Plume detection and characterization from XCO2 imagery: Evaluation of Gaussian method for quantifying plant and city fluxes

SPASCIA

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Summary

An approach for the estimation of CO_2 emissions of localized sources (power plants, cities) from satellite imagery XCO2 has been implemented, based on an optimal estimation method (OEM) fitting the measured images with a Gaussian plume model dealing with multiple and/or extended sources. It provides a full analysis of the retrieval uncertainty. It has been applied on synthetic XCO2 images of two missions in preparation : MicroCarb (CNES) city mode images and GeoCarb (NASA) images.

A comprehensive analysis of the expected precision on the source emissions over a representative set target sites is provided.

A specific case study is performed by using Large Eddy Simulation (LES) model to evaluate the impact of atmospheric turbulence on flux inversions uncertainty budget.

Then the performances and added-value of the gaussian-OEM method is evaluated in real conditions on OCO-2 measurements.

Methodology

A method for point source plume characterization and emission inversion from atmospheric XCO2 images has been developed and tested, including :

- ✓ **A Gaussian modelling of the plume, adapted for single/multiple point sources and for extended sources**
- ✓ **An Optimal estimation method (OEM) inversion scheme fitting all Gaussian parameters in the state vector consistently with a priori values and uncertainties**
- ✓ **An effective wind speed is derived from ancillary data and used for the emission estimate**
- ✓ **A comprehensive uncertainty budget provided together with the estimated flux**

Quality criteria allows the identification of favorable observation cases for the quantification of the emissions : Data flagging and post filtering.

1. **Gaussian plume formulation**
   9 parameters : 6 for gaussian plume, 3 for background

$$X_{CO2}(x,y) = X_{BKG}(x,y) + X_{GAUSS}(x,y)$$

$$X_{BKG}(x,y) = VMR_0 + P_x x + P_y y$$

$$X_{GAUSS}(x,y) = \frac{F}{U}\frac{e^{-\frac{1}{2}\left[\frac{y}{\sigma_y(x)}\right]^2}}{\sqrt{2\pi}\sigma_y(x)} \quad \text{with } \sigma_y(x) = \sigma_0\left(\frac{x}{x_0}\right)^b \text{ transverse spread}$$

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} cos(\varphi_U) & sin(\varphi_U) \\ -sin(\varphi_U) & cos(\varphi_U) \end{bmatrix} \begin{bmatrix} X - XS \\ Y - Y_S \end{bmatrix}$$

φ_U direction of the wind vector in XOY (positive in the trigonometric direction)

➢ Note the distinction between the coordinates XOY (origin at bottom left corner of the image) and the local reference system xSy of the Gaussian plume from the source S (Sx longitudinal axis of the plume, Sy transversal axis perpendicular to Sx)

2. **Capacity to simulate multiple and extended sources**
   Extended source considered as a disc centered on the source with radius r. An elementary plume is computed from each point grid within the disc, then integrated for computing the whole plume

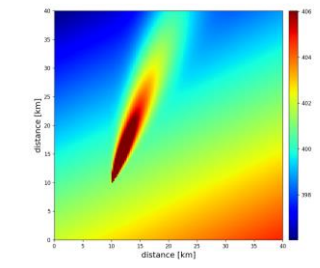
3. **Gaussian model observation operator within a classical OEM framework,** allowing the estimation of the uncertainty on the retrieved parameters and a comprehensive analysis of error sources

Retrieved state vector $\boldsymbol{x}$: $VMR_0, P_x, P_y, F, \varphi_U, b$

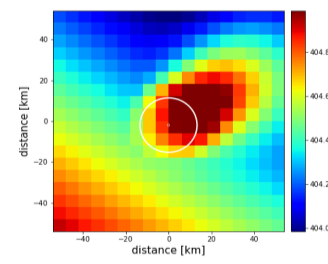
$$X_{CO2}(x,y) = f(VMR_0, P_x, P_y, F, \varphi_U, b, U, \sigma_0, x_0)$$

