Hyperspectral infrared imaging of volcanic plume at Mt Etna during IMAGETNA campaign

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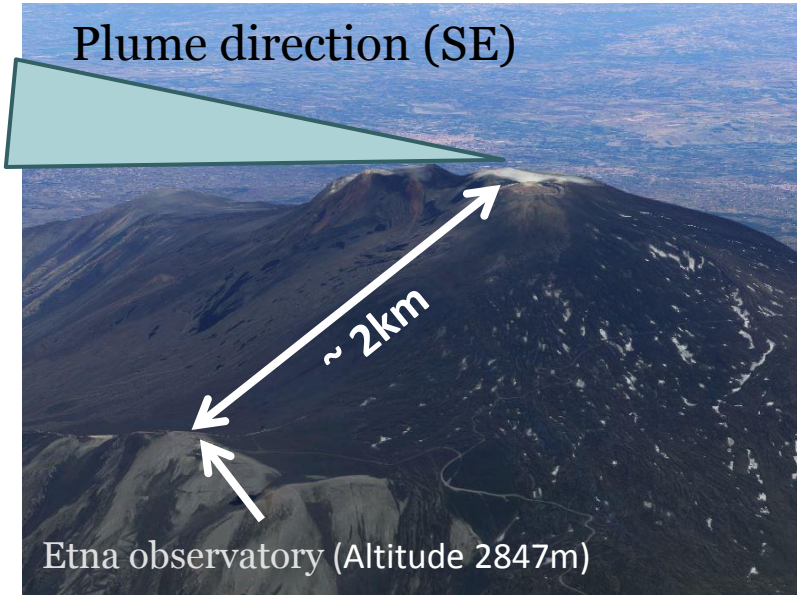
- Context :
  - Know more about the composition and spatial evolution of volcanic plume, to have insights of the processes occurring inside the Earth.
  - Explore the potential of hyperspectral infrared imaging which is a new technology now available.

- Campaign at Mt Etna
  - 21-25 June 2015
  - Pizzi De Neri observatory



Instrumentation involved

Instruments	Characteristics
HyperCam IR imager Telops company	[7.7 – 11.8] µm, spectral resolution 2 cm^{-1}, 320 x 256 pixels
OPAG 33 FTIR Bruker company	[3.5 – 14] µm , spectral resolution 1 cm^{-1} 1 pixel
UV camera INGV	SO_2 Slant column densities (Mori and Burton, 2006)

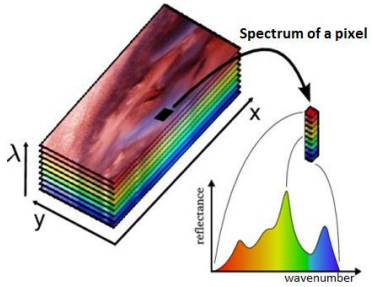
Check the calibration HyperCam imager IR spectra

Comparison of UV and IR SO_2 Slant Column Densities

- And two other IR imagers:

Filament imager ONERA *Under development*	[3 – 5] µm , 24 bands 56 x 56 pixels , 10 cm^{-1}, IFOV 1.1 mrad , 100 Hz
SIBI imager ONERA *Under development*	[3.7 – 4.8] µm, spectral resolution 15 cm^{-1} 640 x 512 pixels , IFOV 1.6 mrad

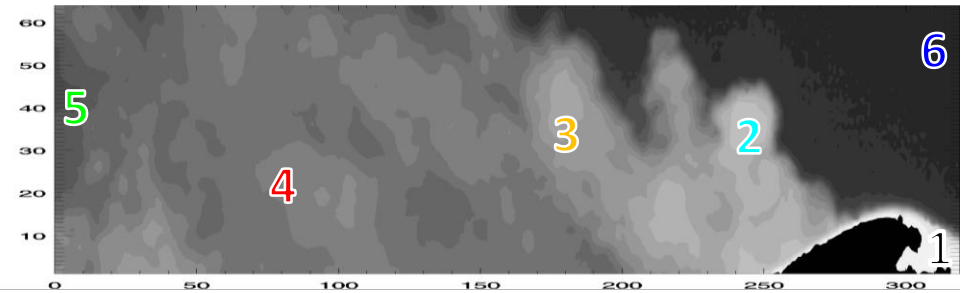
HyperCam IR imager (Telops company)



- Datacubes (3D)
  - → 2 spatial dimensions
  - → 1 spectral dimension

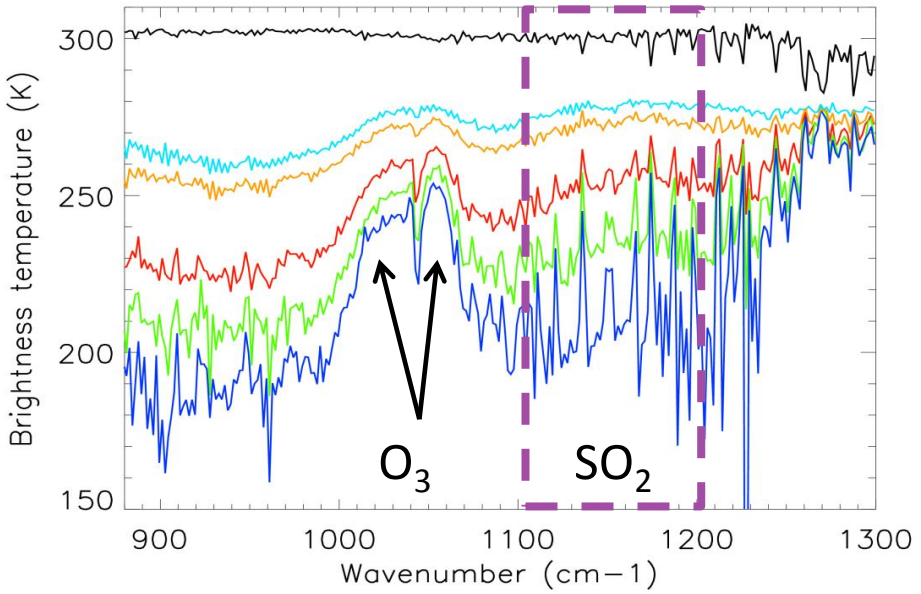
(Acquisition time: 2.5 seconds / datacube ; Resolution2 cm^{-1})

