Plume Quantification tools for Hyperspectral data

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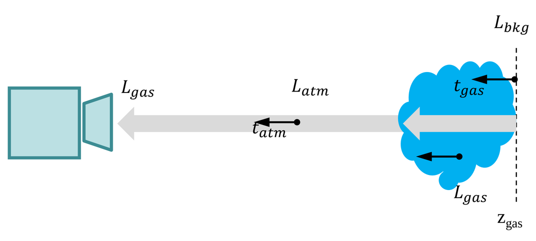
Plume radiative impact – Quantification Methods

Gas quantification (SWIR –LWIR)



Gas Transmission model

$$L_{gas} = \tau_{gas}.\tau_{atm}.L_{bkg} + \tau_{atm}.(1-\tau_{gas}).B(T_{gas}) + L_{atm}$$

$$L_{ref} = \tau_{atm}.L_{bkg} + L_{atm}$$

LWIR case

$$\tau_{gas} = 1 + \frac{L_{gas} - L_{ref}}{(L_{ref} - L_{atm} - \tau_{atm}.B(T_{gas}))}$$

SWIR Case

$$\tau_{gas} = \frac{L_{gas} - L_{atm}}{(L_{ref} - L_{atm})}$$

τ_{gas} cube

- $\boldsymbol{\tau_{atm}}$, $\boldsymbol{L_{atm}}$ — Atmospheric Correction from *In Scene -Like Algorithm* (LWIR) or COCHISE algorithm (SWIR) : extraction of atmospheric « Off plume » radiative terms and Ground Air Temperature T_{atm}
- $\boldsymbol{T_{gas}}$ — Assumption : $T_{gas}=T_{atm}$ or T_{gas}=Tb at gas saturated channel near the source (corrected from atmosphere)
- L_{ref} — (i) Acquisition without gas leak (multi-temporal analysis) / (ii) Estimate Reference radiance from an acquisition with gas leak (single image analysis) : CSB algorithm. Idoughi et al., 2016

Detection map

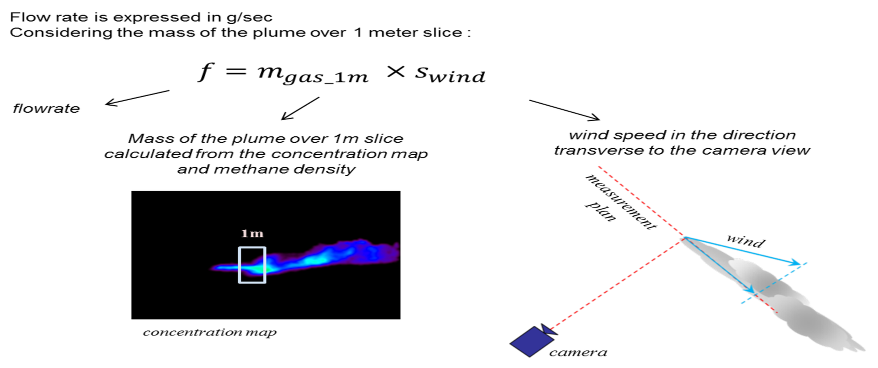
Quantification map

- The first step is the calculation of the gas transmission cube by estimating all parameters of the τ_{gas} equation
- The detection and concentration steps are deduced from the differential and the τ_{gas} cube :
- Detection : correlation map between the estimated transmission and the theoretical transmissions (CTMF like algorithm for low signatures)
- Quantification : Linear spectral retrieval is applied for the transmission or residual minimization for high concentrations.

Flow rate estimate

Flow rate is expressed in g/sec
Considering the mass of the plume over 1 meter slice :

