VOlcanic pLume chAracterization using sounNDing balloOns - VOLANDO

Final Meeting 19 March 2026, INGV-Rome

2025 June Etna field campaign: measurements and products cross-comparison

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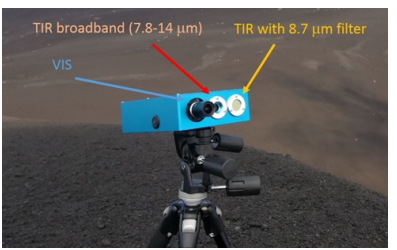
Activities Overview

Date	Volcanosonde	VIRSO2 Camera
02-06-2025 **Lava Fountain & pyroclastic flow**	• Balloon launch from Milo Data shows that the volcanosonde probably cross the plume	• Nicolosi (720 m) & La Montagnola (2630 m) Too much ash for SO2 retrieval
03-06-2025	• Tethered balloon (Walking -Northeast) Two volcanosonde: Good data	• Pizzi de Neri (2845 m) Meteo clouds
04-06-2025	• Tethered balloon (Crater –Northeast) Two volcanosonde: Good data, but one CO2 sensor showed failures.	• Pizzi de Neri (2845 m) Night measurements, Good Data
05-06-2025	• Tethered balloon (Walking southeast) • In-situ measurements (Crater –Northeast) Three volcanosonde: Good data, only one SO2 sensor showed failures.	• La Montagnola (2630 m) Meteo clouds
06-06-2025	• Drone flight experiment with vulcanosonde Good data	• Pian del Lago (2700 m) Meteo clouds

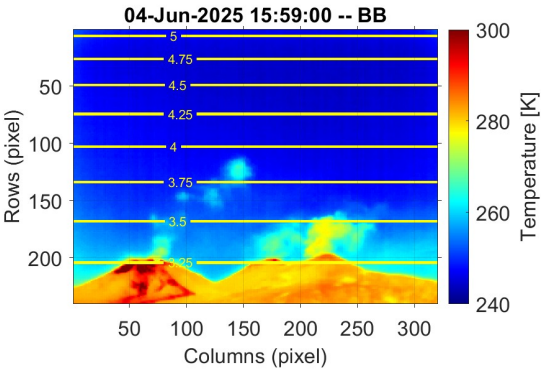
4 June 2025 - Temporal coverage of the data

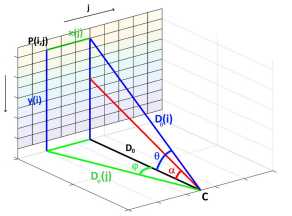
- Volcanosonde:
  15:48 – 02:42 UTC (5D), 15:36 – 01:54 UTC (7D)
- GNSS: 15:39 – 21:41 UTC
- VIRSO2: 15:49 – 00:17 UTC
- ASTER: 19:55 UTC
- TROPOMI: 5 June 2025 11:09 UTC

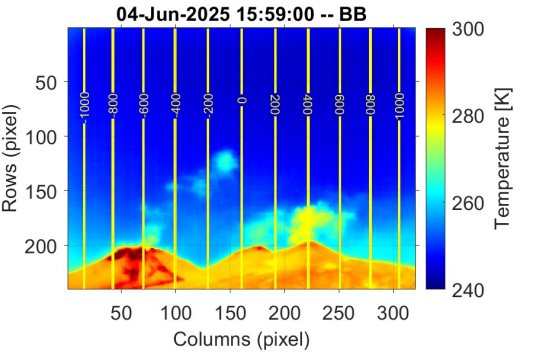
VIRSO2 TIR Camera at Pizzi de Neri 2845 m asl