Mean brightness temperature (K)



1: Ground
2: Plume close to crater
3: Plume close to crater
4: Diluted plume
5: Diluted plume
6: Clear sky

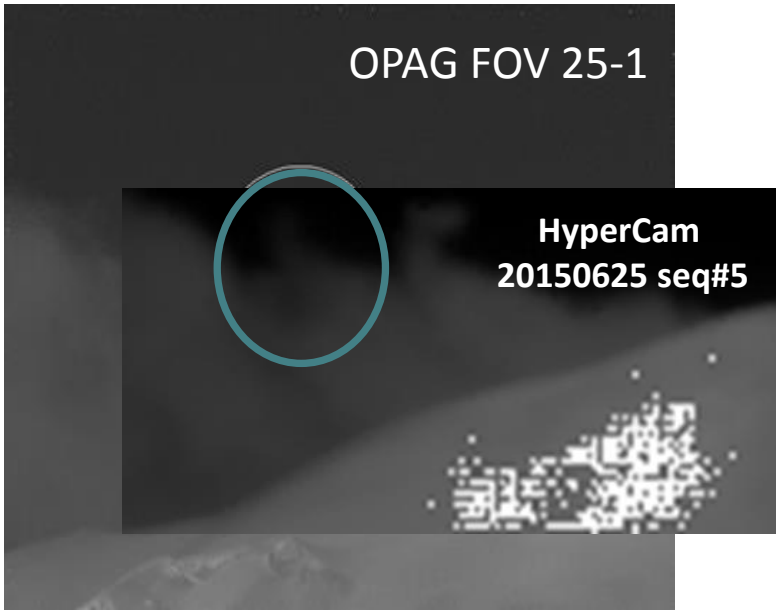
Brightness temperature spectra at different locations

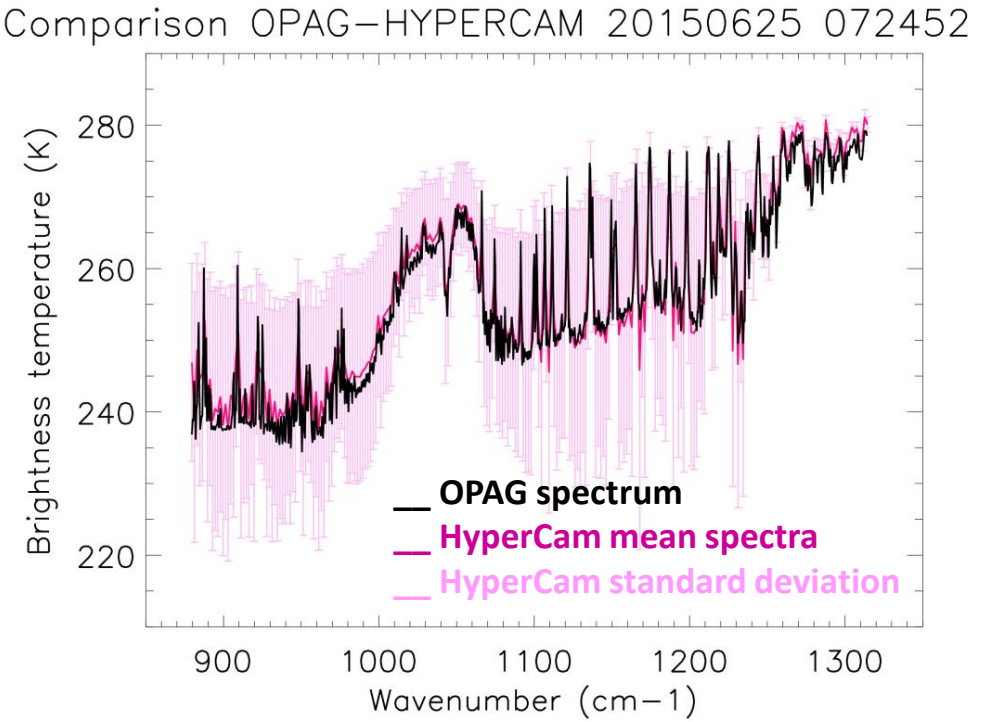


O_3 lines of the atmosphere are visible

In this study we focus on SO_2 spectral region 1100 – 1200 cm^{-1}

HyperCam IR-FTIR OPAG Comparison





- **The OPAG FTIR pixel ~ 930 pixels of HyperCam**
- Good agreement between OPAG FTIR spectrum and HyperCam mean spectra

HyperCam instrument provides good calibrated spectra

Retrieval approach

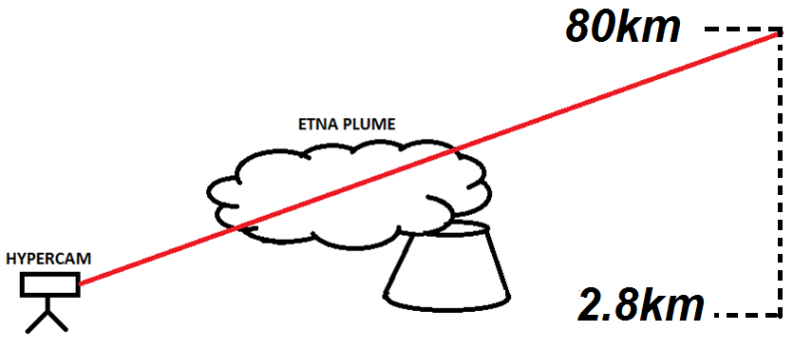
- **Line by line radiative transfer model** associated with the LARA inversion algorithm (Payan et al. 1998, 2010)

