Hyperspectral remote sensing for detection and identification of industrial aerosol plumes with a Cluster-Tuned Matched Filter

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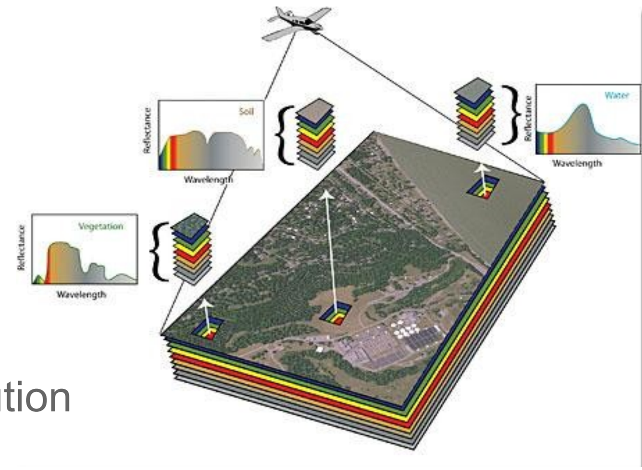
Why studying aerosols?

- Scientific goals: radiative impact on the climate [IPCC 2013] (global warming, clouds/aerosols interactions, ...) and health impact (air pollution, acid rains, ...)
- Defence and security: monitoring industrial activities



Hyperspectral remote sensing to meet the needs

- Metric or decametric spatial resolution
- Spectral domain from 0.4 to 2.5 µm and 10 nm spectral resolution (aerosol impact occurs mainly before 1 µm)
- Need of a signal-to-noise ratio (SNR) high enough to differentiate particles with close optical properties

Goal of this study:

To develop a method for the detection and the identification of industrial aerosol plumes by hyperspectral imaging

INDUSTRIAL AEROSOLS CLASSIFICATION
Aerosols families from major industrial plants releases

- **Absorbing aerosols**:
  - **Soot (or black carbon)**: combustion of coal for energy production
  - **Metals**: metallic dusts of very variable composition from metallurgical industry
- **Scattering aerosols**:
  - **Organic carbon**: organic compounds from biomass combustion, heating and energy production
  - **Sulfates**: a secondary origin aerosol (from SO_2 reaction with atmospheric compounds) produced from fossil fuels, such as in refineries
- **Intermediate behavior aerosols**:
  - **Brown carbon**: light-absorbing organic carbon, derived from the combustion of organic matter, tar materials or coal combustion (highly absorbant in UV domain and less significantly in the visible)
- **Liquid water droplets**: visible water plumes from cooling towers, under atmospheric conditions allowing the condensation of water vapor

Soot plume, Fawley oil-fired power station, Hampshire (GBR)

Sulfates, Suncor Energy refinery, Fort McMurray (CAN)

Cooling towers of Tricastin nuclear plant (FRA)

For each family, we define:
- one refractive index from litterature (respectively from Fenn & Clough 1985, Quinn *et al.* 1995, Hoffer *et al.* 2006, Irvine & Pollack 1968)
- three granulometric modes (fine, accumulation and coarse) except for water droplets (as cumulus clouds, Hanna 1976)

10 aerosol classes used for detection and identification

CLUSTER-TUNED MATCHED FILTER
(Funk et al. 2001)

- Method successfully used for gas plumes such as N_2O, CO_2 and CH_4 (Thorpe *et al.* 2012, Dennison *et al.* 2013, Thorpe *et al.* 2013)

Radiance model

$$r = u + \alpha b + \varepsilon$$

r: radiance modeled as a linear combination of background and target signals

u: mean background radiance
α: amount of target signal in a pixel
b: target signature
ε: sensor noise and clutter in the scene

Hyperspectral image → Ground classification (*k*-means) → Optimal matched filter computation for class *j*:

$$q_j = \frac{C_j^{-1} \cdot b}{\sqrt{b^T \cdot C_j^{-1} \cdot b}}$$

→ CTMF score computation for each pixel *i* in class *j*:

$$f_{i,j} = q_j^T \cdot (r_i - u_j)$$

j: soil class
q_j: optimal matched filter for class *j*
C_j: correlation matrix of the background clutter for class *j*
b: target signature

i: pixel
$f_{i,j}$: score for pixel *i* in class *j*
r_i: radiance for pixel *i*
u_j: mean background radiance of class *j*

We propose to adapt this filter for the case of aerosols, requiring a linearized model for the radiance.

