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DATA REPORT

Real-time mobile GNSS network data acquired during the 2021–2022 unrest at Vulcano island

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Abstract

At the end of the summer 2021, an increase in CO_2 emissions at Vulcano brought an increase in the alert level and, consequently, to the upgrade of the monitoring activities by increasing the number of instruments deployed and the rate of the surveys. One of the new devices installed was a geodetic GNSS mobile network for a real-time and high-frequency monitoring of ground deformation, to increase the detail with respect to the existing permanent network. The mobile stations were initially installed at the northern base of the La Fossa crater, where the highest values of soil degassing were recorded. Two stations were co-located with gravimeters, in order to compare and integrate the data. After this very first period of testing, the mobile GNSS array has been reconfigured, to investigate the mud pool area. Thus, four stations were installed around the degassing area, one of them being in the same site of the gravimeter. Data has been acquired at 1 Hz rate and is used for the weekly reporting to Civil Protection. It was the first experience of a light and quick-to-install geodetic real-time and high-rate GNSS mobile network in this area, and it was the occasion for testing its performance, as well as different approaches for the real-time kinematic (RTK) differential positioning in order to find the most suitable for the ongoing phenomena. Furthermore, direct data communication and archiving in the institutional database have been implemented for immediate querying from the control room tools. We report the experiences collected during the installation phase, site selection, RTK approaches, and ground motion and provide the daily raw data in RINEX format for any future precise postprocessing for the mid- to long-term analyses.

Introduction

Starting from September 2021, monitoring stations and surveys at Vulcano island started recording a gradual and continuous increase in the CO_2 emission from the ground, diffusely on the northern part of the island (Inguaggiato et al. 2022). The northern Vulcano island has been always identified as the most active part of the Lipari-Vulcano Volcanic Complex (Ventura et al. 1999) both from the volcanic and the tectonic deformation (Bonforte and Guglielmino 2008; Mattia et al. 2008; Alparone et al. 2019), with emphasis on the northern slope of La Fossa crater, where fumarolic activity is most intense and also some interaction between hydrothermal and gravitational dynamics has been investigated (Bonaccorso et al. 2010; Harris et al. 2012; Pesci et al. 2013).

The unrest at Vulcano started in September 2021, when a significant increase of CO_2 emission from the ground started to be measured all around the La Fossa cone on the northern part of the island and on the crater rim. CO_2 concentration soon started to be dangerous in closed environments and ground floors. Some casualties of domestic pets were registered, threatening the local people. Detectable ground deformation was reported in September–October 2021, based on GNSS and InSAR data (Bonforte et al., in prep.). This was the first significant unrest of this volcano after the one occurred in the late 1980s, which also generated a dramatic increase in gas emissions and temperature and also detectable ground deformation for many years on the northern part of the island and especially on the northern slope on the La Fossa cone, mainly imputable to the energization of the local hydrothermal system and also a accentuation of the slope instability of the part of the cone affected by continuous and

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intense fumarolic emissions (Bonaccorso et al. 2010; Harris et al. 2012; Pesci et al. 2013; Alparone et al. 2019).

High-rate (HR) and real-time (RT) ground deformation stations provide valuable information for monitoring the ongoing phenomena; it was clearly demonstrated already in 2003, during the experimental application in an active volcanic environment during the ongoing eruption at Stromboli (Puglisi et al. 2005), by placing by helicopter three heavy GPS stations in the Sciara del Fuoco. Continuous and HR ground deformation monitoring is aimed at measuring rapidly evolving phenomena, and at Stromboli, it continued after the 2002–2003 eruptive crisis when it has been applied also for monitoring the stability of the Sciara del Fuoco steep slope and, later, of the big lava fan formed after the 2007 eruption, always by using an optical robotized total station with measurements every 10 min (Bonaccorso et al. 2009). In 2014, a mobile GPS array was temporarily installed at San Miguel volcano (El Salvador, CA) for monitoring its unrest and volcano-tectonic deformation, providing at that time a daily post-processed solution (Bonforte et al. 2016b). Since then, the technology and the entire satellite positioning system has evolved together with the processing approaches (e.g., Lee et al. 2015; Kazmierski 2018), passing from the only GPS to the multi-constellation GNSS system and to more compact and low-power instrumentation, up to very low energy-consuming mono-frequency devices, useful for very local networks and post-processed high-rate differential analyses (Wilkinson et al. 2023). HR GPS may provide useful information on ground deformation related to rapid magmatic processes, especially if coupled with other continuous and highly sensitive instrumentation, such as tiltmeters, as demonstrated by Bonforte et al. (2021) by exploiting GPS data at 1 Hz. Mobile devices used for this application are geodetic stations, multi-constellation, and multi-frequency, guaranteeing a high level of accuracy for real-time and high-rate positioning on a few kilometer-wide monitoring area.

Installation

Installation of all mobile stations started immediately after the acknowledgment of the unrest of the volcano, choosing to locate the sensors on and around the area showing the maximum increase of CO_2 emission from the ground. Mobile GNSS stations, in addition, require a wide field of view of the sky from the antenna, with a lowest horizon as possible, and a good coupling with the ground, preferably installing the antenna on a short pin directly placed on a rocky outcrop (Bonforte et al. 2016a). Satisfying these conditions is not always possible and often a good compromise is the best choice, especially in emergency conditions. Furthermore, one of the aims was to install GNSS stations in the same places of gravimetric ones, in order to have the vertical deformation data for correcting the micro-gravity variations observed. Gravimeters needed a closed and quiet environment, differently from GNSS. In these cases, a small but solid building is often preferred, guaranteeing a good height above trees and/or surrounding buildings and possibly electric power and protection against theft (Fig. 1). After a few months, a reconfiguration of the GNSS mobile network was required, in order to focus and detail the monitoring around the hot mud pool and Porto di Levante main harbor of the island.

Therefore, we can divide the entire monitoring activity in two phases, the first one with a wider configuration and the second one with a more localized network.

First phase—northern Vulcano island (December 1, 2021–May 3, 2022)

In the first phase, the emergency related to the dramatically increased flux of CO_2 from the ground was threatening the entire northern to western slopes and feet of the La Fossa cone, over a wide area on the northern part of the island (Fig. 2). For this reason, on December 1, 2021, some existing benchmarks (VPLI and VLEN) of the Lipari-Vulcano and Vulcano-Nord periodic geodetic network (Bonforte and Guglielmino 2008; Esposito et al. 2015; Alparone et al. 2019) were equipped with real-time mobile stations, adding two further sites in the plain at the northern foot of the crater. These two benchmarks, namely, VPRT (Vulcano Porto) and VCMR (Vulcano Casa Martello) were monumented by 0.500 m aluminum pins anchored to the walls on top of two small edifices. Pins were located on the northern faces of the walls, in order to minimize the effect of direct sun heating on the pins and thermal effects. The buildings were chosen because they were already hosting continuous running micro-gravimetric stations, in order to have ground motion, especially vertical, data for correcting micro-gravimetric observed variations on the same site.

This first installation was the very first occasion for testing the performance of mobile GNSS stations, both in terms of accuracy and precision of real-time positioning solutions and in terms of reliability of data transmission, remote management, and power consumption. That is why this phase is affected by several interruptions and lack of data, due power supply and/or transmission issues. All stations were equipped with UMTS integrated modems for data transmission, 50-W photovoltaic modules, coupled with 36-Ah backup batteries. GNSS equipment consisted of Stonex SC600 receivers with Stonex SA65 compact geodetic antennas (Table 1).

Second phase—hot mud pool (June 28, 2022–April 18, 2023)

After a few weeks, a new configuration of the network was required, since the highest concern of security conditions relevant to soil gas emissions and accumulation was

Fig. 1 Monumentation of the geodetic benchmarks and installation of the mobile stations at Vulcano. The photos in the top row show two phases of the installation of the self-centering benchmark at VCOA station in the harbor: **a** drilling of the hole where putting the benchmark and **b** setup of the brass pin; those on the bottom row show the installation of **c** VCMR and **d** VPRT stations, with the antennas screwed on aluminum pins fixed on the roofs

concentrated in the surroundings of the hot mud pool and coastal fumaroles in the Porto di Levante area. While maintaining the VPRT station as the southern vertex, all other mobile stations were relocated around the monitored area, realizing three new benchmarks: VCST in the village as the western corner, VCOA on the Civil Protection shelter in the harbor as the eastern corner, and the VCAM on the north, in Vulcanello. In this way, a quadrilateral device was set up, surrounding the mud pool area, able to detect displacements related to pressurization of gas beneath the fumaroles (Fig. 2). The configuration of the stations was the same resulting from tests and experience of the first installation.

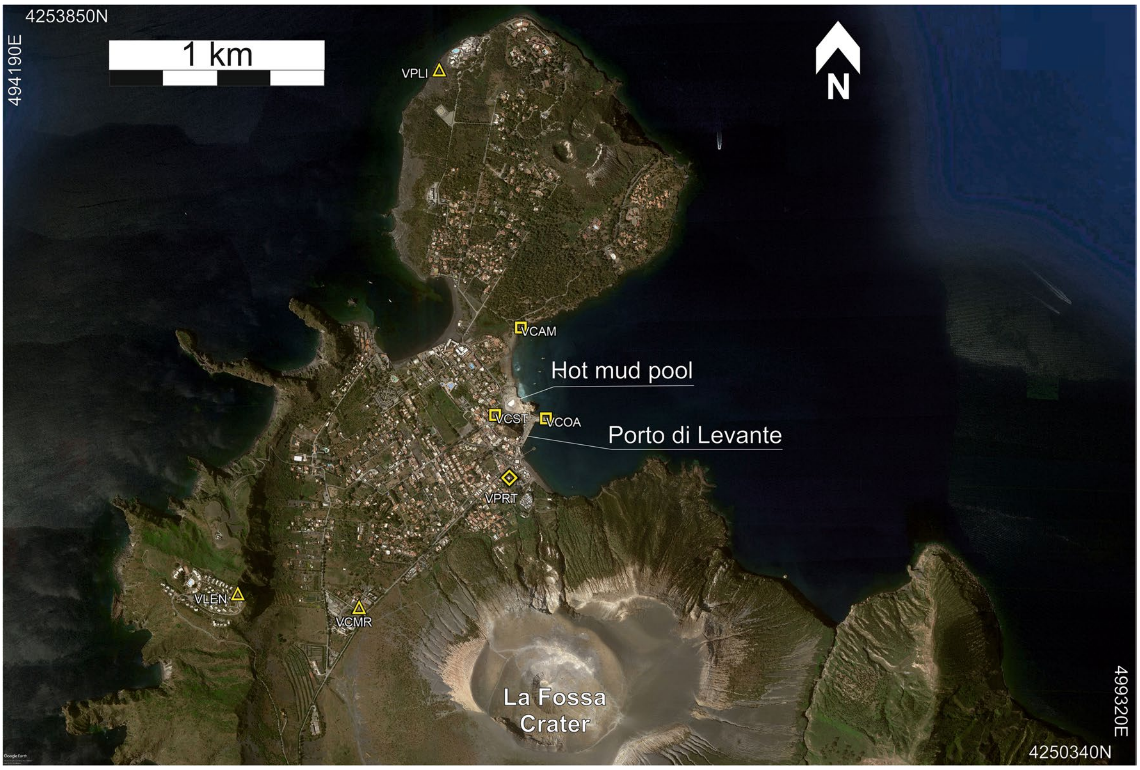

Fig. 2 The two configurations of the mobile network array during the 1st (top) and 2nd (bottom) phases of monitoring. The diamond indicates the station that was active during both phases of monitoring. Triangles indicate the stations installed during the first phase; squares indicate the stations installed during the second phase. Coordinates of the corners are in WGS84, UTM projection, zone 33S

Table 1 Summary of metadata, reporting the configuration of each station of the mobile network. Coordinates are in meters, WGS84, UTM projection, zone 33S

Station code	UTM easting	UTM northing	Date of installation	Receiver model	Receiver serial no.	Antenna model
VPLI	496122.225	4253516.833	December 1, 2021	Stonex SC600	SC60291900042	Stonex SA65
VLEN	495238.519	4251107.624	December 1, 2021	Stonex SC600	SC60291900047	Stonex SA65
VCMR	495792.315	4251051.524	December 1, 2021	Stonex SC600	SC60291900074	Stonex SA65
VPRT	496470.355	4251643.502	December 1, 2021	Stonex SC600	SC60291900065	Stonex SA65
VPRT	496470.355	4251643.502	June 28, 2022	Stonex SC600	SC60291900074	Stonex SA65
VCOA	496633.273	4251916.133	June 28, 2022	Stonex SC600	SC60291900065	Stonex SA65
VCST	496400.654	4251929.232	June 28, 2022	Stonex SC600	SC60291900046	Stonex SA65
VCAM	496513.639	4252330.403	June 28, 2022	Stonex SC600	SC60291900047	Stonex SA65

This is the longest and most continuous time series collected, and we focused on testing, in particular, a different configuration of the differential real-time kinematic (RTK) solution, by setting two stations as "static" and two other stations as "kinematic" to look at the differences in the real-time positioning time series. While the "kinematic" option leaves the position very free, the "static" one assumes that the station is not moving. In theory, the first option should be able to follow better the fluctuations eventually related to ground deformation, but we found that this high degree of freedom results in a much higher noise in the position time series. The static option dramatically reduces the noise, even if showing some isolated spikes and little jumps resulting from more "discretized" changes of the position.

Data description

Raw data were continuously transmitted by the stations at Vulcano to the Osservatorio Etneo in Catania, where they were stored and archived. At the end of each day, data were converted into the standard RINEX 3 ASCII format, resampling them to the

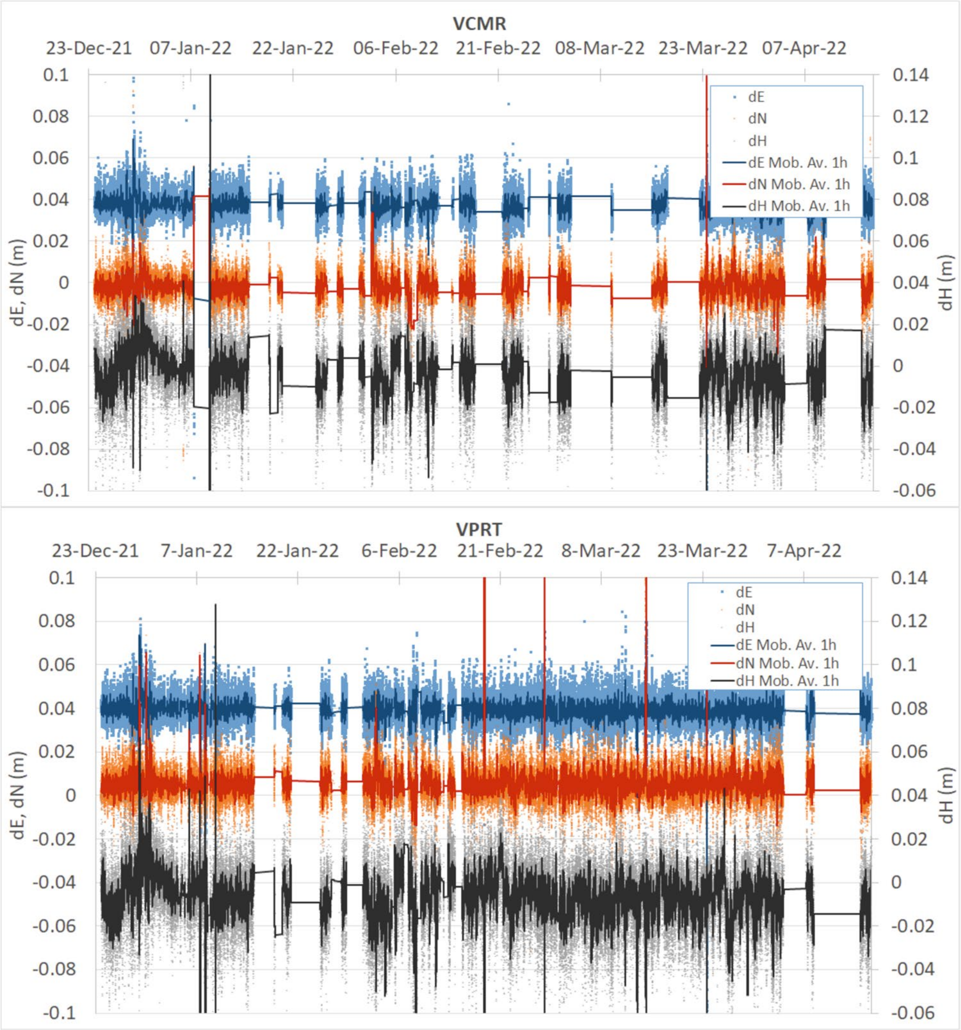

Fig. 3 Displacement time series (1-min averages) and 60-min mobile averages (lines) of the two stations at the foot of La Fossa crater, during the 1st phase. Red series indicate the *N* displacements; blue series indicate the *E* component; gray series indicate the vertical deformation

standard 30 s sampling rate for an eventual more accurate daily solutions post-processing. We provide here the standard RINEX raw GNSS data for all the second phase installation, the most stable and reliable in terms of continuity. The whole dataset provided here (downloadable from PANGAEA public repository; Bonforte et al. 2023a, 2023b, 2023c, 2023d) consists of 1022 files for a total of 13GB of GNSS RINEX raw data, covering the entire second phase installation from June 26, 2022. Raw data of the last days were lost due to a problem with the ring buffer, which was fixed only when stations were removed. The GNSS data archive is organized in four databases, one for each station, named with the site abbreviation (namely, VCAM (Bonforte et al. 2023a), VCOA (Bonforte et al. 2023b), VCST (Bonforte et al. 2023c), and VPRT (Bonforte et al. 2023d)). Within each folder, there are all the raw data files for that station, one for each day of acquisition. Names of the files are structured following the RINEX 3 standard, the first four digits being the station code, that is, an S (for Stonex), and the last three digits of the receiver serial number. The date of acquisition is given by the 11 digits in the central part of the name, in the format YYYYDDDHHMM, namely, 4 digits for the year, followed by 3 digits for the day of the year (from 1 to 365 or 366 for leap years), and then 2 digits for the hour and 2 for the minute of the starting time.

Preliminary results

With two separate phases and layout of the network, we could monitor two different areas of the volcano in two subsequent periods, but we had the opportunity for testing the device in two different conditions. In this way, in fact, we acquired useful experience about the performance of such real-time and high-frequency mobile stations on different layouts of the network, with smaller and longer baselines. In fact, kinematic 1 Hz positioning of each station was obtained by real-time kinematic method for differential positioning, using the “Sicili@net” service provided by INGV-Osservatorio Etneo (Fig. 3) whose software provides, through a NTRIP caster, real-time differential baselines and network corrections using many formats as well as standard RTCM

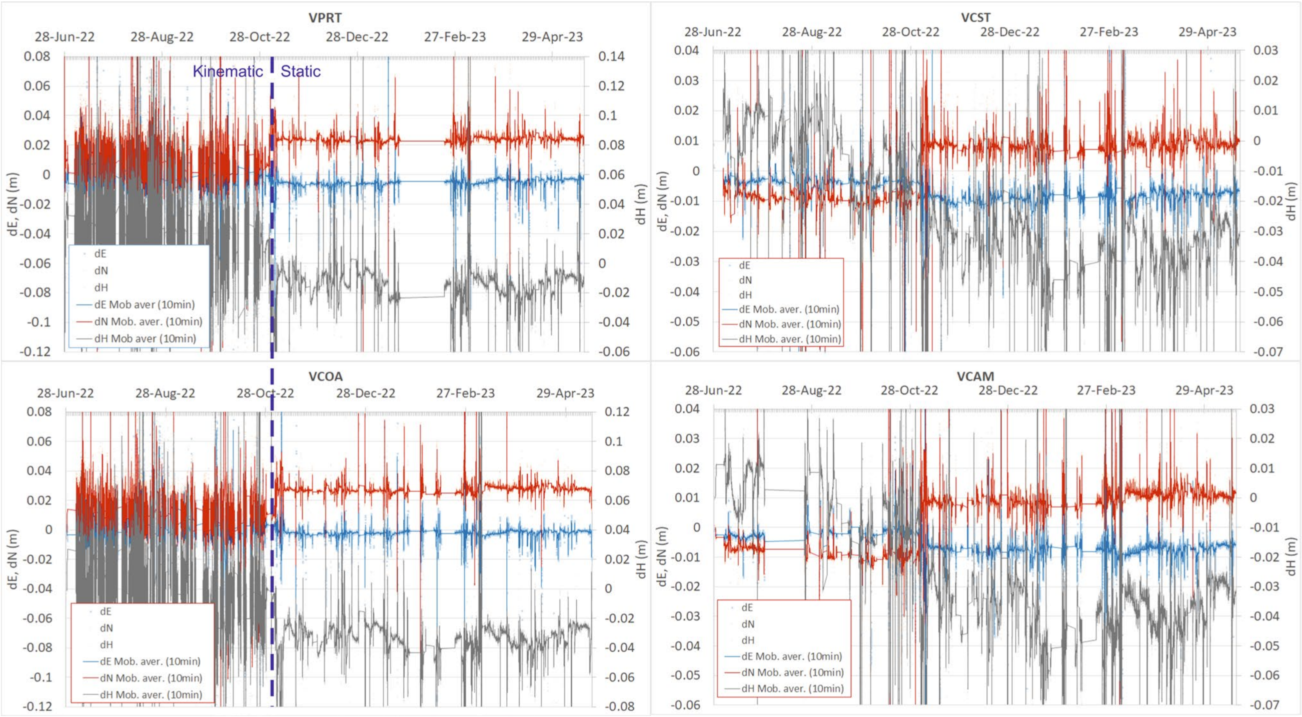

Fig. 4 Displacement time series of 1-min averages (dots) and 10-min mobile averages (lines) of the four stations installed during the 2nd phase. Red series indicate the *N* displacements; blue series indicate the *E* component; gray series indicate the vertical deformation. On the two plots on the left, the switch from "kinematic" to "static" mode in November is marked by the blue vertical dashed line

(URL: https:\\www.ct.ingv.it7index.php/risorse-e-servizi/sicil-net).

During the 2nd phase, in addition to the different layouts, we also tested and compared two different approaches to the positioning constraints, "kinematic" (the mode used during the 1st phase) and "static". Two stations (VCST and VCAM) calculated the position in "static" mode from the beginning; the other two (VPRT and VCOA) started calculating their position in "kinematic" mode and were switched to the "static" one in October 2022, due to the much lower noise of this option. We also report here the preliminary plots of the time series for comparing the results of the two different approaches (Fig. 4).

As a last step, the management and processing software has been implemented in order to send an output with an averaged position of each station every minute to the institutional database of the INGV-Osservatorio Etneo (Fig. 5). This continuous and real-time update of the deformation lets every researcher query the database and have the most up-to-date information.

Real-time time series, as expected, show some high-frequency noise, especially on the vertical component, and some spikes on all components. Most of the spikes and jumps follow few seconds to hours of data losses and might be related to the re-calculation of the position after re-connection to the real-time correction service. These data will be the basis for quality analyses and for correcting the approaches for future applications, as well as correlation analysis with the co-located continuous gravimetric measurements, for understanding the capability of this device to detect rapid deformations that might be related to the magmatic and, especially, hydrothermal system, since this latter seems to be the main responsible of the largest and most rapid deformations observed at least during the most recent crises of this volcano (Gambino and Guglielmino 2008; Bonaccorso et al. 2010; Harris et al. 2012; Alparone et al. 2019).

Conclusions

This real-time/high-rate mobile network application allowed useful and valuable experience to be collected during a real volcanic unrest, for monitoring ground deformation related to, at least, hydrothermal system perturbation due to the underlying magma dynamics at Vulcano island. Data described and provided with this paper will allow further mid- to long-term research for deepening the investigation of the 2022 unrest period to be also compared, validated,

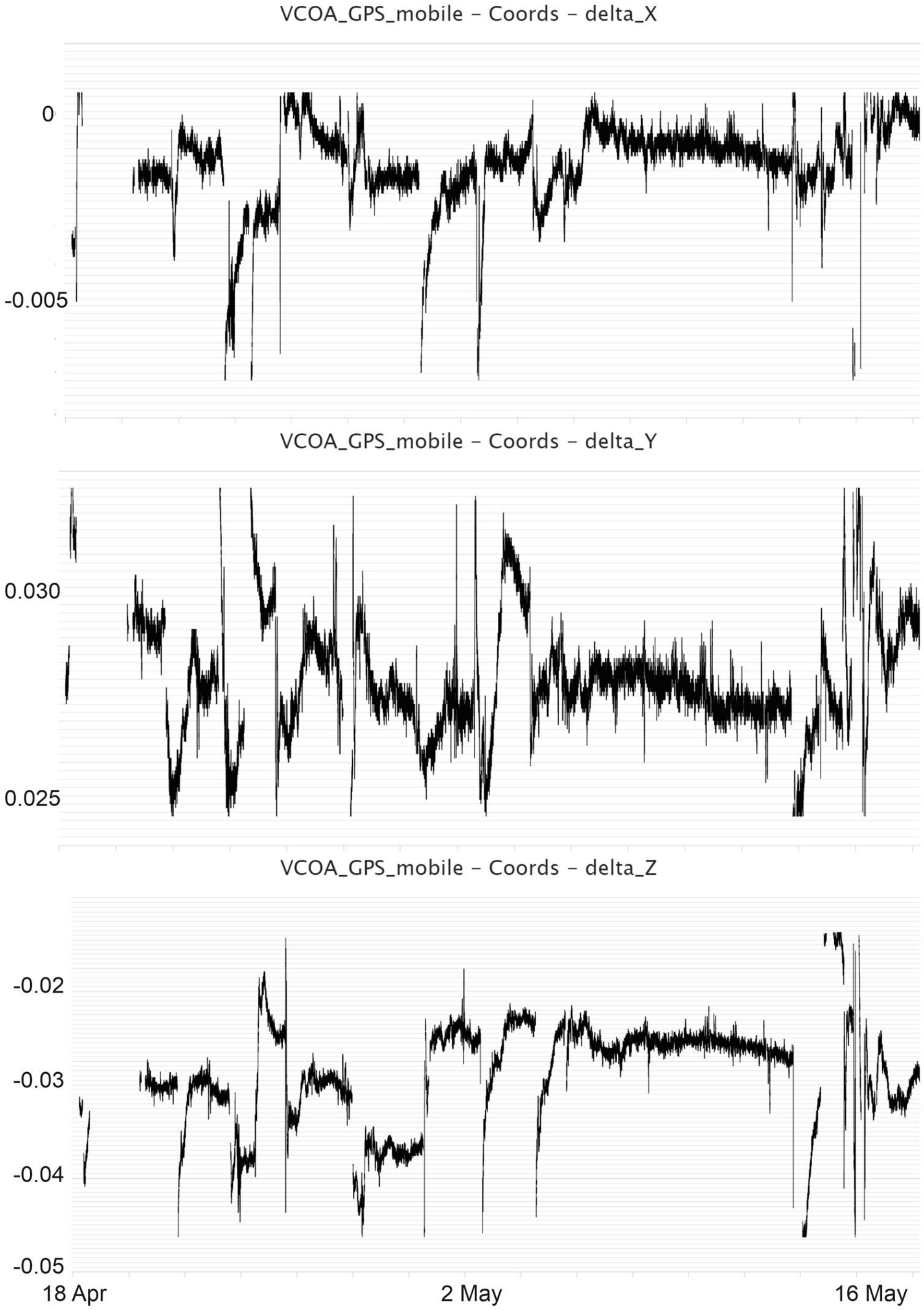

Fig. 5 Examples of plots, as resulting from querying the INGV-OE database for the VCOA mobile GNSS station from April 18 to May 18. From top to bottom: *E*, *N*, and vertical components

and integrated with other multidisciplinary datasets, such as (but not only) micro-gravimetric, thanks to the co-location of the two sensors.

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Data availability PANGAEA public repository: GNSS data acquired during the 2021-2022 unrest at Vulcano island (Italy) by the Real-Time Mobile Network. PANGAEA, https://doi.org/10.1594/PANGAEA.963930 (citation: see references Bonforte et al. 2023a, 2023b, 2023c, 2023d).

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