



Ground Deformation Detected by Permanent Tiltmeters on Mt. Etna Summit: The August 23-26, 2018, Strombolian and Effusive Activity Case



- **Objectives:** Record ground deformation of summit
- **Solution:** Jewell Instruments LILY Borehole Tiltmeter
- **Benefits:** High-precision and exceptional repeatability
- **Results:** Detection of key volcanic activity

Authors

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Abstract

Over the last few years, three tilt deep stations (27-30 meters) have been set up in the summit area of Mount Etna volcano. The aim of this challenging project is to record the ground deformations of the summit craters activity with high precision. We considered data related to the August 23-26, 2018, Strombolian and effusive activity. In this case, tiltmeters recorded variations in the order of 10^{-7} radians, not observed at the other stations. These changes suggest a shallow contraction source just south of the Southeast Crater. This result, related to the volcanic tremor source, points to the presence of a gas/magma reservoir feeding the Strombolian activity at 1200 m above sea level.

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Jewell Instruments is a world leader in the design, manufacture, and distribution of high-precision products. Our expertise includes acceleration and tilt sensors, electronic compasses, avionics components, solenoids, and panel meters. The extensive application knowledge we have obtained through decades of experience allows us to provide custom solutions for a diverse group of industries. In fact, customers from all over the globe contact us for solutions to aerospace, medical, industrial, and telecommunications applications - to name a few.

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Research Article

Ground Deformation Detected by Permanent Tiltmeters on Mt. Etna Summit: The August 23-26, 2018, Strombolian and Effusive Activity Case

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Over the last few years, three tilt deep stations (27-30 meters) have been set up in the summit area of Mount Etna volcano. The aim of this challenging project is to record the ground deformations of the summit craters activity with high precision. We considered data related to the August 23-26, 2018, Strombolian and effusive activity. In this case, tiltmeters recorded variations in the order of 10^{-7} radians, not observed at the other stations. These changes suggest a shallow contraction source just south of the Southeast Crater. This result, related to the volcanic tremor source, points to the presence of a gas/magma reservoir feeding the Strombolian activity at 1200 m above sea level.

1. Introduction

Ground deformation is an important indicator to observe how and why volcanoes change their shape in order to understand and to provide eruption precursors. The geodetic techniques used for this purpose can be classified as continuous and discontinuous [1]. Continuous measurements (e.g., strainmeter, tiltmeters, GPS) include data sampled at brief discrete intervals (from milliseconds to minutes), while discrete measurements are carried out intermittently every few days, months, or years (e.g., leveling, GPS surveys, and radar interferograms).

A tiltmeter is any device that can be used to measure changes in the local tilt of the Earth's surface and several types of instruments allow obtaining high precision measurements; they can be grouped into two main classes: short and long base [2]. The former uses a bubble sensor or a pendulum to define the vertical, the latter the free surface of a liquid as a horizontal reference. Short-base tiltmeters are generally portable and less expensive, making them more suitable for most responses to volcano crises, although long-base tiltmeters are deemed more stable.

Continuous tilt measurements are used for ground deformation monitoring in many active volcanic areas in the world [3] and usually are used to record middle-short term eruption precursors (e.g., [1, 4]).

Slow tilt variations could indicate inflation caused by rising magma prior to the eruption or deflation linked to energy release following eruptions (e.g., [5, 6]), while fast tilt variations (from hours to days) are related to rapid rise of magma and propagation of dikes and eruptive fissures (e.g., [7-10]).

On volcanoes, highly sensitive instruments, accurate and deep (10-15 m or more) installations, and a network geometry comprising stations close to the summit area are the main elements to achieve effective volcano tilt monitoring [1].

Tilt systematic monitoring has been carried out on the Etna by the Istituto Nazionale Geofisica e Vulcanologia-Osservatorio Etneo (INGV-OE) from the late 1970s, by using bubble borehole tiltmeters [11, 12]. Up to the early 2000s, signals from tiltmeters in holes between 2 and 4 meters deep were affected by environmental noise (e.g., [13]). In the last 10 years, very precise instruments, equipped with self-leveling systems and magnetic compass, have enabled

