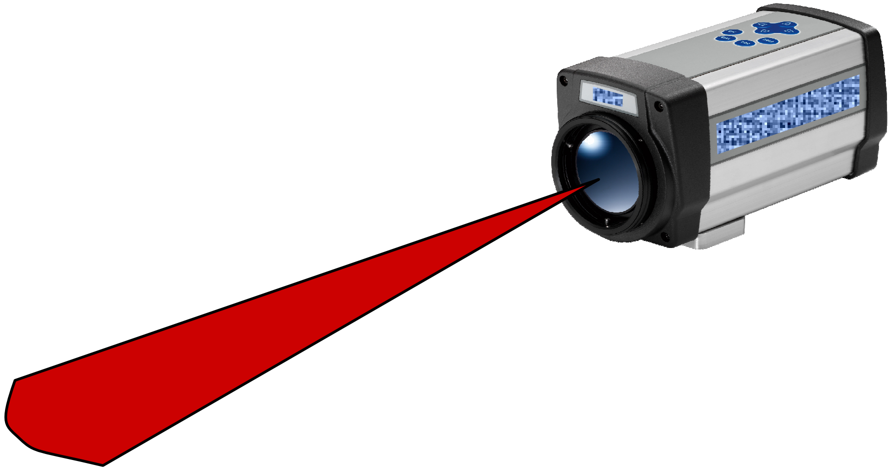
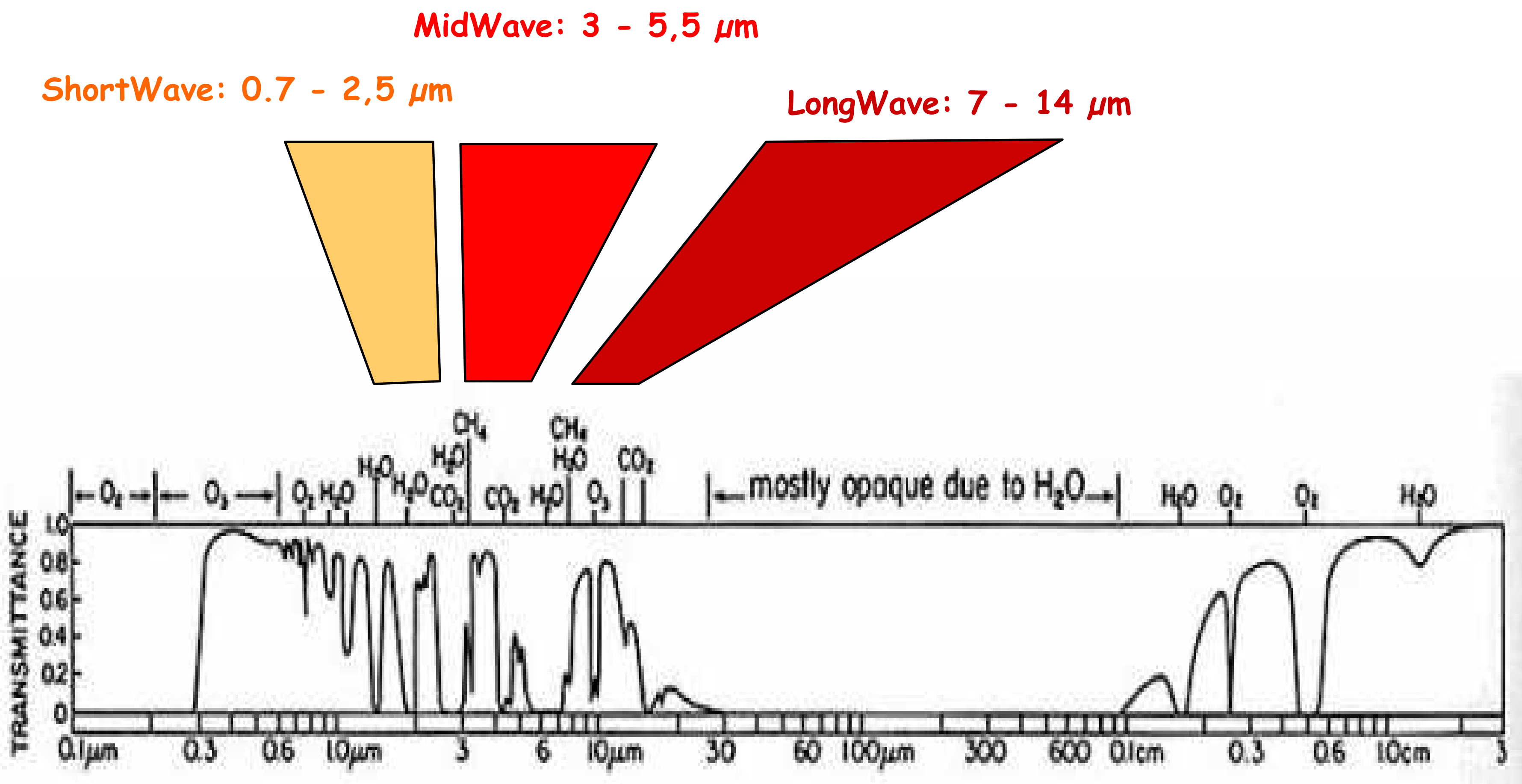
Thermal radiation monitoring



Advantages of the radiation method :

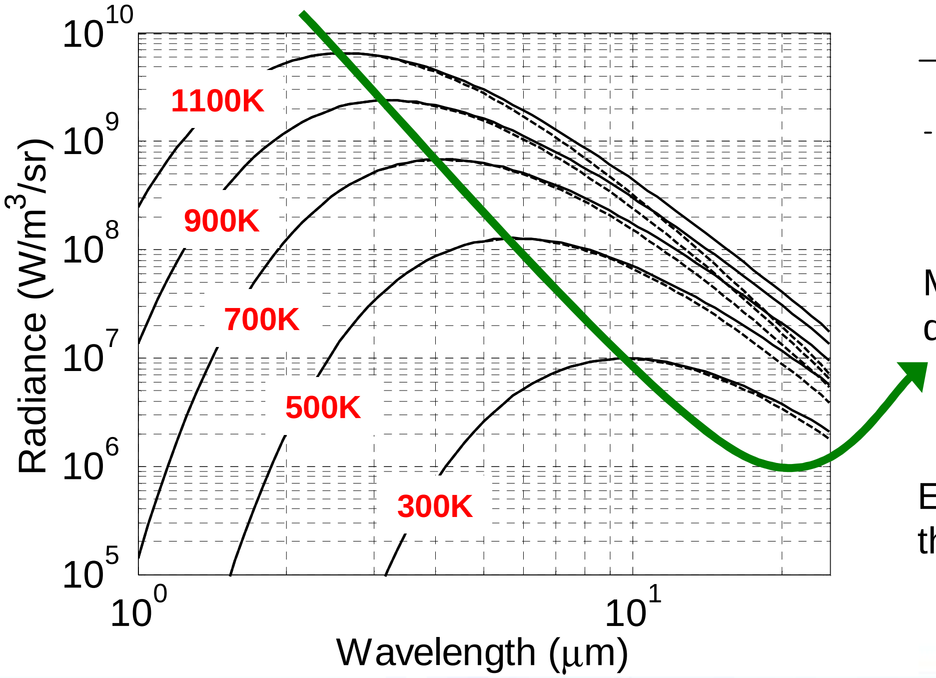
- non-contact
- surface probing (opaque material),
- surface to sub-surface probing (semi-transparent material)
- rapid : detectors with up to GHz bandwidth (and even higher)
- long distance measurement (airborne and satellite remote sensing, astronomy)
- point detectors (local measurement or 2D images by mechanical scanning)
- focal plane arrays (instantaneous 2D images)
- possibility of spectral measurements (multispectral, hyperspectral)

Radiation sensing is dependant on the atmosphere transmission, (absorption bands of air constituents : H_2O, CO_2, O_3, CH_4, …)



Basics (1/4)

- Blackbody: perfect absorber, perfect emitter (~Holy Grail…)
- Spectral radiance given by Planck's law: $B(\lambda,T)=\frac{C_1}{\lambda^5}\frac{1}{\exp\left(\frac{C_2}{\lambda T}\right)-1}$
- Wien's approximation: $B_W(\lambda,T)=\frac{C_1}{\lambda^5}\exp\left(-\frac{C_2}{\lambda T}\right)$



Maximum given by Wien's displacement law: $\lambda_{\max}T = 2898\ \mu mK$

Error of Wien's approximation is less than 1% providing that $\lambda T < 3124\ \mu mK$

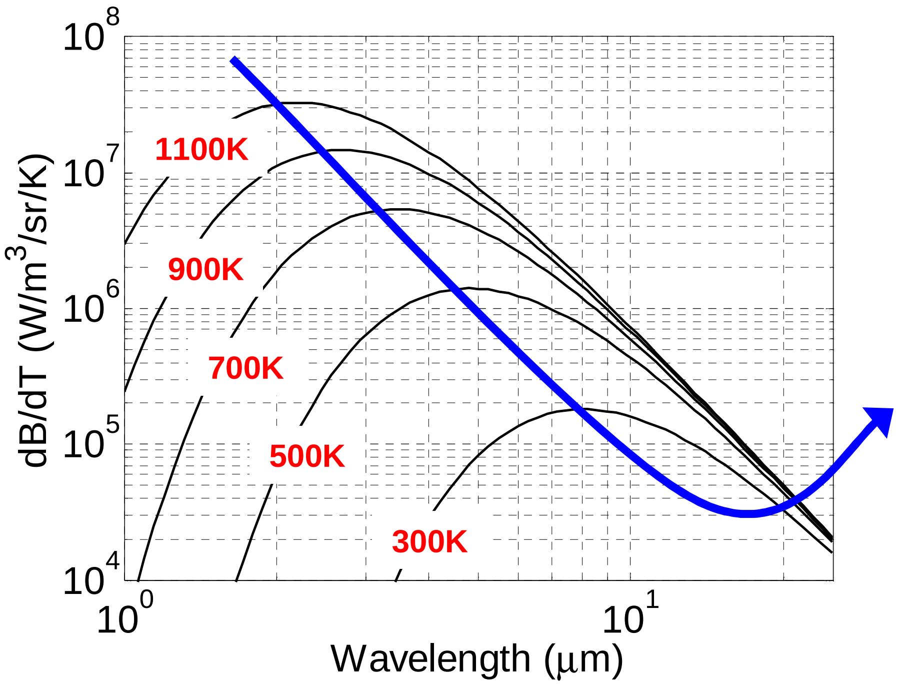
Basics (2/4)

Wavelength selection for temperature measurement

- Maximum of radiance given by Wien's displacement law: $\lambda_{max} T = 2898\ \mu mK$

  ⬇ $\lambda = 9.65\ \mu m$ for T = 300K

- Radiance sensitivity to temperature (*absolute* sensitivity): $\frac{\partial B}{\partial T}$