⇒ Previously used for limb IR balloon spectroscopy and IASI satellite measurements analysis

- **Inputs**:

⇒ HITRAN 2012: spectroscopic parameters

⇒ T and H_2O vertical profiles: Trapani meteorological balloon sounding and ECMWF Era-Interim



line of sight up to 80 km
crossing 43 layers

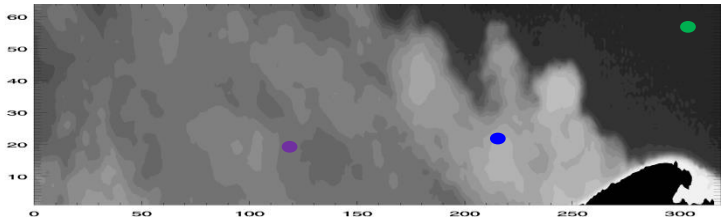
- **For SO_2 : Full physic retrievals**

State vector = H_2O, CO_2, O_3, N_2O, CO, CH_4 , SO_2, Plume parameters

- Spectral and altitude dependency of the plume **optical thickness** : **$\tau(\lambda, z)$**
- **$\Delta T = T_{plume} - T_{atmosphere}$**
- **Altitude** of the plume center,
- Plume **thickness**

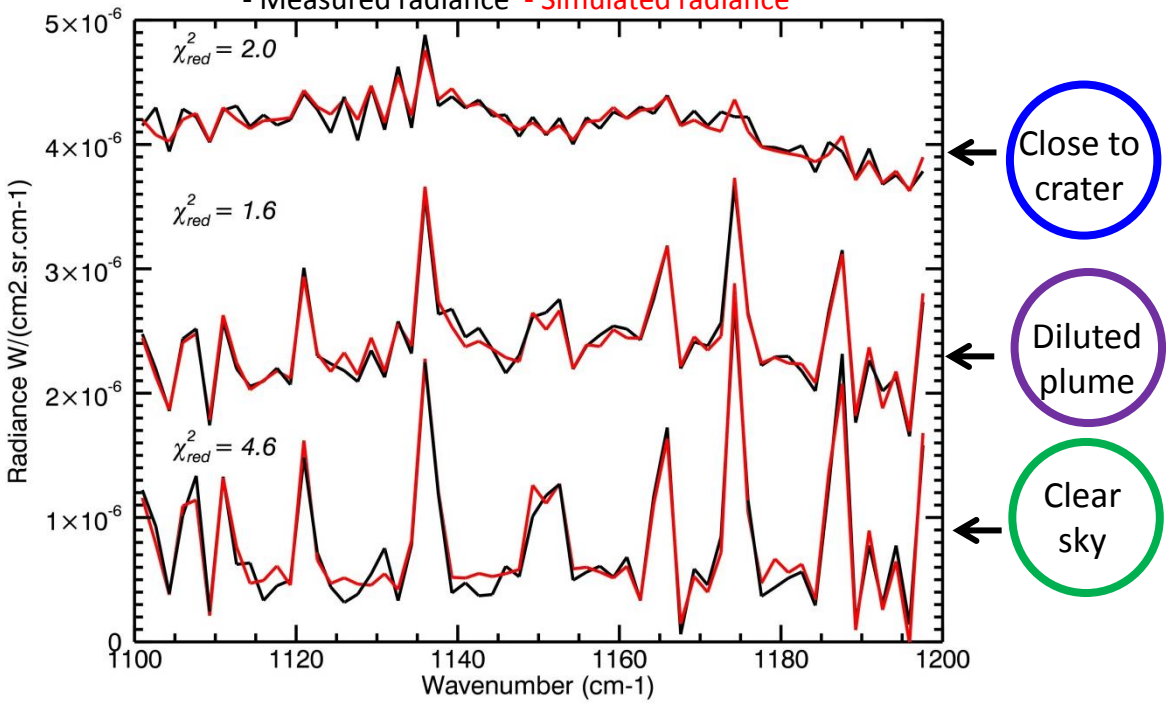
SO_2 window spectral fit

Mean brightness temperature image (K)