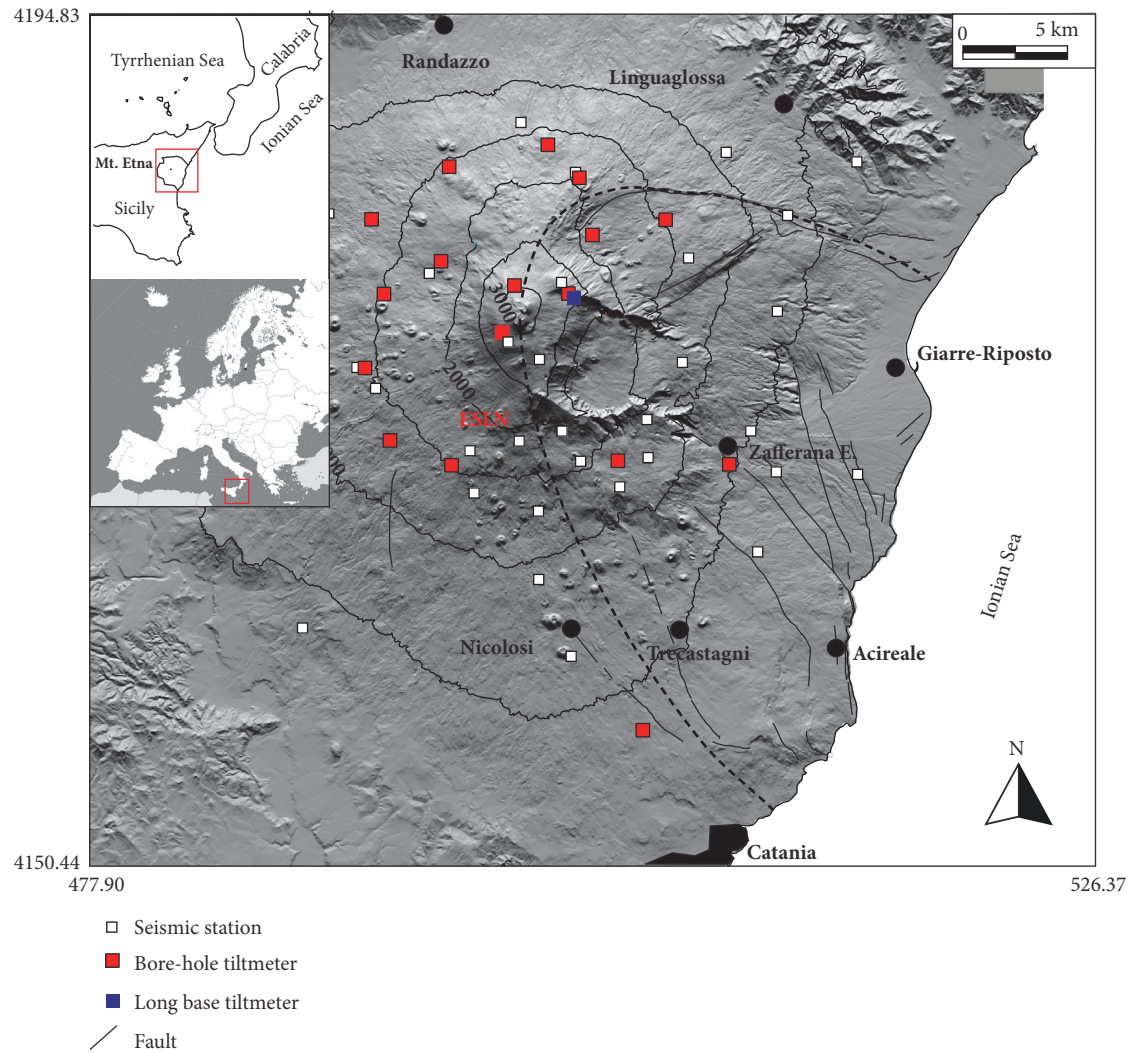


FIGURE 1: Map of the permanent tilt and seismic networks operating on Mt. Etna.

installation at greater depths with relative simplicity. The first installation was carried out in 2007 at a depth of 30 m and the results obtained [14] prompted renovating the network in this direction (Figure 1).

In particular, thanks to European Structural Funds (PON Vulcamed Project), three 27-30 meter deep sensors have been installed in the summit area of the volcano (Figure 2) and the existing sensors placed at greater depths.

High precise data on the summit area enable recording ground deformation of the crater area such as during Strombolian activity [15] or lava fountains [16] that lower and farther stations do not detect. In this paper, we discuss data and results obtained related to the recent Strombolian and effusive activity of August 23-26, 2018.

2. Volcanological Settings of Mt. Etna

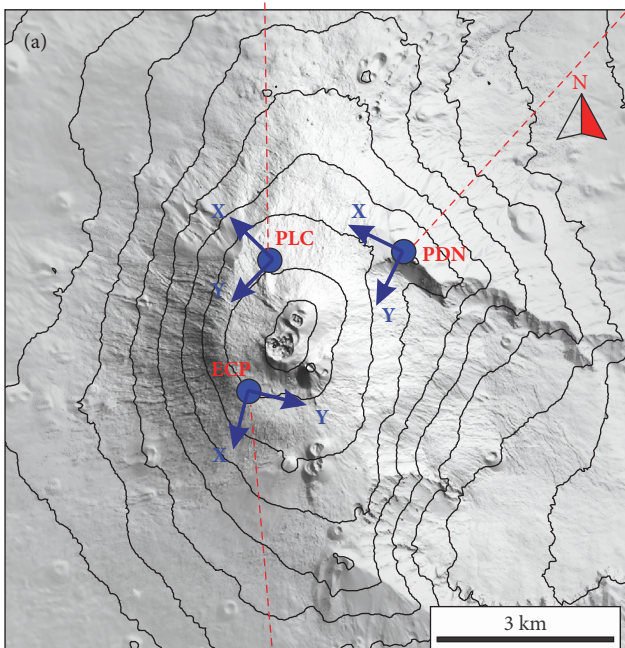
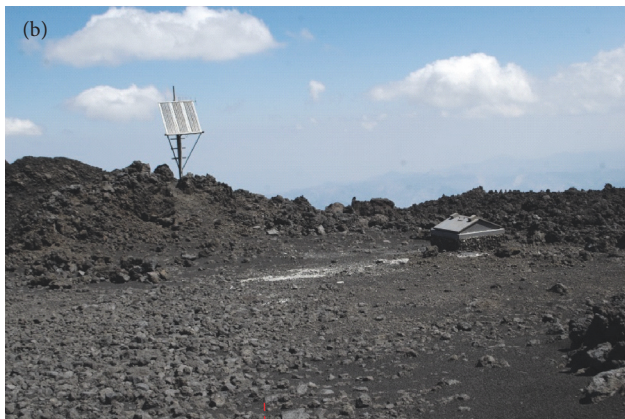
Mt. Etna is a basaltic volcano with a basal diameter of about 40 km, just over 3300 m in altitude, located on the eastern coast of Sicily, and represents one of the most active and monitored volcanoes in the world.