Maximum corresponding to: $\lambda T = 2410\ \mu mK$

⬇ $\lambda = 8.05\ \mu m$ for T = 300K

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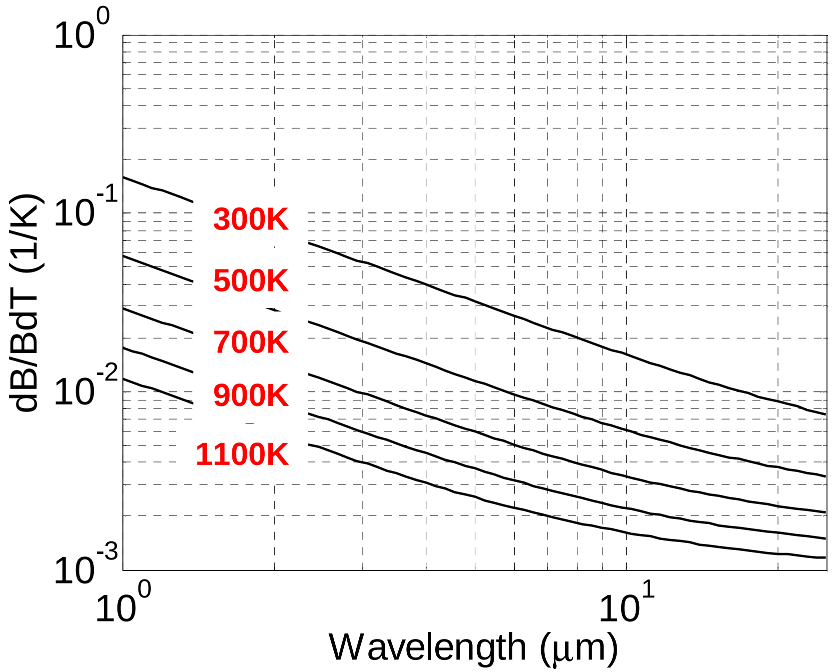
Basics (3/4)

Wavelength selection for temperature measurement

- Radiance sensitivity to temperature (*relative* sensitivity): $\frac{1}{B}\frac{\partial B}{\partial T}$



for T = 300K :
2% radiance increase per K at 8µm
16% radiance increase per K at 1µm

Advantage of performing measurements at short wavelengths (sensitivity is nearly in inverse proportion to wavelength)

Interest in visible pyrometry or even UV pyrometry ?

Basics (4/4)

Real materials (non-perfect emitters)

- with respect to blackbody, the emitted radiance $L(\lambda,T,\theta,\varphi)$ is reduced by a factor called emissivity:

$$L(\lambda,T,\theta,\varphi)=\varepsilon(\lambda,T,\theta,\varphi)B(\lambda,T) \qquad 0\leq\varepsilon\leq 1$$

- emissivity depends on wavelength, temperature, and direction
- second Kichhoff's law between emissivity and absorptance:

$$\varepsilon(\lambda,\theta,\varphi)=\alpha(\lambda,\theta,\varphi)$$

- relation between absorptance and directional hemispherical reflectance from the energy conservation law for an opaque material (the energy that is not absorbed by the surface is reflected in all directions):

$$\alpha(\lambda,\theta,\varphi)+\rho'^{\cap}(\lambda,\theta,\varphi)=1$$

Emissivity can be inferred from a reflectance measurement (integrating sphere)
Drawback : need to bring the integrating sphere close to the surface

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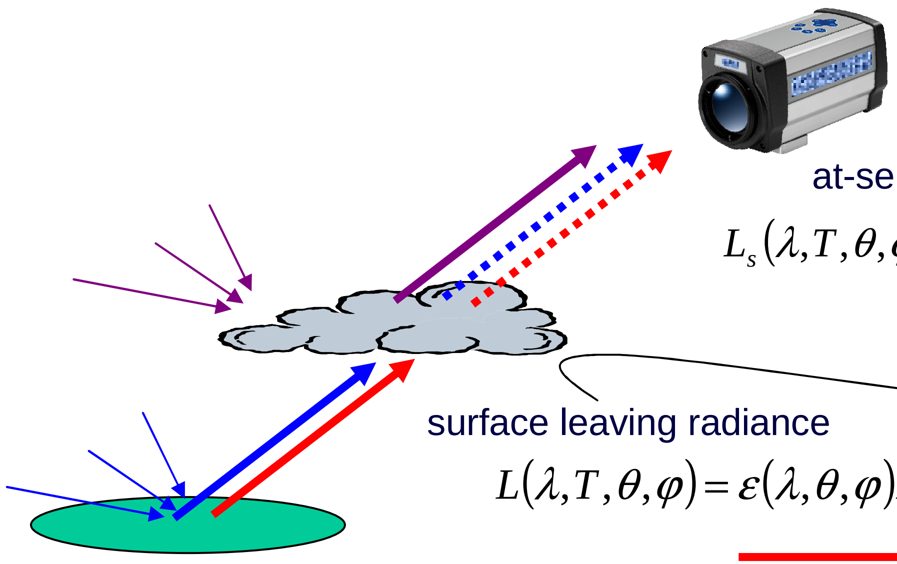
Contributors to the optical signal

- the surface reflects the incoming radiation (non-perfect absorber)
  - downwelling radiance: $L^{\downarrow}(\lambda,\theta_i,\varphi_i)$
  - bidirectional reflectance : $\rho''(\lambda,\theta,\varphi,\theta_i,\varphi_i)$
- the radiation leaving the surface is attenuated along the optic path (absorption, scattering by atmosphere constituents: gases, aerosols – dust, water/ice particles)
  - transmission coefficient : $\tau(\lambda,\theta,\varphi)$
- atmosphere emits and scatters radiation towards the sensor
  - upwelling radiance $L^{\uparrow}(\lambda,\theta,\varphi)$



at-sensor radiance

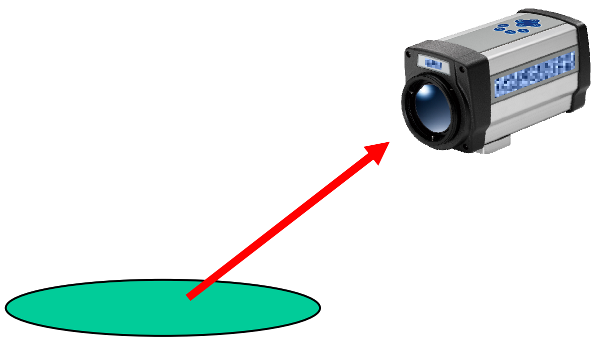
$$L_s(\lambda,T,\theta,\varphi)=\tau(\lambda,\theta,\varphi)L(\lambda,T,\theta,\varphi)+L^{\uparrow}(\lambda,\theta,\varphi)$$

surface leaving radiance

$$L(\lambda,T,\theta,\varphi)=\varepsilon(\lambda,\theta,\varphi)B(\lambda,T)+\int_{2\pi}\rho''(\lambda,\theta,\varphi,\theta_i,\varphi_i)L^{\downarrow}(\lambda,\theta_i,\varphi_i)\cos\theta_i d\Omega_i$$

First considered case

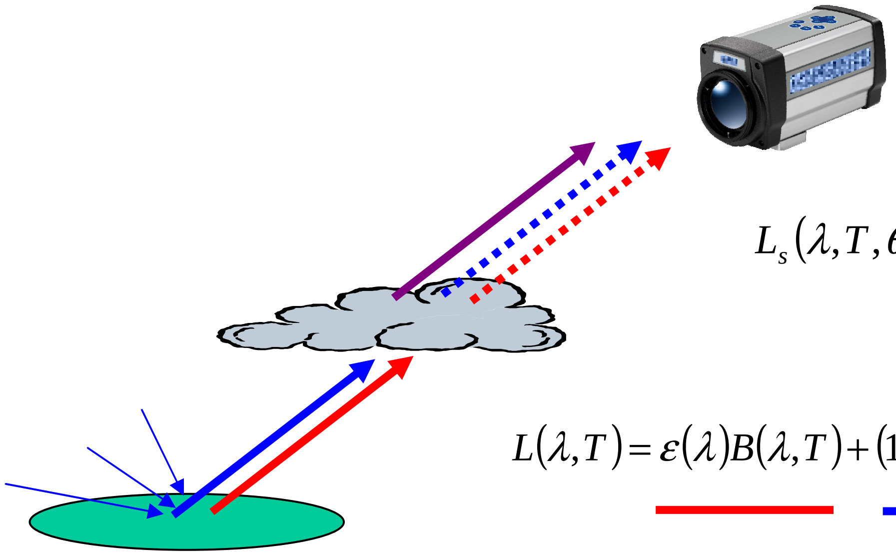
- Pyrometry of high temperature surfaces
  - sensor at close range (limited or even negligible atmosphere contributions)
  - environment much colder than the analyzed surface



$$L_s(\lambda,T,\theta,\varphi)=\underline{\varepsilon(\lambda,\theta,\varphi)B(\lambda,T)}$$

Second considered case

- Airborne/satellite remote sensing
  - hypothesis of lambertian surface: isotropic reflectance ⟹ isotropic emissivity
    - mean downwelling radiance $$L^{\downarrow}(\lambda)=\frac{1}{\pi}\int_{2\pi} L_{env}(\lambda,\theta_i,\varphi_i)\cos\theta_i d\Omega_i$$
  - need for atmosphere compensation step



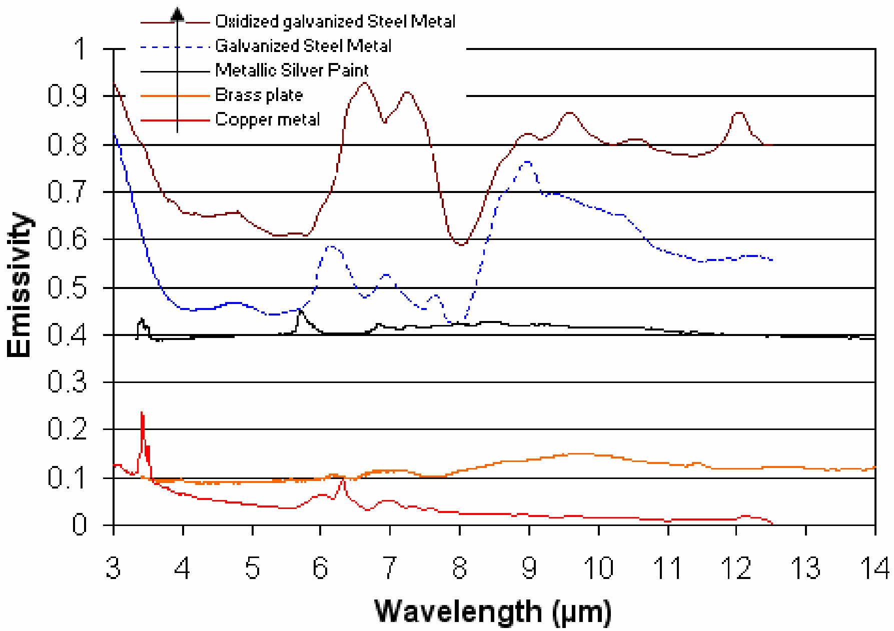
$$L_s(\lambda,T,\theta,\varphi)=\tau(\lambda,\theta,\varphi)L(\lambda,T)+L^{\uparrow}(\lambda,\theta,\varphi)$$