CTMF FILTER ADAPTED FOR AEROSOLS (1/2)

Radiative transfer equation (RTE)

- **RTE in the reflective domain (0.4 to 2.5 µm) in clear sky conditions**

$$L^{sensor}(\lambda) = L^{atm}(\lambda) + \frac{E^{surf}(\lambda)}{\pi} . \rho_{soil}(\lambda) \cdot T^{atm}(\lambda)$$

- **RTE in the reflective domain (0.4 to 2.5 µm) in the presence of an aerosol plume**
  - Each radiative term is affected by the aerosol plume, both in absorption and scattering.

$$L^{sensor}_{plume}(\lambda) = L^{atm}_{plume}(\lambda) + \frac{E^{surf}_{plume}(\lambda)}{\pi} . \rho_{soil}(\lambda) \cdot T^{atm}_{plume}(\lambda)$$

No analytical model because of the multiple scattering components of radiative terms (involving integrals over all space)

CTMF FILTER ADAPTED FOR AEROSOLS (2/2)

Target aerosol signature building

Radiance model

$r = u + \alpha b + \varepsilon$

We can show that the differential radiance can be written as:

$$\Delta L^{sensor}(\lambda) = L^{sensor}_{plume}(\lambda) - L^{sensor}(\lambda) = \underbrace{\frac{\tau^{550}}{\tau^{550}_{ref}}}_{\alpha} \cdot \underbrace{\left[\Delta L^{atm} + \frac{\rho_{soil}}{\pi} \cdot \left(\Delta E^{surf} \cdot T^{atm} + E^{surf} \cdot \Delta T^{atm} + \Delta E^{surf} \cdot \Delta T^{atm}\right)\right]}_{b}$$

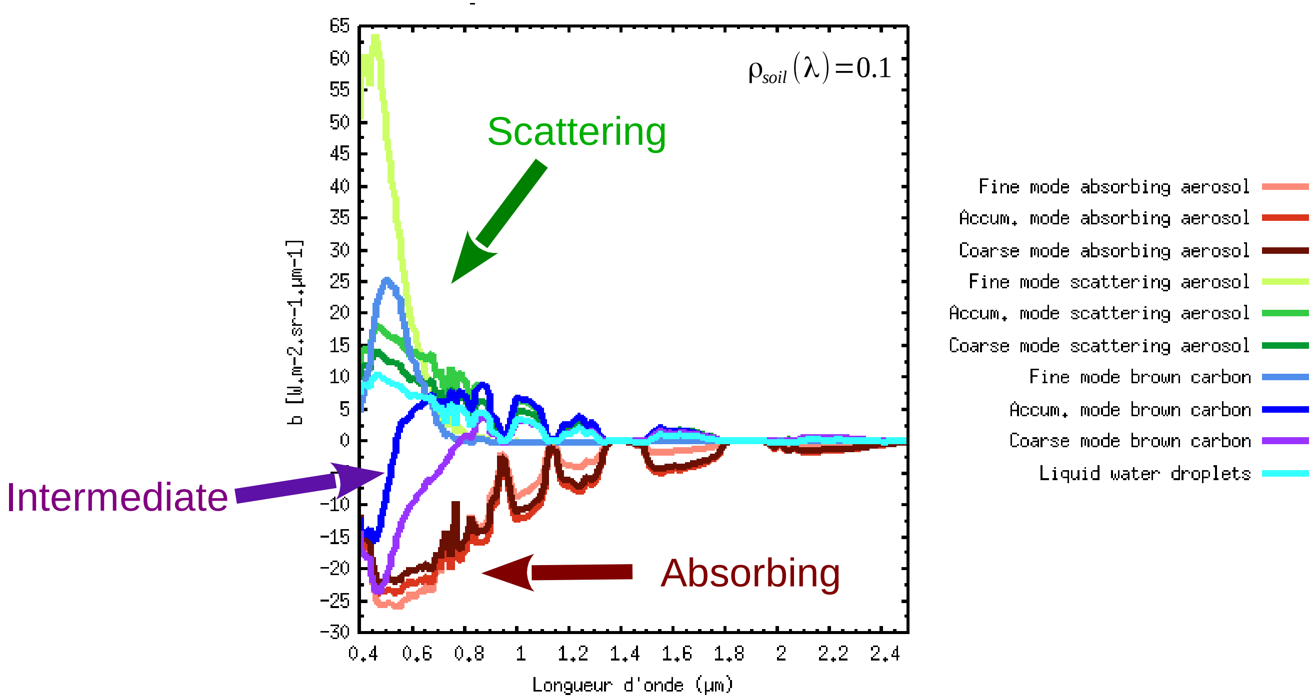
- ρ_{soil} is estimated thanks to an atmospheric correction (ATCOR).
- E^{surf} and T^{atm} are computed with MODTRAN (atmospheric parameters from ATCOR outputs), without taking the plume into account.
- ΔL^{atm}, ΔE^{surf} and ΔT^{atm} (radiative term with plume minus the same without) are computed with MODTRAN (same atmospheric parameters) for a plume AOT equal to τ^{550}_{ref}.
- The reference AOT τ^{550}_{ref} is defined to be close enough to AOT of observed plumes τ^{550} (equal to 0.25 in our practical cases).