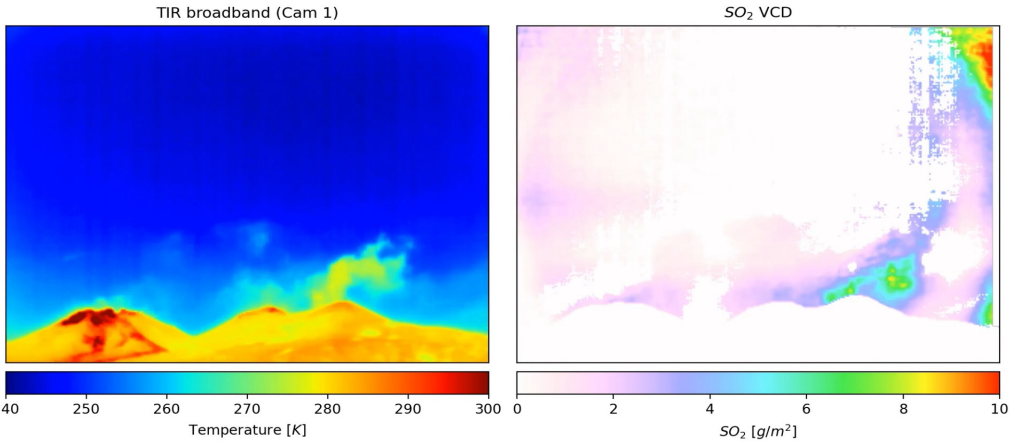


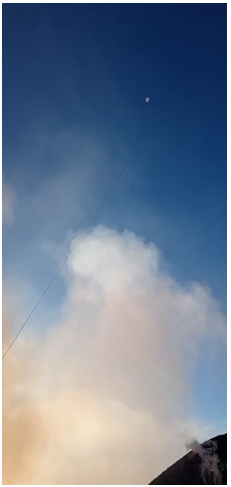
VIRSO2 TIR Camera Geometry



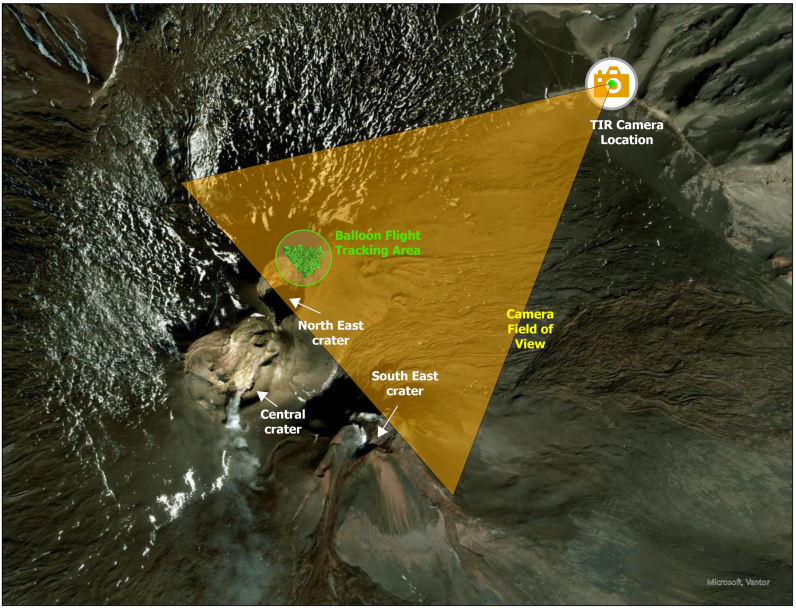





2025-06-04 | 15:49:28 UTC
TIR broadband (Cam 1)
SO_2 VCD
240
250
260
270
280
290
300
Temperature [K]
0
2
4
6
8
10
SO_2 [g/m^2]



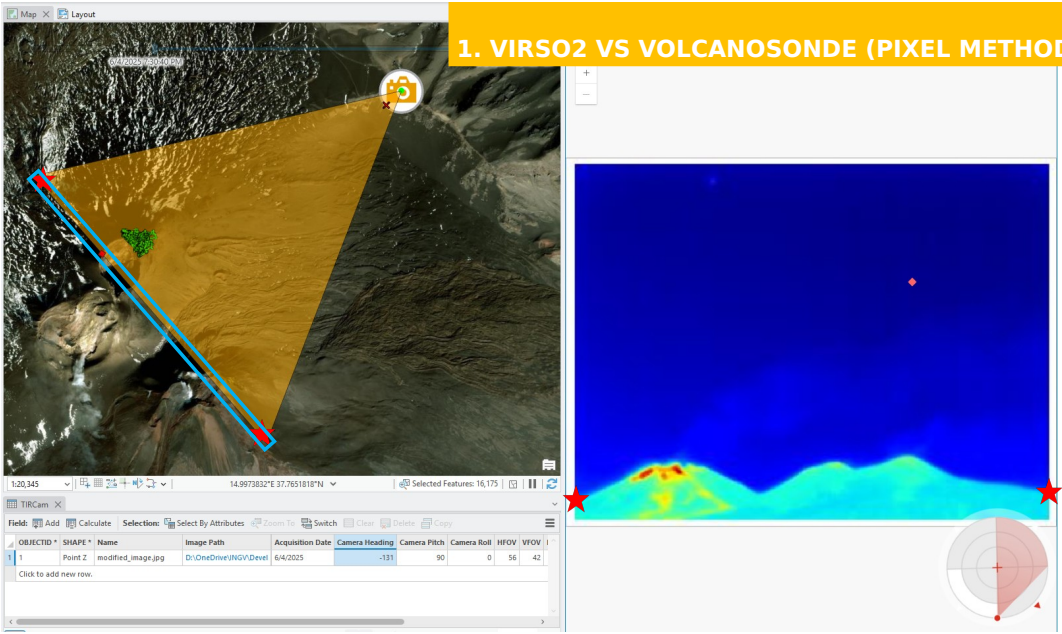
Tethered balloon at North-East Crater 3300 m asl


TIR Camera
Location
Balloon Flight
Tracking Area
North East
crater
Camera
Field of
View
South East
crater
Central
crater
Microsoft, Vantor

Cross-comparison Summary:

- 1) VIRSO2 vs VOLCANOSONDE (pixel method)
- 2) VIRSO2 vs VOLCANOSONDE (flux method)
- 3) VIRSO2 vs TROPOMI (flux method)
- 4) VIRSO2 vs ASTER ???

1. VIRSO2 VS VOLCANOSONDE (PIXEL METHOD)



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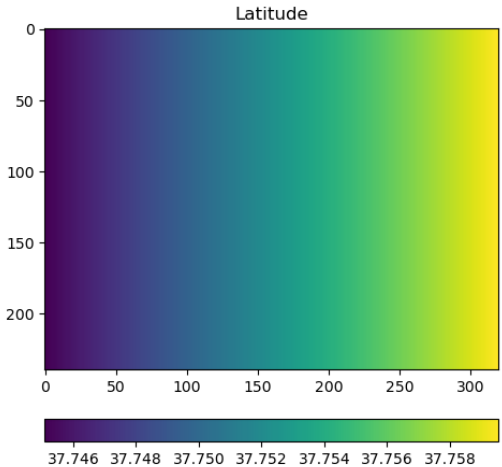