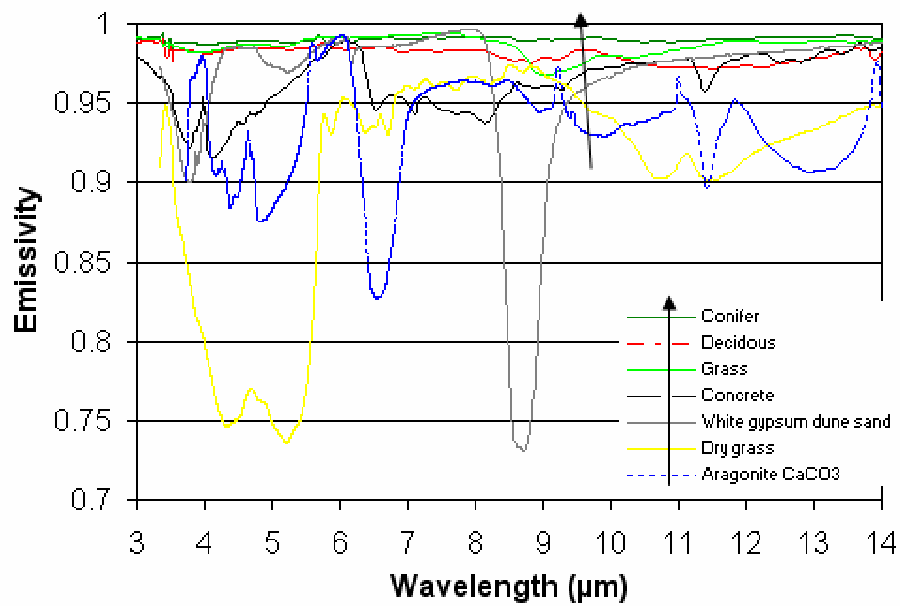
$$L(\lambda,T)=\varepsilon(\lambda)B(\lambda,T)+(1-\varepsilon(\lambda))L^{\downarrow}(\lambda)$$

What about emissivity ?

In all cases we need an information on emissivity to get temperature

- relations for emissivity : **only for ideal materials**, for example Drude law for pure metals (satisfactory only for $\lambda > 2\mu m$, not valid for corroded or rough surfaces)
- databases for specific materials **in particular state** of roughness, corrosion, coatings, contaminant, moisture content …





- **Practical solution : simultaneous evaluation of temperature and emissivity**

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Single-color pyrometry

- Measurement is performed in a narrow to large spectral band
- In any case, after sensor calibration, the retrived radiance is of the form

$$L_s(\lambda,T) = \varepsilon(\lambda)B(\lambda,T)$$

One equation, two unknown parameters

One has to estimate the emissivity (a priori knowledge)

- Sensitivity of temperature to an error in emissivity estimation:

$$\frac{dT}{T} = -\left(\frac{T}{B}\frac{dB}{dT}\right)^{-1}\frac{d\varepsilon}{\varepsilon} \approx -\frac{\lambda T}{C_2}\frac{d\varepsilon}{\varepsilon}$$

at 1µm and T= 1100K : -0.8K/% error
at 10 µm and T= 300K : -0.6K/% error

- advantage in working at short wavelength (visible or UV pyrometry): sensitivity to emissivity error drops.
- However, the signal drops at short wavelength → compromise

Two-color pyrometry (1/2)

- Adding a new wavelength adds an equation but also an unknown parameter namely the emissivity a this additional wavelength.
- Two spectral signals: $\begin{cases} L(\lambda_1,T)=\varepsilon(\lambda_1)B(\lambda_1,T) \\ L(\lambda_2,T)=\varepsilon(\lambda_2)B(\lambda_2,T) \end{cases}$
- by ratioing the signals: $\ln\left(L_2\lambda_2^{\ 5}\right)-\ln\left(L_1\lambda_1^{\ 5}\right)=\ln\left(\frac{\varepsilon_2}{\varepsilon_1}\right)-\frac{C_2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)$

effective wavelength: $\lambda_{12}=\frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}$

Effective wavelength can be high : bad news !!

- The problem can be solved if one has a knowledge about the emissivity ratio.
- Common hypothesis (but not necessary) : « greybody » assumption $\varepsilon(\lambda_1)=\varepsilon(\lambda_2)$
- Sensitivity of temperature to an error in emissivity estimation:

$$\frac{dT}{T}\approx-\frac{\lambda_{12}T}{C_2}\left(\frac{d\varepsilon_1}{\varepsilon_1}-\frac{d\varepsilon_2}{\varepsilon_2}\right)$$

at 1µm/1.5µm and T= 1100K : -2.5K/% error **= 3 times higher**
at 10µm/12µm and T= 300K : -3.7K/% error **= 6 times higher**

Ratio pyrometry vs 1-color pyrometry

	1-color	2-color	3-color
Input	ε_1	$\frac{\varepsilon_2}{\varepsilon_1}$ (slope)	$\frac{\varepsilon_2{}^2}{\varepsilon_1\varepsilon_3}$ (curvature)
Error amplification on temperature	$-\frac{\lambda T}{C_2}$	$\times\frac{\lambda}{\Delta\lambda}$	$\times\left(\frac{\lambda}{\Delta\lambda}\right)^2$

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Two-color pyrometry (2/2)

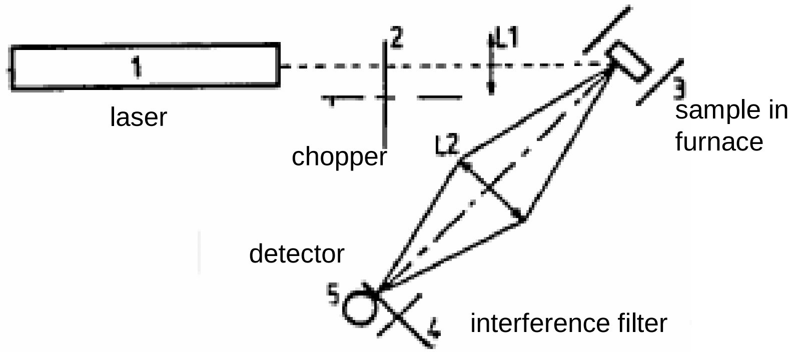
- Sensitivity of temperature to an error in emissivity estimation can be reduced by decreasing the effective wavelength (by increasing $1/\lambda_1 - 1/\lambda_2$)

  ➡ dilemma when spreading the wavelengths : will the “greybody” assumption still hold ?

- Advantage of ratio pyrometry over single color pyrometry : **immune to partial occultation, to variations of optical path transmission**

- 2-color photothermal pyrometry:

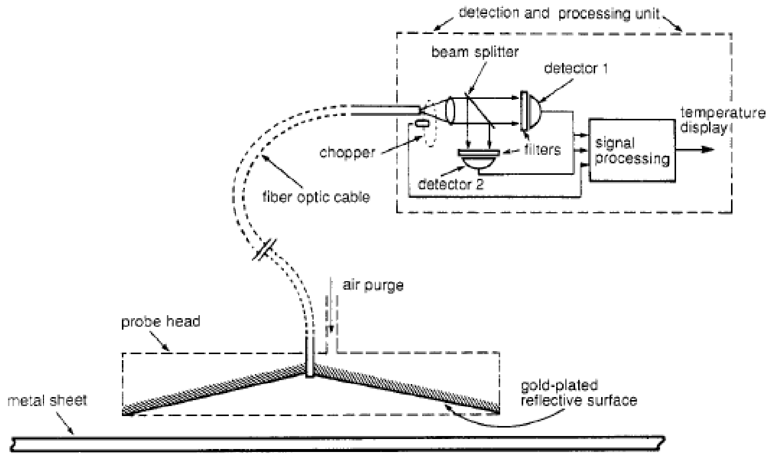
  A laser is used to periodically heat the surface.
  A lock-in detection is implemented to capture the modulated radiance deprived from any reflection.
  The signal ratio is: $$\frac{\varepsilon(\lambda_1)\partial B/\partial T(\lambda_1,T)}{\varepsilon(\lambda_2)\partial B/\partial T(\lambda_2,T)}$$



T. Loarer at al., 1990

- Emissivity-enhanced 2-color pyrometry

  Additional reflective surface for introducing a cavity effect (increase of both apparent emissivities, reduction of spurious reflections)



J.-C. Krapez at al., 1990

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Multiwavelength pyrometry (MWP)

- Emissivity-temperature separation is essentially an underdetermined inverse problem:

N observables → $L_s(\lambda_i, T) = \varepsilon(\lambda_i) B(\lambda_i, T) \qquad i = 1, N$

N unknown parameters ($\varepsilon(\lambda_i)$); 1 unknown parameter (T)

whatever the number of wavelengths/equations, there are always one more unknown parameters

- Two types of solutions:
  - reduce by one the degree of freedom of the discretized emissivity spectrum
    - N equations, N unknowns → the problem should be solvable (?)

    → interpolation-based method
  - regularization by using a low-order emissivity model (continuous or step function)
    - N equations, much less unknowns

    → least-square based method
- Long time controversy: does MWP bring a real advantage as compared to single-color or two-color pyrometry ?

Multiwavelength pyrometry. Interpolation-based method (1/2)

"Just as needed" regularization : approximating the emissivity (or its log.) by a N-2 degree polynomial

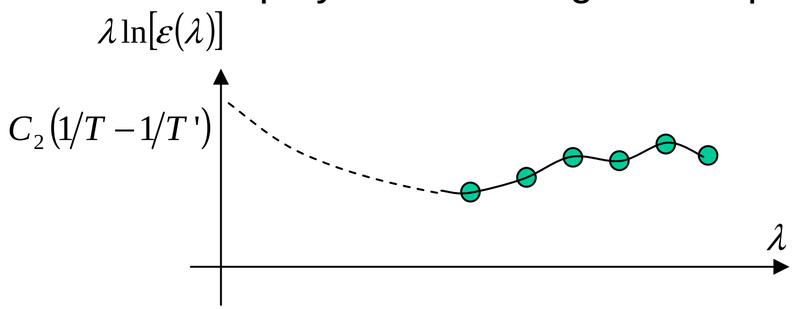
By considering the Wien approximation and taking the logarithm, Coates showed that this may lead to "catastrophic" results:

$$\begin{cases} \ln\left[L(\lambda_i,T)\lambda_i^5/C_1\right] = \ln(\varepsilon_i) - C_2/\lambda_i T & i=1,N \\ \ln\left[L(\lambda_i,T)\lambda_i^5/C_1\right] = \sum_{j=0}^{N-2} a_j \lambda_i^j - C_2/\lambda_i T' & i=1,N \end{cases}$$

approximation

induced temperature error

polynomial of degree N-1 passing through the N values $\lambda_i \ln[\varepsilon(\lambda_i)]$

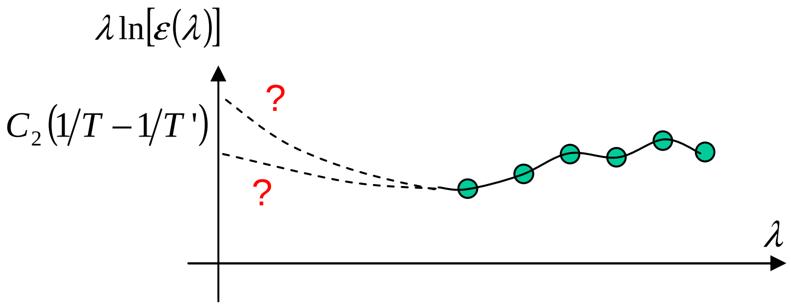


constant parameter = temperature error $C_2(1/T - 1/T')$

i.e. extrapolation result at $\lambda = 0$

Multiwavelength pyrometry. Interpolation-based method (2/2)

there would be no error if a N-2 degree polynomial could be found passing ***exactly*** through the N values $\ln[\varepsilon(\lambda_i)]$ → highly improbable !