$$f = m_{gas\_1m} \times s_{wind}$$



Linearisation of the transmission

$$\tau_{gas} = 1 - \rho_{ref}\ ILSF * A_{gas\_m} = 1 - \rho \quad A_{gas}$$

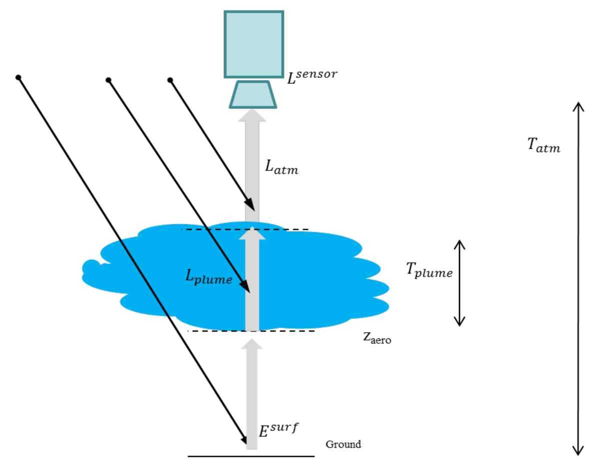
Monochromatic transmission hypothesis

$$\tau_{gas} = e^{-\rho\ ILSF * A_{gas\_m}} = e^{-\rho \quad A_{gas}}$$

Gas transmission pre-calculations.

$$\tau_{gas} = ILSF * e^{-\rho \quad A_{gas\_m}}$$

Aerosol quantification (SWIR)



Aerosol impact model

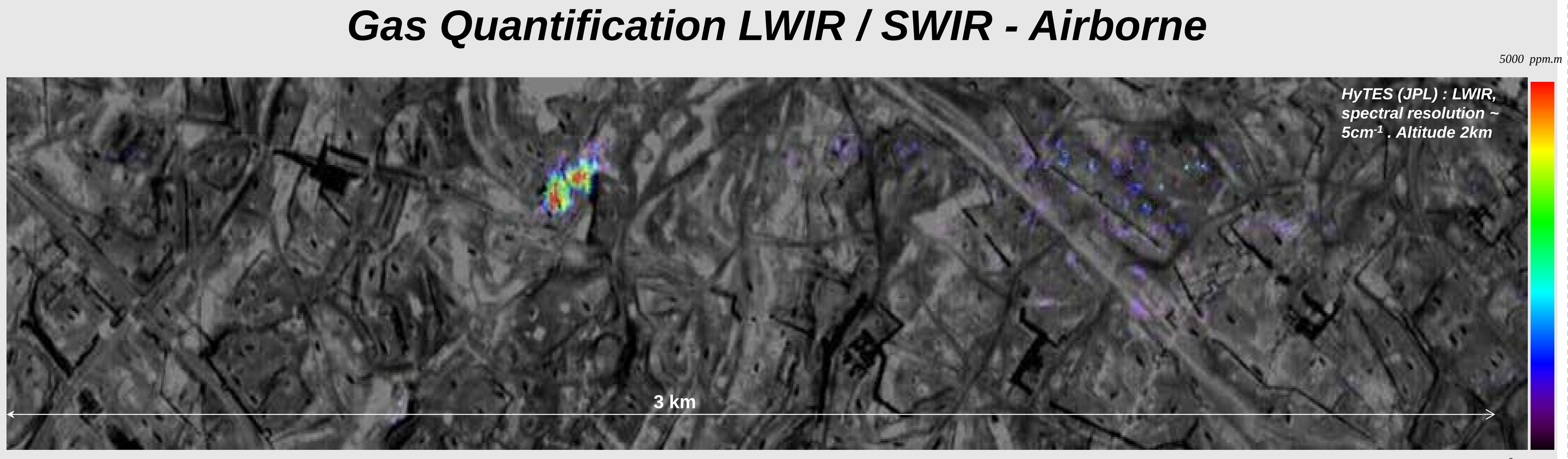
$$L^{sensor}(\lambda) = L^{atm}(\lambda) + \frac{E^{surf}(\lambda)\cdot T^{atm}(\lambda)\cdot \rho_{soil}(\lambda)}{\pi\cdot(1-\rho_{soil}(\lambda)\cdot S^{atm}(\lambda))}$$

$$\Delta L^{sensor}_{aero}(\lambda) = \Delta L^{atm}_{aero}(\lambda) + \frac{\rho_{soil}(\lambda)}{\pi.\cdot(1-\rho_{soil}(\lambda)\cdot S^{atm}(\lambda))} \cdot \Delta L^{surf}_{aero}(\lambda)$$