Examples of retrieved radiance spectra

- Measured radiance - Simulated radiance

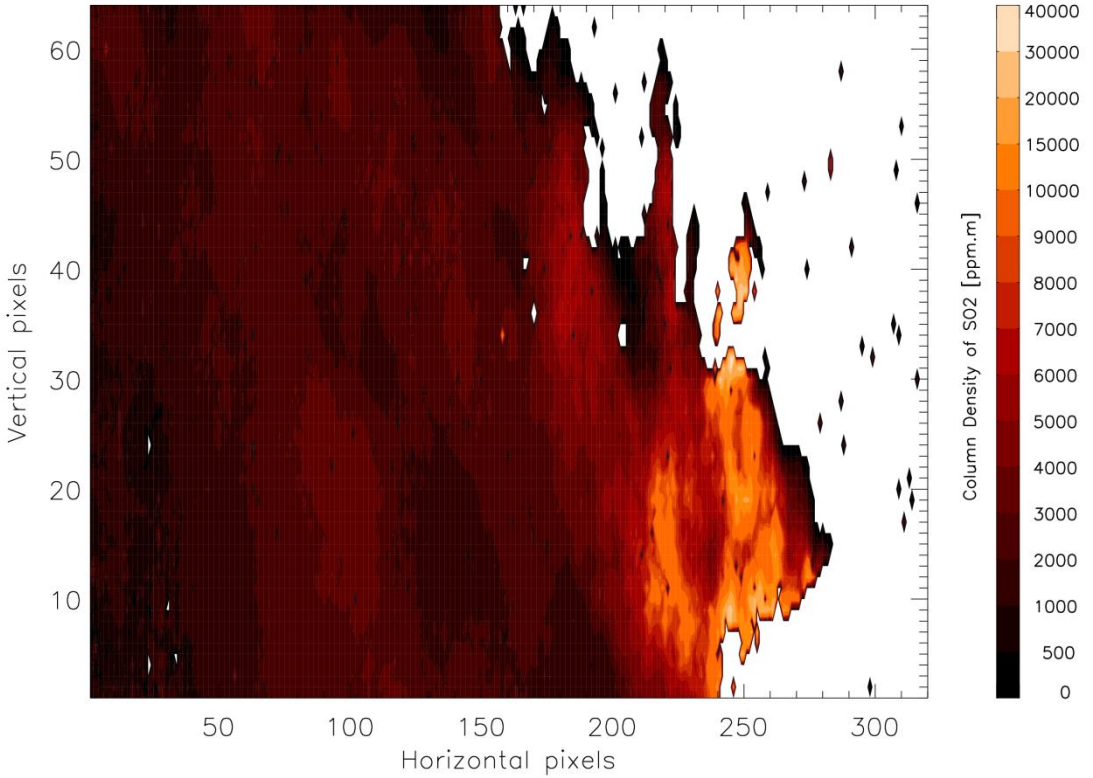


- Reduced $X^2 < 10$
- Good agreement between measurements and calculations

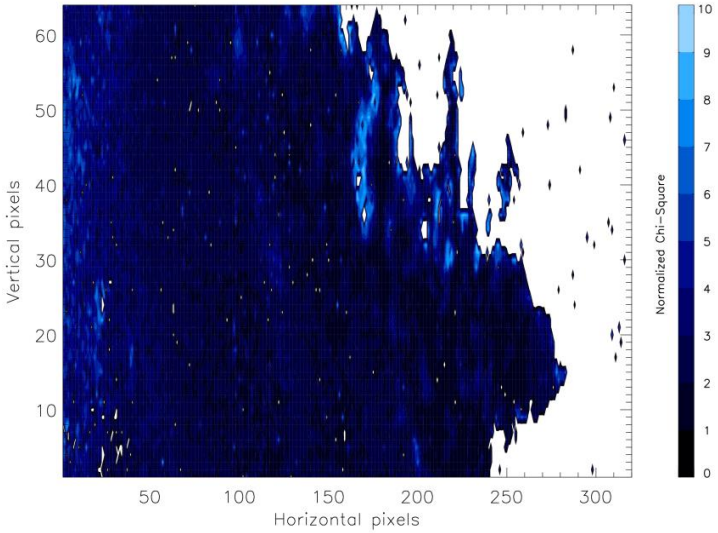
SO_2 window easily fitted with LARA model