Mt. Etna's activity may be grouped into two types: lateral flank eruptions occurring along fracture systems and persistent activity, comprising phases of degassing alternating with Strombolian activity, which may evolve into lava fountains and effusive events [17, 18].

Monitoring this activity is carried out by means of the several surveillance cameras of the INGV-OE [19] and by field surveys (e.g., [20]).

Flank eruptions at Etna are more hazardous than the continuous summit activity and may have serious consequences in terms of material damage and/or the loss of life; the interval between two such eruptions spans from several months to few decades. Some of these eruptions, such as the 1991-93 event, have produced major lava flows and in some cases lava flows have covered both main flanks of the volcano, as during the 2001 and 2002-03 eruptions (e.g., [21]).

The continuous summit activity is related to four active summit craters: Northeast Crater (NEC), Voragine (VOR), Bocca Nuova (BN), and Southeast Crater (SEC). Moreover, a new summit crater (named NSEC) is built up around a pit that had opened on the SEC eastern flank in late 2009 (Figure 3).



Pinnacle Technologies Series 5000 Tiltmeter Specifications (e)

Specification	Value
Tilt Resolution at sensor	1 nR
Range	±10 degrees from vertical
Gain (Max)	1000 mV/uR
Gain Levels	4
Leveling Ability	Self Leveling
Data Storage (30 sec. sample rate)	30 Days*
Data Storage Type	Internal A/D & storage
A/D Resolution	24 bits
Data Collection Rate	38,400 Baud
Orientation	Int. magnetic compass (±2°)
Installation Depth	Unlimited (typically 3–12 m)
Borehole Diameter	Min 7 cm
Dimensions	6.4 cm dia × 107 cm
Operating Range	-40 °C to 85 °C**
Mass	4 kg
Avg. Power Consumption	280 mW

* Internal memory stores 88,000 data points. Sampling rate can vary from 1 sec to 4 minutes.
 ** 125 °C version available



FIGURE 2: Map of the three summit tilt stations with axis direction (a) and photos related to installation phases (b, c, d). (e) reports the Pinnacle Series 5000 tiltmeter specifications.

TABLE 1: Coordinates (UTM, in m) of the three summit tilt stations.

Station	Name	Latitude	Longitude	Height m a.s.l.
PLC	Punta Lucia	499134	4179855	2928
PDN	Pizzi Deneri	501418	4179910	2808
ECP	Cratere Del Piano	498895	4177418	3010

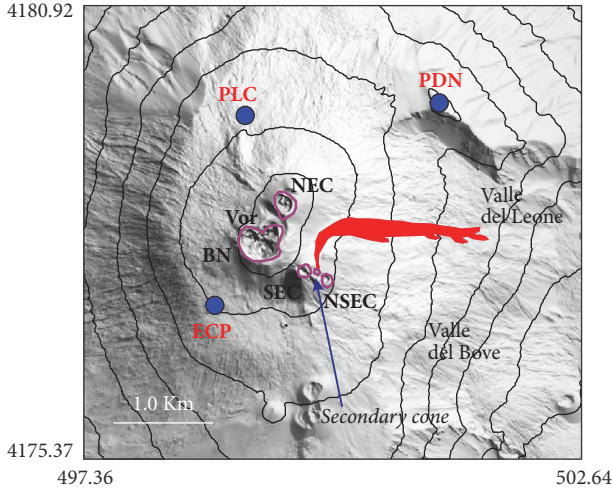


FIGURE 3: Map of the summit crater area showing the position of the 23-26 August eruptive fissure and lava flow. BN = Bocca Nuova; VOR = Voragine; NEC = Northeast Crater; SEC = Southeast Crater; NSEC = New Southeast Crater.

Since the 1990s, more than 150 summit paroxysmal episodes and numerous effusive events have occurred [22]. The most common explosive activity of Etna volcano ranges from mild Strombolian explosions to violent lava fountaining episodes consisting of vigorous, continuously sustained jets of magma and gas, often accompanied by voluminous ash emissions and lava flows (e.g., [23]).