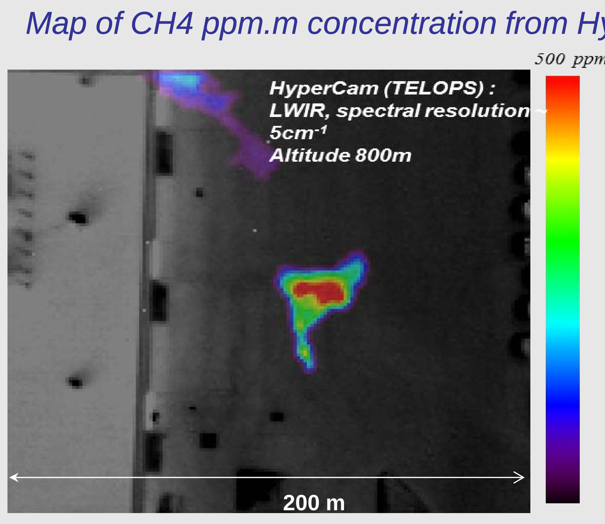
$$\Delta L^{sensor}_{plume}(\lambda, \tau^{550}) = \sum_{i=0}^{N} q^i . \Delta L^{sensor}_i(\lambda, \tau^{550}_{ref})$$

- Atmospheric Correction COCHISE Algorithm : **extraction of the « Off plume » radiative terms**
- **Reflectance estimation** from scene classification (or multi-temporal analysis)
- **Detection** using 10 main aerosols modes : Radiative Calculation of normalized aerosols impact $\Delta L^{atm}_{aero}(\lambda, \tau^{550}_{ref})$ and $\Delta L^{surf}_{aero}(\lambda, \tau^{550}_{ref})$ using COMANCHE and **fast calculation of aerosol normalized signature** for each class (or pixel). Correlation map pixel by pixel (or CTMF map, Philippet et al. 2018)
- Mean Aerosol signature extraction from the detected plume : **optimization of the main aerosol mode** (type, size, AOT)
- **Iterative Positive Linear multimodal abundance retrieval pixel by pixel** (type, size, AOT, up to 3 aerosols)
- **Flow rate estimation** of each aerosol mode using AOT / mass conversion

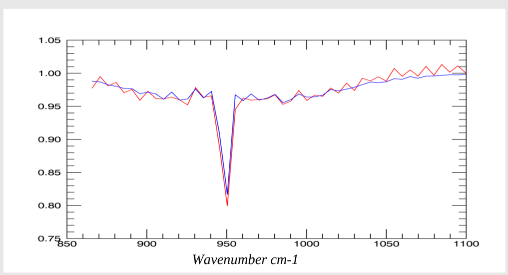
Gas Quantification LWIR / SWIR - Airborne



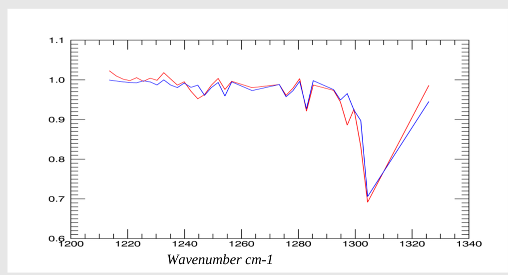
Map of CH4 ppm.m concentration from HyTES LWIR (JPL) acquisition on Californian Kern River oil&gas industry



Map of Ethylene ppm.m concentration from HyperCam (Telops) acquisition estimated release at 3,2g/h (ground truth at 4g/h).



