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Thibaud Toullier, Jean Dumoulin, Laurent Mevel

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Sensitivity of different methods for simultaneous evaluation of emissivity and temperature through multispectral infrared thermography simulation

Introduction and nomenclature

This study focuses on the simultaneous evaluation of temperature and emissivity with multispectral infrared thermography (IRT). It leans on the study and development of an IRT simulator able to address 3D scene in static or dynamic configuration. The sensitivity of 4 different temperature and emissivity joint estimation methods are then evaluated.

$\Delta\lambda_i$	Wavelength interval of i^{th} band	$B_{k,\Delta\lambda_i}$	Radiosity of patch k on $\Delta\lambda_i$
$\epsilon_{k,\Delta\lambda_i}$	Emissivity of patch k in $\Delta\lambda_i$	$M_{k,\Delta\lambda_i}$	Emittance of patch k on $\Delta\lambda_i$
T	Object's temperature	$V_{kj} = \{0,1\}$	Visibility between patches k and j

IRT Simulator through the radiosity method

View factor

Geometrical coefficient for radiative exchange between two diffuse elements

$$F_{1 \rightarrow 2} = \int_{A_1} \int_{A_2} \frac{\cos(\theta_1) \cos(\theta_2)}{\pi r^2} dA_1 dA_2$$

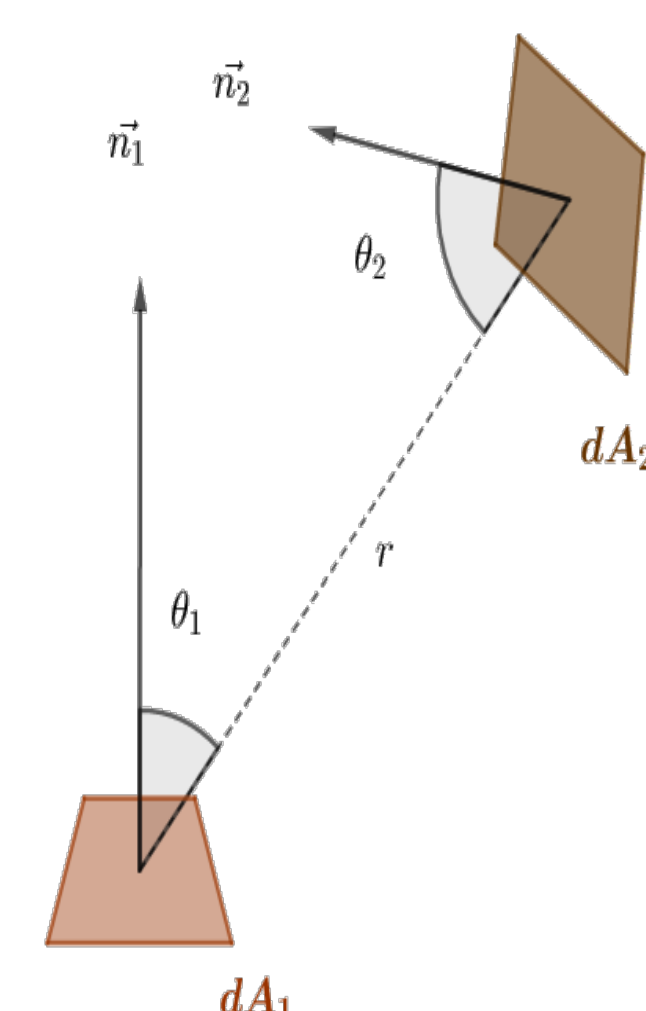


Fig. 1 : Geometry for two infinitesimal elements

Radiosity equation¹

$$B_{k,\Delta\lambda_i} = M_{k,\Delta\lambda_i} + (1 - \epsilon_{k,\Delta\lambda_i}) \sum_{j=1, j \neq k}^{j=N_{\text{elements}}} V_{kj} F_{k \rightarrow j} B_{j,\Delta\lambda_i}$$

C++ Implementation

- GPU acceleration through OpenGL's API
- User-friendly graphical interface
- Python interpreter for user-case scenarios
- Use models from literature : \Rightarrow Get the solar spectral radiation at ground
- Sensor model for radiative illumination to image \Rightarrow Sensor model for radiative illumination to image

