Validation of TROPOMI observations of SO_2 fluxes from volcanoes using ground-based observations

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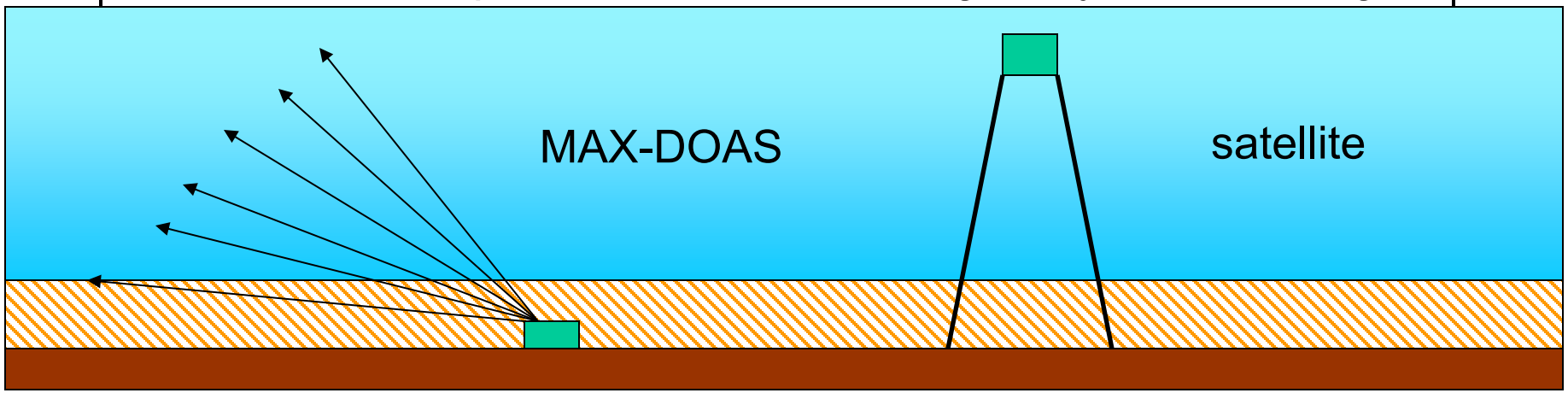
- Problems of the direct SO_2 VCD validation of volcanic plumes
- Validation of SO_2 flux as proxy for the validation of SO_2 VCDs
- Methods for the determination of SO_2 fluxes from satellite and from ground-based observations
- Conclusions & Outlook

The validation of satellite trace gas products is usually performed by direct comparison of vertical column densities (VCDs)