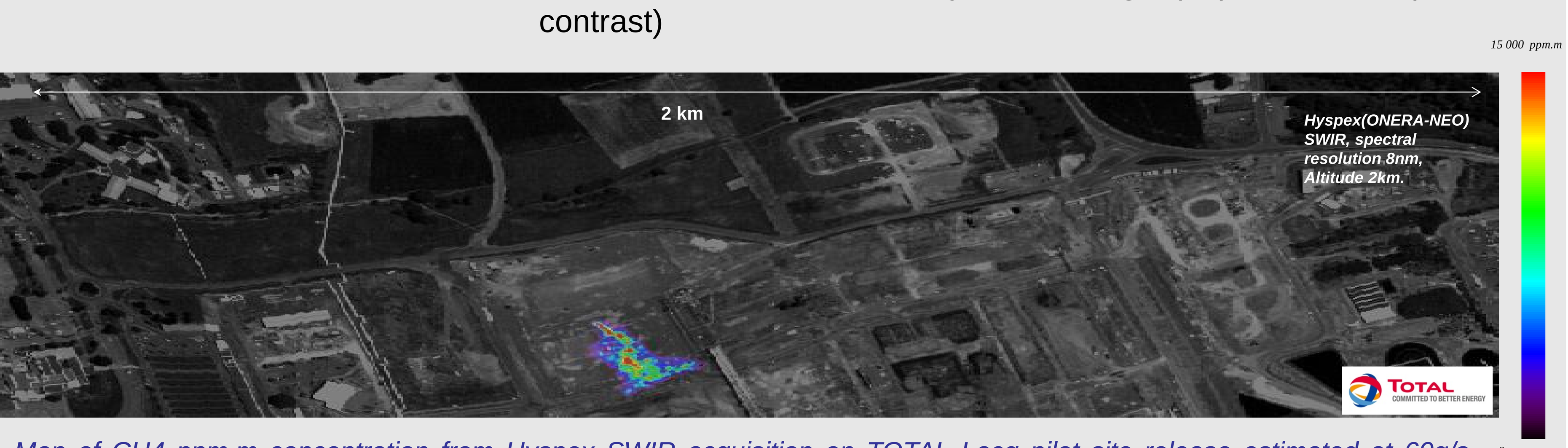
Ethylene transmission in red : theory, in blue : retrieved from data)



Methane transmission in red : theory, in blue : retrieved from data)

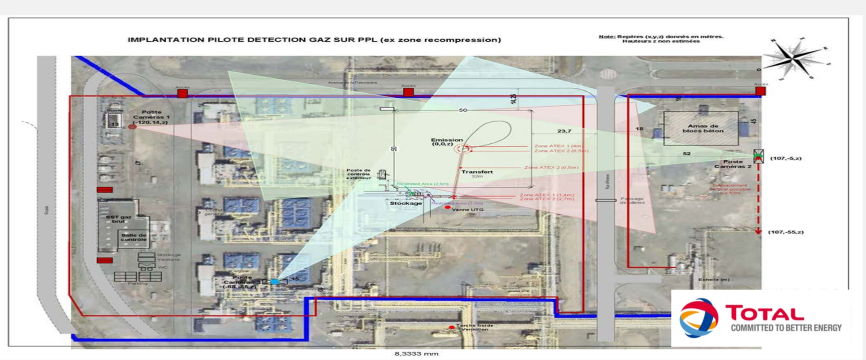
LWIR quantification algorithm validation on Methane and Ethylene
SWIR quantification algorithm validation on Methane

SWIR CH4 flow rate sensibility ~ 10g/s (for low SNR instrument at 2km height)
LWIR CH4 flow rate sensibility less than1g/s (depends on temperature contrast)



Map of CH4 ppm.m concentration from Hyspex SWIR acquisition on TOTAL Lacq pilot site release estimated at 60g/s release (ground truth at 50g/s)

Gas Quantification LWIR – Ground (NAOMI project)