Strombolian activity is a typically explosive phenomenon with almost continuous, intermittent explosions. By contrast to Stromboli, where this activity is almost continuous, such behavior occurs episodically on Mt. Etna, often preceding paroxysmal lava fountains and accompanying the opening of eruptive fissures and effusive eruptions (e.g., [22]). Strombolian activity is generally explained in terms of bubble dynamics, where large ($<100 \text{ m}^3$) gas bubbles rise in a near-static open magma conduit and explode close to the surface when the gas overpressure exceeds the external pressure (e.g., [15]).

3. Tilt Network

Mt. Etna permanent tilt network (Figure 1) currently comprises 17 biaxial instruments installed in shallow boreholes and one fluid (mercury) long-base instrument set inside two 80-m-long tunnels at the Volcanological Observatory of Pizzi Deneri [3, 24].

The borehole instruments use a high precision electrolytic bubble sensor to measure the angular movement and each tiltmeter is made up of two perpendicular axes.

At Mt. Etna, continuous tilt monitoring was first attempted during the 1970s (e.g., [25]). In the 1990s, the network was expanded, reaching a configuration of nine biaxial, shallow borehole instruments at about 3 meters deep, equipped with AGI Mod 722 and Mod 510 tiltmeters [11, 18, 26].

Starting from 2007, we installed further deep stations (from 10 to 30 meters) using new high-resolution (10^{-8} – 10^{-9} radians) self-leveling instruments with onboard magnetic compass (LILY by Applied Geomechanics/Jewell and Pinnacle 5000 by Pinnacle/Halliburton). A constant temperature characterizes the sensors installed at these stations and signals have low noise, which has allowed detecting diurnal and semidiurnal tilt tides [27–29].

At present, most of the stations are programmed for 1 data/min, including acquisition of tilt, air and ground temperatures, air pressure, and instrumental control parameters. Some stations are also programmed for faster acquisition (1 data/sec).

3.1. Summit Stations Installation. Starting from 2012, three 27-30 meter deep stations (PDN, PLC, and ECP) have been installed on Mt. Etna's summit (Figure 2, Table 1).

The project was made possible thanks to the European Structural Funds within the PON Vulcamed Project, which funded both setting up these stations and upgrading the existing middle-altitude stations.

After choosing the appropriate sites and obtaining authorization from the Park Authority, we began the drilling phase (Figure 2(b)). This work, as well as building the structures (Figures 2(b) and 2(c)), encountered various problems. Foremost was the brief period enabling the work, limited to July, August, and September when it is possible to use the access roads, but also several logistic problems, not least the 2013-2014 ash and lapilli emissions from the summit craters.

Finally, the holes were prepared by removing the residual water and pouring a little sand into the hole. The instrument was then lowered and secured by pouring fine quartz sand.

The installed tiltmeters are Pinnacle Series 5000, consisting of a stainless steel cylindrical body weighing 4.0 kg, 1070 mm long and 64 mm in diameter, which contains two tilt sensors at the base placed orthogonally to each other, a thermometer and a solid state magnetic compass sensor (Figure 2(e)). In order to level the instrument, a motorized system enables tilting the sensors up to ± 10 degree.

The instrument is calibrated by the manufacturer and showed no sensitivity changes over time; the two axes are oriented to detect two components (X and Y) orthogonal to each other; positive values of X and Y axes indicate deflation; negative values instead indicate inflation. The compass