Therefore, in general, one has to count on **extrapolation** properties.
Unfortunately, extrapolation based on polynomial interpolation leads to **increasingly high errors as the polynomial degree rises** !

→ **unpredictably high errors when adding new wavelengths**

Previous errors are **systematic**, i.e. **method errors** (errorless signal).

Same bad results are observed for **measurement errors** (they add to the previous ones).

The calculated temperatures are increasingly sensitive to measurement errors as the number of channels increases : **OVERFITTING** problem

Multiwavelength pyrometry. Low-order emissivity models (1/2)

The only solution : reduce the model complexity (low order model !)

Some examples of models :

$$\varepsilon(\lambda_i) = \sum_{j=0}^{m} a_j \lambda_i^{\ j} \quad i = 1,\ldots,N \quad m < N-2$$

$$\ln[\varepsilon(\lambda_i)] = \sum_{j=0}^{m} a_j \lambda_i^{\ j} \quad i = 1,\ldots,N \quad m < N-2$$

$$\varepsilon(\lambda_i) = 1 / \left(1 + a_0 \lambda_i^{\ 2}\right) \quad i = 1,\ldots,N$$

- Polynomials of $\lambda^{1/2}$ or $\lambda^{-1/2}$ for $\ln[\varepsilon(\lambda)]$
- Functions involving the brightness temperature $T_R = B^{-1}(\lambda, L_s)$
- Sinusoïdal function of wavelength
- Step function (**grey-band model** with N_b bands).
    - -2 or 3 channels per band
    - -up to N-1 single-channel bands and one dual channel band

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Multiwavelength pyrometry. Low-order emissivity models (2/2)

measurement error (noise)

Observable : $Y_i = \ln\left[L(\lambda_i,T)\lambda_i^5 / C_1\right] + e_i$

Wien approximation

Polynomial approx. of $\ln[\varepsilon(\lambda_i)]$

Minimizing the weighted sum $\sum_{i=1}^{N} \sigma_i^{-2} \left(Y_i - \left(\sum_{j=0}^{m} a_j \lambda_i^{\,j} - \frac{C_2}{\lambda_i T} \right) \right)^2$

→ Linear least squares problem

measurement error (noise)

Observable : $Y_i = L(\lambda_i,T) + e_i$

Planck's law

Polynomial approx. of $\varepsilon(\lambda_i)$

Minimizing the weighted sum $\sum_{i=1}^{N} \sigma_i^{-2} \left(Y_i - B(\lambda_i,T) \sum_{j=0}^{m} a_j \lambda_i^{\,j} \right)^2$

→ Non-linear least squares problem

Multiwavelength pyrometry. Linear least squares problem (1/5)

One is looking for the polynomial coefficients and the temperature such that:

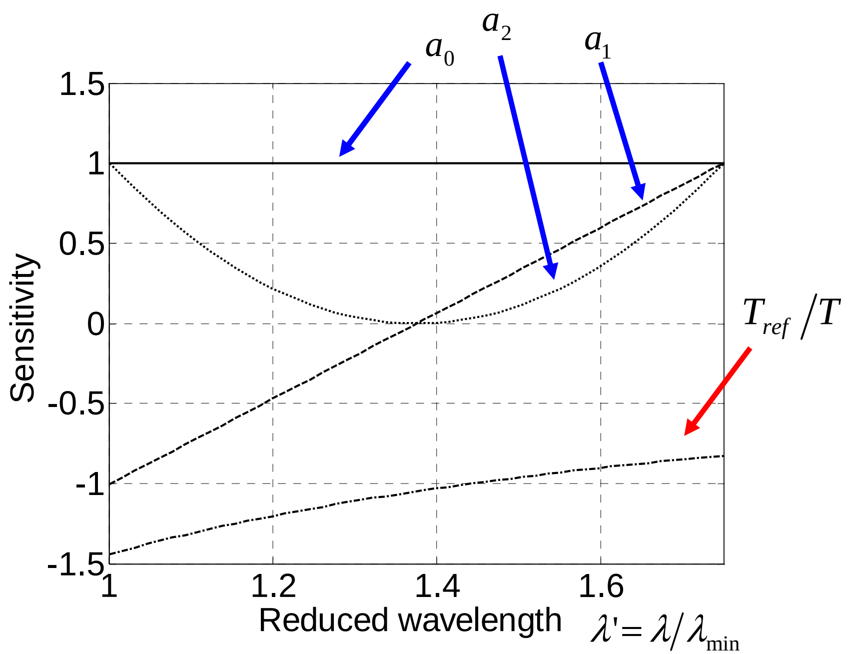
$$\hat{\mathbf{P}} = \begin{bmatrix} \hat{a}_0 & \dots & \hat{a}_m & \hat{T} \end{bmatrix}^T = \underset{a_j, T}{\arg Min} \sum_{i=1}^{N} \left(Y_i - \left(\sum_{j=0}^{m} a_j \lambda_i^{\,j} - \frac{C_2}{\lambda_i T} \right) \right)^2$$

Parameter reduction for numerical purposes:

$$\lambda_i * = 2 \frac{\lambda_i - \lambda_{\min}}{\lambda_{\max} - \lambda_{\min}} - 1 \qquad P_T * = T_{ref} / T \quad \text{such that} \quad C_2 / \lambda_i T_{ref} \approx 1$$

Sensitivity matrix to the reduced parameters:

$$\mathbf{X} = \begin{bmatrix} 1 & \lambda_1 * & \lambda_1 *^2 & \dots & \dfrac{-C_2}{\lambda_1 T_{ref}} \\ \dots & \dots & \dots & \dots & \dots \\ 1 & \lambda_N * & \lambda_N *^2 & \dots & \dfrac{-C_2}{\lambda_N T_{ref}} \end{bmatrix}_{N, m+2}$$



The sensitivity to the temperature inverse is very smooth, close to linear. We can thus expect a **strong correlation between the parameters (near collinear sensitivity vectors).**

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Multiwavelength pyrometry. Linear least squares problem (2/5)

Assuming that the measurement errors are additive, uncorrelated and of uniform variance, an estimation of the parameter vector $\hat{\mathbf{P}}*$ in the least squares sense is obtained by solving the linear system :

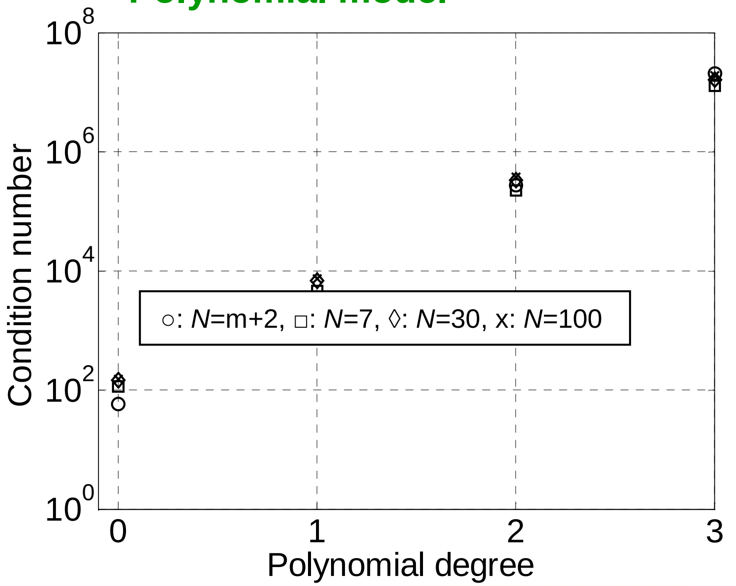
$$\left(\mathbf{X}^T\mathbf{X}\right)\hat{\mathbf{P}}* = \mathbf{X}^T\mathbf{Y}$$

Near collinear sensitivity vectors lead to a **high condition number** of $\left(\mathbf{X}^T\mathbf{X}\right)$

The **condition number** (ratio of maximum to minimum eigenvalue) indicates the rate at which the identified parameters will change with respect to a change of the observable (sensitivity to measurement errors)

$\lambda_{max}/\lambda_{min} = 1.75$

Polynomial model



Huge increase of the condition number with the polynomial degree

Problems are expected with models of degree 2 and more

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Multiwavelength pyrometry. Linear least squares problem (3/5)

Condition number : only an upper bound of error amplification.

The diagonal of the covariance matrix $\left(\mathbf{X}^T\mathbf{X}\right)^{-1}$ is of greater value for analyzing the error propagation

$$\left[\sigma_{P*}{}^2\right] = diag\left(\left(\mathbf{X}^T\mathbf{X}\right)^{-1}\right)\sigma^2$$

assumed uniform variance of the observable

error around the mean estimator value due to **radiance error propagation to the parameters**
(does not include the bias due to model error, i.e. misfit between true emissivity and emissivity model)

Error amplification factors

K_ε

$$\frac{\sigma_\varepsilon}{\varepsilon} = K_\varepsilon \frac{\sigma_L}{L}$$

K_T

$$\frac{\sigma_T}{T} = K_T \lambda_{\min} T \frac{\sigma_L}{L}$$

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Multiwavelength pyrometry. Linear least squares problem (4/5)