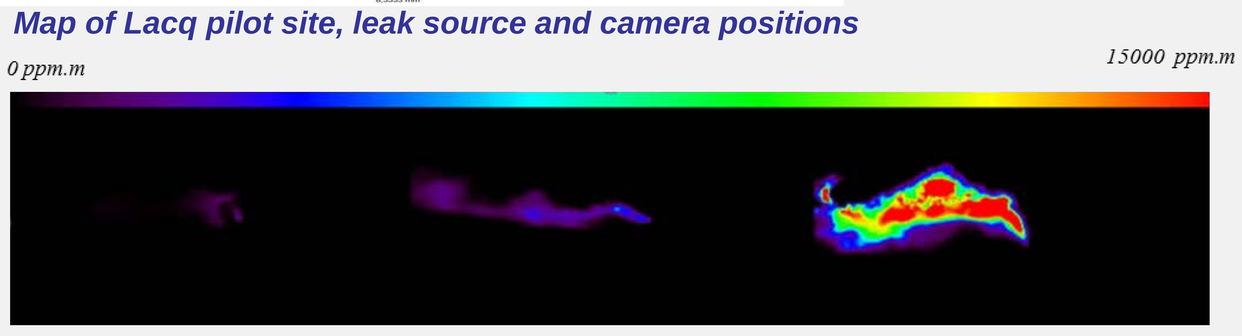


Map of Lacq pilot site, leak source and camera positions

2 campaigns on TOTAL Lacq pilot site (2015 and 2017 for CH4 and SF6).
HyperCam (Telops) instrument, distance ~ 100m, Spectral resolution from 2 to 10 cm-1
Flow rate validation from 1 to 100g/s

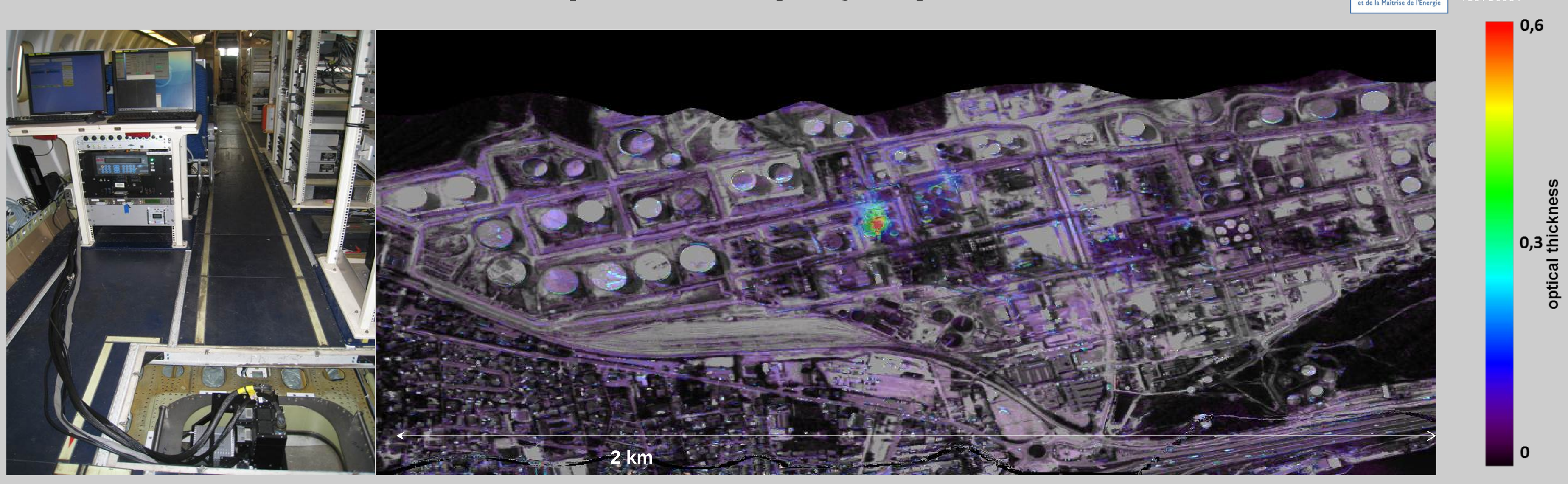
test	real	IMGSPEC
S1-14	0.7	1.4
S1-15	0.7	0.7
S2-05	0.7	0.8
S2-06	0.7	0.5
S1-03	1	1.3
S1-04	1	1.4
S1-06	1	1.1
S1-13	1	2.2
S1-16	1	3.1
S2-03	1	0.7
S2-04	1	0.8
S2-19	1	1.8
test	real	IMGSPEC
S1-01	10	9.2
S1-02	10	9.3
S1-11	10	6.9
S1-12	10	9.3
S1-19	10	10.2
S2-01	10	9.4
S2-02	10	7.3
S2-17	10	10.0
S2-23	10	11.7
S1-21	20	15.8
S2-09	20	17.5
S2-10	20	19.3

Table of comparisons from retrieved flow rate (IMGSPEC) and real release during the 2017 campaign