The basic assumption is horizontal homogeneity of the trace gas



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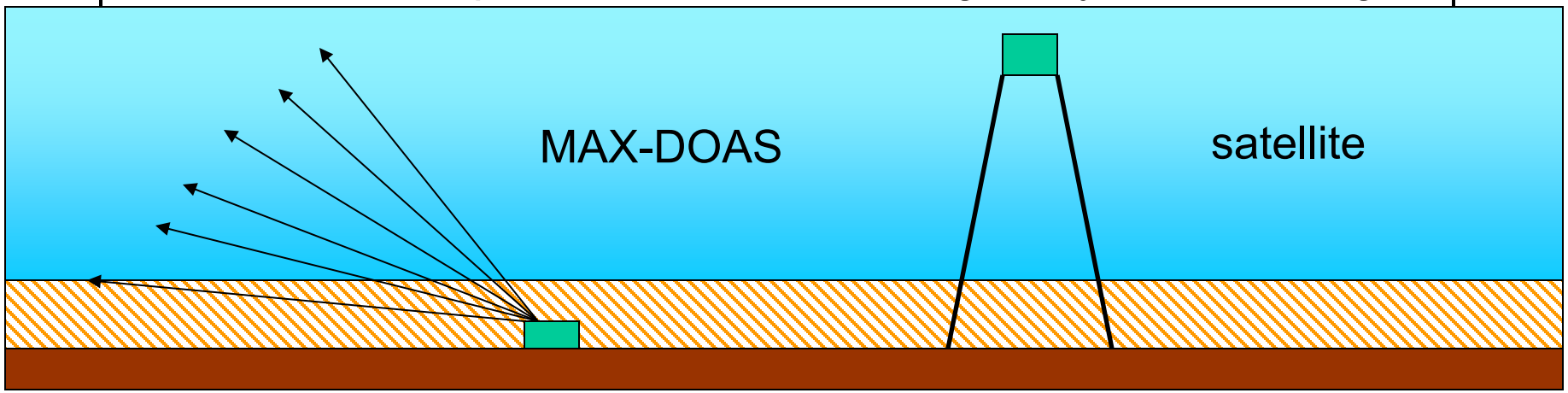
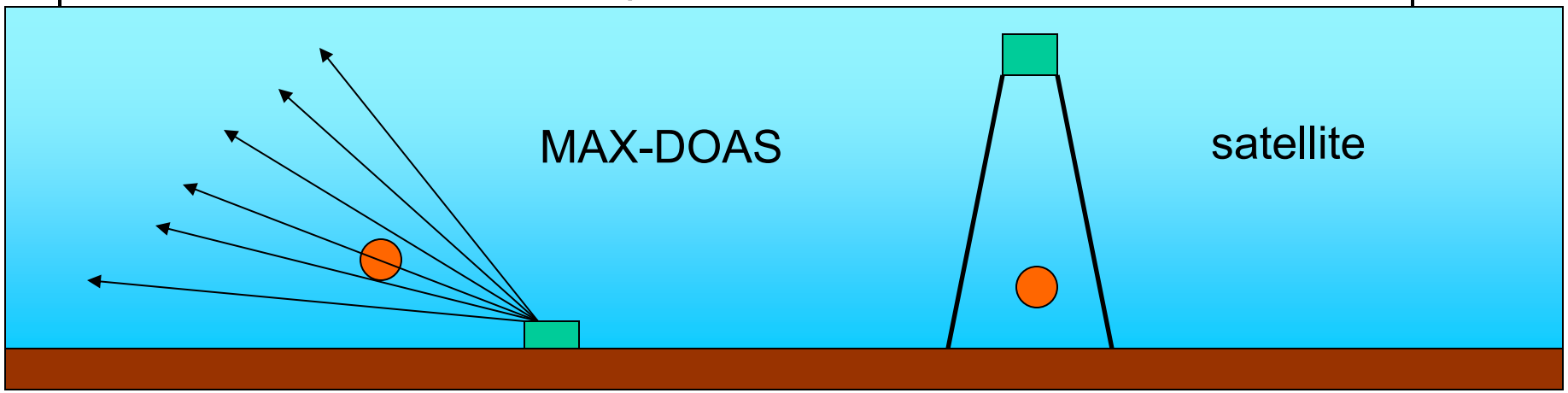
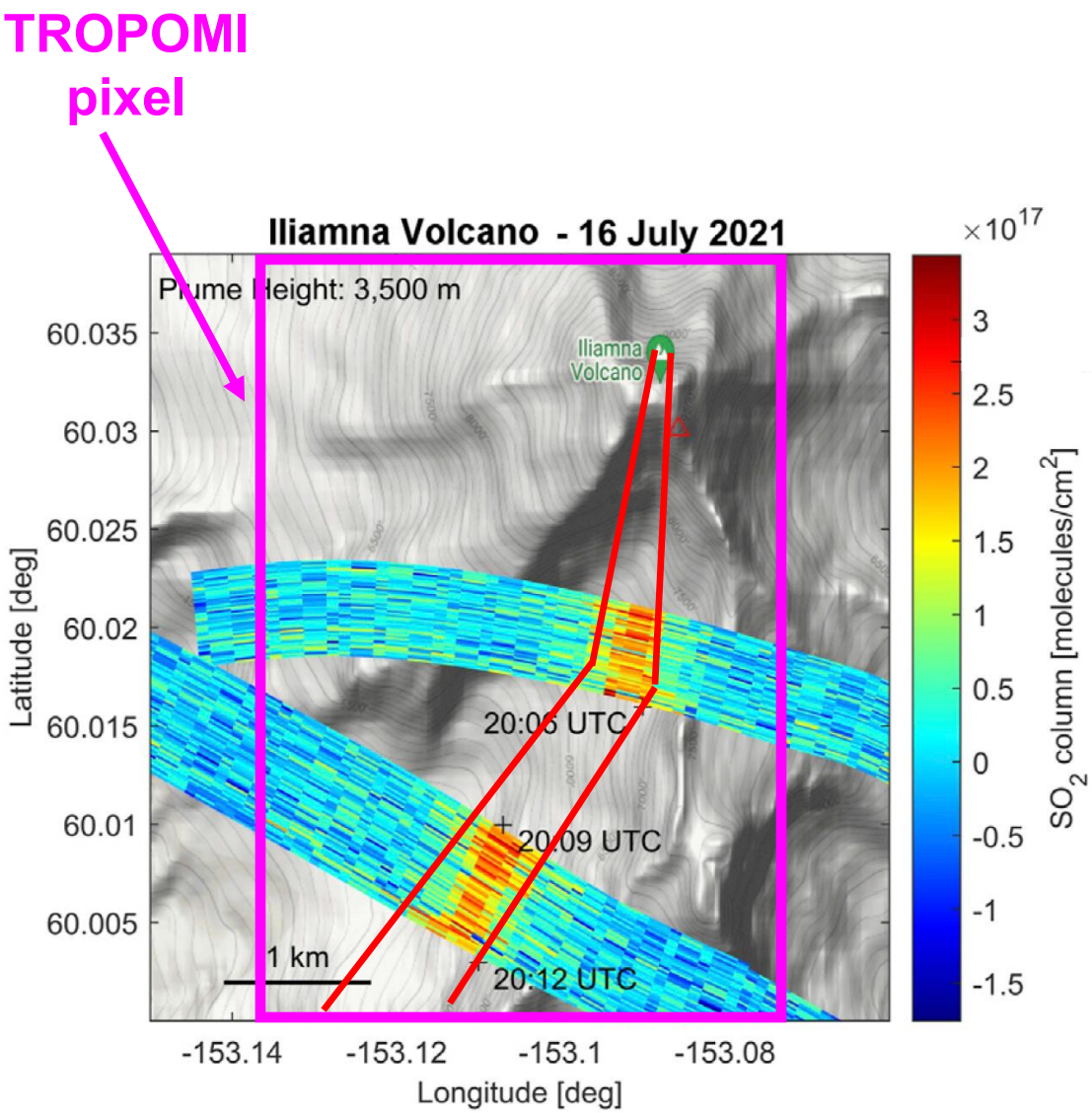


For volcanic plums this is not fulfilled



How is VCD defined in such cases?