Polynomial model

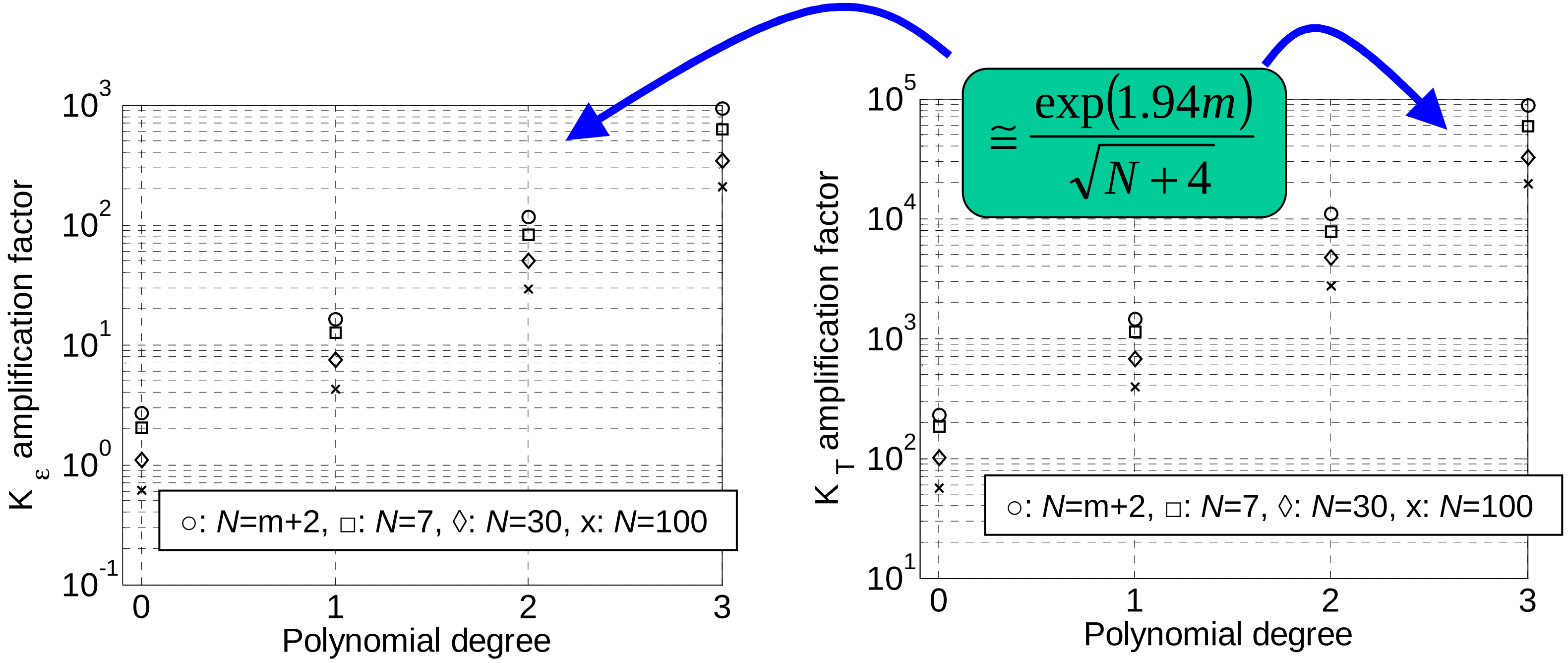


Illustration for

$\lambda_{max} / \lambda_{min} = 1.75$

The errors are rapidly rising with the degree of freedom

Multiwavelength pyrometry. Linear least squares problem (5/5)

Practical application :
- target at 320K,
- 1% radiance noise
- radiometer with **seven wavelengths** between 8 and 14µm

Polynomial model

Polynomial degree	σ_T (K)	σ_ε
0	1.5	0.02
1	9.4	0.13
2	64	0.83

The mentioned standard errors only reflect what happens when noise corrupts the radiance emitted by a surface **which otherwise *perfectly follows the chosen model (polynomial model of degree 0, 1 or 2*)**

Multiwavelength pyrometry. A look to the ETS solutions (1/2)

To each estimated temperature value $\hat{T}$ one can associate an emissivity profile $\hat{\varepsilon}(\lambda,\hat{T})$ according to:

"true" emissivity — "true" temperature

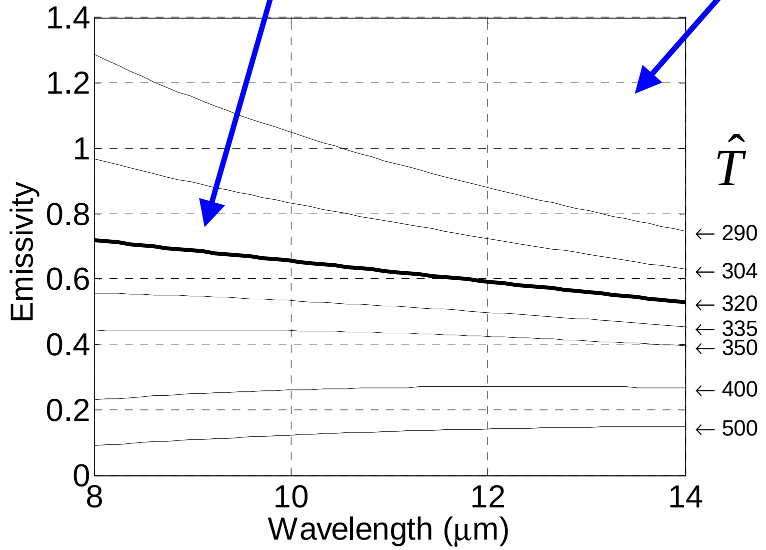
$$\hat{\varepsilon}(\lambda,\hat{T})=\frac{L(\lambda,T)}{B(\lambda,\hat{T})}=\varepsilon(\lambda)\frac{B(\lambda,T)}{B(\lambda,\hat{T})}$$

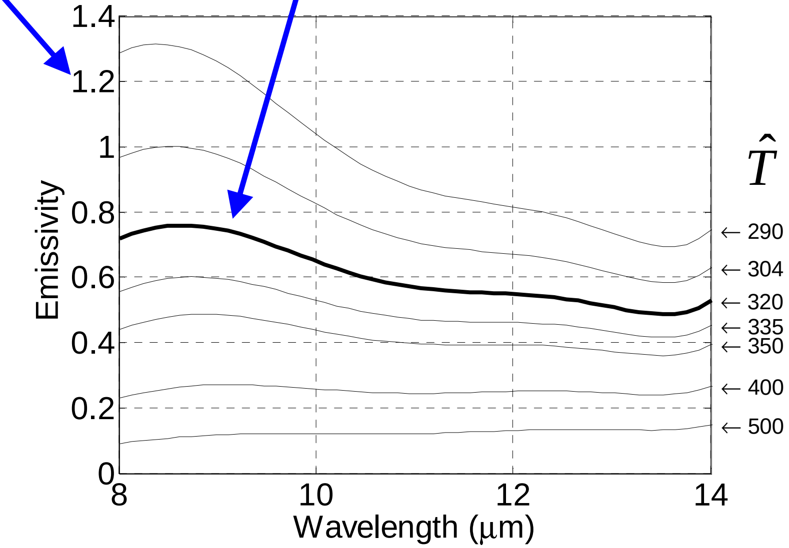
They constitute an infinite number of perfect solutions to the underdetermined problem.

"true" emissivity is linear

"true" temperature $T=320K$

"true" emissivity is a 6-order polynomial





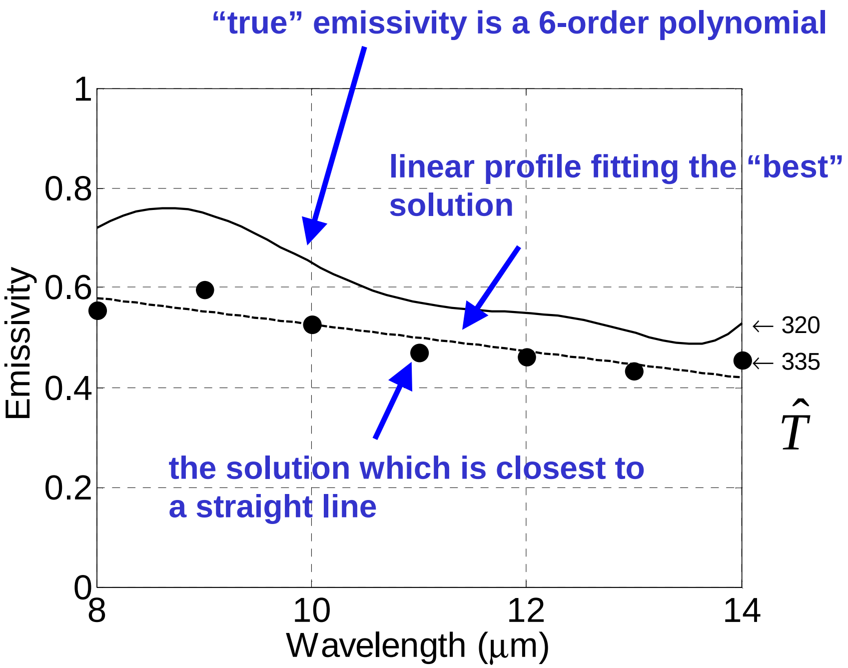
Let us now consider a 1-degree emissivity model. **Which, among all candidate profiles, fits a straight line at best ?**

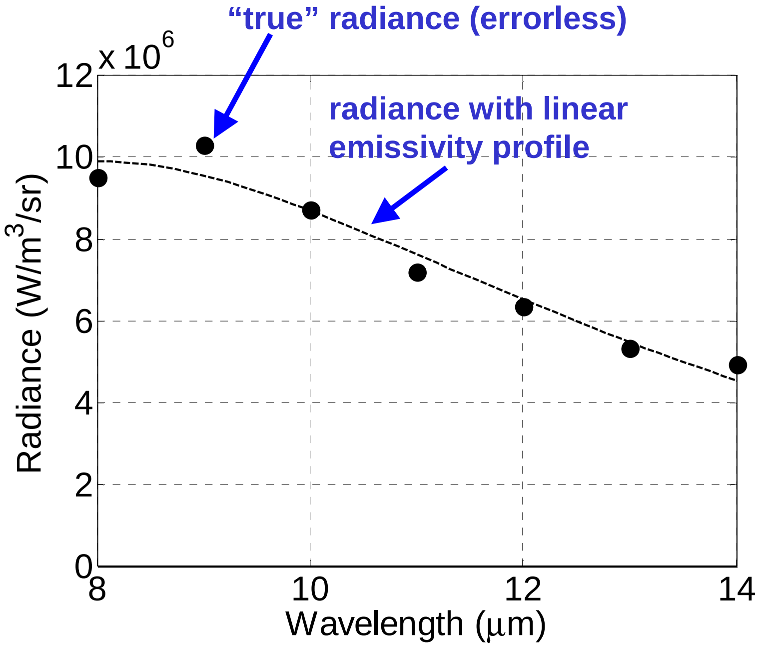
Multiwavelength pyrometry. A look to the ETS solutions (2/2)

Misleading idea : « the chosen model is used to fit the true emissivity profile »

Actually, the least squares method selects among all possible solutions, the one which conforms at best to the model, taking into account a weighting by $B(\lambda, \hat{T})$

7-channels pyrometer [8-14µm]





Errorless radiance leads to a 15K bias for temperature and 0.06 to 0.2 emissivity underestimation (**systematic or model error**)

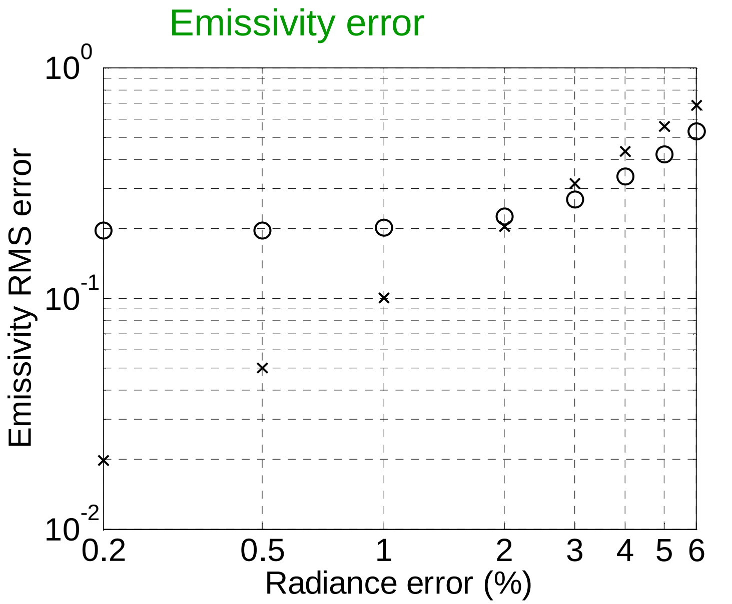
With a 2-degree polynomial model, the results are even worse : $\hat{T}$ =230K, $\hat{\varepsilon}$ >2 !