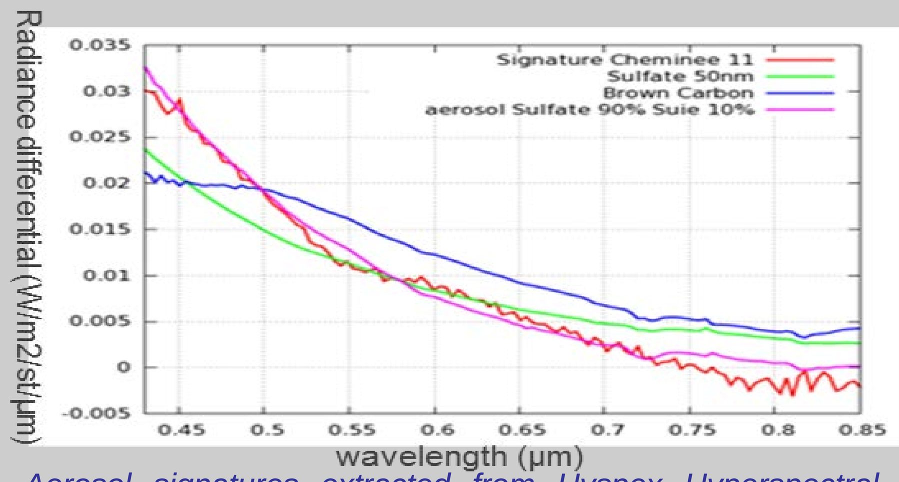


Example of CH4 ppm.m map retrieved for 3 different flow rate leaks (Doz et al. 2018))

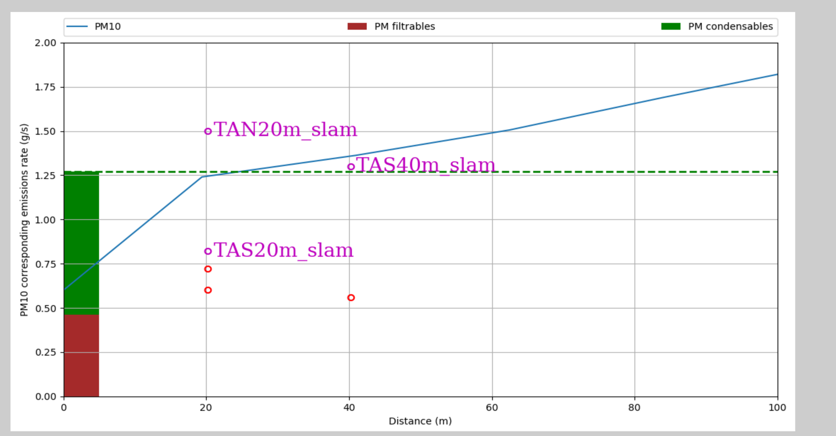
Aerosols quantification map Multi-temporal approach (TEMMAS project)



Left : Airborne Hyperspectral acquisitions. Hyspex Cameras [0,4-2,5µm] on board SAFIRE ATR-42. Right : Example of "Sulfate 50-100nm" aerosol mode optical thickness map retrieved from Hyspex hyperspectral data. Aerosol map is overlaid over the 500nm band. Zoom over the main emission stack of TOTAL LaMede refinery(spatial resolution 2m). Foucher et al.2017.

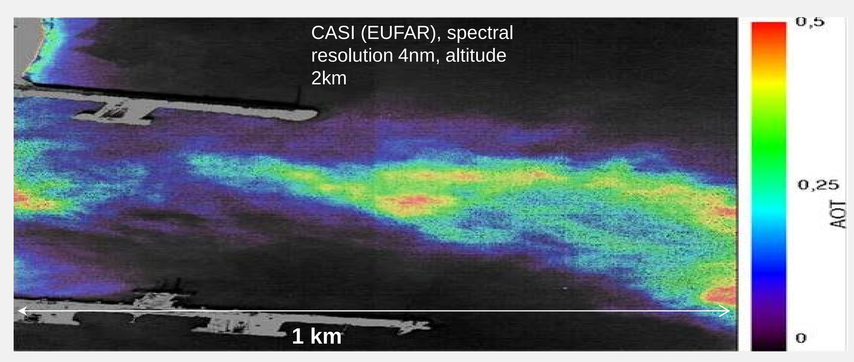


Aerosol signatures extracted from Hyspex Hyperspectral data (red) and from the multi modes optimal fit (purple) : 0,05µm mean radius scattering aerosol (sulfate) and 0,05µm black carbon aerosols