Further problem: different spatial scales of the measurememt and plume



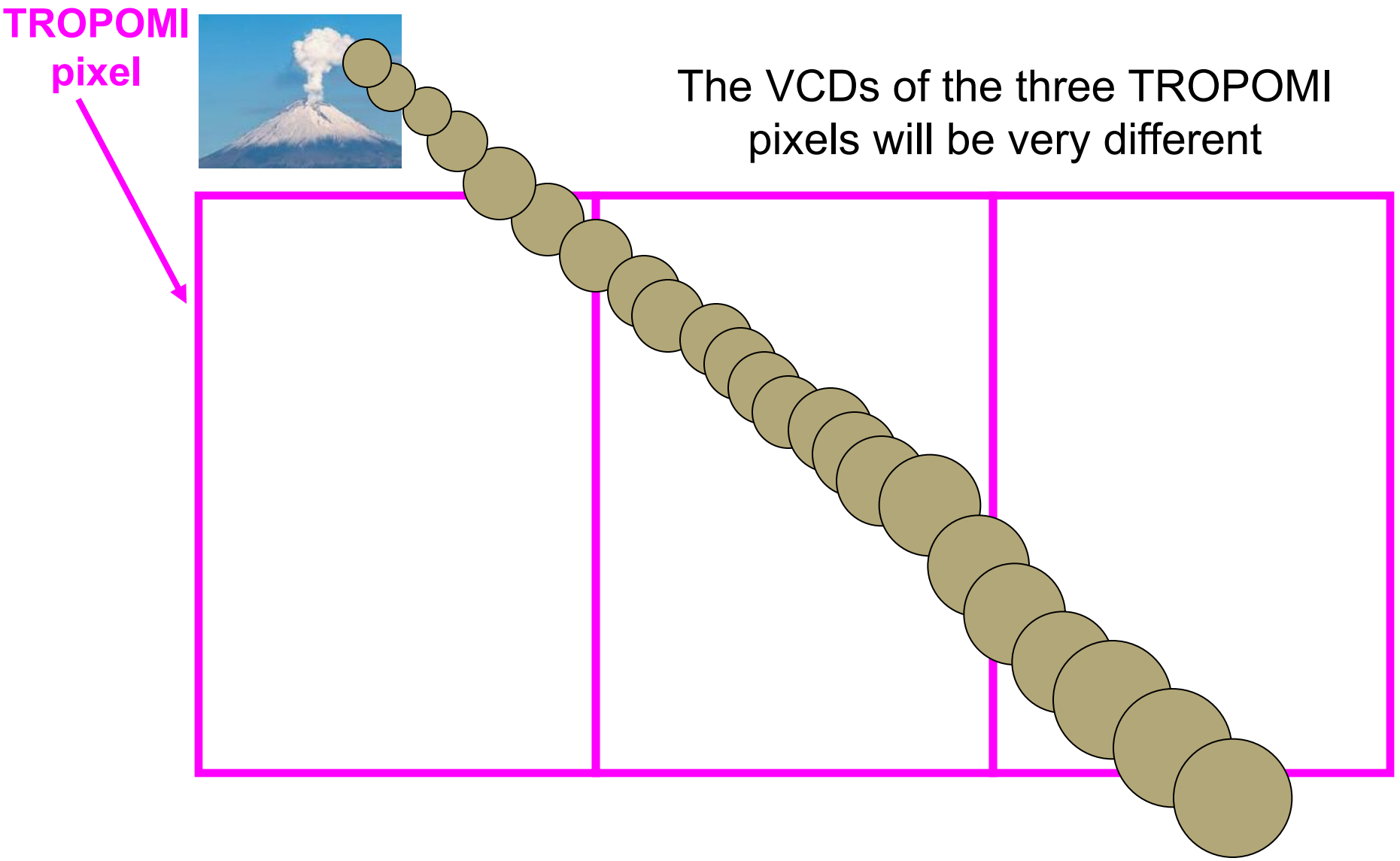
Kern and Kelly, Front. Earth Sci, 2023.

=> The VCDs from satellite and ground differ systematically

In the example on the left, the plume fills only about 10% of a TROPOMI ground pixel

=> The satellite VCD will be at least 10 times smaller than measured from ground

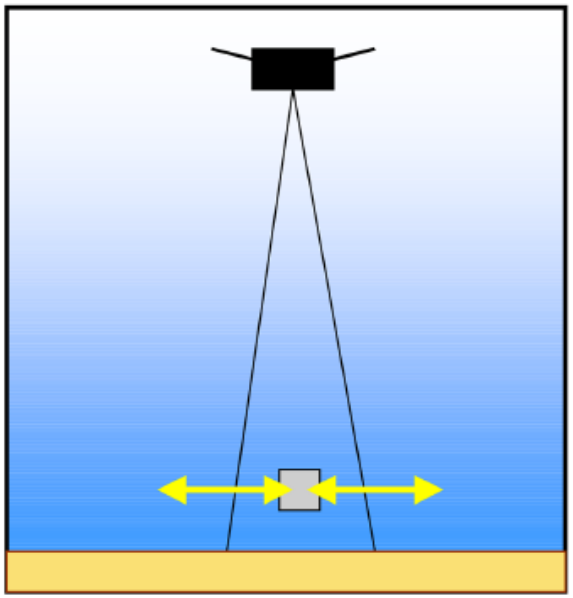
it can even be even worse:



There are some more subtle (3D-RTM) effects

For satellite observations:

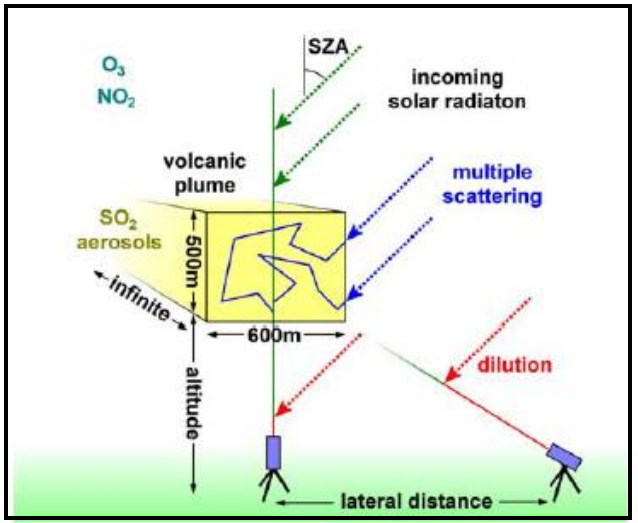
=> horizontal light mixing



Wagner et al., 2023

For ground-based observations

=> light dilution

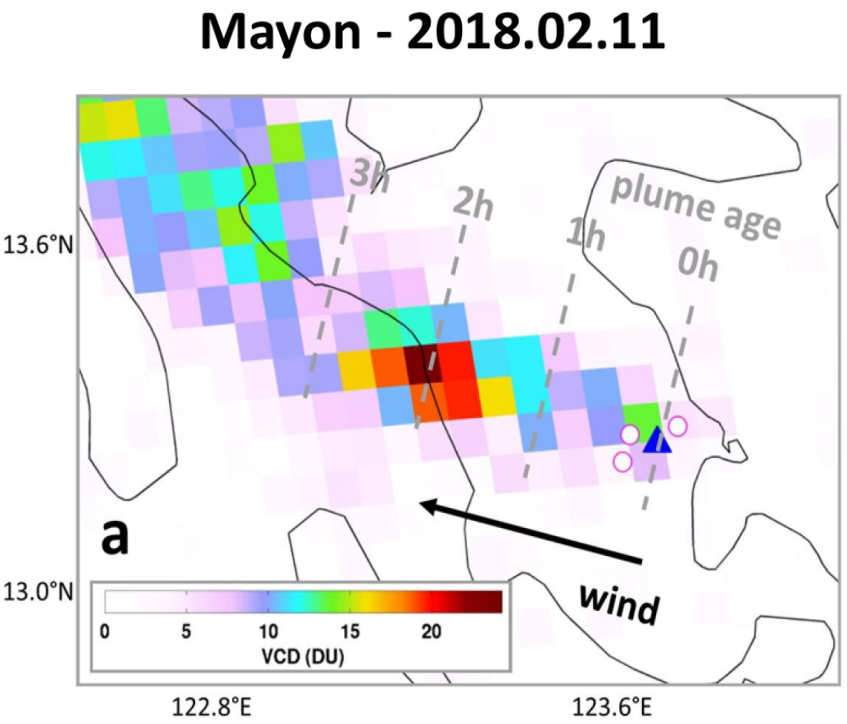


Kern et al., 2009

The solution could be an indirect validation: compare SO_2 fluxes from ground-based and satellite observations

- for both observation geometries, methods for the determination of the SO_2 flux were developed during recent years (for the basic principles see next slides)
- for all algorithms, an important aspect is to determine the plume height
- initial comparison studies are very promising and were already published
- but they were based on few examples; also details of the methodologies are not finally decided
- besides satellite validation, the determination of SO_2 fluxes is in itself highly relevant (improvement of global emission inventories)