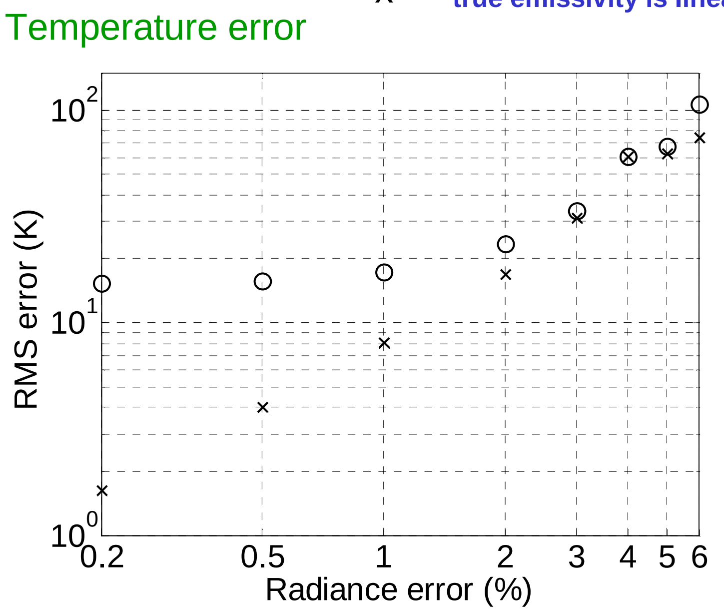
Multiwavelength pyrometry. Non-linear least squares and Monte-Carlo analysis (1/3)

- Measurements are simulated by adding artificial noise to the theoretical emitted radiance (Gaussian distribution with a spectrally uniform standard deviation : 0.2% to 6% of the maximum radiance value)
- Statistical analysis on 200 simulated experiments
- Chosen model : 1-degree polynomial

○ true emissivity is a 6-order polynomial

x true emissivity is linear





High systematic error when the emissivity model (1-degree polynomial) doesn't match with the true profile (>15K RMS !).
Otherwise, 0.1 emissivity error and 8K temperature error for 1% radiance error. Same holds when the true profile departs by 1% from a straight line !

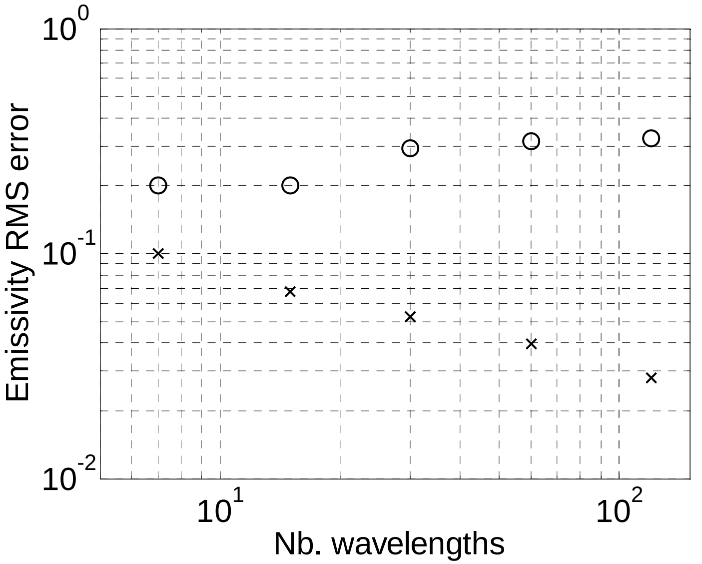
Multiwavelength pyrometry. Non-linear least squares and Monte-Carlo analysis (2/3)

- Does it help to increase the number of spectral channels ?

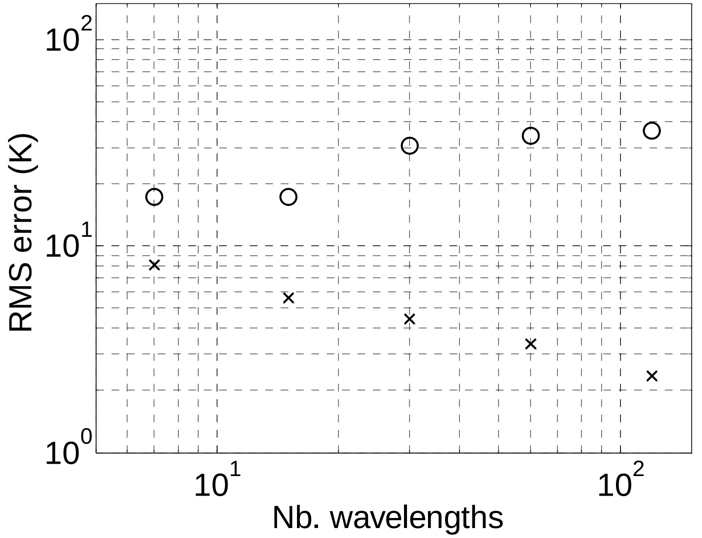
○ **true emissivity is a 6-order polynomial**

x **true emissivity is linear**

Emissivity error



Temperature error



When the emissivity model (1-degree polynomial) matches with the true profile we observe the classical $N^{-1/2}$ uncertainty reduction.

Otherwise, emissivity and temperature RMS error remain high (systematic errors always dominate); they even increase with N for present example !

Conclusion on LSMWP with low-order emissivity models

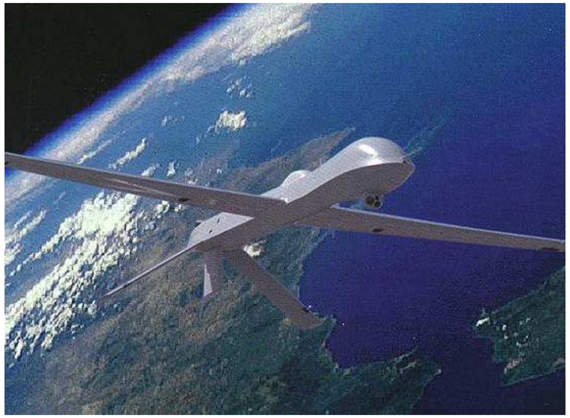
- Reasonable RMS values can be obtained only when the implemented emissivity model perfectly matches the real emissivity spectrum. Otherwise, there are important systematic errors
- When can we guaranty that a specific model perfectly matches to reality ?
- LSMWP focuses on **profile shape rather than on magnitude** → Add a penalization based on emissivity level (mean or local) to force the solution to remain close to a predetermined level (*a priori* information)

↳ back to one-color pyrometry !

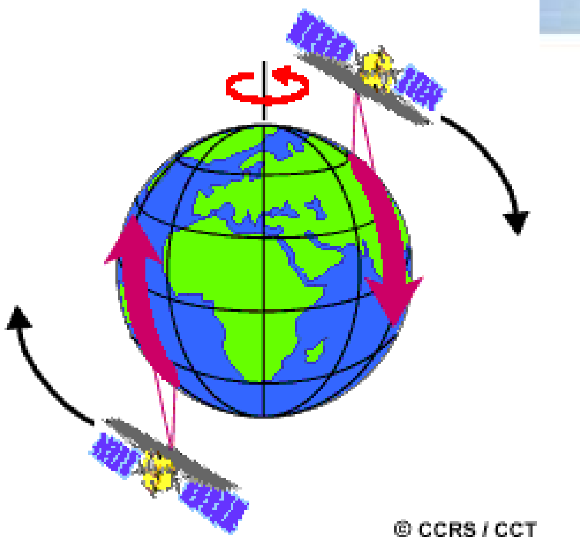
- When using **only** the **emitted** spectral radiance, there is no valuable reason for implementing MWP instead of the simpler one-color or bispectral pyrometry

ETS in the field of remote sensing

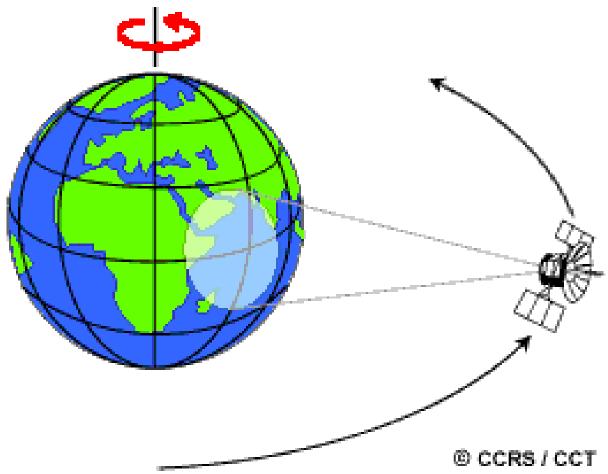
Low-altitude airborne remote sensing



High-altitude airborne remote sensing

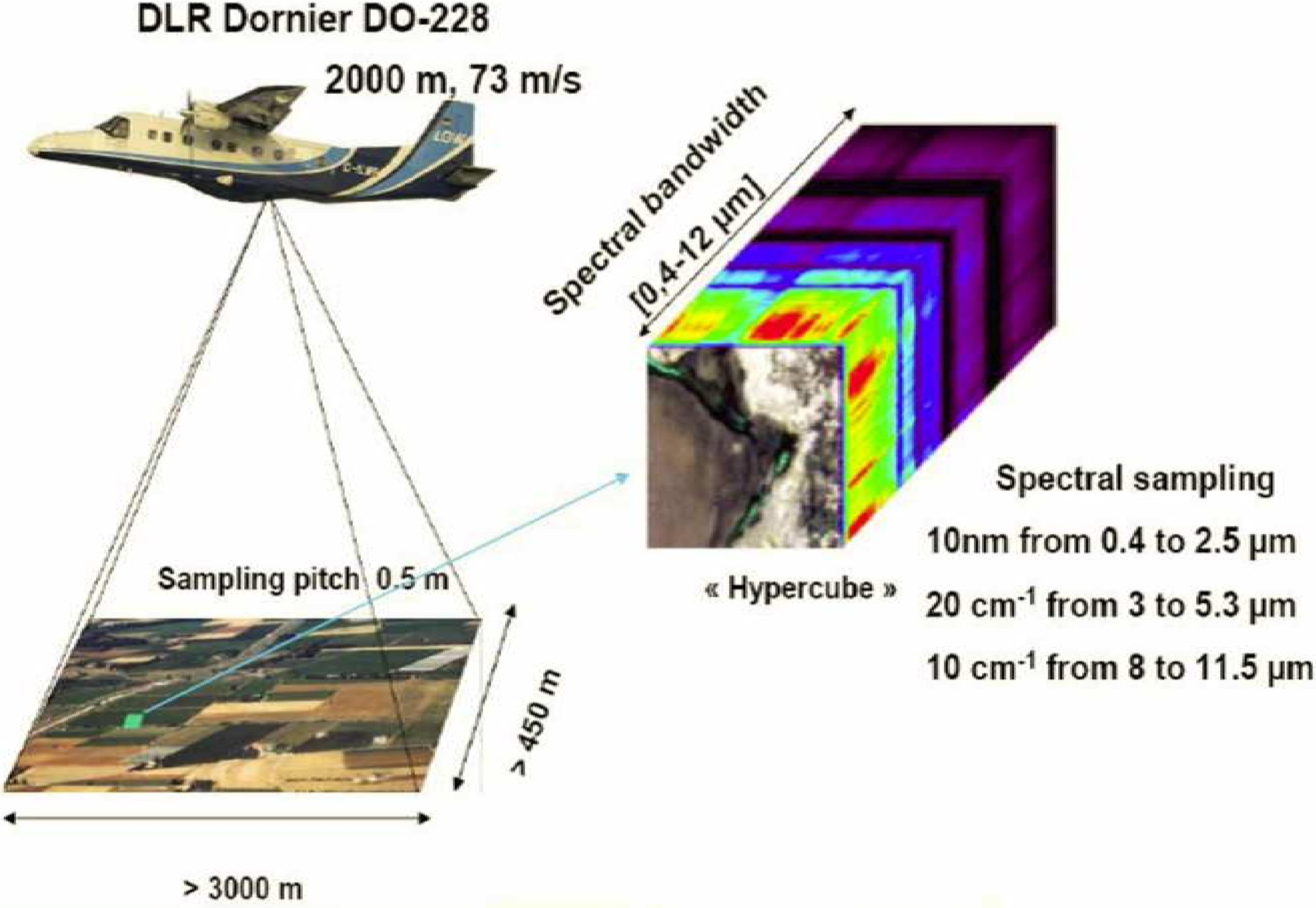


Polar-orbiting satellites (low-earth orbit)