From this, we obtain the 10 target signatures *b*.

EXAMPLE OF TARGET AEROSOL SIGNATURES

Impact of an aerosol plume on hyperspectral signal

$$b = \Delta L^{atm} + \frac{\rho_{soil}}{\pi} \cdot \left(\Delta E^{surf} \cdot T^{atm} + E^{surf} \cdot \Delta T^{atm} + \Delta E^{surf} \cdot \Delta T^{atm} \right)$$



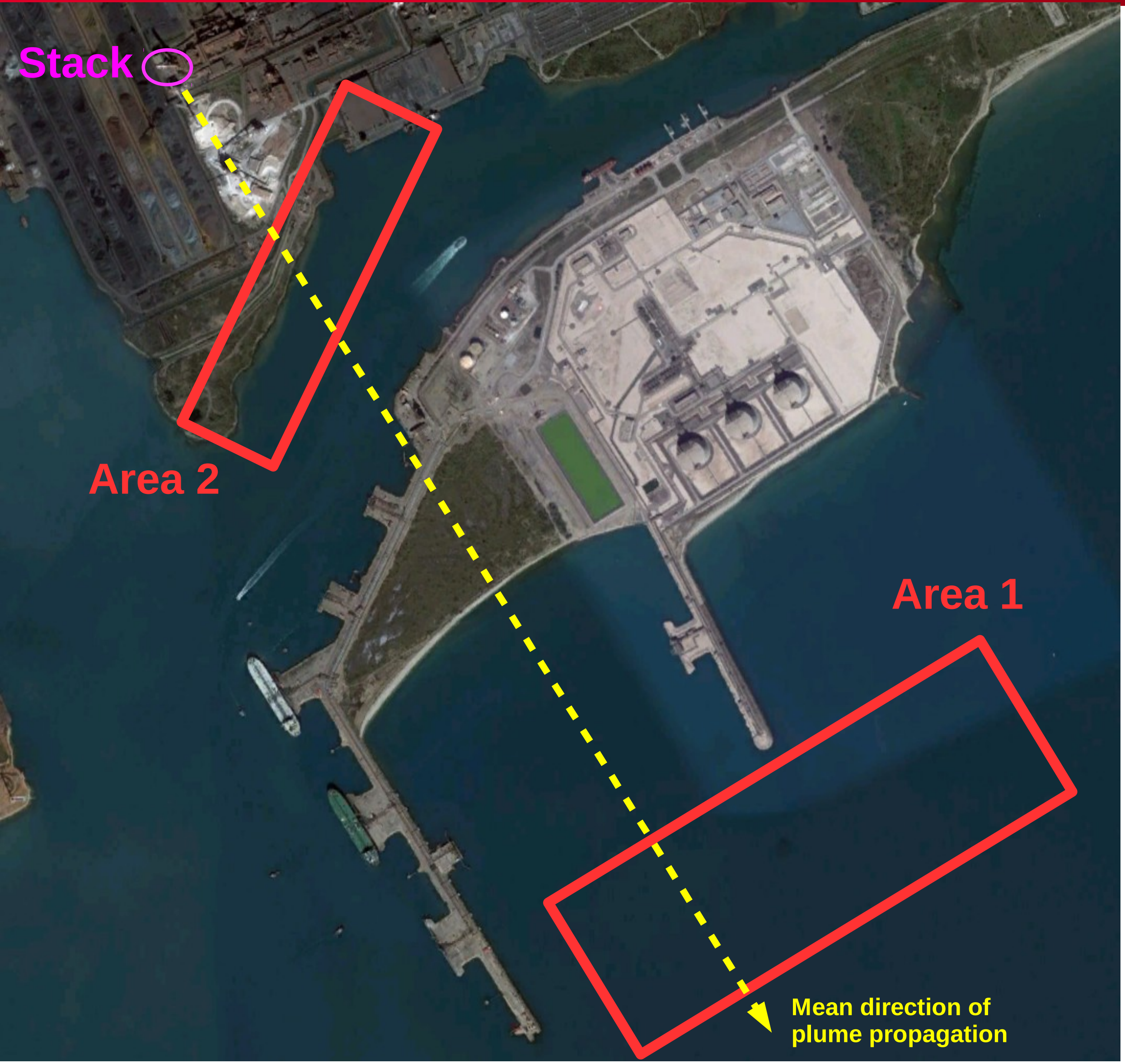
Three distinct behaviors between absorbing, scattering and intermediate aerosols.

