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Sentinel-4 Capabilities for Volcanic Emission Monitoring and ML-Enhanced Retrievals

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INTRODUCTION

Sentinel-4 is a new geostationary remote sensing instrument designed to provide high temporal resolution measurements of atmospheric composition over Europe. Installed aboard the Meteosat Third Generation – Sounder (MTG-S) satellites, it features a high-performance UV-VIS-NIR spectrometer that will deliver near-continuous observations of key atmospheric species, including trace gases and aerosols. Its combination of an 8 × 8 km² spatial resolution with hourly updates across the entire domain enables the detection of rapid atmospheric changes with unprecedented temporal continuity. These characteristics make Sentinel-4 particularly well suited for monitoring volcanic emissions. The frequent revisit cycle allows near-real-time tracking of sudden variations in SO2 and ash concentrations, and supports improved analysis of plume formation, transport, and chemical evolution. Compared with current low-Earth-orbit missions, Sentinel-4 introduces a paradigm shift by coupling geostationary coverage with spectral bands traditionally employed for volcanic gas retrieval. The large volume of high temporal and spectral resolution data produced by Sentinel-4 also presents new challenges for processing and interpretation. Machine learning methods offer promising solutions for enhancing gas retrieval accuracy, accelerating operational workflows, and improving short-term forecasts of the dispersion of volcanic plumes. Here, we present an overview of the operational and scientific potential of Sentinel-4 mission for volcanic emission monitoring and provide a comparison with the TROPOMI sensor aboard Sentinel-5P. The analysis highlights how Sentinel-4 combines the temporal resolution advantages of geostationary platforms with the spectral capabilities of TROPOMI, offering new opportunities - further strengthened by machine learning techniques - for advanced monitoring and modelling of volcanic plumes.

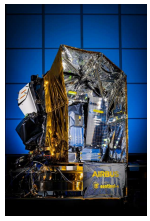
SPATIAL, SPECTRAL AND TEMPORAL CHARACTERISTICS

Sentinel-4 provides continuous monitoring of air quality and trace gas emissions over Europe, North Africa, and parts of the Middle East from the Meteosat Third Generation platform. Its geostationary orbit enables hourly daytime observations, allowing near-real-time tracking of volcanic plumes. The instrument achieves a spatial resolution of ~8 × 8 km² (at nadir), suitable for monitoring regional-scale emission sources. Continuous coverage includes active volcanic regions such as Mount Etna and Stromboli, making Sentinel-4 particularly effective for observing persistent degassing and rapidly evolving eruptions.

Table 1: Main design and performance parameters of SENTINEL 4

Parameter	UV-VIS values	NIR values	Comments
Spectral			
Wavelength range	305-500 nm	750-775 nm	
Spectral Resolution	0.5 nm	0.12 nm	Oversampling is Resolution divided by spectral pixel sampling
Spectral Oversampling	3	3	
Spectral Calibration Accuracy	0.0017 nm	0.0020 nm	
Geometric and Temporal Coverage			
Spatial Sampling Distance (SSD)	Value(s): 8 km x 8 km (E/W) (N/S)		Comments: On-ground-projected SSD at reference point in Europe (45°N latitude; sub-satellite-point longitude);
Integrated Energy	70% over $1.47SSD_{EW} * 1.13SSD_{NS}$, 90% over $1.72SSD_{EW} * 1.72SSD_{NS}$		Integrated energy is a measure for the spatial resolution of the instrument
N/S slit FOV (nearly)	4.0°		
E/W coverage & Repeat cycle	See Fig. 1		See Fig. 1
Daily Earth observation time	Summer max: 01:40 – 21:40 Winter min: 03:40 – 19:40		Adjusted to seasonally varying solar Earth illumination on monthly basis
Spatial co-registration	Intra-detector: 10% of SSD Inter-detector: 20% of SSD		2-dimensional (E/W & N/S) absolute co-registration
Radiometric			
Optical Throughput	~50% (in UV)	~60%	End-to-end scanner-to-detector
Radiometric Aperture	70 mm	44 mm	Circular diameter
Earth SNR	UV: >160 VIS: >1000	739-770nm: >90 Rest NIR: >600	For specified Earth radiance reference scene
Earth Absolute RA	< 2%	< 2%	For Earth radiance & reflectance
Sun Absolute RA	< 2%	< 2%	For sun irradiance
Polarization Sensitivity	< 1%	< 1%	
Polarization spectral features	< 0.042%	< 0.076%	
Sun diffuser spectral features	< 0.015%	< 0.1%	Caused by speckle effect

[2]

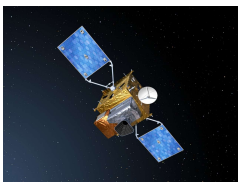


From a **spectral standpoint**, Sentinel-4 operates in the ultraviolet, visible, and near-infrared (UVN) spectral ranges, covering key absorption bands of key atmospheric trace gases such as SO_2, NO_2, O_3, and HCHO. Sentinel-4 features a UVN (Ultraviolet–Visible–Near Infrared) spectrometer covering ~305–400 nm (UV), 400–500 nm (Visible), and 750–775 nm (NIR), enabling the detection of key atmospheric species such as SO_2. Trace gas retrievals are based on the Differential Optical Absorption Spectroscopy (**DOAS**), which exploits narrow absorption features and requires high spectral resolution and accurate calibration.