Geostationary satellite

SYSIPHE main caracteristics

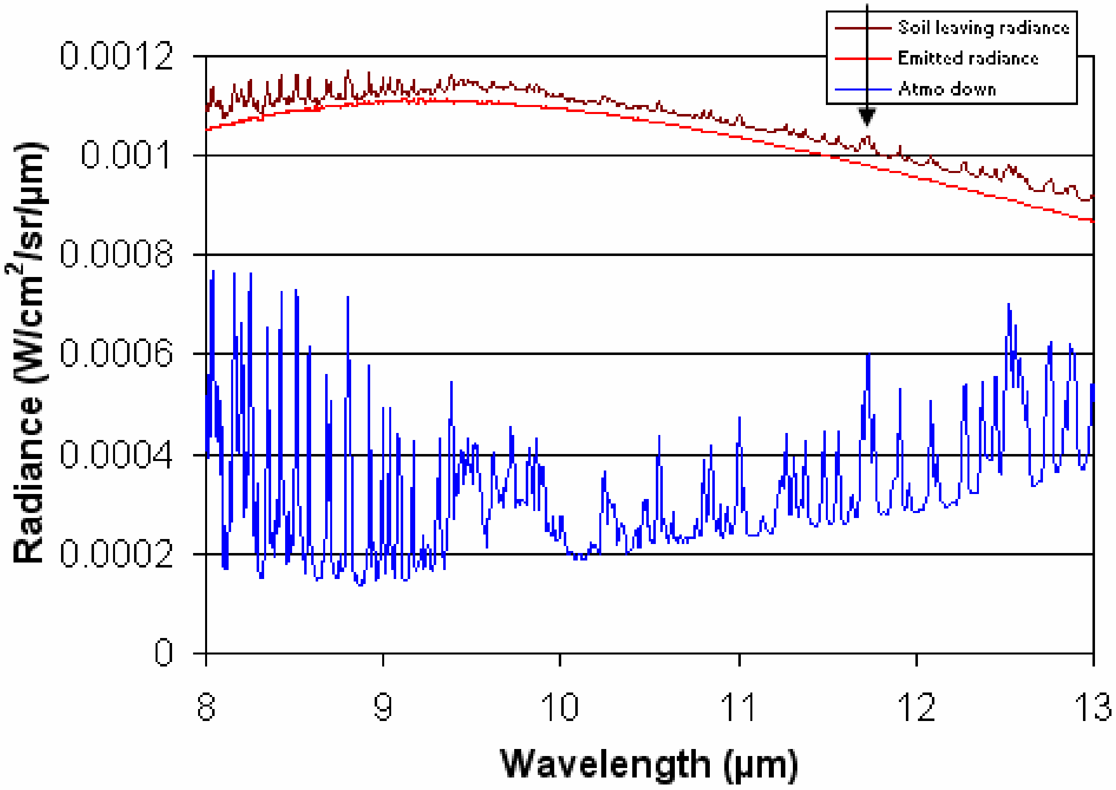


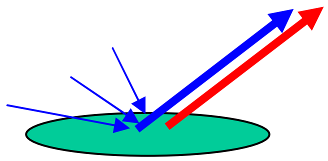
Specific features of IR remote sensing

- Measurements are highly conditioned by the **radiative properties of the atmosphere** (transmission, emission toward the earth surface and then reflection, emission along the optical path, scattering, …). Optical path in air from ~100 m to several km.
  - **Atmosphere compensation** is necessary
  - Atmosphere properties considered **uniform** in images of several km^2
- Footprint is generally large: from ~10 cm for low altitude airborne sensors to ~2 km for sensors on geostationary satellites ⟹ **aggregation** of various materials and temperatures (**desaggregation = inversion problem**)
- In [8-14µm] band, natural surfaces (soil, vegetation, water) have **high emissivity values** (> 0.9). Generally considered as Lambertian.

Evaluation of atmosphere contributions

- Example of a grey surface (ε=0.9) at T=313K
- Radiative transfer simulations with MODTRAN; (mid-latitude summer atmospheric model; rural aerosols)





$$L(\lambda,T)=\varepsilon(\lambda)B(\lambda,T)+(1-\varepsilon(\lambda))L^{\downarrow}(\lambda)$$

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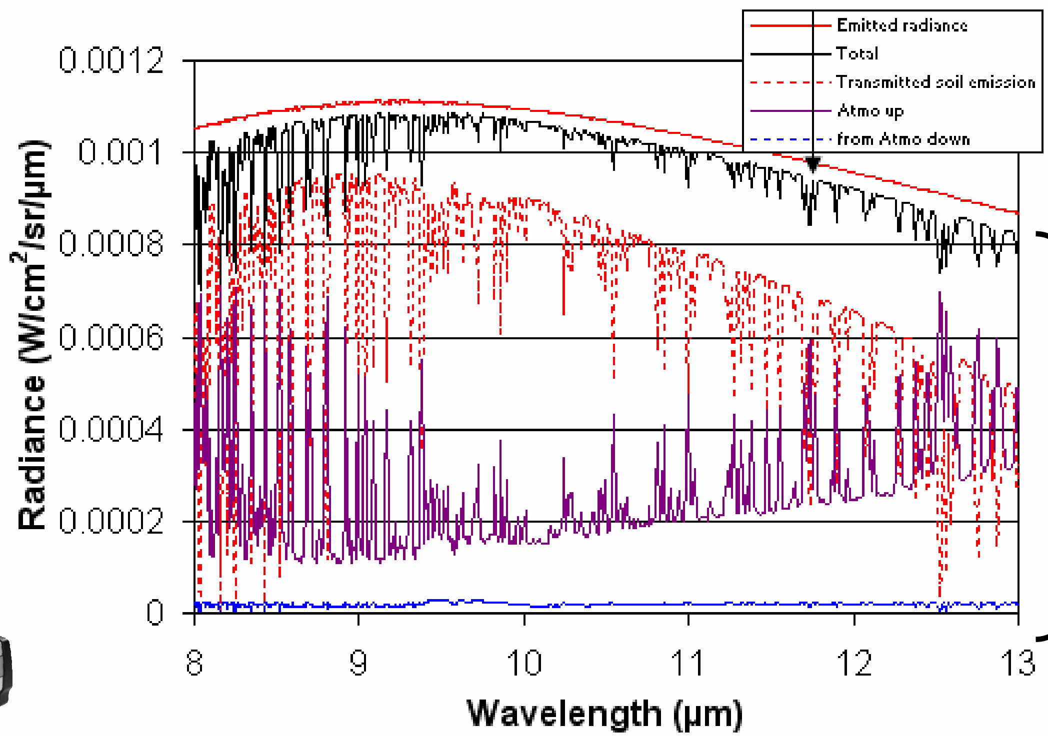
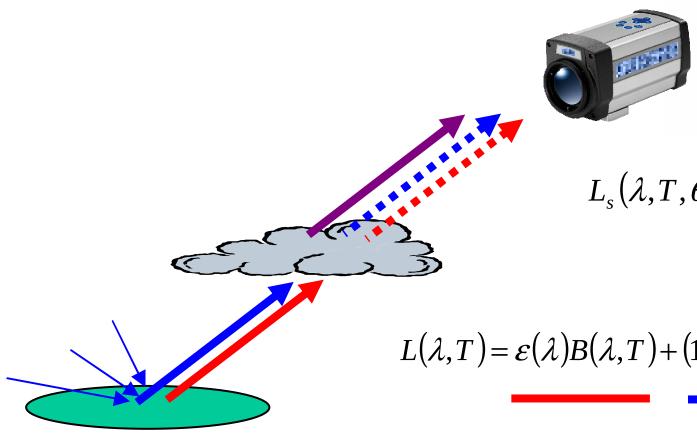
Evaluation of atmosphere contributions

- Example of a grey surface (ε=0.9) at T=313K sensed by an IR instrument at 1900 m altitude.
- Radiative transfer simulations with MODTRAN; (mid-latitude summer atmospheric model; rural aerosols)





$$L_s(\lambda,T,\theta,\varphi)=\tau(\lambda,\theta,\varphi)L(\lambda,T)+L^{\uparrow}(\lambda,\theta,\varphi)$$

at-sensor radiances

$$L(\lambda,T)=\varepsilon(\lambda)B(\lambda,T)+(1-\varepsilon(\lambda))L^{\downarrow}(\lambda)$$

Atmosphere separate compensation

Radiative transfer simulation (MODTRAN, MATISSE…) with:

- standard atmospheric models (temperature+humidity profiles)/climate/season/aerosols
- radiosonde data → profiles of pressure, temperature, constituents
- IR sounding near 4.3µm for CO_2 and between 4.8-5.5µm for H_2O + neural networks allows retrieving mean atmosphere temperature and columnar water vapor under the sensor. These values are then used to scale a set of standard atmosphere profiles used in MODTRAN and get closer to the true atmosphere profiles. Final MODTRAN computation

$$\Rightarrow \begin{cases} \tau(\lambda,\theta,\varphi) \\ L^{\uparrow}(\lambda,\theta,\varphi) \\ L^{\downarrow}(\lambda) \end{cases}$$

Emissivity-Temperature separation

- Proper atmosphere compensation provides **ground leaving radiance**:

$$L(\lambda,T)=\frac{L_s(\lambda,T)-L^{\uparrow}(\lambda)}{\tau(\lambda)}=\varepsilon(\lambda)B(\lambda,T)+(1-\varepsilon(\lambda))L^{\downarrow}(\lambda)$$

Emissivity estimation $\hat{\varepsilon}(\lambda)$ from a temperature estimation $\hat{T}$ according to