3D Model

A target with 4 different materials properties

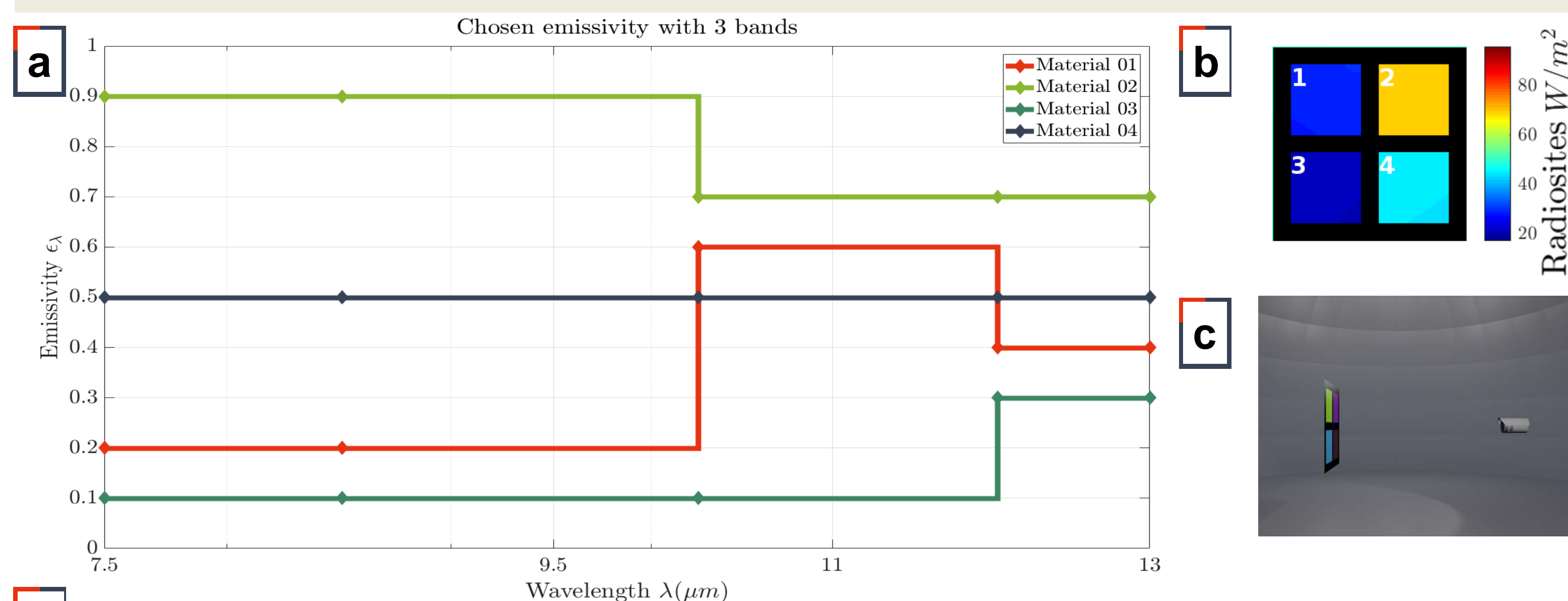


Fig. 2 : (a) Spectral emissivity distribution of 4 artificial materials for the target in the $7.5\mu\text{m} - 13\mu\text{m}$ bandwidth (b) Simulation results for $T = 313.15\text{K}$ (c) Camera, target and environment in the visible (d) Temperature ranges

	T (K)	T (K)		T (K)
Simulation 1	293.15	Simulation 3	333.15	
Simulation 2	313.15	Simulation 4	353.15	

Temperature and emissivity retrieval

With Bouguer's law and for infinitesimal surfaces²:

$$E_{\text{sensor},\Delta\lambda_i} = \frac{I_{\text{object},\Delta\lambda_i} \cos(\theta_{\text{sensor}})}{r^2} = \frac{\cos(\theta_{\text{object}}) \cos(\theta_{\text{sensor}}) dS_{\text{object}}}{r^2} L_{\text{object}}(\Delta\lambda_i, T)$$

\Rightarrow Undetermined system with $\epsilon_{\Delta\lambda_i}$ and T unknowns

$$E_{\text{capteur},\Delta\lambda_i} = g(\theta_{\text{capteur}}, \theta_{\text{objet}}, r) \epsilon_{\Delta\lambda_i} L^o(\Delta\lambda_i, T)$$