Model parameters $\boldsymbol{b}$ (site-specific characterisation) : U, σ_0, x_0

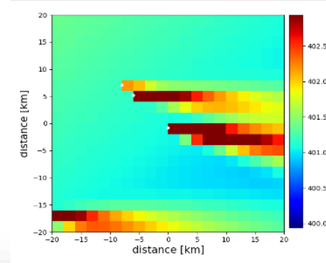
Point source



Extended source



Multiple sources



Performance analysis : MicroCarb city mode

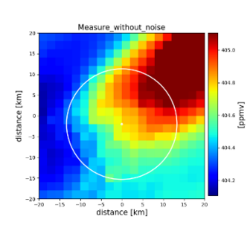
Good performances for most of the sites, including "relatively small" sites like Dunkerque or Karlsruhe (average DOFS > 0.5).
MicroCarb city mode characteristics (image size and resolution) appears able to capture power plant plume information (i.e., number of pixels effectively capturing the plume and gradient information, capability to capture multiple point sources).

Site	type	Reference flux [TC/h]	Retrieved flux [TC/h]	DOFS	Instantaneous uncertainty %	Uncertainty on monthly average [TC/h] (%)
Dunkerque	plant	152	170	0.58	61 +/-35	25 (15%)
Weisweiler	plant	700	656	0.79	22 +/-7	35 (5%)
Duisburg	plant	552	515	0.70	25 +/-7	31 (6%)
Niederaussem	plant	575	545	0.93	33 +/-25	39 (7%)
Karlsruhe	plant	92	73	0.62	72 +/-31	19 (26%)
Amer	plant	195	196	0.70	66 +/-43	19 (10%)

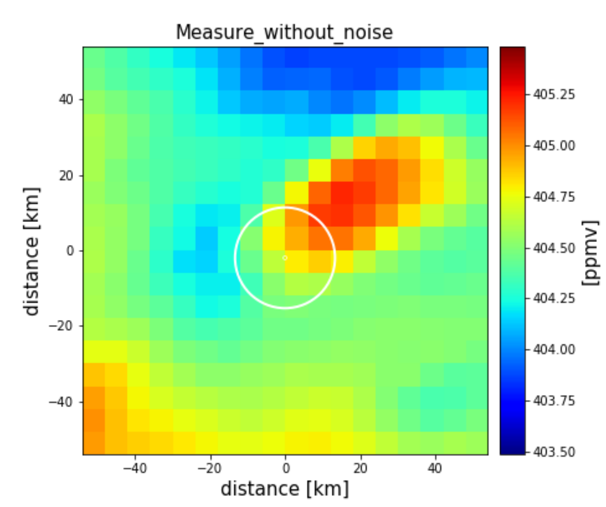
MicroCarb can exploit the City mode to demonstrate and test emission quantification performances for intense, isolated plant (e.g., Weisweiler) as well as for a smaller and complex site (Dunkerque) and cities (Paris)

Illustrative synthetic images over Paris city

MicroCarb city mode:
2x2 km² resolution, 40x40 km² extension
1 ppm noise



GeoCarb-like mode:
6 km x 6 km resolution, large extension,
1 ppm noise



Performance analysis : GeoCarb mode

The total uncertainty on city emission estimate is between 30-40% depending on the site.
The impact of the presence of clouds with cloud cover less than 50% has been assessed. This impact remains less than 5% (in terms crease in retrieval uncertainty) regardless of the site observed.