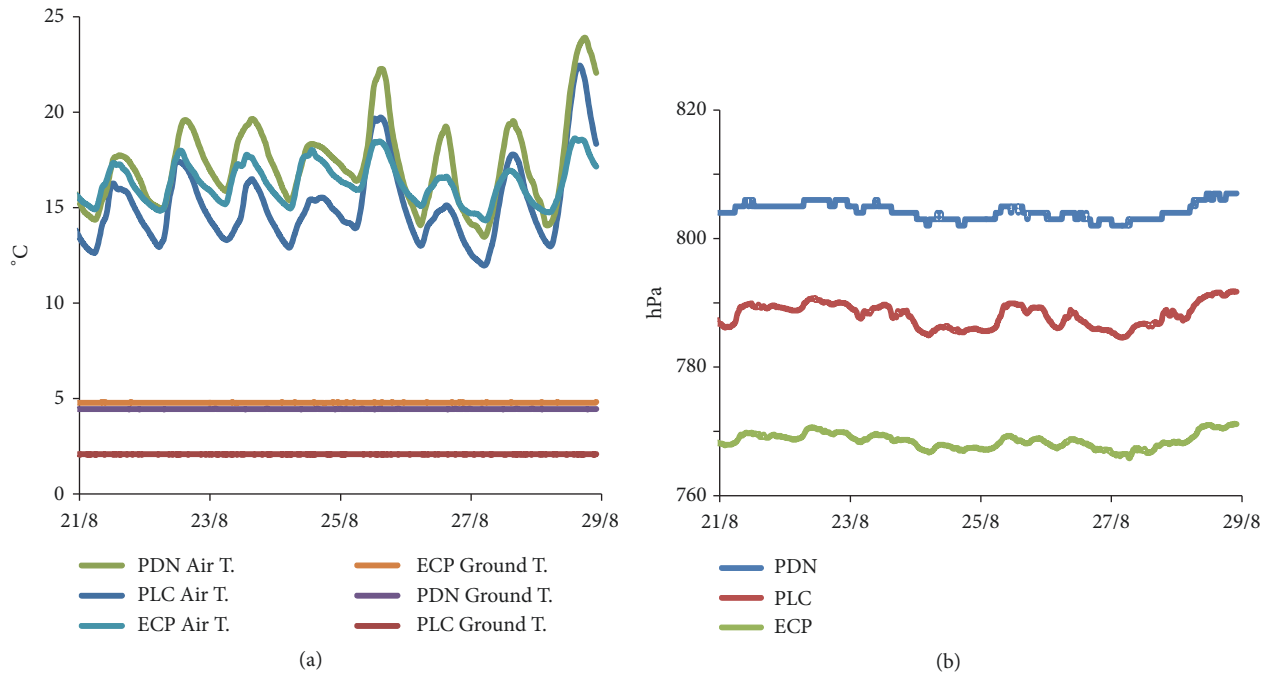


FIGURE 4: Temperatures (a) and air pressure (b) at the three stations in the 21-29 August period.

indicates the axis orientation that for the three stations is reported in Figure 2.

For acquisition, we chose to use a Campbell CR6 datalogger with memory storage of up to 16 GB with removable microSD flash memory card.

Campbell software polls the tiltmeter every second acquiring the two components (X and Y), tilt temperature, and compass. The data requested are stored in a circular memory of 4 Mbytes. We decided to use different sampling times: 10 minutes, 1 minute, and 1 second (actually only for ECP).

The station hardware also comprises a power supply filter and a condition circuit that allows reading other physical parameters including the voltage of the solar panels and battery, instrument power supply, air temperature, and atmospheric pressure.

The stations have been linked to the existing INGV-OE VHF network radio communication. Via this network, we can communicate and send bidirectional data and information by using a NMS-3AS SATEL radio modem with a fully 9600 bps communication rate.

The linkage between tiltmeter and datalogger, as well as the development of the transmission and acquisition systems, was undertaken at the INGV-OE laboratory of Nicolosi (Catania) ([30] and successive implementations).

Finally, all data are stored in the general INGV-Database, named TSDSystem, which graphically displays all the acquired signals [31].

4. The August 23-26, 2018, Strombolian and Effusive Activity

Strombolian activity occurred at the NSEC, starting on 23 August at approximately 18:00 UTC [32]. This activity

involved a secondary cone located between the SEC and NSEC (Figure 3) and consisted of an initial mild Strombolian activity that rapidly became intense, producing almost continuous explosions with the launch of coarse material up to a height of 100-150 m.

Shortly after 18:30 UTC, a lava flow issued (about 500.000 m³, Stefano Branca personal communication) from the cone, flowing north-eastwards into the Valle del Leone (Figure 3).

Strombolian explosions continued throughout the next day (24th) with variable intensity. On August 25th and 26th, the intensity of Strombolian activity at the cone gradually decreased and the ash emission was weak and occasional; the lava flow remained confined to the upper part of the Valle del Leone.

5. Tilt and Meteorological Data

Tilt sensors in a deep hole reduced the bias of meteorological factors on measurements allowing recording high signal-to-noise signals. Mt. Etna summital stations, deeper than 25 meters, show, in the period 21-29 August (Figure 4(a)), very stable ground temperatures between 2°C and 5°C and daily changes on air temperatures; no significant variations are also present on air pressure data (Figure 4(b)).

Figure 5 shows tilt data recorded at the three summit stations in the observed period. Signals are modulated by the diurnal and semidiurnal Earth tide components. Although tilt resulting from Earth tides is small, we measured amplitudes of the tilt variations not higher than 0.1 microrads at all the three stations (Figure 5(b)).

The signals recorded more evident changes during the 23-26 activity (Figure 5); in particular, the ECP station showed the largest changes of about 0.3 and 0.75 microrads on the

TABLE 2: Measured tilt variations during the phases of volcanic activity shown in Figure 5, at the three tilt stations.

	Phase 1 (microrads)	Phase 2 (microrads)	Phases 1+2 (microrads)
From	23/8 H:16:00	25/8 H:01:00	23/8 H:16:00
To	25/8 H:01:00	26/8 H:06:00	26/8 H:06:00
PLCX	-0.15	-0.04	-0.19
PLCY	0	0	0
ECPX	0.30	0	0.30
ECPY	0.52	0.23	0.75
PDNX	0.20	0.08	0.28
PDNY	0.11	-0.03	0.08

two components, while changes of about 0.2-0.3 microrads were detected at PDN and PLC stations (Table 2). No evident variations were recorded at the other lower stations causing their distance from the source.

In particular the tilt station showed a main variation from 16:00 UTC on 23 August to the early hours of the 25th (phase 1 in Figure 5(b), Table 2) and successively minor changes until 06:00 UTC on 26 August (phase 2 in Figure 5(b)) when tilt returned to a “normal” trend. Moreover a fast small variation, of 20-25 nanorads, was recorded before the onset of activity (23th at 15:17, contemporaneously at ECP and PLC Figure 5(b)).