These spectral capabilities allow for reliable quantification of volcanic gas emissions and improved monitoring of degassing processes.

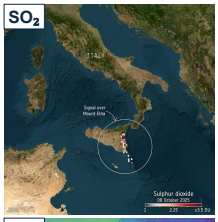
SENTINEL-4 vs SENTINEL-5 TROPOMI

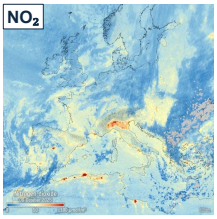
Instrument	Technical Concept	Spectral Range (nm)	Spatial Resolution (km x km)	Coverage	Revisit Time	Orbit
TROPOMI	Push-broom (nadir-fixed)	UV-VIS-NIR-SWIR (270–2385)	7 x 7	Global	**1 day**	**Polar**
Sentinel-4	Push-broom (scanning)	UV-VIS-NIR (305–775)	8 x 8	Europe + parts of North Africa and the Atlantic	**1 hour**	**Geostationary**

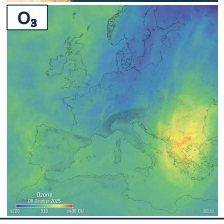


VOLCANIC TRACE GAS OBSERVATIONS (S4)

Level-2 Product : Georeferenced Data And Calculated Atmospheric Parameters







Images provided by the European Space Agency (ESA)

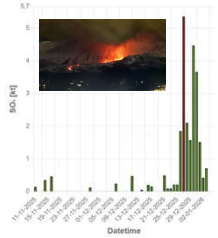
Prospective Volcanic Gas and Aerosol Products

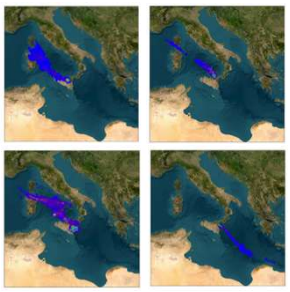
- SO_2 and NO_2 Column Densities
- Aerosol Optical Depth (AOD) and Particle Properties
- Plume Height and Transport
- **Time-Series Analysis of Volcanic Emissions**

INTEGRATION OF SENTINEL-4 DATA WITH AI TECHNIQUES

Daily TROPOMI SO_2 emissions monitoring [1]

Useful for tracking trends but limited for capturing rapid variations during effusive recent activity of Mount Etna (December 2025 – January 2026).



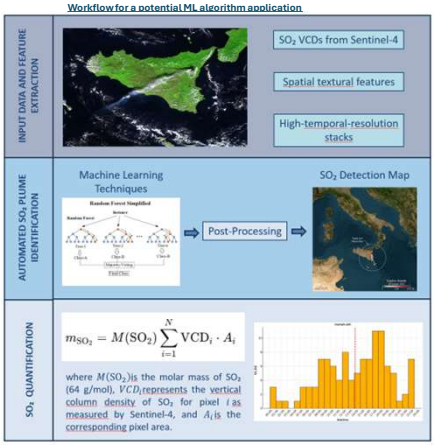


Developed by the **TECHNOLAB** group of INGV-OE. (https://www.ct.ingv.it/technolab/volchazard)

[1] Corradino, C.; Jouve, P.; La Spina, A.; Del Negro, C. Monitoring Earth's atmosphere with Sentinel-5 TROPOMI and Artificial Intelligence: Quantifying volcanic SO2emissions. Remote Sens. Environ. 2024,315, 114663

Compared to TROPOMI, **Sentinel-4 will allow monitoring of Etna's SO_2 emissions on an hourly basis, capturing rapid variations that daily data cannot detect.**

Workflow for a potential ML algorithm application



Future Works

- Simulating volcanic SO_2 dispersion with Sentinel-4 to analyze spectral, spatial, and temporal responses compared to other satellite sensors
- Applying artificial intelligence techniques to quantify SO_2 emissions using Sentinel-4 data

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Conclusion

Sentinel-4 enables near real-time monitoring of volcanic emissions with high temporal and spectral resolution. Combined with satellite synergy and Machine Learning, it significantly improves plume tracking, gas retrievals, and our understanding of volcanic dynamics.

Acknowledge: this work was developed within the framework of the Laboratory of Technologies for Volcanology (TechnoLab) at the INGV in Catania (Italy).

[2] Gulde, S. T., Kolm, M. G., Smith, D. J., Maurer, R., Bazalgette Courrèges-Lacoste, G., Sallusti, M., & Bagnasco, G. (2014). ***Sentinel-4: a geostationary imaging UVN spectrometer for air quality monitoring – status of design, performance and development.***