For scattering and intermediate aerosols, satisfying discrimination between fine mode and others.

Water droplets acts like coarse scattering oganic aerosols.

The size of the particles mainly impacts scattering, not absorpion.

APPLICATION ON INDUSTRIAL SCENE (1/3)
Site presentation



Screenshot from Google Earth (2016 Digital Globe images)

Campaign EUFAR 2011
Fos-sur-Mer (south-eastern France)
Plume from ArcelorMittal plant
(metallurgical industry)

Sensor:
- CASI (Compact Airborne Spectrographic Imager)
- 144 spectral channels on [0.36 ; 1.05] µm
- Spectral resolution: 4.8 nm
- Spatial resolution: 1.58 x 0.96 m
- Flight altitude: 1950 m (airborne)
- Used channels: 57 on [0.40 ; 0.67] µm + 33 on [0.74 ; 0.89] µm (from SNR considerations)

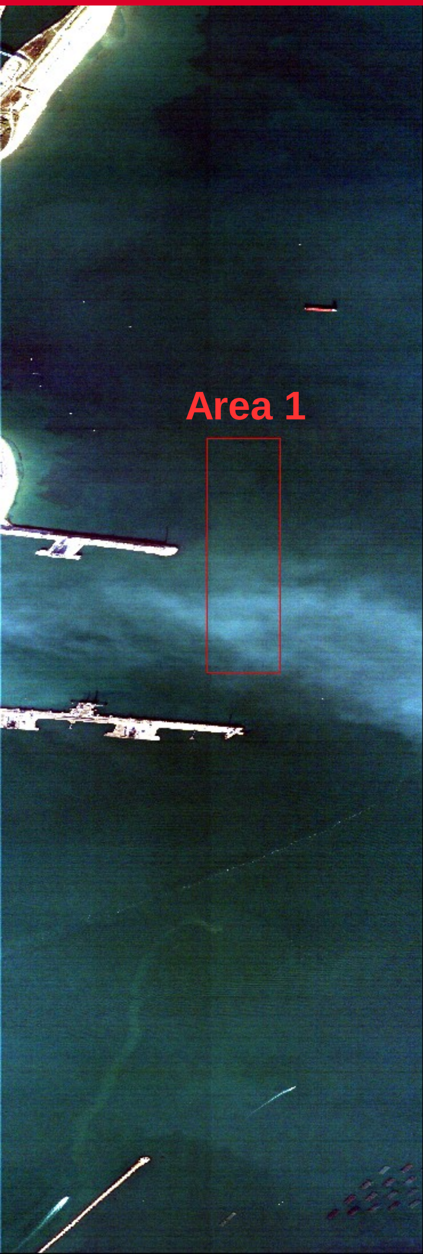
Ground truth (LPCA, 2013):
- Sinter plant, stack releasing inorganic materials (calcium salts), aluminosilicate minerals