Multistation variations are more significant compared to those recorded at a single station [33] that may be related to a local effect (an example, on August 26th at ECP). In our case, a small fast process (a fracture?) seems to precede the beginning of the volcanic activity by about 40 minutes.

Tilt vectors estimated for the 23-26 period (Figure 6) indicate a general lowering toward SE for ECP and PLC and WSW for PDN suggesting a summital shallow depressurizing source, closer to ECP, which showed higher tilt variation.

6. Volcanic Tremor

At Mt. Etna volcanic tremor is a continuous background seismic signal, typically recorded at basaltic volcanoes with persistent activity.

The causes of volcanic tremor are commonly attributed to the movement of magma within the volcano edifice or to unsteady stirring in a gas-rich magma (e.g., [34–36]). However, the origin of tremor is still a matter of debate although numerous models and mechanisms have been produced depending on the studied volcano.

Volcanic tremor is a feature with a close relationship to Mt. Etna eruptive activity that shows clear variations in amplitude, frequency, and source location during volcanic activity (e.g., [37, 38]).

We report a calculation of the time changes of tremor energy, as the RMS of the seismic signals recorded at the vertical component of ESLN station (see Figure 1 for location) in the band 0.5–2.5 Hz within 10 min long sliding windows in the period 21-29 August.

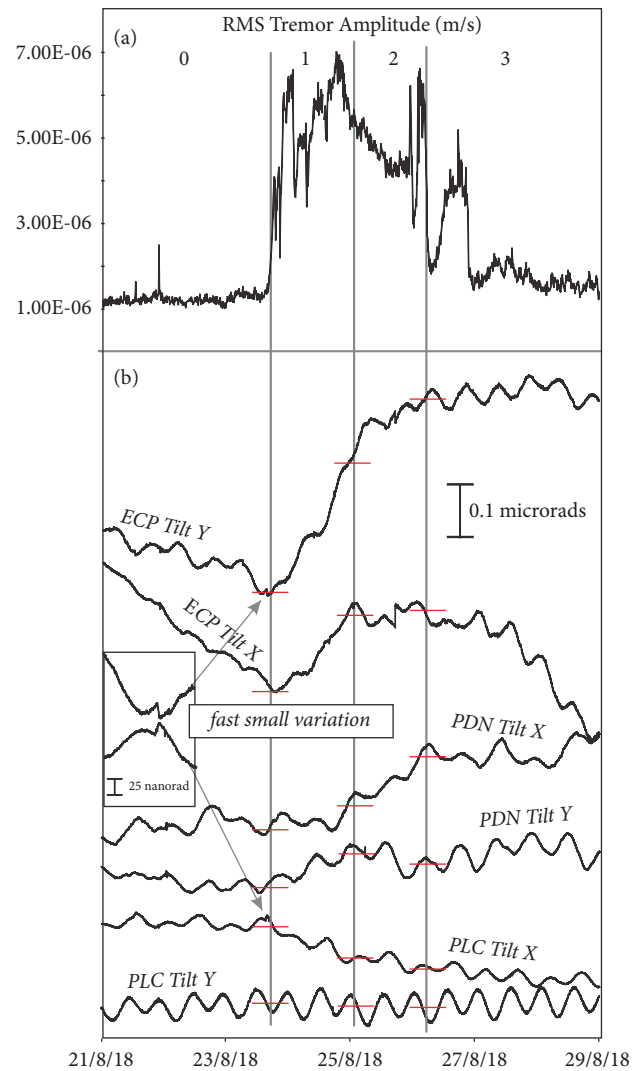


FIGURE 5: Volcanic tremor (a) and tilt components at the three stations (b). Red dashes mark the measured reference points for tilt changes (see also Table 2). Numbers indicate the preactivity (0), main variations (1), minor changes (2), and end of activity (3) phases. Inset reports the magnification of the small fast variation recorded at ECP and PLC just before onset of volcanic activity.

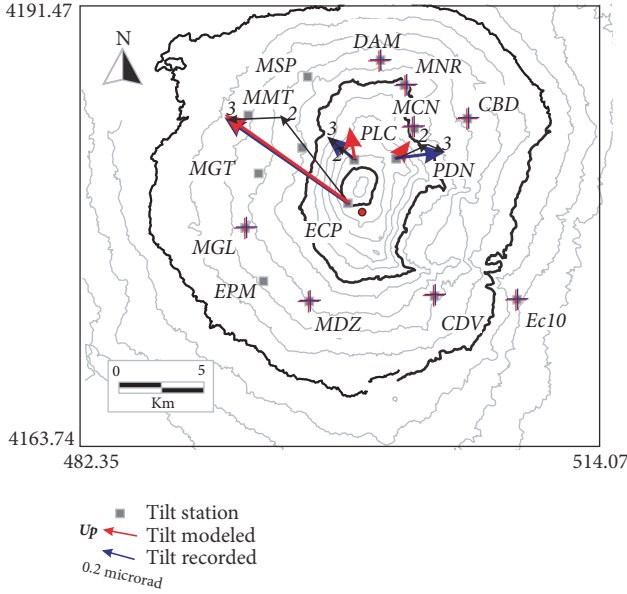


FIGURE 6: Comparison between observed (blue) and modeled (red) tilt vectors. Black tilt vectors are related to phase 1 and phase 2 evidenced in Figure 5 (see also Table 2).