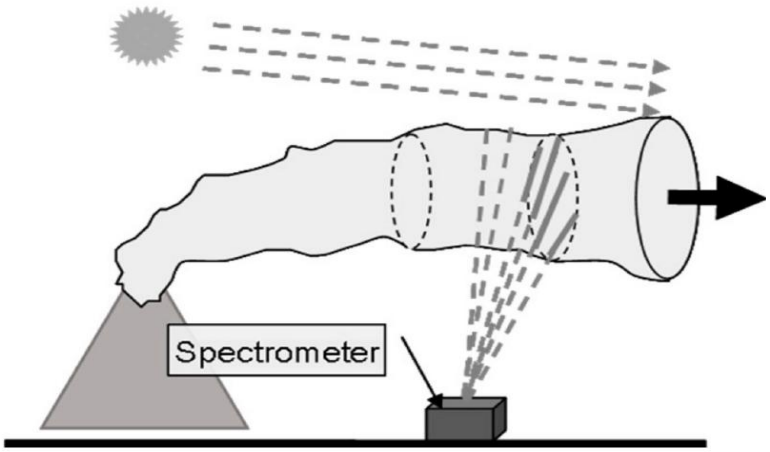
Flux determination from satellite



Theys et al., *Sci Rep*, 2019

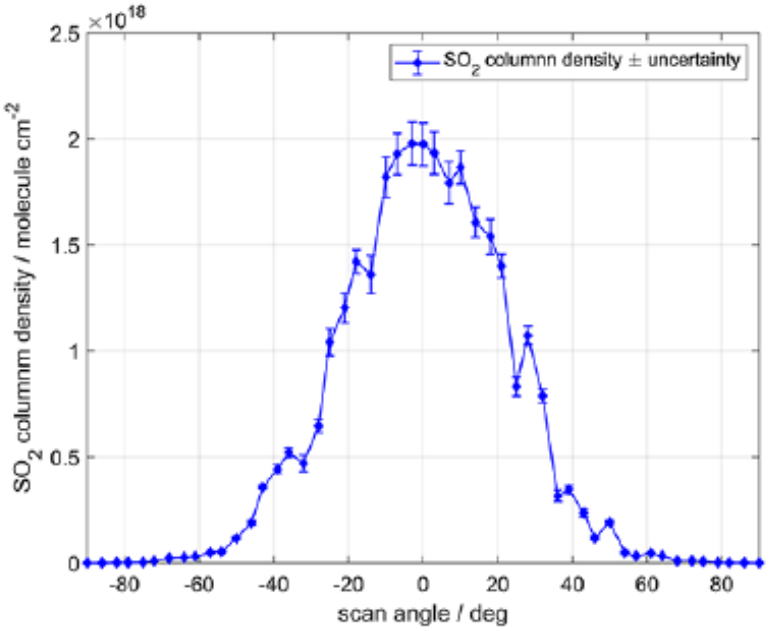
- plume fuxes are calculated by accross plume integration and multiplication with wind speed
- assumptions on plume height and wind speed have to be made (or can be estimated from comparison of plume direction with wind fields / trajectories)
- fluxes at different distances represents emissions at different times

Flux determination from ground



Platt et al., Geosciences, 2018

- plume fuxes are calculated from angular plume scans and multiplication with wind speed
- also plume height is determned
- wind speed can be taken from models or be determined from correlation analyses of scans at different distances
- fluxes can be continously derived



Example of a plume scan

Arellano et al., Earth Syst. Sci. Data, 2021.

We plan to use the following algorithms

Satellite retrievals:

- **PlumeTraj** - University of Manchester
- **PlumeRing** - University of Palermo / INGV Catania
- **Disk method** - University of Lille/CNRS, Lille, University of Paris

They mainly differ in their way to determine the plume height

Ground-based retrievals:

- **NOVAC** - Chalmers University, Gothenburg
- **FLAME** - INGV, Osservatorio Etneo Catania

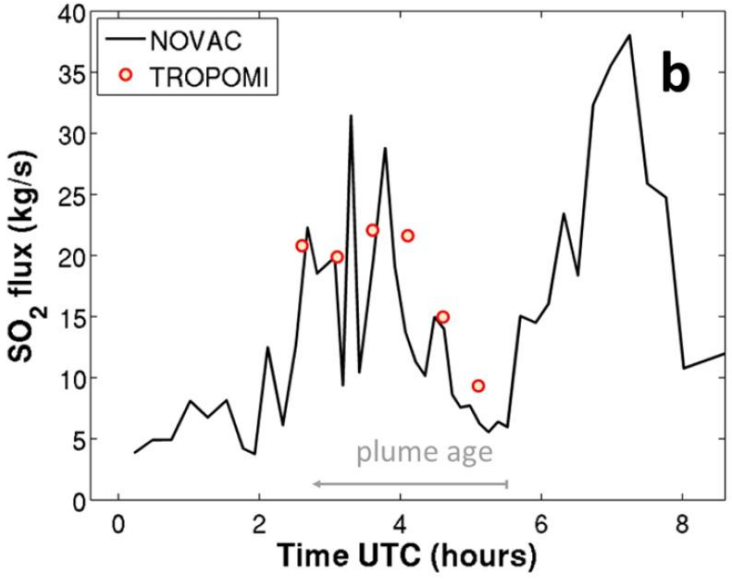
We propose to focus on the following volcanoes

Volcano (country)	Elevation (m ASL)	Location	Ground-based network	Some characteristics	Ground-based SO_2 flux data availability
Etna (Italy)	3357	37.7°N, 15.0°E	FLAME	Trachybasalt, wide range of volcanic activity	2018 - 2025
Sabancaya (Peru)	5960	15.8°S, 71.9°W	NOVAC	Andesite, frequent ash emission, dry atmosphere	2018 - 2025
Nevado del Ruiz (Colombia)	5279	4.9°N, 75.3°W	NOVAC	Andesite, high cloud cover	2018 - 2023

- persistent degassing over the period 2018-2025 (2023)
- eruptions of different strenghts
- different tectonic settings & volcanic and degassing processes
- different meteorological conditions / cloud cover
- large variability of emissions: 500-20000 t/d of SO_2