Compared methods

Non linear optimization

$$\text{argmin} \sum_{i=1}^N \left[\gamma_{\Delta\lambda_i} - \epsilon_{\Delta\lambda_i} \int_{\Delta\lambda_i} L^o(\lambda, T) d\lambda \right]^2$$

$$\epsilon_{\Delta\lambda_i} = \sum_{j=0}^M a_j \Phi_j(\Delta\lambda_i); \quad 0 \leq \epsilon_{\Delta\lambda_i} \leq 1;$$

$$(\Phi_j)_{1 \leq j \leq M} \text{ orthonormal basis (Tchebychev-1)}$$

$$200\text{K} \leq T \leq 400\text{K}$$

« Temperature Emissivity (TES) Method »³

$$T(\Delta\lambda_i) = L^{o-1} \left[\frac{\gamma_{\Delta\lambda_i} - L_{\text{env}}(\Delta\lambda_i)}{\epsilon_{\text{max}}} + L_{\text{env}}(\Delta\lambda_i) \right],$$

$$\tilde{T} = \max_{\Delta\lambda_i} (\text{sgn}(\gamma_{\Delta\lambda_i} - L_{\text{env}}(\Delta\lambda_i)) T(\Delta\lambda_i))$$

$$\tilde{\epsilon}(\Delta\lambda_i) = \frac{\gamma_{\Delta\lambda_i} - L_{\text{env}}(\Delta\lambda_i)}{L^o(\Delta\lambda_i, \tilde{T}) - L_{\text{env}}(\Delta\lambda_i)}, \quad \beta(\Delta\lambda_i) = \frac{\tilde{\epsilon}(\Delta\lambda_i)}{\tilde{\epsilon}(\Delta\lambda_i)}$$

$$\epsilon_{\text{min}} \approx a - b(\beta_{\text{max}} - \beta_{\text{min}})^c$$

$$\hat{\epsilon}(\Delta\lambda_i) = \beta(\Delta\lambda_i) \frac{\epsilon_{\text{min}}}{\beta_{\text{min}}}$$

Multi-temperature⁴

$$\text{argmin} \sum_{i=1}^N \left[\gamma_{\Delta\lambda_i, T_1} - \epsilon_{\Delta\lambda_i} \int_{\Delta\lambda_i} L^o(\lambda, T_1) d\lambda \right]^2 + \left[\gamma_{\Delta\lambda_i, T_2} - \epsilon_{\Delta\lambda_i} \int_{\Delta\lambda_i} L^o(\lambda, T_2) d\lambda \right]^2$$

$$\epsilon_{\Delta\lambda_i} = \sum_{j=0}^M a_j \Delta\lambda_i^j; \quad 0 \leq \epsilon_{\Delta\lambda_i} \leq 1; \quad 200\text{K} \leq T_1 \leq 400\text{K}; \quad 200\text{K} \leq T_2 \leq 400\text{K}$$

Bayesian (Monte-Carlo Markov Chain (MCMC))⁵

A priori known laws:

$$\epsilon \approx \mathcal{N}(\mu_\epsilon, \Sigma_\epsilon)$$

$$T \approx \mathcal{U}(T_{\text{min}}, T_{\text{max}})$$

$$\text{With } \mu_{\text{epsilon}} = \begin{pmatrix} 0.6 \\ 0.6 \\ 0.6 \end{pmatrix}, \Sigma_{\text{epsilon}} = \begin{pmatrix} 1 & 0.8 & 0.8 \\ 0.8 & 1 & 0.8 \\ 0.8 & 0.8 & 1 \end{pmatrix}$$

Draw variables ϵ and T by using the targeted distributions $p(\epsilon|\gamma)$ and $p(T|\gamma)$ with a *Slice-within-Gibbs* sampler.