The mean amplitude of the volcanic tremor remained at average levels up to about 16:00 UTC on 23 August, when there was a noticeable and sharp increase led to higher amplitude level (Figure 5(a)).

The volcanic tremor, although with some wide fluctuations, always remained at high values until 26 August when, in the late evening, the amplitude returned to values just slightly higher than those preceding the increase on 23 August.

The tremor source locations were retrieved by using a grid-search approach that inverts the spatial distribution of the tremor amplitude [39] recorded at the broadband stations located at altitudes higher than 1000 m above sea level (a.s.l.).

In this study we applied the method using a 1 h long sliding time windows on the resultant of three-component seismic signals filtered in the frequency band 0.5–2.5 Hz, assuming propagation in a homogeneous medium. Errors, related to this method, are up 500–600 meters on horizontal and 1000 meters for depth [39–41].

Before August 23, the tremor source is located below BN and Voragine craters, in the depth range between 2500 and 3000 m of elevation a.s.l. (Figure 7); successively, corresponding to the increase in volcanic tremor amplitude, the source moved 500–700 meters south-eastwards of the SEC (Figure 7).

7. Modeling

Using an open source software package developed within INGV-OE (Cannavò, personal communication), we inverted tilt data in order to image the observed deformation pattern under the boundary conditions of a homogeneous, isotropic, and elastic half-space. In particular, we used the tilt changes occurred between August 23 and 26 (see Table 2).

TABLE 3: Location and volume obtained through the point source modeling.

Model parameters	Latitude	Error
East Coordinate	499570	400 [m]
North Coordinate	4176850	1000 [m]
Depth	1200 m a.s.l.	200 [m]
ΔVol	-21000 m ³	3000 [m ³]

We performed an analytical inversion of clinometric data, describing the pressure source with a point-source approximation of the magma body [42]. We chose this source model among the other models published in literature, since, in this case, it has a good trade-off between the number of degrees of freedom and the obtained data fit. The point Mogi pressure source is described by four parameters: the coordinates “x”, “y”, and “z” of the point-source and the volume variation “ ΔV ”. Model parameters were estimated performing an inversion by means of the Pattern Search technique [43] together with a local Genetic Algorithm Search [44]. The best solution is reached by minimizing the following error function:

$$err = \sum_{j=x,y} \frac{(T_{ij} - TC_{ij})^2}{\epsilon_j} \quad (1)$$

where T_i is the measured tilt components with an error ϵ_i at the i -th station, which we estimated equal to about $0.05 \mu\text{rad}$.

Moreover the uncertainty of each model parameter was estimated adopting a Jackknife resampling method [45]. The technique requires several optimizations. First, we estimated the solution by using all available data, D_n , composed of n data. Then, by removing one input measurement at a time, we estimated the solution $D_{n-1,i}$, where the subscript indicates the size of the data set and the index of the removed measurement. Then new solution estimator is derived as

$$D_n^* = nD_n - (n-1)\bar{D}_{n-1} \quad (2)$$

where

$$\bar{D}_{n-1} = \frac{\sum_{i=1}^n D_{n-1,i}}{n} \quad (3)$$

Variance is estimated:

$$\sigma_J^2 = \frac{n-1}{n} \sum_{i=1}^{n-1} (D_{n-1,i} - \bar{D}_{n-1})^2 \quad (4)$$

We also included the effects of the topography using the varying-depth model of Williams and Wadge [46]. This model assumes a different elevation for each recording station corresponding to the elevation of the point. The medium was assumed to be homogeneous and isotropic with a Young modulus of 75 GPa and a Poisson ratio of 0.25, typical values used for Etna volcano (e.g., [47]).

Figure 6 shows recorded and modeled tilt vectors and Table 3 shows the estimated model parameters with related