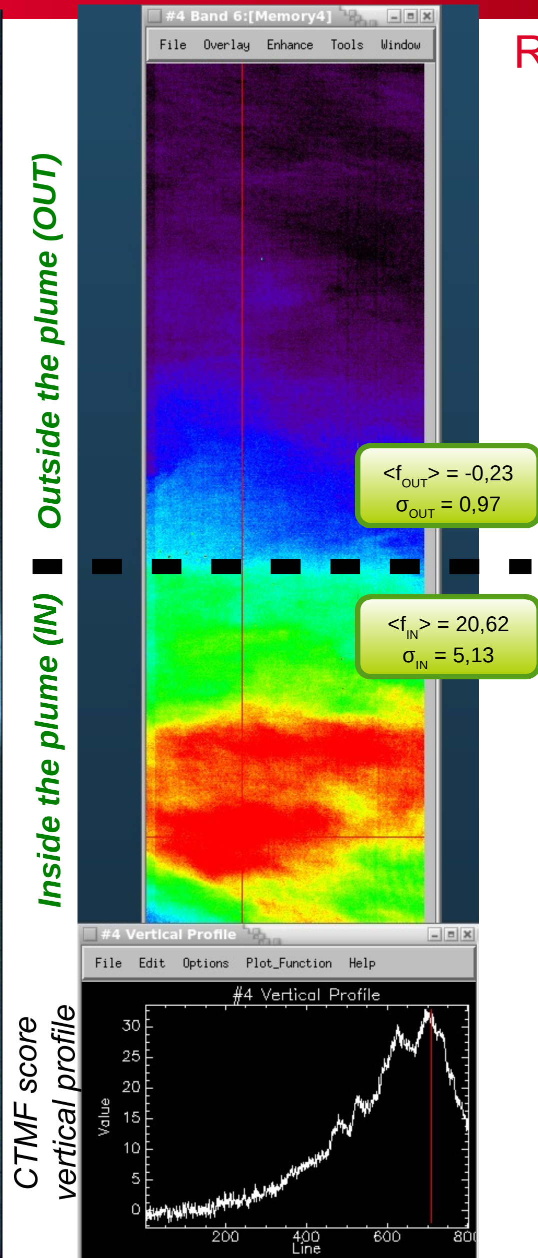
Area 1: plume above water

Area 2: plume above several soils

APPLICATION ON INDUSTRIAL SCENE (2/3)

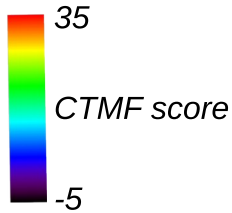
Area 1: plume above water





Results:

- CTMF mean score value of 0 and sigma of 1 outside the plume
- Score increases to center of the plume on a vertical section
- CTMF score value slightly biaised outside the plume: probably due to spatial mask not covering exactly the whole plume