SO_2 Slant Column Density Results

- SO_2 slant column density (ppm.m) - 20150626 – 08:27:45



Reduced χ^2 values of SO_2 retrieval



Reduced χ^2 is mostly ≤ 5

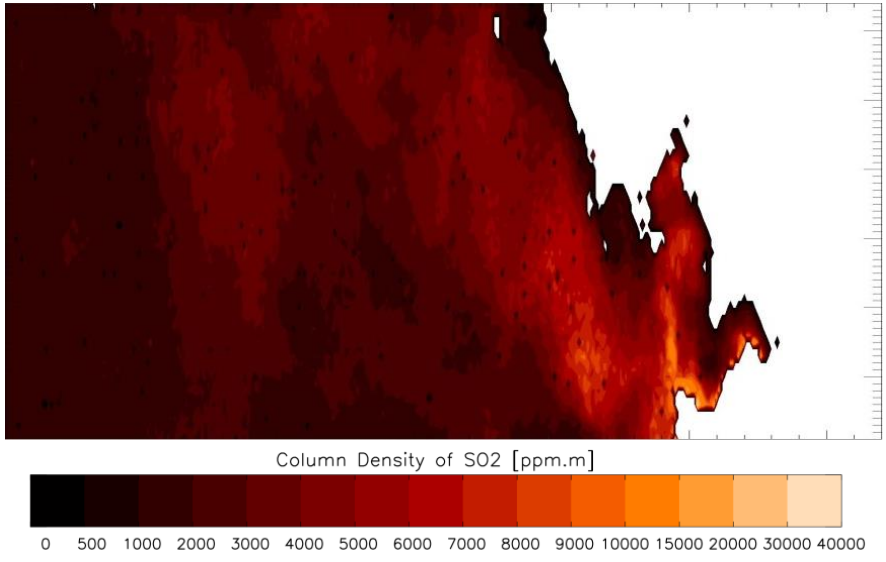
→ Good quality of retrieval

Comparison of SO_2 IR and UV SCDs

- Simultaneous sequence 20150626 – 082743 UTC

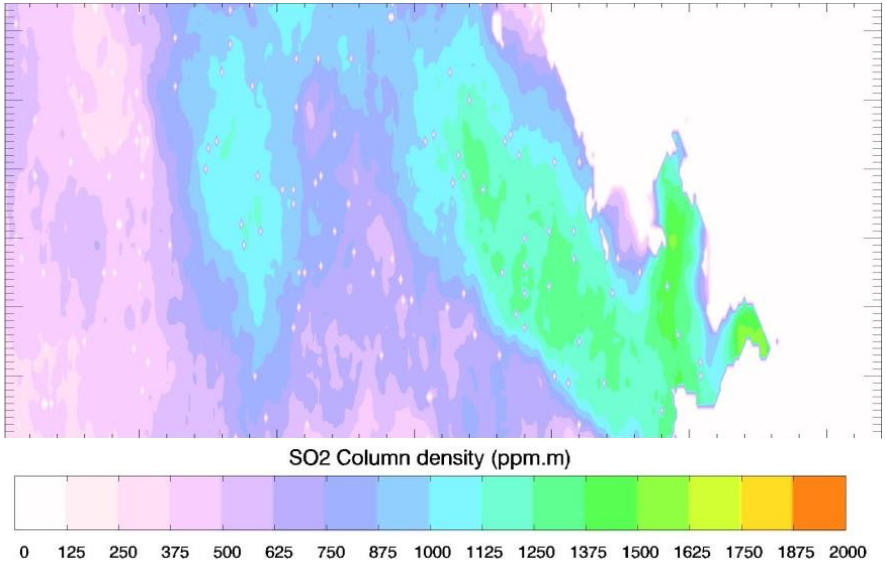
HyperCam

*SO_2 Slant Column Density retrieved **in the IR***



UV Camera

*SO_2 Slant Column Density retrieved **in the UV***

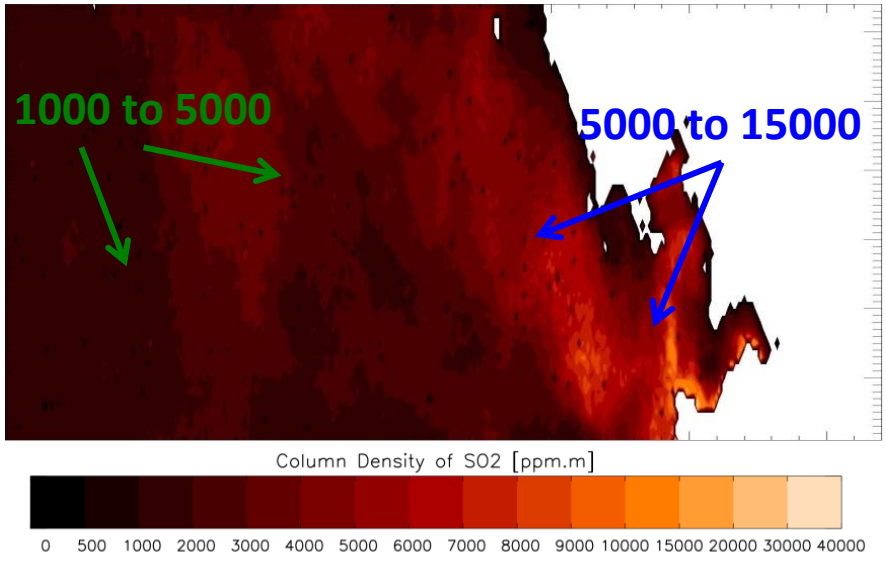


Same SO_2 dilution structures observed by both instruments

Comparison of SO_2 IR and UV SCDs

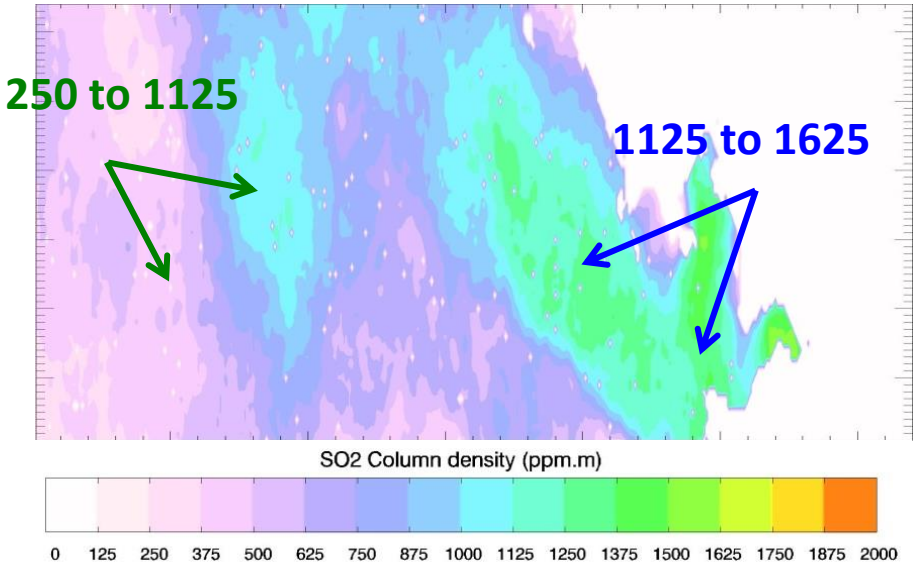
HyperCam

*SO_2 Slant Column Density retrieved **in the IR***



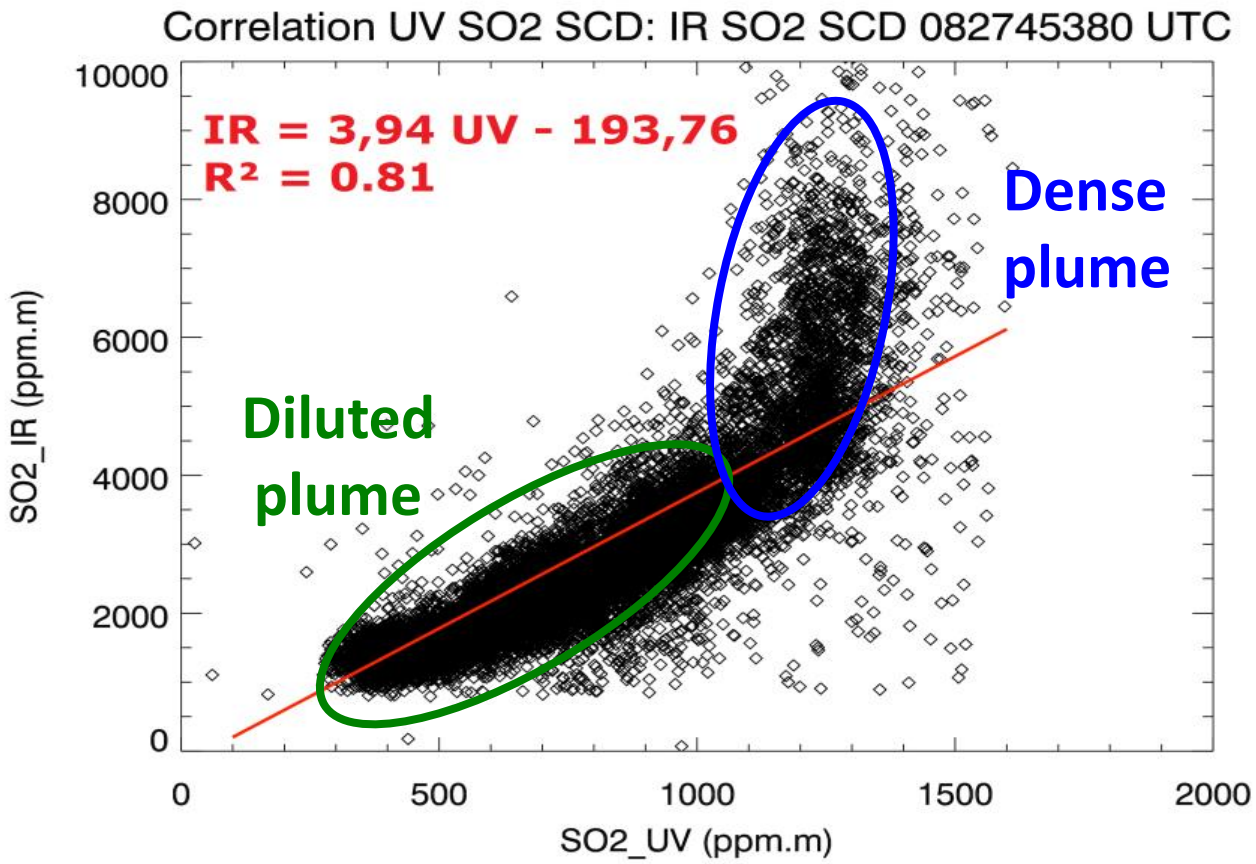
UV Camera