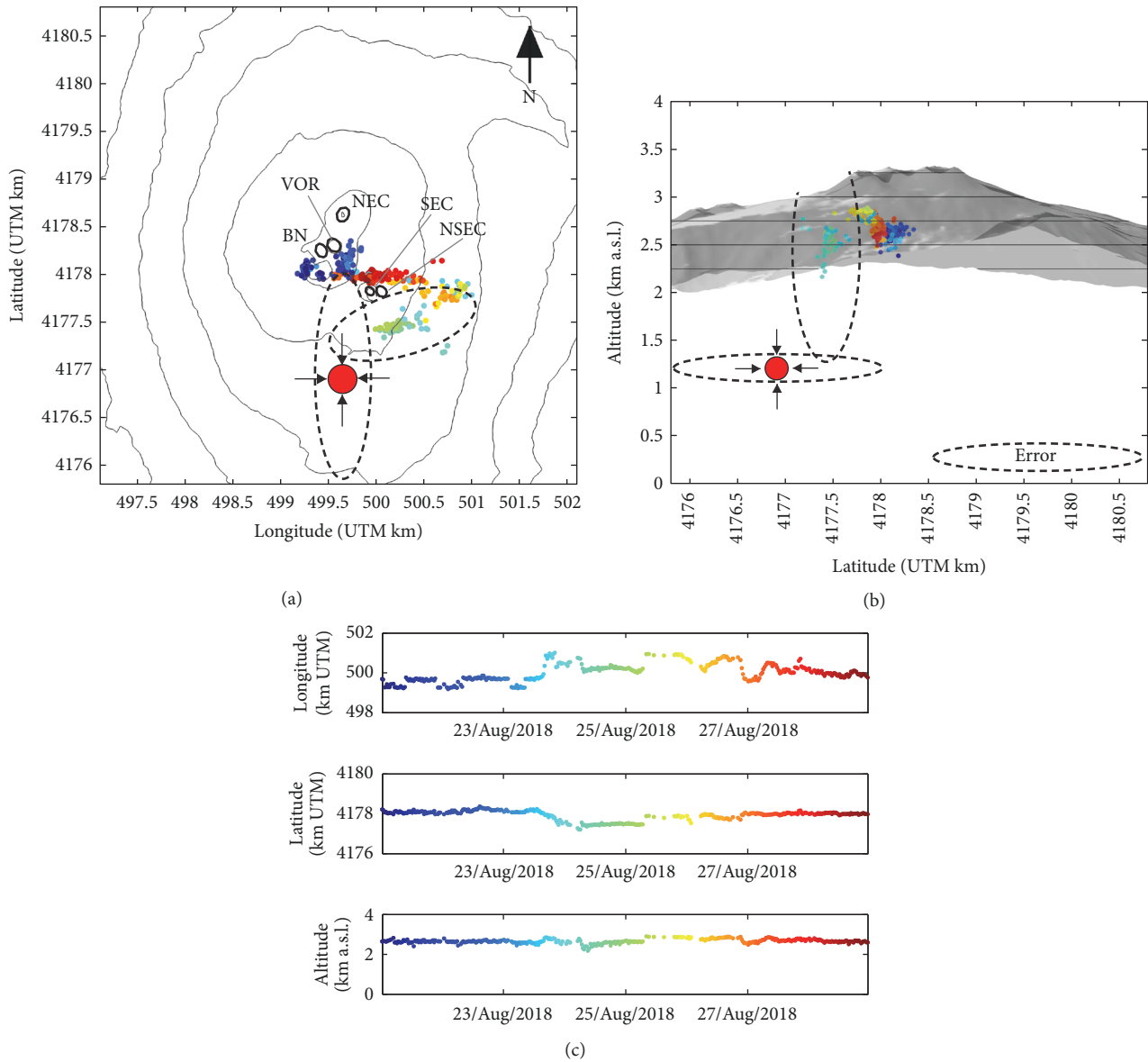


FIGURE 7: Map showing the locations (a) and E-W section (b) of the modeled results; errors are represented by ellipses. Volcanic tremor source coordinates and altitude variations (c). The color code is time related.

uncertainties, estimated as explained before. We retain that the obtained point-source pressure is well constrained except for the north position. In fact, there are not tilt stations, southern from the source, recording not zero tilt variation and, therefore, it is not possible to model the tilt signal decay toward the south direction. We obtained a large uncertainty with respect to the other estimates for the model parameters. Nevertheless, the error ellipse is not larger than the zone where the volcanic tremor sources and the eruptive fissure are located, and, therefore, we retain that our pressure source is enough reliable. The obtained deflating source is located at a depth of about 1200 m (a.s.l.), at about 1000 m South with respect from SEC.

8. Discussion and Conclusions

Tilt signals at Mt. Etna have allowed detecting and studying volcanic processes such as magma intrusion, fracture propagation, and volume changes of magmatic or hydrothermal systems (e.g., [24]).

Over the last decade, deep stations and high-resolution self-leveling instruments enabled detecting smaller ground deformations as during lava fountains (e.g., [23]).

With the aim of improving tilt monitoring close to crater area, three deep (27-30 m) stations have been installed on the volcano summit, though not without problems in planning, drilling, infrastructure, and instrument installations.

On August 23–26, 2018 a Strombolian and effusive activity occurred at the NSEC; summit tiltmeters recorded variations of a few tenths of microradians that were not observed at the other stations.

These changes are a coherent indication of a contraction source south to SEC. We obtained a model for these deformations with a final optimal solution (Figure 7) that shows a deflation source under the summit area at 1.2 Km a.s.l. located 1 km south of SEC. Directions of tilt vector of phase 1 and phase 2 (Figure 6) suggest a possible shift toward the north of the source.

The calculated tremor source locations also showed a progressive shift from a position located under BN and VOR area (at depths from 2.2 to 2.7 km a.s.l.), to a position 500–700 meters southeast of SEC (Figure 7) and moved to shallower depths toward the SEC during the Strombolian activity.

Volcanic tremor testifies to the presence of the movement of gas and magma within a conduit below the SEC; we believe that the obtained ground deformation source represents the gas/magma reservoir with modest volume change (21.000 m³) supplying the Strombolian activity and causing volcanic tremor.

In conclusion, highly sensitive tilt instruments, with accurate and deep installations, have allowed (for the first time) to record ground deformation occurring during a Strombolian episode at Mt. Etna.

Data Availability

The tilt and seismic data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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