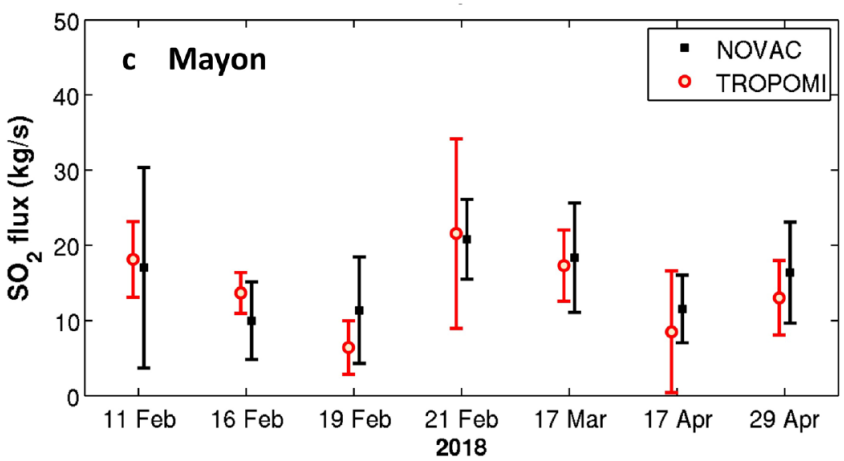
Summary & Outlook

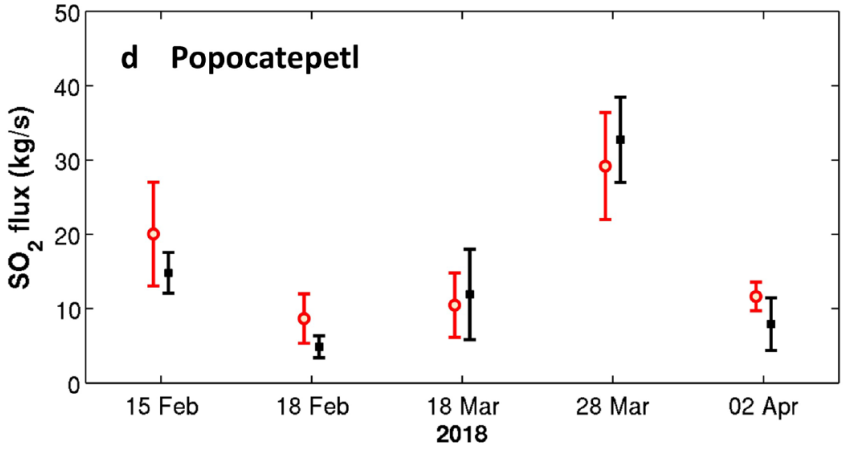
- Validation of SO_2 fluxes is proposed as ‚replacement' for direct VCD validation of volcanic plumes
- Team of 3 satellite and 2 ground based teams is formed
- Proposal sent to ESA, waiting for feedback
- Expected outcome:
    - Validation results for different volcanoes / different meteorological conditions / different emissions strengths / different viewing geometry
    - Also comparison of plume height (incl. operational TROPOMI product
    - Recommendations for CH_4 flux validation
    - Results and methods will be important for further missions: S4, S5, GEMS, TEMPO



Comparison of the plume fluxes for emissions at different times of a day.