*SO_2 Slant Column Density retrieved **in the UV***



Strong differences between
the UV SO_2 SCD and IR SO_2 SCD values

SO_2 IR : SO_2 UV SCDs correlations

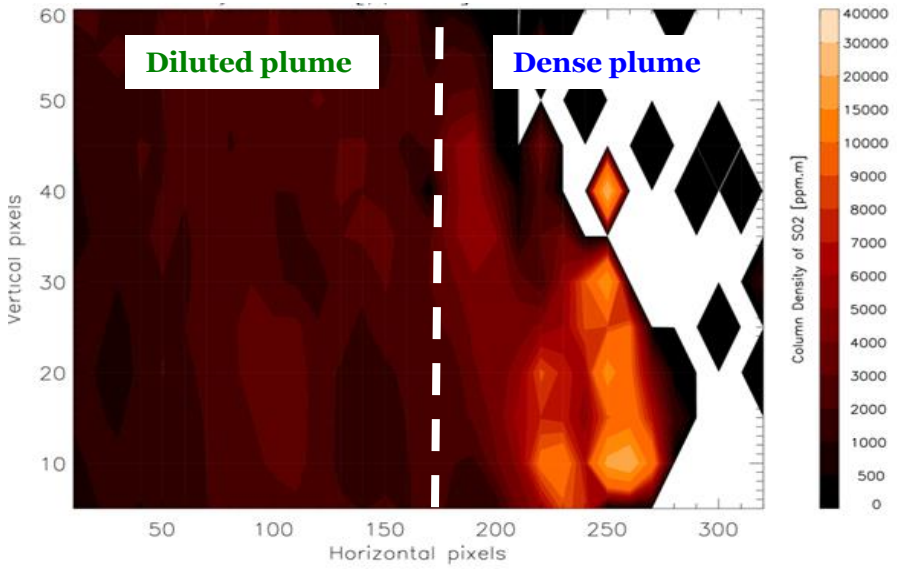


- **Compact IR:UV SCDs correlation**

- **Two regions:**
  - **Factor of 4 in diluted plume**
  - **Factor > 6 in dense plume**

Sensitivity tests on plume parameters for SO_2 SCD IR retrieval

Plume parameters	Plume thickness	ΔT
Reference configuration	400 m	1K
Tested values	65 m	0,5 K
	200 m	5 K
	600 m	10 K



From previous correlation we investigate two regions:

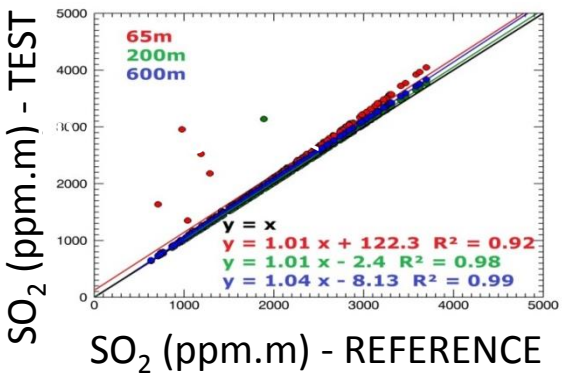
- **Diluted plume**
- **Dense plume**

Sensitivity tests - Results

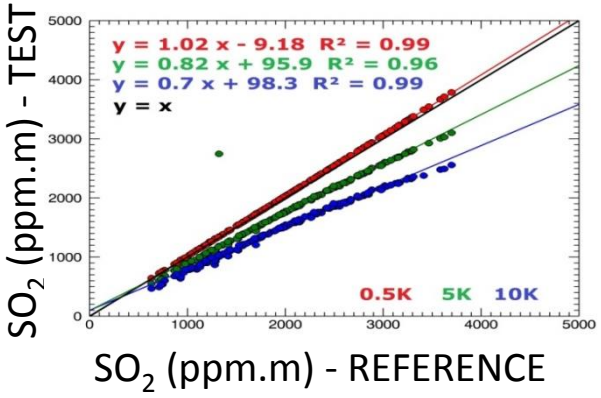
Reference configuration
Thickness: 400m ; ΔT = 1K