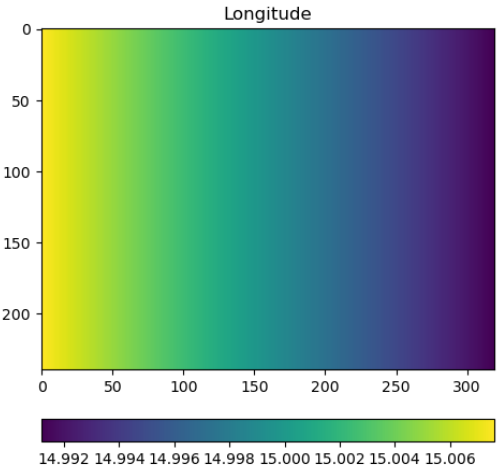

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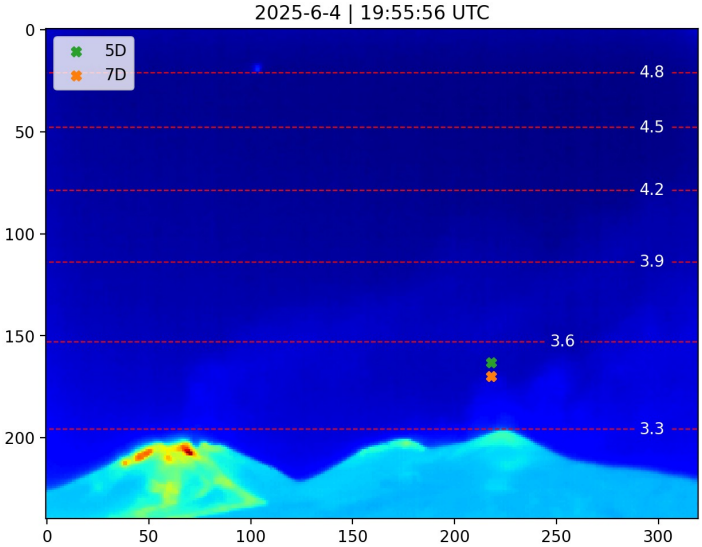

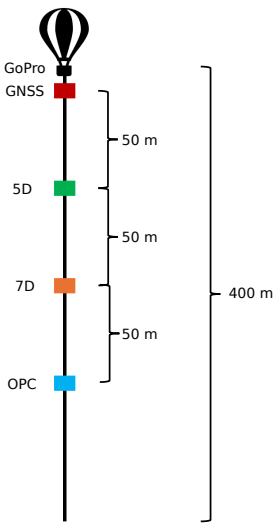

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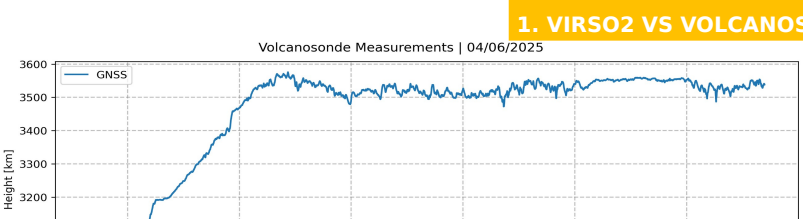

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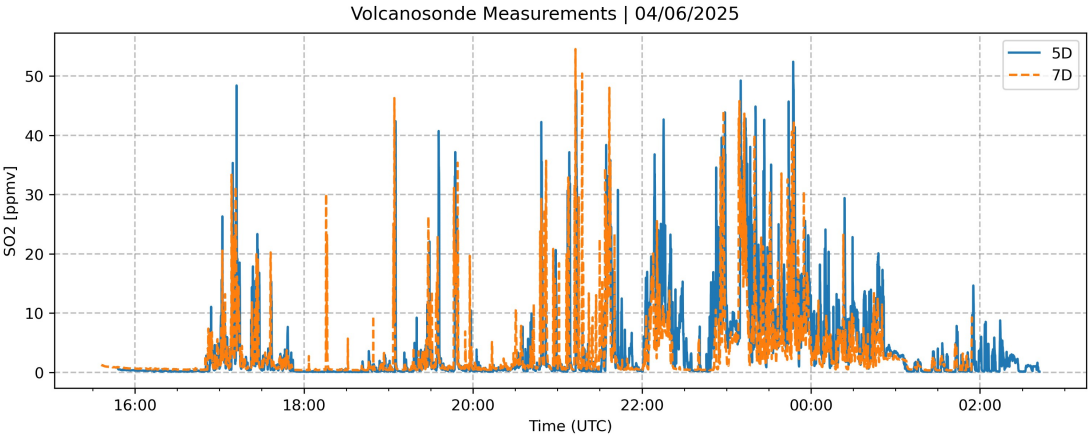
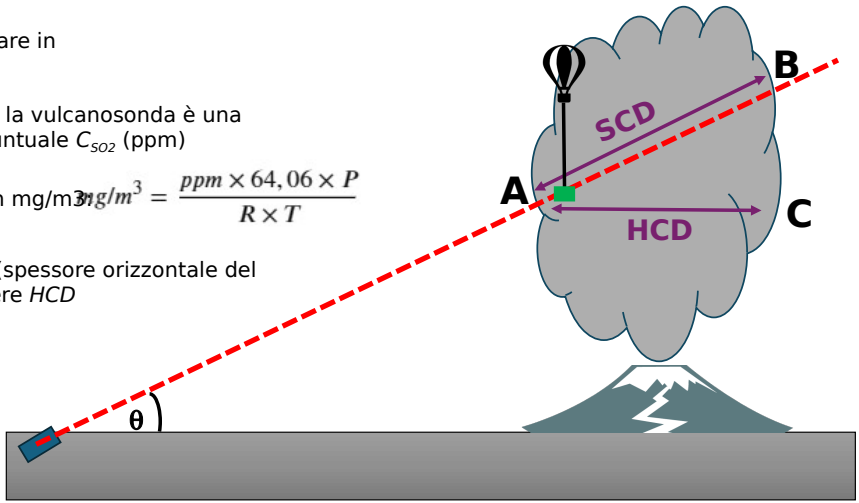