Results

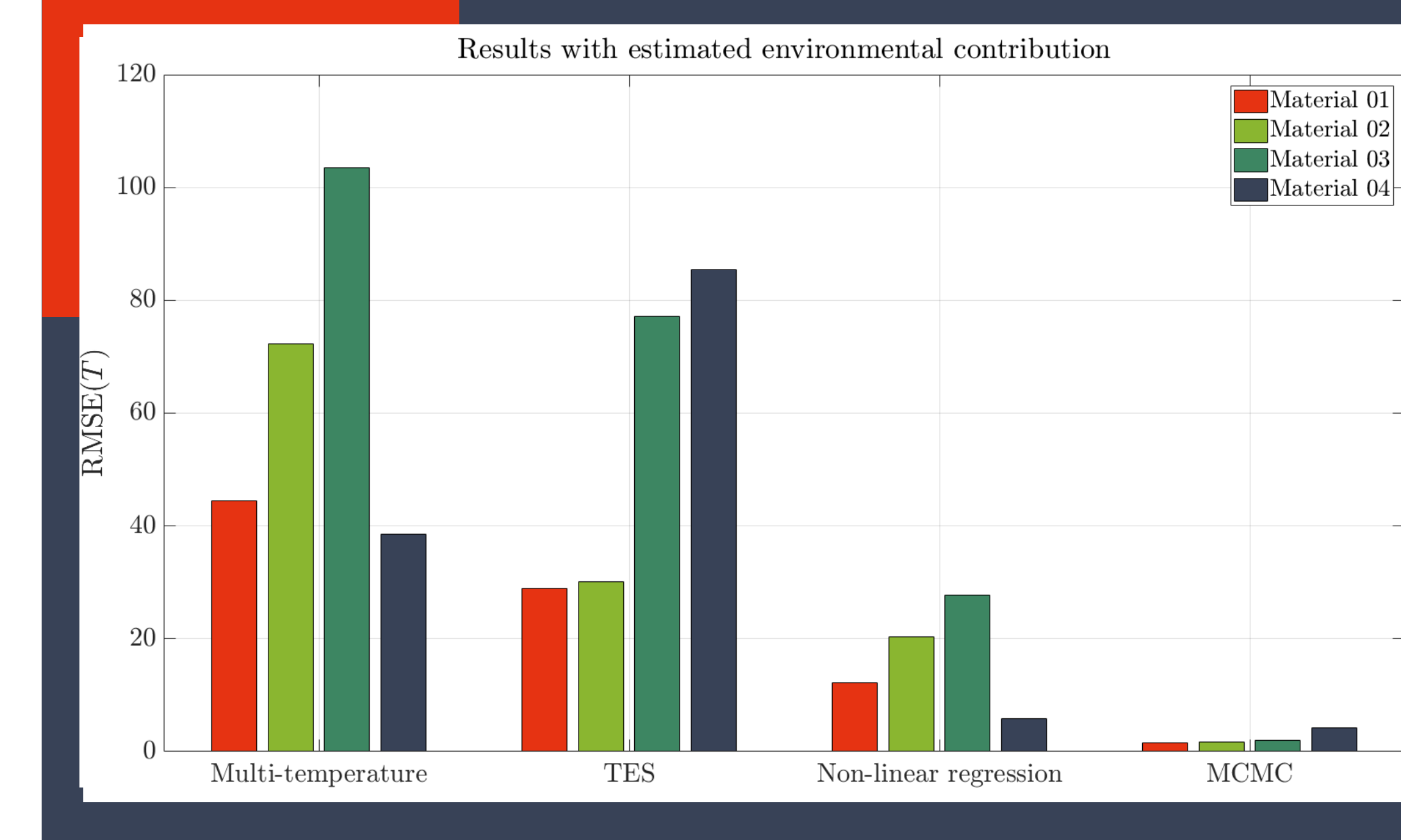


Fig. 3 : Temperature estimation for the 4 different methods

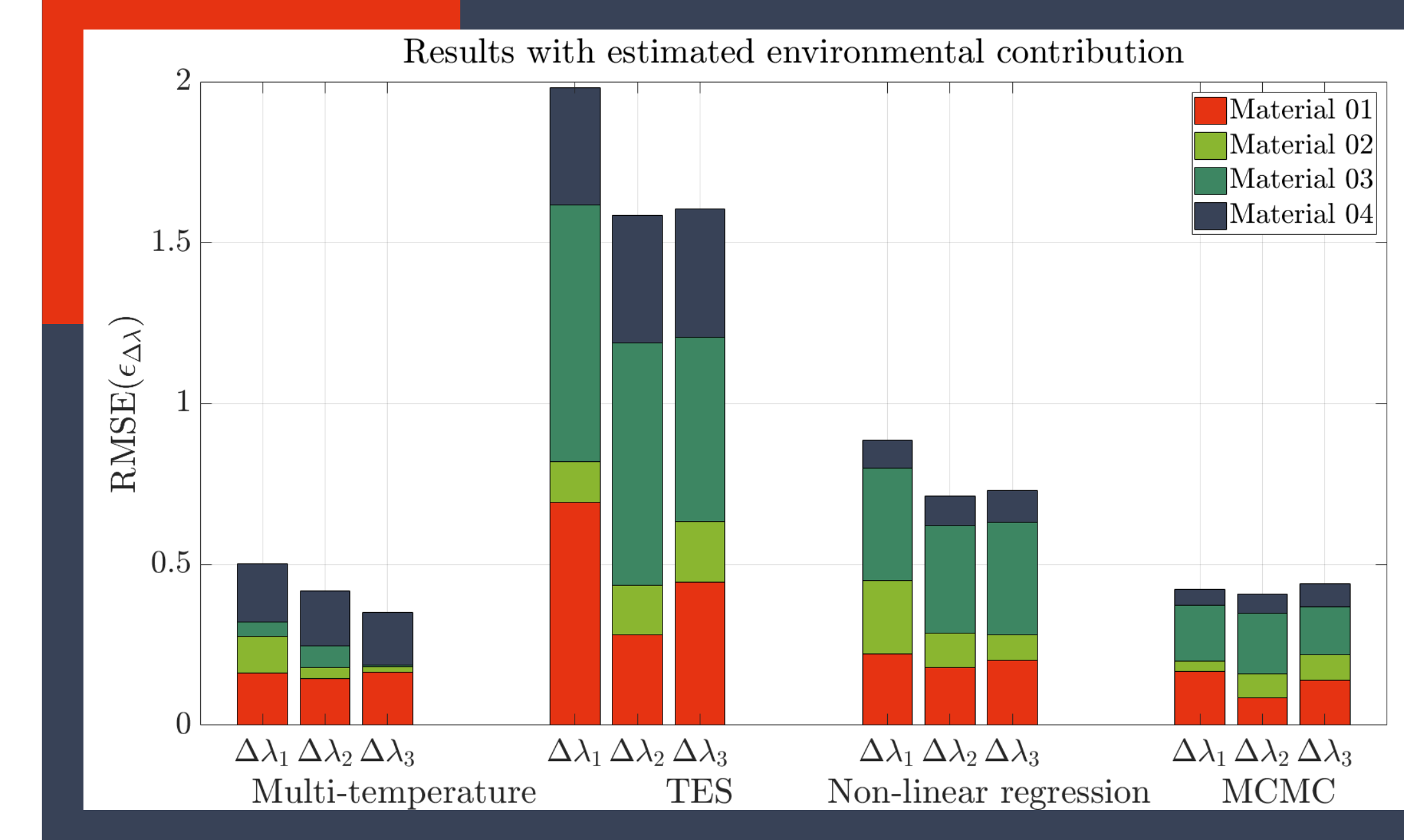


Fig. 4 : Emissivity estimation for the 4 different methods

Stopping criteria

- Optimization algorithms \Rightarrow local minimum
- Metaheuristic \Rightarrow 10000 iterations

$$RMSE(x) = \frac{1}{N_{\text{simu}} \times N_{\text{pixels}}} \sum_{k=1}^{N_{\text{simu}}} \sum_{j=1}^{N_{\text{pixels}}} \sqrt{(x_{k,j} - x_{\text{objective},k})^2}$$

Observations

- Non linear methods find a local minimum without any guarantee on the physical solution
- TES relies on a correlation based on a database linked with airborne based applications
- MCMC is a metaheuristic that requires a long time and effort to be computed

Conclusion and perspectives

Conclusion:

- Comparison of 4 methods to estimate simultaneously emissivity and temperature
- Study and development of a 3D scene IRT simulator

Perspectives:

- Add measurement noises in the simulation process to observe their effect
- Combine temporal and spatial information in Bayesian methods for further improvements of joint estimation

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