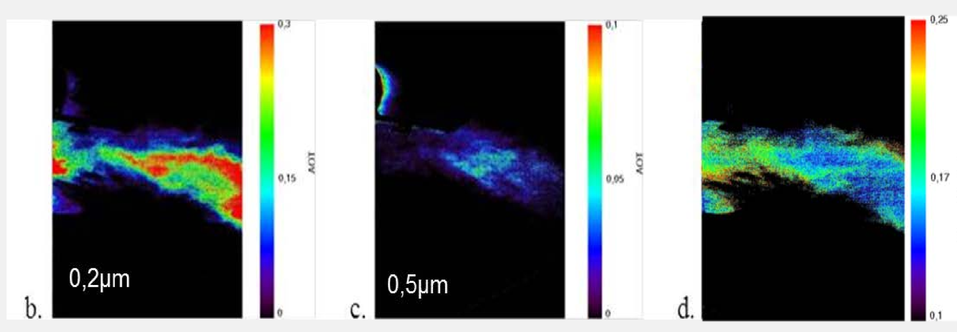


PM10 flow rates at different distances from the source from modelling (blue), chimney in-situ measurements (green) and from hyperspectral data (purple points). Duclaux et al. 2017.

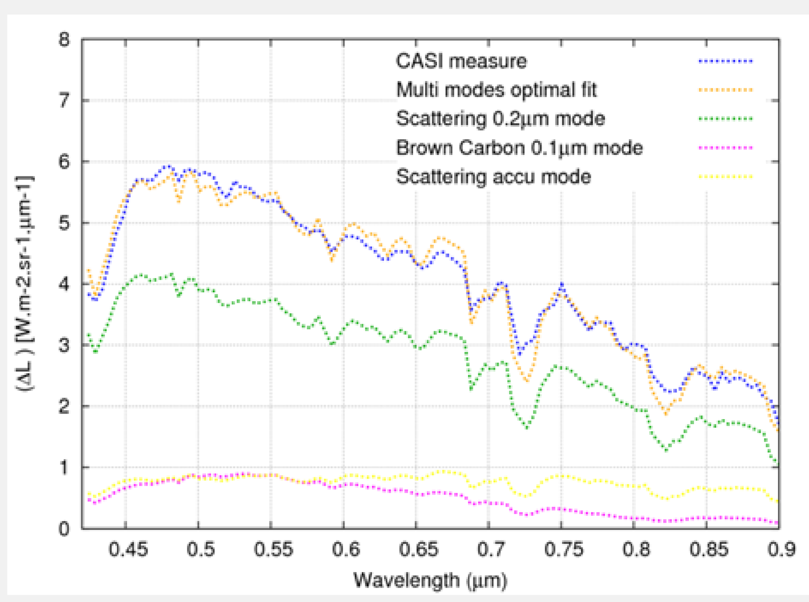
Aerosols quantification map - Single image approach



Map of aerosol optical thickness over metallurgic plant plume (Fos/Mer)



Left : AOT contribution due to the 0,2µm radius aerosol mode, Middle : AOT contribution due to the 0,5µm radius aerosol mode, Right: Spatial evolution of the size aerosol parameter (Philippet e al., 2018)



Aerosol signatures extracted from CASI Hyperspectral data (blue) and from the multi modes optimal fit (orange) : 0,2µm mean radius scattering aerosol (organic), 0,5µm scattering aerosol (organic) and 0,1µm Brown Carbon aerosols

Perspectives

- **Application to near future hyperspectral SWIR satellite missions and UAV systems**
- **Coupling concentration map to fine scale modelling : refinement of plume dispersion evolution and forecast**
- **Crisis management operational systems : Real time algorithms for gas concentration**

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