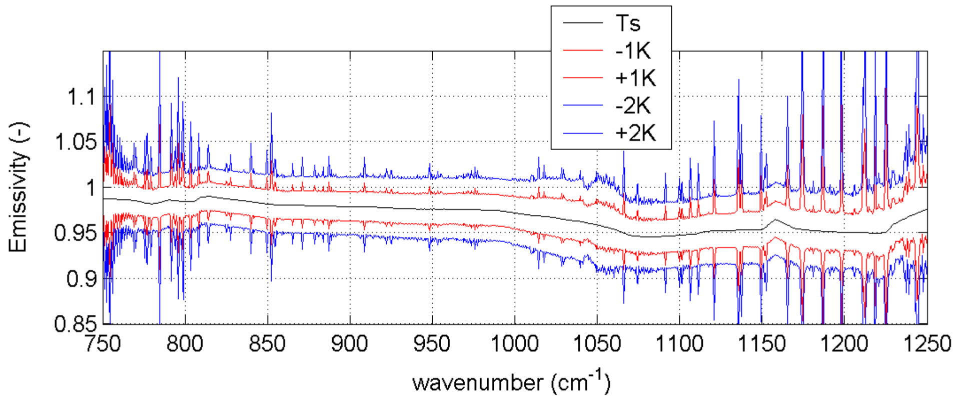
$$\hat{\varepsilon}(\lambda)=\frac{L(\lambda,T)-L^{\downarrow}(\lambda)}{B(\lambda,\hat{T})-L^{\downarrow}(\lambda)}$$

Spectral Smoothness method (SpSm) (1/2)

- When temperature estimation $\hat{T}$ **is in error**, the profile will contain **detailed spectral features** originating from $L(\lambda,T)$ and $L^{\downarrow}(\lambda)$ (gas absorption bands)

$$\hat{\varepsilon}(\lambda)=\frac{L(\lambda,T)-L^{\downarrow}(\lambda)}{B(\lambda,\hat{T})-L^{\downarrow}(\lambda)}$$

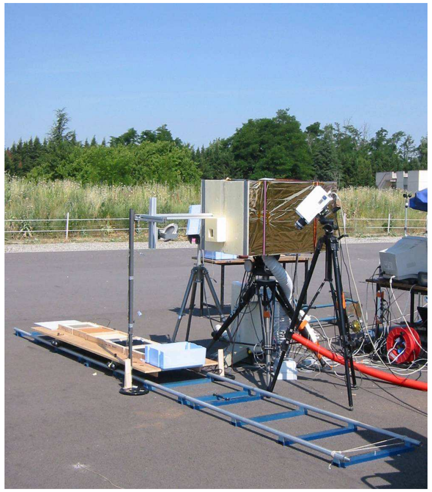
- Adjust $\hat{T}$ until $\hat{\varepsilon}(\lambda)$ is deprived of these artifacts → "smooth" emissivity spectrum



Knuteson, 2006

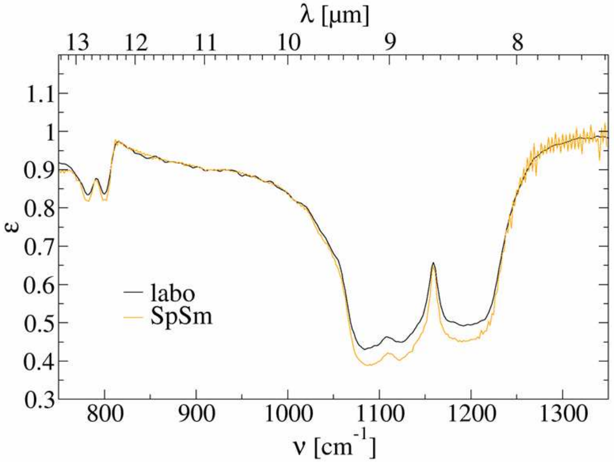
Spectral Smoothness method (SpSm) (2/2)

- Field tests at ONERA (K. Kanani thesis)



Spectroradiometer : BOMEM MR254

- SpSm requires the atmospheric compensation to be very precise
- SpSm requires high spectral resolution (< 10 cm^{-1}) in order to capture sufficient details of the atmosphere spectral features. Restricted to hyperspectral data. Spectral calibration errors are highly detrimental
- Radiance error of 0.5% → 1.6K RMS and 0.8K bias for temperature and 0.023 RMS and 0.027 bias for emissivity



Multi-temperature method : a pitfall ? (1/3)

one more unknown
N more data
⇨ **is the ill-conditionning solved ???**

- N_T temperature levels
- N channels

⇨

- N+N_T unknowns
- NxN_T equations

⇨ Solvable (**in principle**) if $N \geq 2$

However, using Wien 's approximation, it can be shown that, when there is no reflection contribution, the problem remains ill-conditionned !

- With errorless radiance, there is an infinite number of solutions defined by:

$$\begin{cases} \dfrac{1}{\hat{T}_t} = \dfrac{1}{T_t} + cst \\ \hat{\varepsilon}(\lambda) = \varepsilon(\lambda)\exp\left(\dfrac{C_2}{\lambda} cst\right) \end{cases}$$

- For two temperatures, the sensivity matrix is

$$\mathbf{X} = \begin{bmatrix} & \dfrac{-C_2}{\lambda_1 T_{ref}} & 0 \\ \mathbf{I}_N & \cdots & \cdots \\ & \dfrac{-C_2}{\lambda_N T_{ref}} & 0 \\ & 0 & \dfrac{-C_2}{\lambda_1 T_{ref}} \\ \mathbf{I}_N & \cdots & \cdots \\ & 0 & \dfrac{-C_2}{\lambda_N T_{ref}} \end{bmatrix}_{2N,N+2}$$

Sensitivities are correlated as $\det\left(\mathbf{X}^T\mathbf{X}\right) = 0$

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Multi-temperature method (2/3)

- The problem remains badly conditioned when using Planck's law
- Degeneracy is alleviated thanks to the presence of reflections
- Inversion robustness depends on the spectral richness of the reflections

Case of two temperatures.

Nonlinear least-squares approach for identifying the N emissivities and the two temperatures

$$[\varepsilon_i, T_1, T_2]^T = \underset{\varepsilon_i, T_1, T_2}{\arg Min} \sum_{i=1}^{N} \begin{matrix} \left(L(\lambda_i, T_1) - \left(\varepsilon_i B(\lambda_i, T_1) + (1-\varepsilon_i) L^{\downarrow}(\lambda_i)\right)\right)^2 + \\ \left(L(\lambda_i, T_2) - \left(\varepsilon_i B(\lambda_i, T_2) + (1-\varepsilon_i) L^{\downarrow}(\lambda_i)\right)\right)^2 \end{matrix}$$

Illustration for the case of a greybody (ε=0.9) at T_1 =320K.

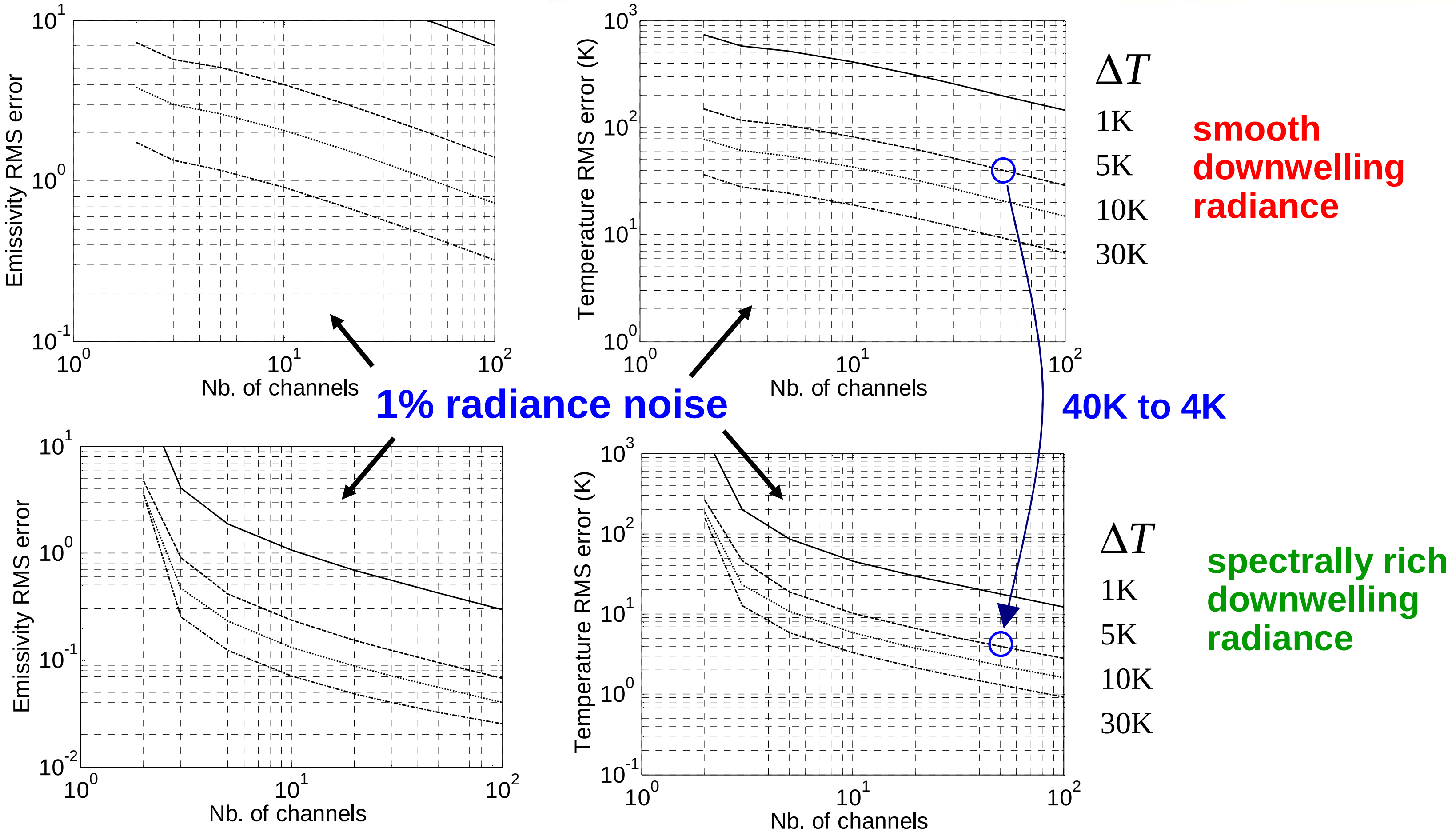
Second temperature is 1K, 5K, 10K or 30K higher.

Downwelling radiance is either:

- blackbody radiance at 300K
- same by weighting with a uniform random distribution (simulation of the presence of detailed spectral features)

Standard errors of identified parameters obtained from covariance matrix (local linearization)

Multi-temperature method (3/3)



Better results are obtained by increasing the number of channels and the temperature difference

High constraints to get a temperature RMS error lower than 1K !

Constraints on images co-registration, emissivity stability.

Conclusion

- Radiative temperature measurement
  - advantage : non-contact
  - disadvantage : underdetermined inverse problem due to emissivity
- « Mirage » of multiwavelength pyrometry
  - only very low order emissivity models could be considered (ex: 1 degree polyn.)
  - no significant benefit vs. single or two color pyrometry
- IR remote sensing takes profit from high emissivity of natural surfaces and from their spectral smoothness with respect to downwelling radiance
  - SpSm method : implementation phase for Sysiphe hyperspectral camera
  - Multi-temperature method
    - ineffective without reflections from spectrally rich and well characterized environment
    - additional constraints