Comparison of daily averages for several days

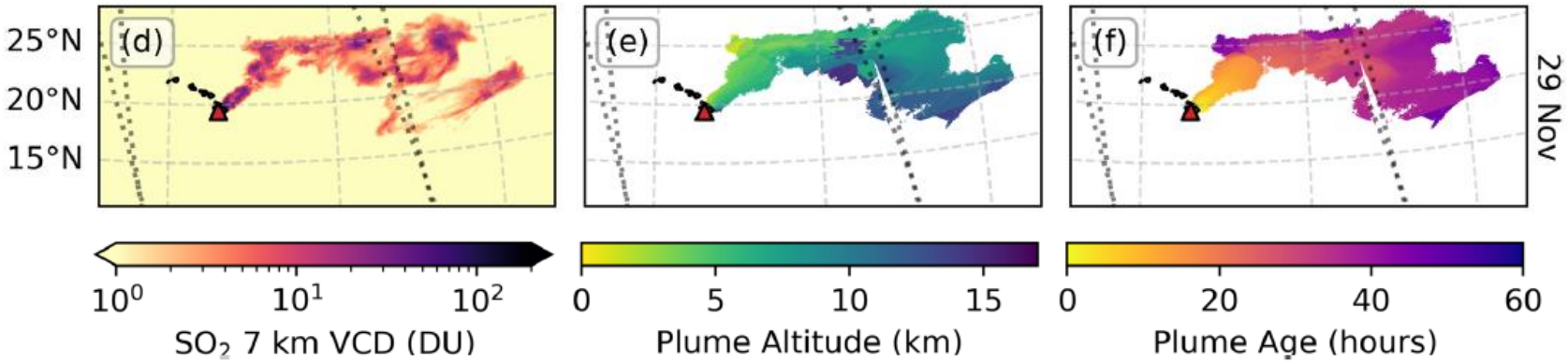




Theys et al., *Sci Rep*, 2019

PlumeTraj - University of Manchester

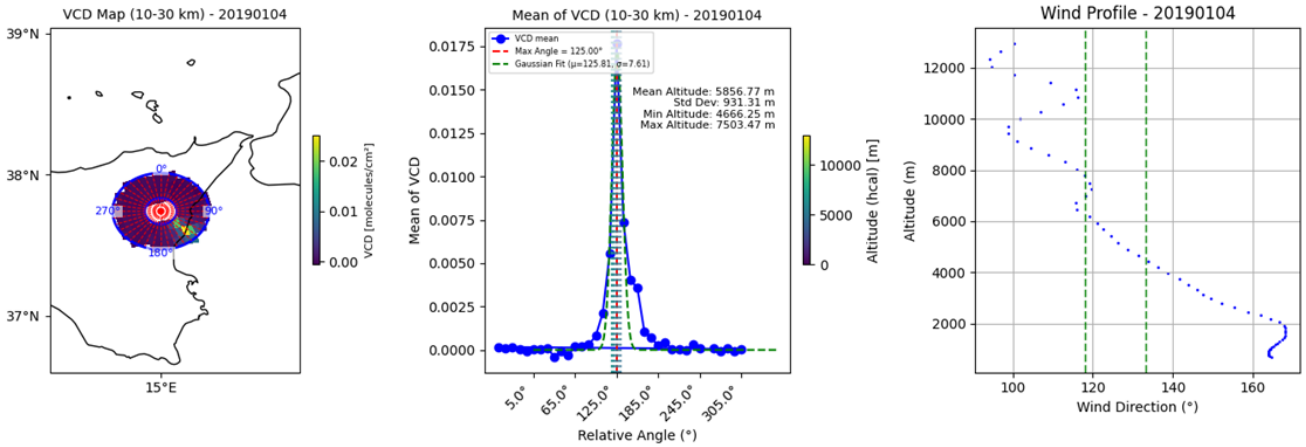
Combination of trajectory analyses with TROPOMI plume patterns:



Esse, et al. Bull Volcanol 87, 69 (2025).

PlumeRing - University of Palermo / INGV Catania

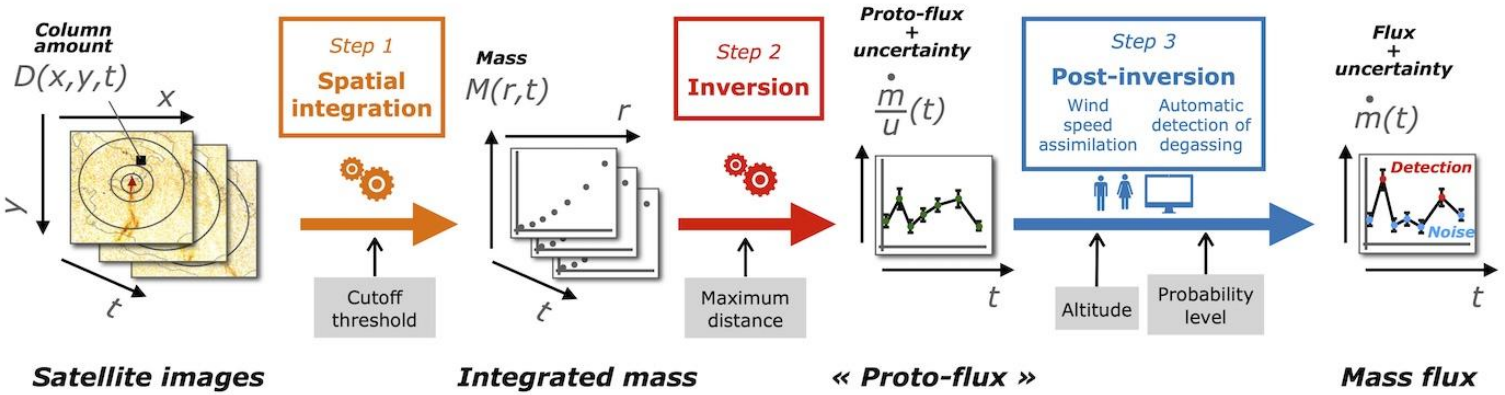
Comparison of TROPOMI plume directions with profiles of wind direction:



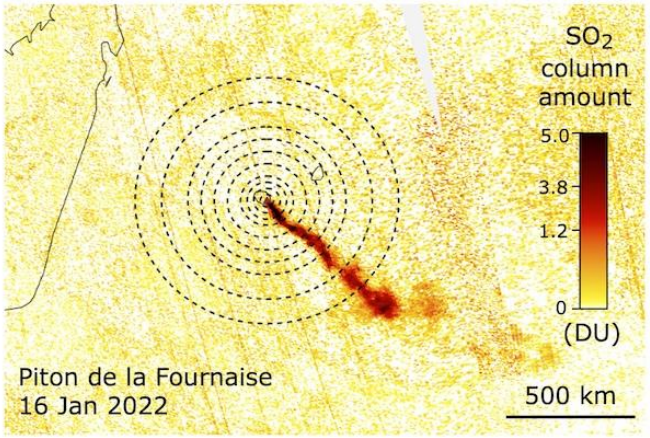
Dozzo, et al., Poster at Living Planet Symposium (2025)

Algorithm from the Volcano Space Observatory – "Disk method"