Coarse mode scattering aerosols detected and identified

- Quite good SNR
- Results in agreement with ground truth measurements

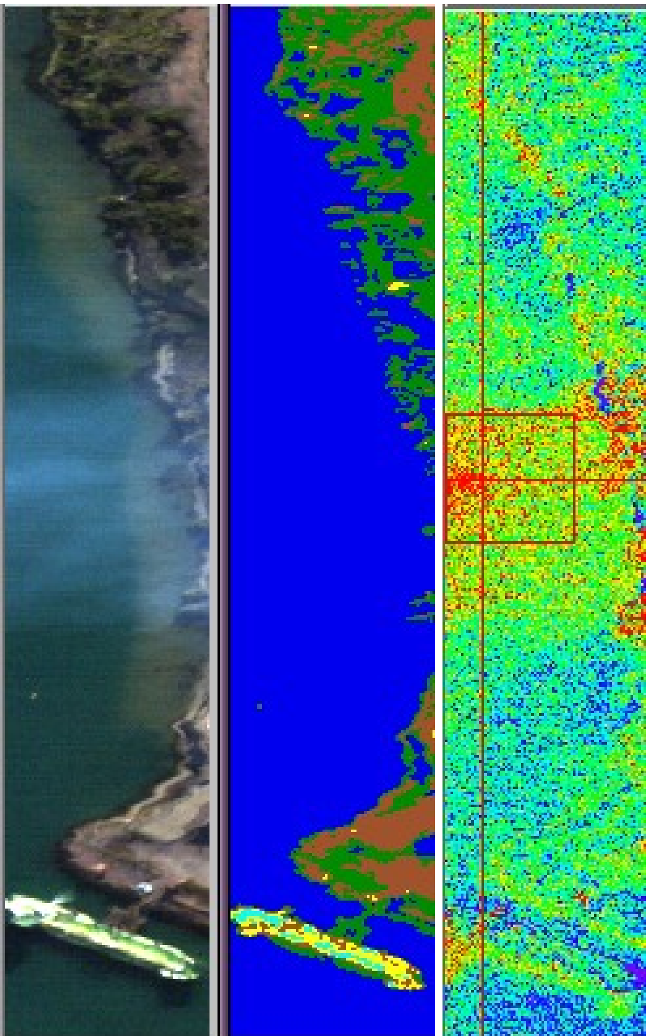
APPLICATION ON INDUSTRIAL SCENE (3/3)

Area 2: plume above several soils

At left: thumbnail image (area 2)

At center: k-means classification (water in blue, vegetation in green, bare soil in brown, artificial surfaces in yellow and cyan)

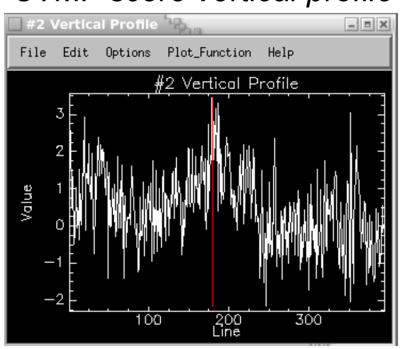
At right: CTMF score map



$\langle f_{OUT} \rangle = -0{,}10$
$\sigma_{OUT} = 0{,}73$

$\langle f_{IN} \rangle = 1{,}72$
$\sigma_{IN} = 0{,}80$

CTMF score vertical profile



Results:

- Results more biaised/noisy than previously, particularly above emerged soils
- K-means not so efficient as expected under the plume, causing errors on mean background reflectance used for computation of the target signature

Scattering aerosols detected and identified

- Low SNR
- Detection noise makes the choice of granulometric mode too difficult

CONCLUSIONS AND PERSPECTIVES

Conclusions:

- Handmade classification of industrial aerosols:
  - Optical properties computed (Mie theory, with microphysical properties from the litterature)
  - Differentials of radiative transfer terms can be stored into a database (with a reference AOT choosen to be close to AOT of expected observed plumes)
- Semi-analytical model developed for the differential radiance (radiance with plume minus radiance without plume)
- CTMF filter adapted to the case of industrial aerosols
  - Preliminary results on a real test case demonstrate the faisibility of this approach

Perspectives:

- Study of averages and standard deviations of CTMF scores
- Sensitivity studies on semi-analytical model and inversion method (and especially soil classification and modes for aerosol classes)
- Tests on other industrial plumes, with other sensors
- AOT estimation for quantitative retrievals
- Aerosols mixtures

MERCI POUR VOTRE ATTENTION

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APPENDICE / APPLICATION ON INDUSTRIAL SCENE

Area 1: detection maps for several aerosol classes