SEISMO-VRE: a tool to perform an automatic multiparametric investigation of earthquake, volcano eruption and other natural or artificial hazards

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Sharing is encouraged

Abstract

The study of the preparation phase of earthquake occurrence is essential to better understand our planet and assess the seismic hazard (Marchetti et al., 2024). However, different approaches are generally provided without the possibility of a direct comparison. Consequently, even the nature of the extracted anomalies before an earthquake is the object of scientific discussion.

In this work, we present SEISMO-VRE, a free tool available on GitHub (https://github.com/dedalomarchetti/SEISMO-VRE), developed as Jupyter Notebooks with Python or MATLAB kernels, to serve a broader user community following the open science paradigm. The tool performs several analyses of the lithosphere, atmosphere and ionosphere, extracting anomalies and trends for each geo-layer. It produces graphs and tables of the extracted anomalies and, in particular, a summary graph for the comparison of the trends in the lithosphere, atmosphere and ionosphere. suggesting potential interactions between Earth's geo-layers.

Data are retrieved from the European Plate Observing System (EPOS) Platform (Bailo et a., 2023) and integrated with NASA and ESA atmospheric and ionospheric measurements using a dedicated notebook to download them, that we provided in the same public GitHub repository.

Given the ease of reproducibility of SEISMO-VRE across different case studies, we present results in response to earthquakes and volcanic eruptions. Case studies include the Italian Seismic sequence 2016 (M6.0 and M6.5 as larger events), the Turkey Marmara region 23 April 2025 M6.2 earthquake, La Palma (Canarian archipelagos, Spain) volcano eruption of 19 September 2021 (Volcanic Explosive Index, VEI = 3) and the Etna volcano eruption on 3 December 2015 (VEI = 3).

Whenever it's possible, we will also compare the results of the SEISMO-VRE with published papers to discuss the similarities and differences. This allow us to scientifically discuss the possible reasons for differences in the identified trends for different earthquakes. In fact, epicentre location (sea or land), focal mechanism, and magnitude appear to play a major role in the preparation phase of earthquakes.

Finally, we propose this tool not only to provide a universal and shared framework for the multiparametric investigation of earthquakes, volcanic eruptions and other natural and anthropogenic hazards, but also to highlight the advantages of using the EPOS pan-European research Infrastructure platform.

Italian Seismic sequence 2016 (Mw = 6.0 24-Aug-2016 & Mw=6.5 30-Oct-2016)

The Italian seismic sequence started on 24 August 2016 in the Central Apennine was used as a reference case study. The main two events were the Mw = 6.0 Amatrice earthquake, which occurred on 24 August 2016 at 1:33 UT, and the Mw = 6.5 Norcia earthquake, which occurred on 30 October 2016 at 6:40 UT. Epicentre locations, together with a foreshock that occurred on 26 October 2016 close to Visso town, are represented in **Figure 1**. The main active faults are overlaid on the same map, taking advantage of the integrated visualisations of the EPOS Data Portal (**https://www.epos-eu.org/dataportal**). One can see that the earthquakes occurred in a very dense region of faults dominated by extensional tectonic stress. The focal mechanisms of these events are in agreement with a normal focal mechanism solution. A multiparametric study of this seismic sequence was provided by (Marchetti et al., 2019).

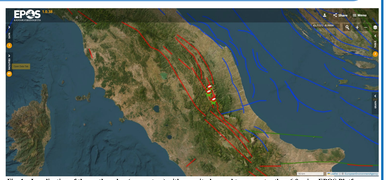


Fig. 1—Localization of the earthquakes (green stars) with magnitude equal to or greater than 6.0 using EPOS Platform Bailo et al., 2023). The focal mechanisms of the same events were overplotted using the EPOS Service "Moment tensor data for modern earthquakes (2013-present)" provided by TCS Seismology. The active faults were shown on the same map, and their colour indicates the tectonic mechanism (red = extensional, blu = compressional, green = transcurrent).

Fig. 2—Picture representing the chain of processes in lithosphere atmosphere and ionosphere before the Italian seismic sequence 2016-2017 proposed as the result of the preparation of this long seismic sequence by Marchetti et al., 2020.

The paper also involved previous investigations of specific parameters (e.g., Piscini et al., 2017). Collecting analyses from the lithosphere, atmosphere and ionosphere, it was possible to detect a chain of phenomena that preceded the start of the seismic sequence of Amatrice-Norcia 2016 (see **Figure 2**).