1. VIRSO2 VS VOLCANOSONDE (PIXEL METHOD)

- Quello che la camera vede, per un certo pixel, è il contenuto colonnare tra A e B (*SCD*, in g/m2)
- Lo posso trasformare in
- Quello che misura la vulcanosonda è una concentrazione puntuale C_{SO2} (ppm)
- Trasformo i ppm in mg/m3 $mg/m^3 = \frac{ppm \times 64,06 \times P}{R \times T}$
- Moltiplico per AC (spessore orizzontale del plume) per ottenere *HCD*



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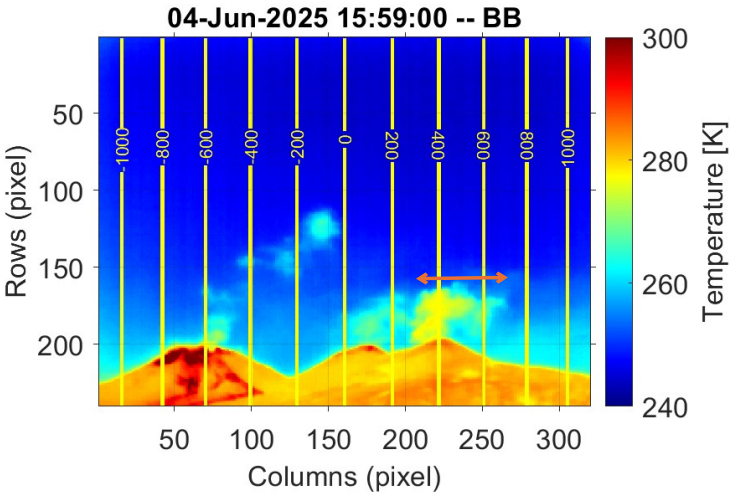
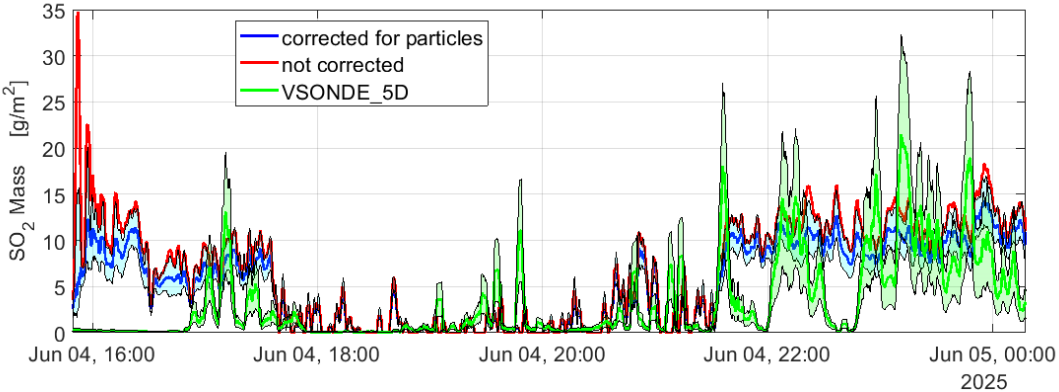


AC (spessore orizzontale del plume):

400 +/- 200 m

1. VIRSO2 VS VOLCANOSONDE (PIXEL METHOD)



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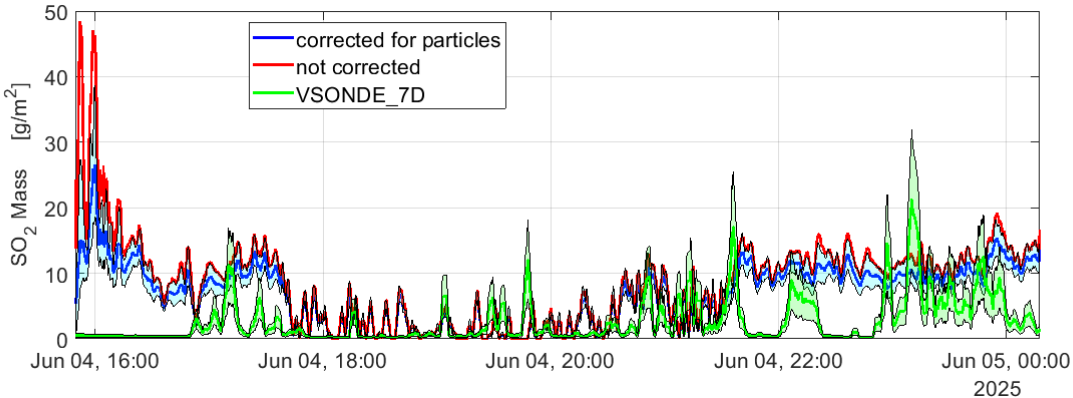


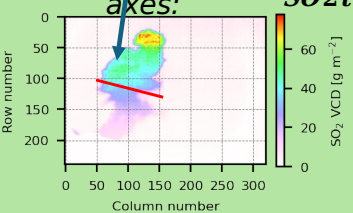
Uncertainties

- Associated with latitude, longitude, and height variations: Automatic pixel localization.
- Volcanic plume thickness: Use ASTER data to improve it
- The Volcanosonde measurements show a high degree of variability (probably due to the position inside/outside the plume)
- Uncertainties related to the VIRSO2 retrieval: plume direction, particle's size (water vapour droplets), other uncertainties due to the retrieval algorithm.

SO_2 Flux Computation «*Traverse Procedure*»

(Theys et al., 2013; Corradini et al., 2021)

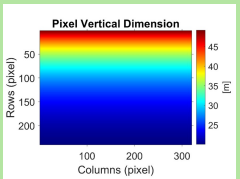
Define a Transect perpendicular to the plume axes:

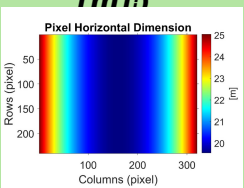


Plume Speed (*v [m/s]*)

$$F_{SO2\,t}[g/s] = \sum_{l=1}^{l2} v_l \cdot M_l \cdot l$$

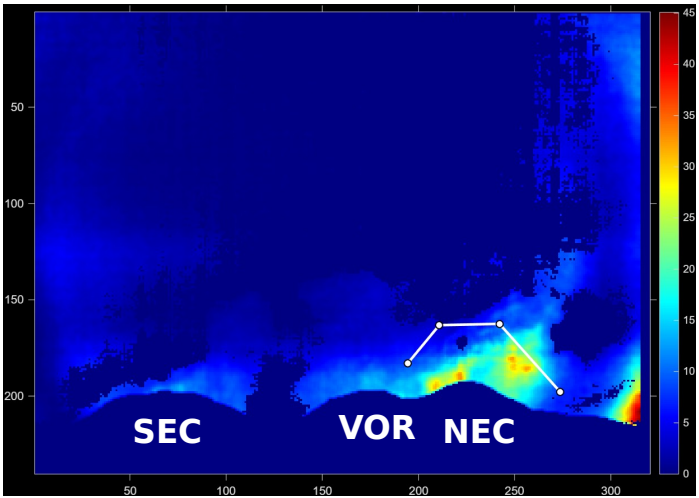
Pixels width (*l [m]*$_i$)





SO_2 columnar aboundance (*M [g/m2]*$_i$)

VIRSO2 VS VOLCANOSONDE (FLUX METHOD)

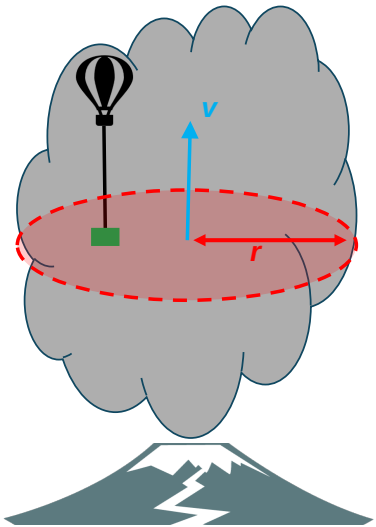


- La misura della vulcanosonda si riferisce solo al NEC
- Transetto costituito da 3 spezzate a causa della rotazione del plume nel tempo
- Velocità: 2 m/s

2. VIRSO2 VS VOLCANOSONDE (FLUX METHOD)

- Misura della vulcanosonda è una concentrazione puntuale C_{SO2}(ppm)
- Trasformo i ppm in mg/m3
- Moltiplico per la sezione circolare del plume. r = AC (spessore horz del plume) / 2
  200 +/- 100 m
- Moltiplico per la velocità del plume (2 m/s)

$$F\,SO2[mg/s]=C\,SO2[mg/m3]\cdot \pi\, r2[m2]\cdot v[m/s]$$



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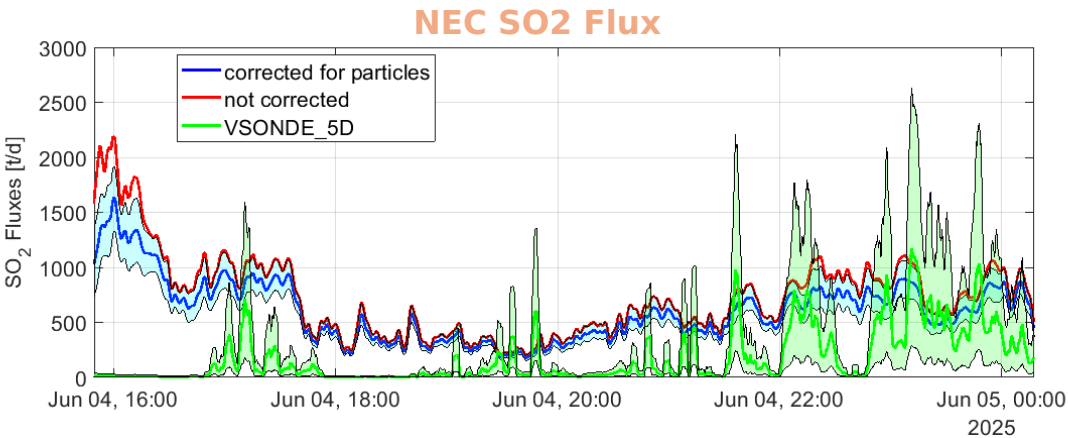

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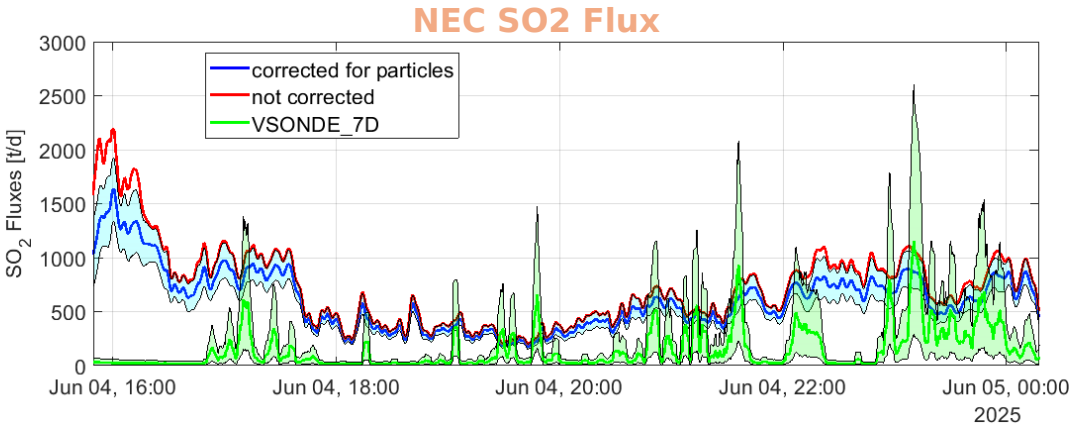
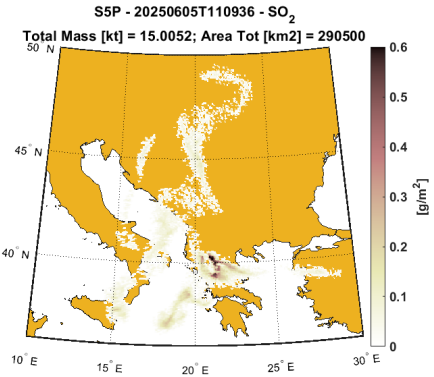


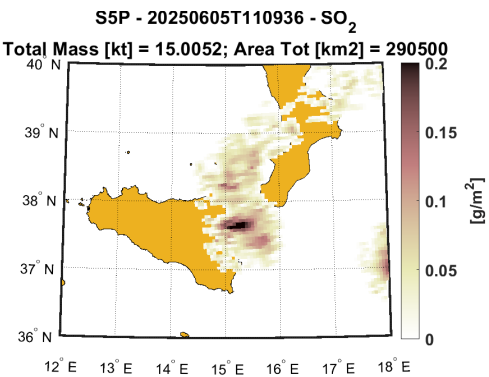
Uncertainties

- Volcanic plume thickness: Use ASTER data to improve it
- The Volcanosonde measurements show a high degree of variability (probably due to the position inside/outside the plume)
- Uncertainties related to the VIRSO2 retrieval: plume direction, particle's size (water vapour droplets), other uncertainties due to the retrieval algorithm.
- (plume speed, we use the same for VIRSO2 and VSONDE)

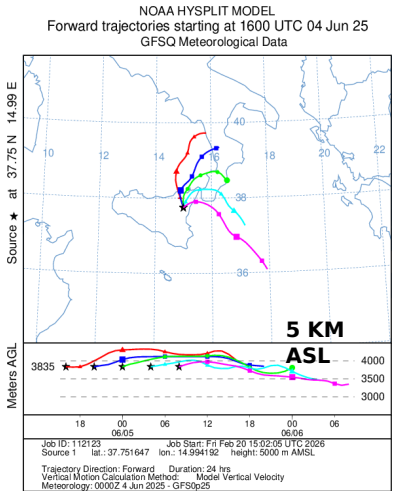
3. VIRSO2 VS TROPOMI (FLUX METHOD)

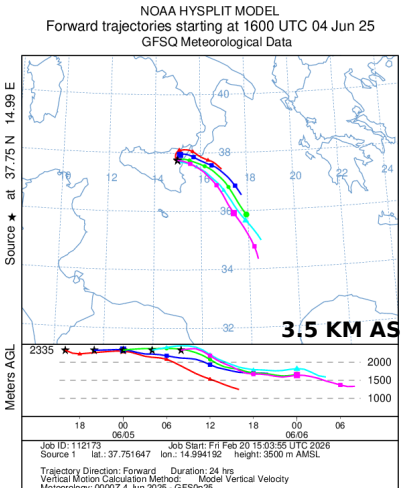
Sensor	Satellite	Orbit	Type	Spectral Range	Spatial Resolution (km^2)	Temporal Resolution (@ Midlatitudes) (Per Day)	Algorithm for SO_2 retrievals (*) = Operational Products	SO_2 Absorption Band	Detection Limit (t/km^2) (DU)	Errors (%)
TROPOMI	Sentinel5p (ESA)	LEO	Hyper	UV-SWIR (270–500 nm; 675–775 nm; 2305–2385 nm)	3.5 × 7.2 (3.5 × 5.5 since 6 August 2019)	1–2	DOAS (Differential Optical Absorption Spectroscopy) [57,58]	UV (312–326 nm, 325–335 nm, 360–390 nm)	0.009–0.02 (0.3–0.7)	35 [58]



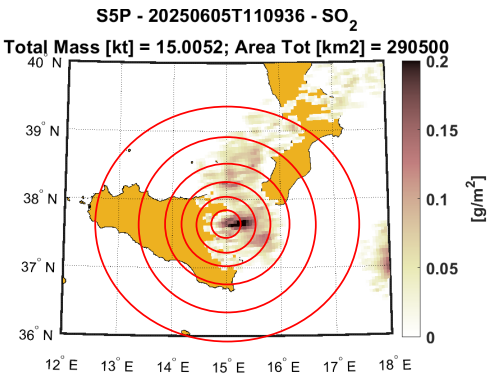


Plume Altitude ?



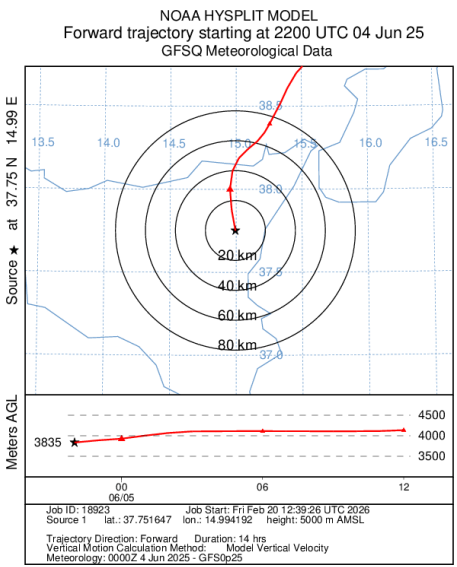


The Flux computation is realized using the «Traverse Procedure» by considering circular transects around volcanic crater



V = wind speed [m/s]= 2.6
M_i = SO2 columnar content [g/m²] (mean of the i-th circular transect)
$L_i = 2*\pi*r_i$ [m]

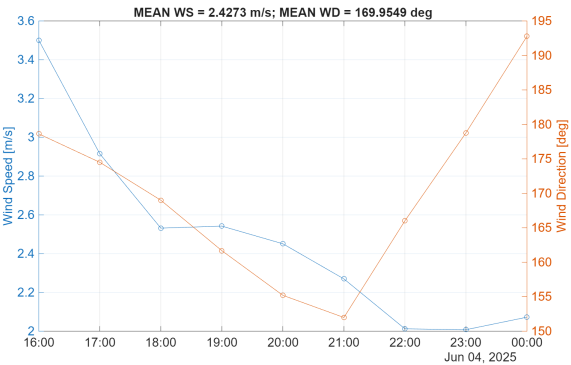
Plume Speed ?



3. VIRSO2 VS TROPOMI (FLUX METHOD)

10 km/h = 2.78 m/s

ERA5 over Etna at 5 km asl



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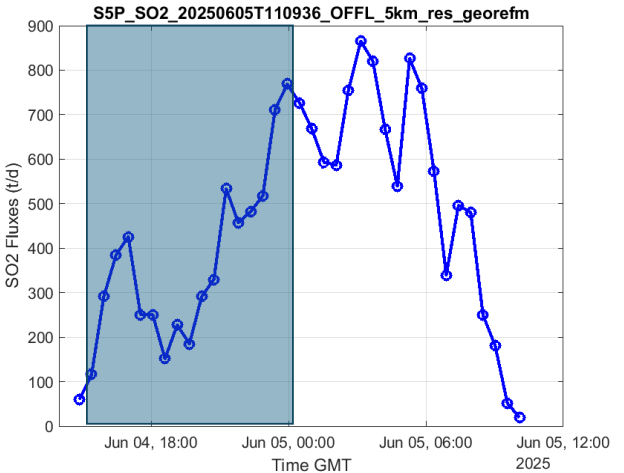

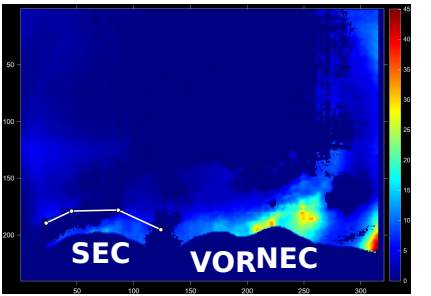

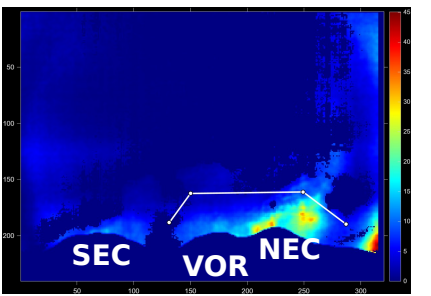

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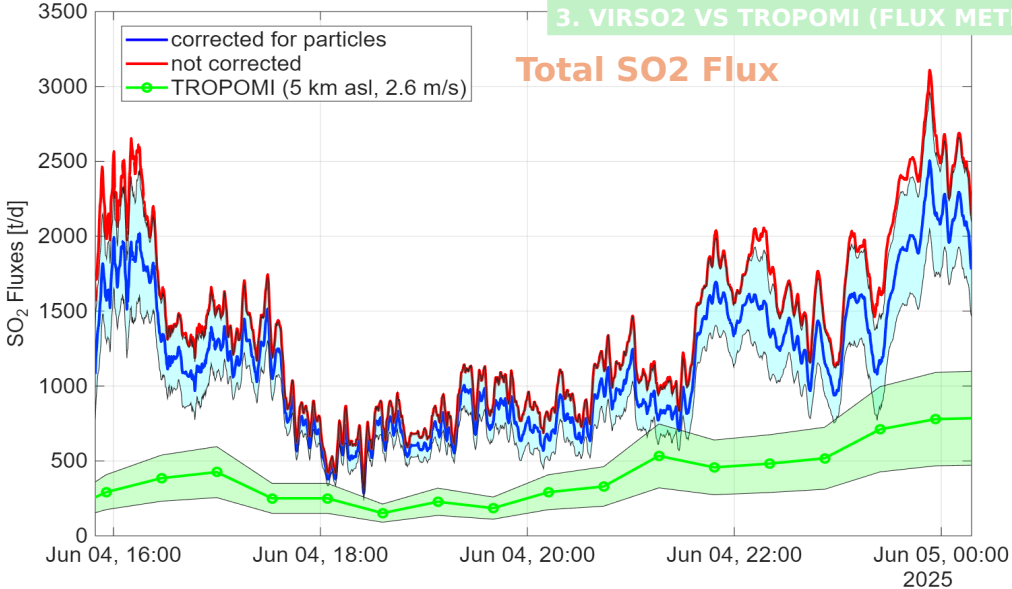
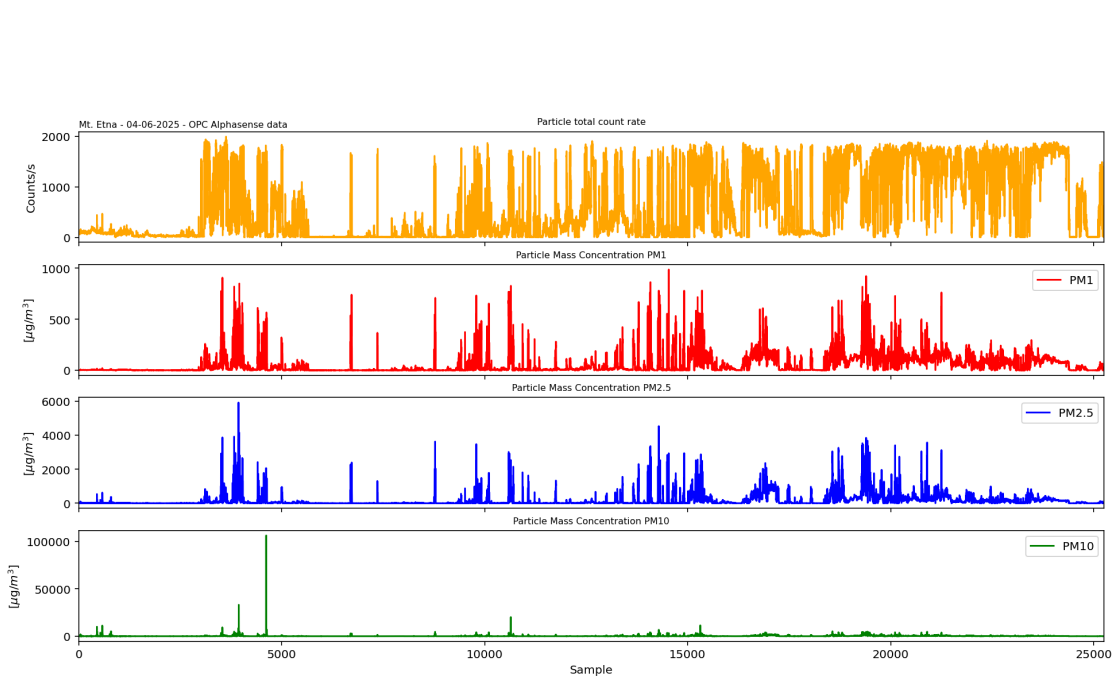


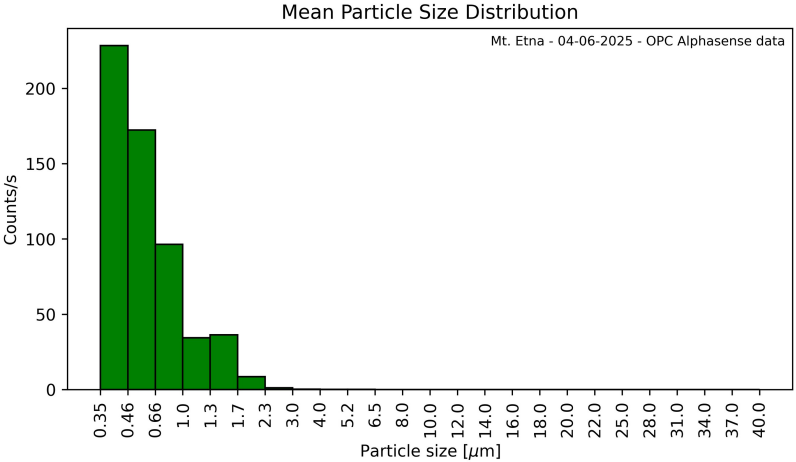
Uncertainties

- Uncertainties related to the VIRSO2 retrieval: plume direction, particle's size (water vapour droplets), other uncertainties due to the retrieval algorithm.
- Plume altitude, for TROPOMI
- Plume speed, different position VIRSO2 and TROPOMI
- Plume dilution for TROPOMI (more than 12 hours later)


Thanks !!

OPC data


Mt. Etna - 04-06-2025 - OPC Alphasense data
Particle total count rate
Counts/s
2000
1000
0
Particle Mass Concentration PM1
[μg/m³]
1000
500
0
PM1
Particle Mass Concentration PM2.5
[μg/m³]
6000
4000
2000
0
PM2.5
Particle Mass Concentration PM10
[μg/m³]
100000
50000
0
PM10
0
5000
10000
15000
20000
25000
Sample


Mean Particle Size Distribution
Mt. Etna - 04-06-2025 - OPC Alphasense data
Counts/s
0
50
100
150
200
0.35
0.46
0.66
1.0
1.3
1.7
2.3
3.0
4.0
5.2
6.5
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
25.0
28.0
31.0
34.0
37.0
40.0
Particle size [μm]