		Estimated uncertainty on flux retrieval	Empirical errors	
Sites	Spatial resolution [km]	Total uncertainty	Without clouds	With clouds
Dallas-FortWorth	3.2 x 3.6	36%	35%	36-41%
Buenos-Aires	3.75 x 3.8	39%	32%	32-35%
Chicago	3.1 x 4.2	30%	32%	30-32%
Paris	2 x 2	31%	25%	-
Paris	4 x 4	32%	34%	-
Paris	6 x 6	38%	34%	-
All	-	30-40%	25-35%	30-40%

The study of the GeoCarb mode is done in collaboration with the University of Oklahoma. Analyses over Dallas, Buenos-Aires and Chicago are based on OLAM simulations provided by Andrew Schuh (Colorado State University)

Dealing with turbulent plumes

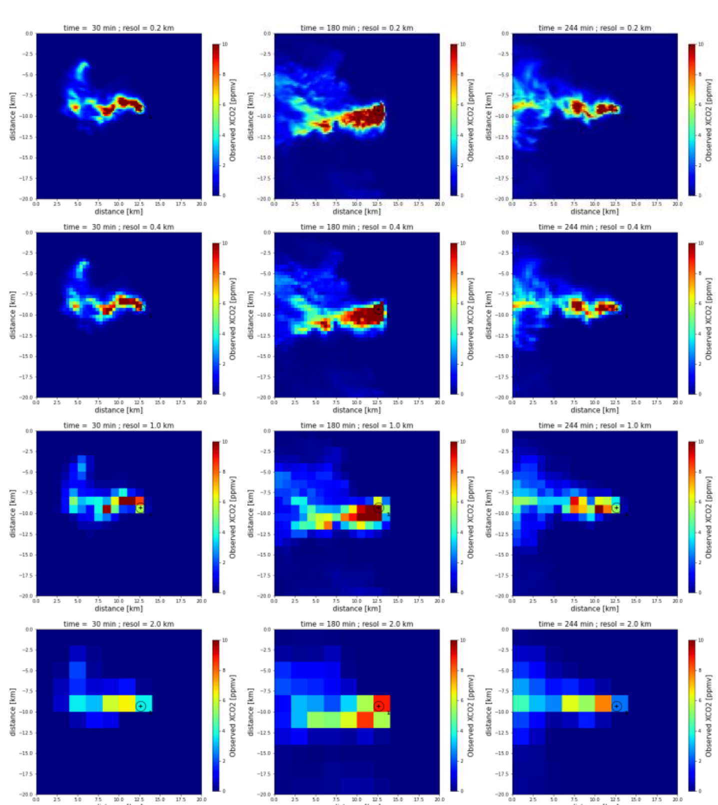
Quantification of the impact of turbulence effects on the restitution of CO2 fluxes with the Gaussian-OGEO method:

We estimate The impact on emission retrieval of inverting turbulent, high resolution plumes simulated by EULAG. The impact is ~13% (total error) at MicroCarb resolution (small but significant)

It can be taken into account by transporting (through the OGEO method) a defined uncertainty in the observation vector.

This analysis confirms the relevance of using the Gaussian model, even in turbulent conditions, at the scales we analyzed.

In the case of MicroCarb (2 km resolution) or GeoCARB (3-4 km resolution) observations, the wind fields provided by ECMWF at a resolution of the order of 10 km are suitable for estimating effective wind. Exploiting higher spatial resolution observation would require wind fields provided at higher spatial resolution.



3 examples of plumes simulated by the Large Eddy Simulation (LES) model EULAG, at T = 30 min (column 1), 180 min (column 2) and 244 min (column 3), and at 4 spatial resolutions : 200 m (line 1, original resolution of the simulation), 400 m (line 2), 1 km (line 3) and 2 km (line 4). Stationary source emission.

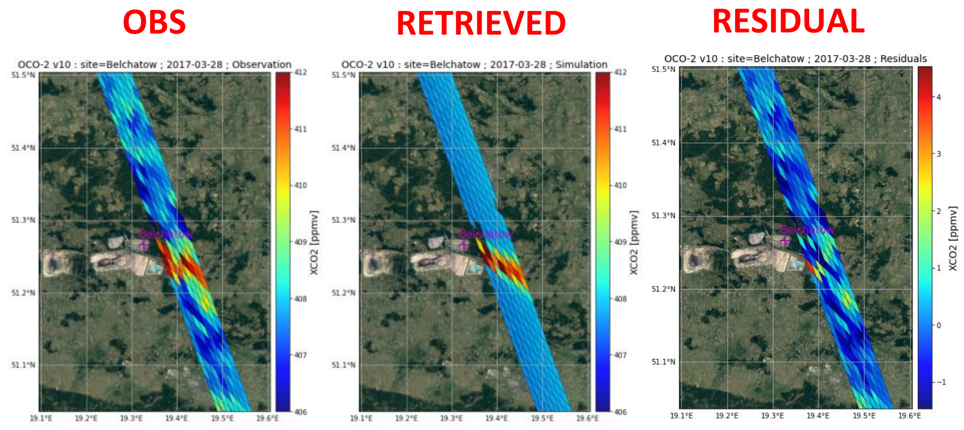
Emission retrieval tests from OCO-2

XCO_2 observed by OCO-2 v10 over Belchatow power plant

Gaussian parameterization without optimisation.

The retrieved flux and uncertainty is consistent with results by Nassar et al., 2021: 102.5 ± 12.3 $ktCO_2$/day (Nassar : 98.2 ± 11.9 $ktCO_2$/day). But the χ^2 has a strong value (1.32) due to significant discrepancies between simulated and observed plume. Such results should be rejected by the quality criteria applied in Gaussian-OGEO processing.

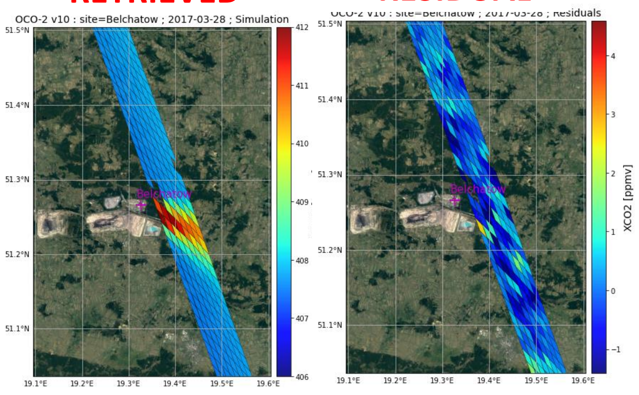
OBS **RETRIEVED** **RESIDUAL**



Adjusted gaussian parameterization.

Parameter	*Unit*	*Variable*	*Value a priori*	*Uncert. a priori*	*Value a posteriori*	*Uncert. a posteriori*
Reference distance	m	x0	500	10%	-	-
½ width at x0	m	σ0	121	10%	-	-
Effective wind	m/s	U	6.26	1.0	-	-
b parameter	-	b	0.894	0.05	0.897	0.035
Flux	$ktCO_2$/day	F	88.0	88.0	113.9	15.6
Plume direction	degré	ϕ	118.4	25.0	116.0	1.4
χ2 test	-	χ2	-	-	1.08	-

RETRIEVED **RESIDUAL**



- Optimisation of the $\mathbf{x_0}$ reference distance from the source (where the half-width of the plume is σ_0)
- Surface wind and effective wind computed from ERA-5, impacting the value of σ_0.
- The **b** parameter is adjusted by the retrieval
- Uncertainties on $\mathbf{x_0}$, σ_0, **b** are considered

Significant improvement of the χ^2 : 1.08, and significant modification of the retrieved flux : 114 $ktCO_2$/day.
Larger uncertainty (than without optimisation) : 15%, reflecting a more comprehensive analysis of error sources.

Preliminary conclusions: Gaussian plume simulation and OEM formalism have been assessed for plant and cities emission retrieval, and have been used to estimate expected performances from MicroCarb city mode and GeoCarb XCO2 images. **Site-specific preprocessing can critically improve results** : an analysis of the site based on representative simulations of the high-resolution plume (type LES or WRF/CHIMERE) would make it possible to better understand and constrain gaussian plume parameters and effective wind. **MicroCarb and GeoCarb complementarities :** Combined measures of MicroCarb high resolution images and GeoCarb temporal repetitivity and large frame over targeted sites should be assessed. **Selection criteria and examples for targeted sites are proposed for MicroCarb City mode.**