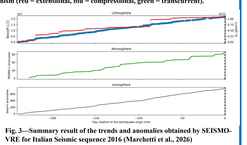


Fig. 3—Summary result of the trends and anomalies obtained by SEISMO-VRE for Italian Seismic sequence 2016 (Marchetti et al., 2026)

Applying the SEISMO-VRE to this important case study for Italy (see **Figure 3**), we obtained a similar result and some new hints, due to the updates to the implemented algorithms and ingestions of new data (e.g., GNSS from EPOS). In particular the VRE provided the investigation of the GNSS weekly time series data extracting interesting patterns (see **Figure 4**).

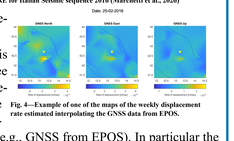
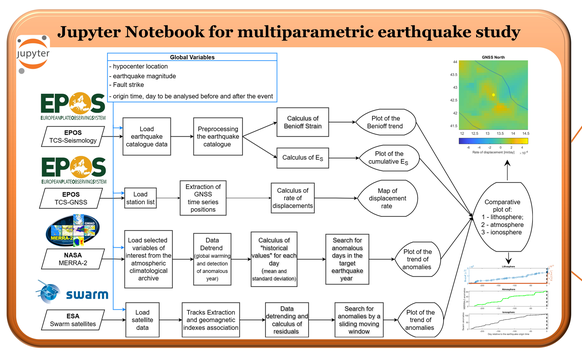
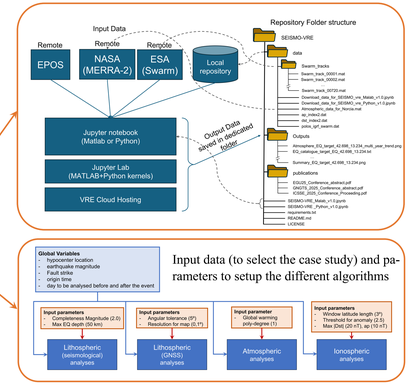


Fig. 4—Example of one of the maps of the weekly displacement rate estimated interpolating the GNSS data from EPOS.

Jupyter Notebook for multiparametric earthquake study





Input data (to select the case study) and parameters to setup the different algorithms

La Palma (Canarian Archipelagos) volcano eruption of 19 Sep 2021 (VEI = 3)

On 19 September 2021 La Palma volcano started an eruption classified as Volcanic Explosive Index (VEI) equal to 3. The eruption was originated by Cumbre Vieja volcanic field and long persisted for about 3 months (Zhang et al., 2023). Investigation of the preparation phase of this eruption in the 6 month before searching for possible effects in atmosphere and ionosphere was published by Marchetti et al., 2022 and here reported in **Figure 8**. We applied SEISMO-VRE on the same case study and the same interval of time obtaining the result shown in **Figure 9**. We noticed that the seismicity trends are very similar, but in the SEISMO-VRE the earthquake catalogue was automatically downloaded by EPOS (see **Figure 10**), while in the paper it was manually retrieved from IGN Spanish Geophysical Institute. The atmospheric trend is very similar and both are based on same dataset of MERRA-2, while ionospheric trends are different, as in the paper the data of China Seismo Electromagnetic Satellite (CSES-01) was integrated in the analysis and they provided interesting Ne anomalies possibly coupled to the atmospheric perturbations.

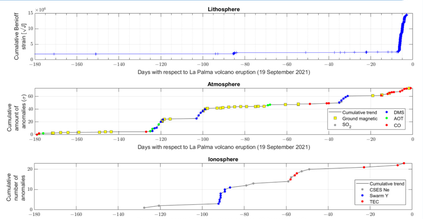


Fig. 8—Summary figures extracted from Marchetti et al., 2022 of the trends and anomalies in lithosphere, atmosphere and ionosphere in the six months before the La Palma 2021 volcano eruption.

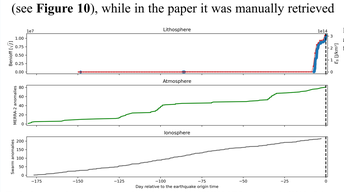


Fig. 9—Summary of the trend and anomaly results obtained by SEISMO-VRE applied to the 2021 La Palma volcano eruption.