→ In **diluted** plume

Thickness



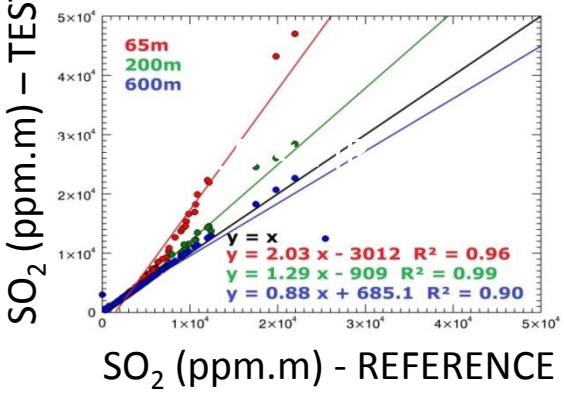
ΔT



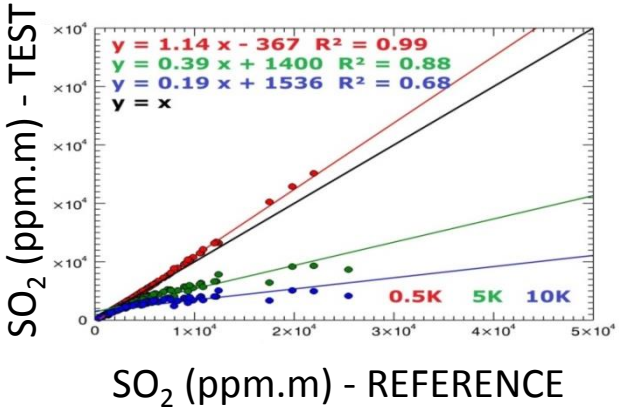
- **No impact of plume thickness on SO_2 SCD**
- **Small impact of ΔT on SO_2 SCD**

→ In **dense** plume

Thickness



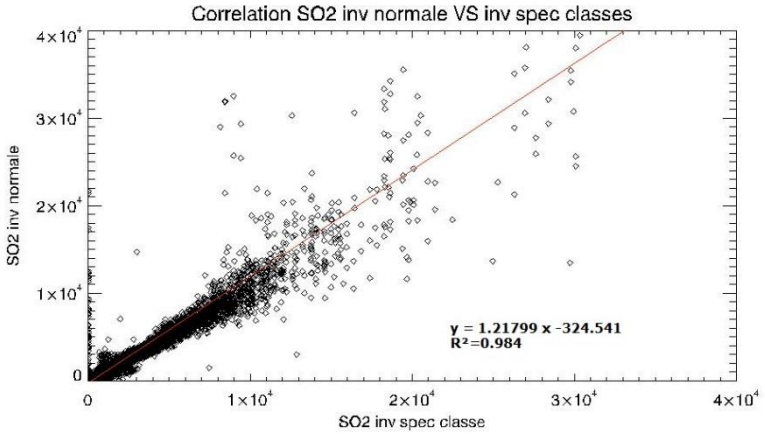
ΔT



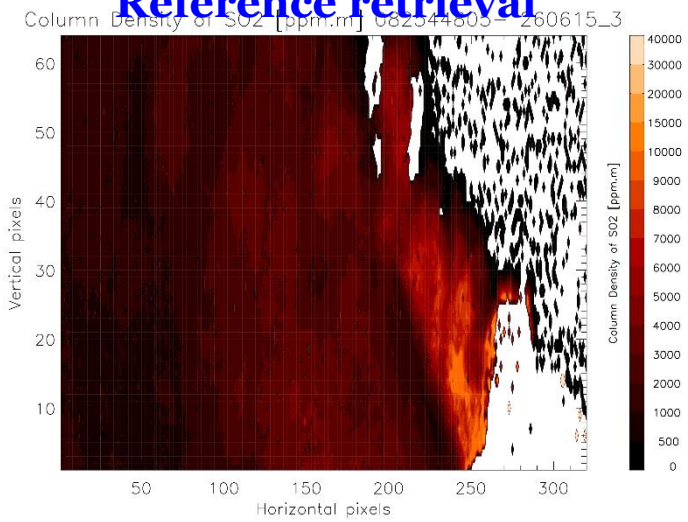
- **Thickness impact SO2 SCD**
  → Increase or decrease
- **ΔT impacts SO_2 SCD**
  → Factor of 5 for 10K

Toward Near Real Time Calculation ?

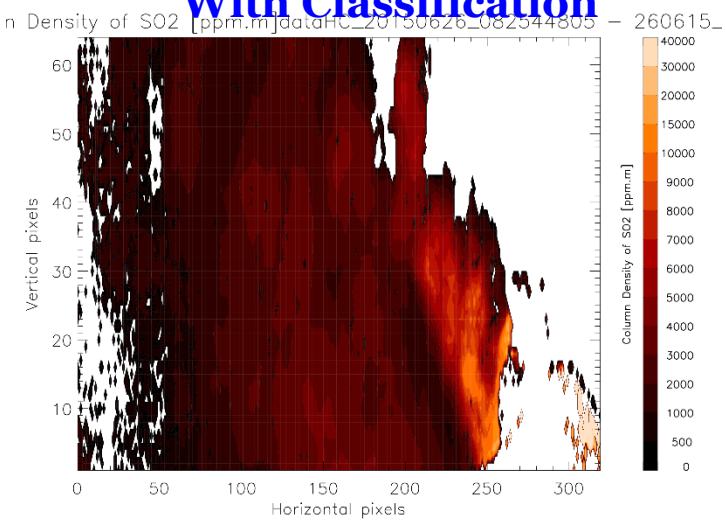
- **Simple classification based on radiative caracteristics of spectra (Brightness temperature)**
- **$T_i = A\,\sigma_i + B$** **classe [B] = 1 K**
- **$T_{moy} = (\Sigma\, T_i) / N$** **classe [$T_{moy}$] = 1K**