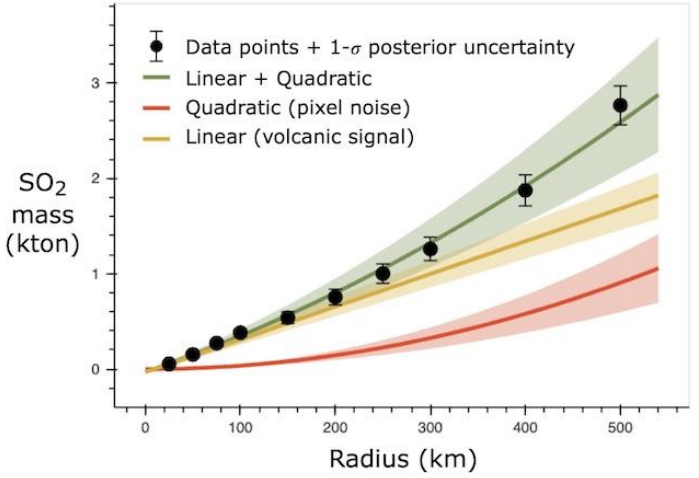
(a) « Disk method » workflow

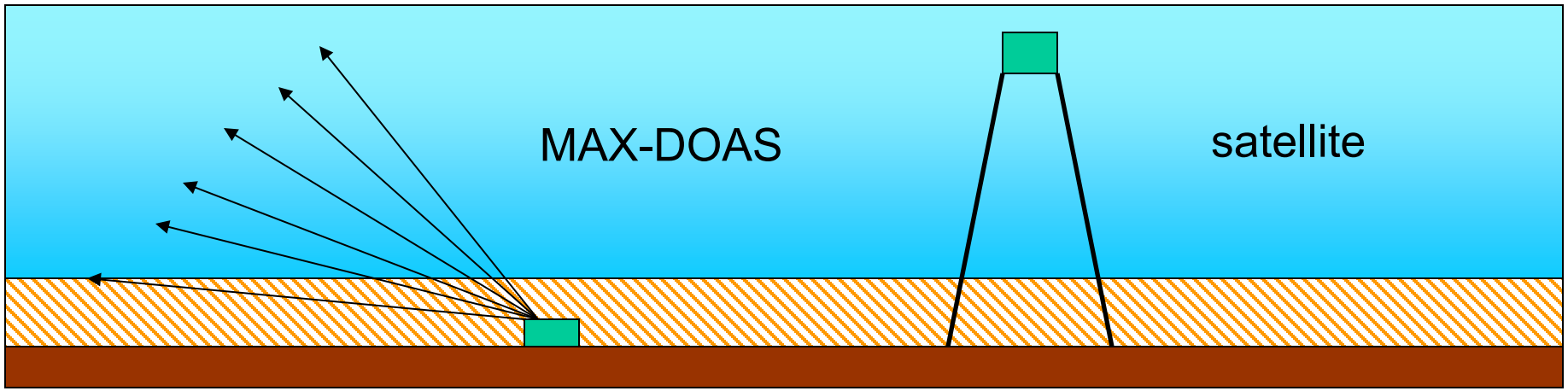


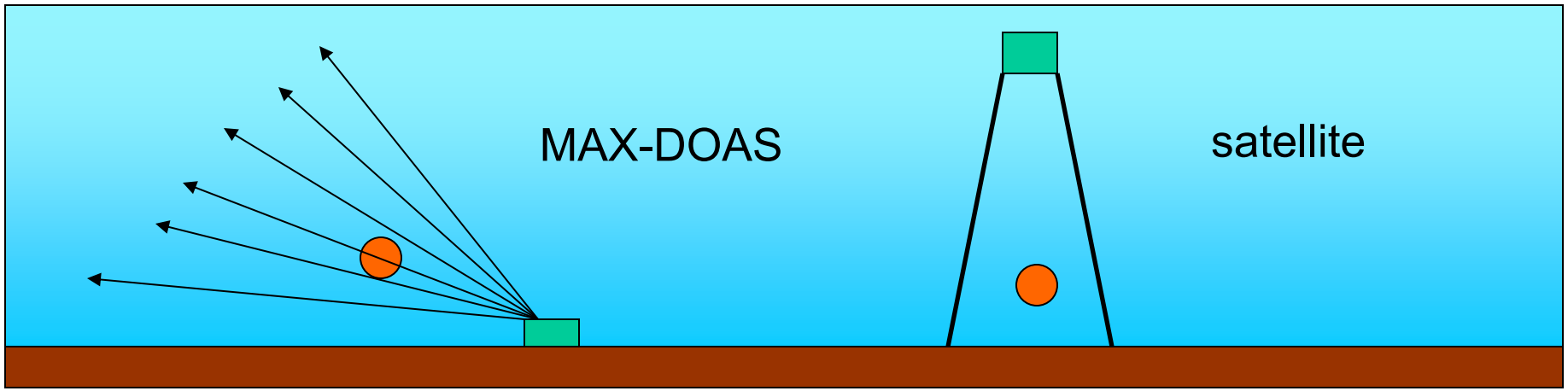
(b) TROPOMI Level-2 SO_2 (7 km product)



(c) SO_2 mass versus disk radius




MAX-DOAS
satellite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