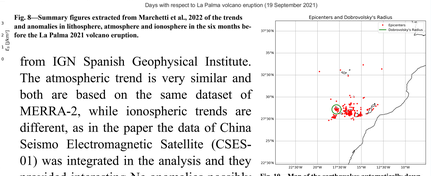


Fig. 10—Map of the earthquakes automatically downloaded by EPOS Data platform. The green circle is the selected research area.

Etna (Italy) volcano eruption of 3 Dec 2015 (VEI = 3)

On 3 December 2015, Etna volcano experienced a larger eruption (VEI = 3) from Voragine crater. We used this case in the supplementary Materials of the SoftwareX paper (Marchetti et al., 2026) to explain how change the parameters of SEISMO-VRE to study a volcano eruption. The results, summarised in **Figure 11**, are quite interesting, especially for the increase of seismicity about two months before the eruption. Furthermore the atmosphere presents an increase of anomalies that could be due to degassing caused by the eruptions and an increase of anomalies about 80 days prior to the event. Finally, SEISMO-VRE provide a quick look of the investigation in one unified framework to pave the way for deeper studies.

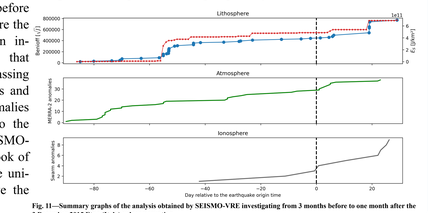


Fig. 11—Summary graphs of the analysis obtained by SEISMO-VRE investigating from 3 months before to one month after the 3 December 2015 Etna (Italy) volcano eruption.

Turkey Marmara Mw = 6.2 23-Apr-2025

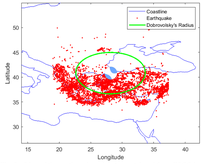


Fig. 5—Map of the earthquake epicentres retrieved from EPOS in the 6 months before the occurrence of Mw=6.2 Turkey-Marmara 2025 seismic event.

On 23 April 2025 at 9:49:11 UTC, an earthquake of moment magnitude Mw = 6.2 hit the Marmara region in Turkey about 67 km west-southwest of Istanbul. According to USGS analyses, the earthquake's rupture was mainly strike slip focal mechanism. The epicentre was entirely localised in the Sea of Marmara, and the corresponding hypocentre was at a depth of 12.7 km. Consequently, this earthquake can be considered a case study with some analogies to the Italian 2016 case (e.g., similar magnitude and depth) but also some differences (e.g., the location in the sea, the focal mechanism and the more active tectonic setting of Turkey compared to the central Apennines of Italy).

We applied SEISMO-VRE to this case study using the same parameter as the above investigation. **Figure 5** reports the map of the earthquakes retrieved by EPOS before applying the constrain of selection (i.e., M≥Mc, Depth constrains, Dobrovolsky's area, etc...). It's evident the more seismicity recorded in this area and how this is concentrated in the active plate borders between Eurasian, African and Anatolian plates. However, part of the distribution of the earthquakes could be influenced from the density of seismic station network, especially in the Northern sector. An important feature for seismological point of view is depicted in **Figure 6** by a large value of E_S immediately before the mainshock. This value was due to the presence of a foreshock about 30 minutes before the target earthquake: M3.9 at 9:13:05 UTC on 23 April 2025 (epicentral distance of about 250m). Finally the summary trends of seismicity in lithosphere and anomalies in atmosphere and ionosphere is reported in **Figure 7**.

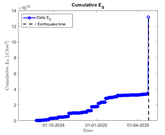


Fig. 6—Daily E_S parameter (earthquake released energy over square distance of the target earthquake) in the 6 months before the occurrence of Mw=6.2 Turkey-Marmara 2025 seismic event.

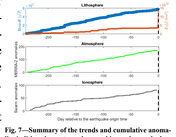


Fig. 7—Summary of the trends and cumulative anomalies in lithosphere atmosphere and ionosphere calculated by SEISMO-VRE applied to the Mw=6.2 Turkey-Marmara 2025 seismic event.

You want to try SEISMO-VRE, but don't know where to start? (don't worry...)

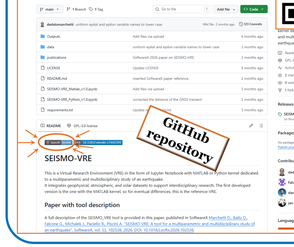
1) Firstly we suggest to look at the GitHub repository. Please, note that if you open a Jupyter Notebook you can see a preview inside the GitHub repository, including the output. https://github.com/dedalomarchetti/SEISMO-VRE or scan the QR-Code below!

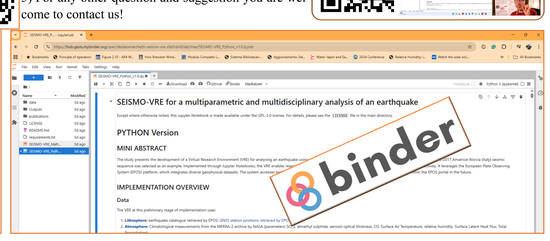
2) Try to run the SEISMO-VRE inside the free virtual environment of "Binder" (the link is provided in the GitHub repository). You don't need to install nothing as binder already have an image of the system with all the dependencies and requirements.

3) Inside the SoftwareX paper you can find a complete "step-by-step" guide in the Supplementary Material

4) You can watch the video-tutorial on Youtube

5) For any other question and suggestion you are welcome to contact us!





References

- Bailo, D.; Paciello, R.; Michalek, J.; Cocco, M.; Freda, C.; Jeffery, K.; Atakan, K.; 2023: The EPOS Multi-Disciplinary Data Portal for Integrated Access to Solid Earth Science Datasets. Sci Data , 10, 784, https://doi.org/10.1038/s41597-023-02697-9
- Marchetti, D.; Bailo, D.; Falcone, G.; Michalek, J.; Paciello, R.; Piscini, A. SEISMO-VRE: A Tool for a Multiparametric and Multidisciplinary Study of an Earthquake. SoftwareX 2026, 33, 102538, doi:10.1016/j.softx.2026.102538.
- Marchetti, D., Bailo, D., Falcone, G., Michalek, J., Paciello, R., & Piscini, A. (2025). SEISMO-VRE. GitHub. https://github.com/dedalomarchetti/SEISMO-VRE
- Marchetti, D.; Bailo, D.; Michalek, J.; Paciello, R.; Falcone, G.; Piscini, A. (2025). A Multiparametric Investigation of an Earthquake by a Jupyter Notebook: The Case Study of the Amatrice-Norcia Italian Seismic Sequence 2016-2017. In Proceedings of the ICCSA 2025 Workshops; https://doi.org/10.1007/978-3-031-97657-5_19
- Marchetti, D.; De Santis, A.; D'Arcangelo, S.; Poggio, F.; Piscini, A.; A. Campuzano, S.; • De Carvalho, W.V.J.O. Pre-Earthquake Chain Processes Detected from Ground to Satellite Altitude in Preparation of the 2016–2017 Seismic Sequence in Central Italy. Remote Sensing of Environment, 2019, 229, 93–99, doi:10.1016/j.rse.2019.04.033.
- Marchetti, D.; Yuan, Y.; Zhu, K 2024. Editorial of Special Issue "Remote Sensing Observations to Improve Knowledge of Lithosphere–Atmosphere–Ionosphere Coupling during the Preparatory Phase of Earthquakes". Remote Sens. 2024, 16, 1064. https://doi.org/10.3390/rs16061064
- Marchetti, D.; Zhu, K.; Zhang, H.; Zhima, Z.; Yan, R.; Shen, X.; Chen, W.; Cheng, Y.; He, X.; Wang, T.; et al. Clues of Lithosphere, Atmosphere and Ionosphere Variations Possibly Related to the Preparation of La Palma 19 September 2021 Volcano Eruption. Remote Sensing 2022, 14, 5001, doi:10.3390/rs14195001.
- Piscini, A.; De Santis, A.; Marchetti, D.; Cianchini, G.; 2017: A Multi-Parametric Climatological Approach to Study the 2016 Amatrice–Norcia (Central Italy) Earthquake Preparatory Phase. Pure Appl. Geophys., 174, 3673–3688, doi:10.1007/s00024-017-1597-8
- Zhang, H.; Zhu, K.; Cheng, Y.; Marchetti, D.; Chen, W.; Fan, M.; Wang, S.; Wang, T.; Zhang, D.; Zhang, Y. Atmospheric and Ionospheric Effects of La Palma Volcano 2021 Eruption. Atmosphere 2023, 14, doi:10.3390/atmos14081198.