Reference retrieval

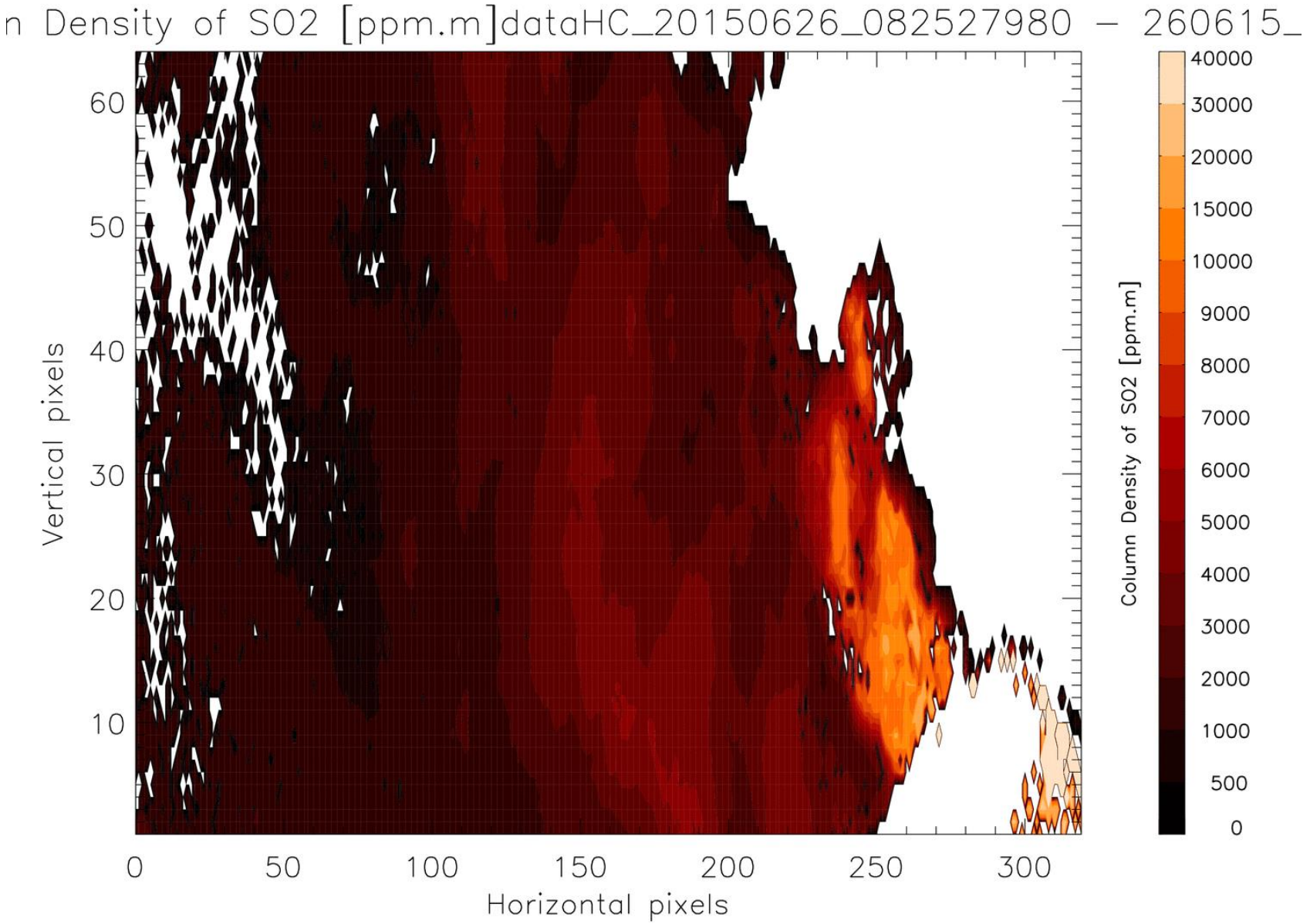


With Classification



- **412 HC**
- **20480 px**

- **Great Job !**
- **But ….**


n Density of SO2 [ppm.m]dataHC_20150626_082527980 – 260615_
Vertical pixels
10
20
30
40
50
60
0
50
100
150
200
250
300
Horizontal pixels
Column Density of SO2 [ppm.m]
40000
30000
20000
15000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
500
0

Conclusion and next steps

- HyperCam IR hyperspectral imager is relevant for volcanic plume studies

- Sensitivity tests:
  ⇒ For diluted plume SO_2 SCD is not sensitive to assumptions made in our IR retrievals

- UV & IR comparison:
  ⇒ Strong differences with underestimation of SO_2 SCD in the UV by a factor 4 in the diluted plume

  ⇒ Has already been highlighted by *Kern et al., JGR, 2012 (radiative transfert, UV spectroscopy)* and *Boichu et al., ACP, 2015* (SO_2 fluxes, IASI measurements, UV ground-based)

To go further*:*
- Develop NRT retrieval approach : any ideas ?
- Latest campaign: September 2017 (Mt Etna and Stromboli)
  IR hyperspectral imager (HyperCam) and a solar occultation FTIR (LOA, Lille)
  ⇒ Investigate aerosols and ash type and composition → better analysis of dense plume measurements
- Explore potential of IR hyperspectral imaging to map other species in volcanic plumes : SiF_4, CO_2, OCS, CH_4, …

Acknowledgment

- Labex Voltaire (ANR-10-LABX-100-01) and French program LEFE-CHAT, for funding the project

- INGV for providing great conditions of work during the campaign

Supplement

- Aerosols contribution parametrization: