



Review of early ground deformation observations by electronic distance measurements (EDM) on active Sicilian volcanoes: valuable data and information for long-term analyses

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Abstract

Electronic distance measurements (EDM) represent one of the first methods to detect ground deformation on volcanoes. Used since 1964, they enable acquiring precise distance measurements, whose time repetition may highlight changes related to volcanic activity. This technique was widely used on volcanoes from the 1970s to the early 2000s and has been used many times to model position, geometry, and volumes of magmatic and hydrothermal sources. This paper reports the EDM experiences, results and data acquired on Sicilian volcanoes (Etna, Vulcano, Stromboli and Pantelleria) from the early 1970s, which have played a major role in the birth of the volcano-geodesy for volcanic process knowledge, making the Sicilian volcanoes among those with the longest geodetic record in the world.

Keywords Geophysics · Volcanology · Ground deformation · Slope distances measurements · Volcanic processes

1 Background and summary

Ground deformation measurements provides data on how volcanoes slowly change their shape or dimensions in time, in order to infer and study their internal dynamics and how to predict eruptions. The methodologies used for measuring ground deformation are standard land-surveying techniques (e.g., tilt, EDM, leveling) or satellite geodesy methodologies (e.g., GNSS—Global Navigation Satellite Systems and DInSAR—Differential Interferometric Synthetic Aperture Radar) collecting data discretely or continuously (Dzurisin 2003, 2007). Electronic-optical Distance Measurement (EDM) with leveling, GNSS surveys and radar interferometry, are measurement techniques that can provide ground deformation measurements with daily or longer intervals.

EDM is an instrumental technique that measures the distances electronically by using light waves as carrier. EDMs are comprised of two parts each set-up over a monument. The active end includes a source of coherent light, usually a red laser, that is modulated with at radio frequency. The passive

end is the distant corner cube reflector. The distance measurement is made by comparing the phases of the transmitted pulse and the reflected pulse. Introduced after World War II, this technique was first repeated on volcanoes across Kilauea Caldera in October 1964, when a 3.0 km line (Uwekahuna-Keanakakoi) showed a lengthening of 12 cm and successively a rapid shortening of 28 cm, a few days after the beginning of the March, 1965 flank eruption (Decker et al. 1966).

Ground deformation measurements with EDM have been acquired in numerous volcanic areas, such as Merapi (Saepuloh et al. 2013; Aisyah et al. 2018), Soufriere Hills (Jackson et al. 1998) Mount Baker (Hodge et al. 2010), Colima (Ramirez-Ruiz et al. 2002), Kuju (Nakaboh et al. 2003), Usu (Aoyama et al. 2009), Vesuvius (Pingue et al. 2000), Arenal (Muller et al. 2015), Unzen (Matsushima and Takagi 2000), Santorini (Stiros et al. 2003), Anatahan (Rowland et al. 2005), Campi Flegrei (Amporuso et al. 2008) and Long Valley Caldera (Tizzani et al. 2009).

In Sicily, the first EDM measurements were made on Mt. Etna, by British researchers that set up a network of 19 benchmarks close the summit craters, showing large surface deformation of the area in the period 1971–74 (Wadge et al. 1975; Wadge 1976); this network was successively enlarged by about 5 km toward the south (Murray and Pullen 1985).

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In June 1973, the Istituto Internazionale di Vulcanologia (IIV, now INGV-OE) made the first experimental observations on the Lipari-Vulcano area with the setting up of 13 benchmarks in the northern sector of the island of Vulcano, to carry out high-precision triangulations. The network was expanded in 1974 covering the entire island of Vulcano and the central-southern part of Lipari (LIPVUL network) and the method was switched to trilateration which allowed very long distance measurements in a short time interval. The results obtained in the 1974–75 period through the trilateration surveys were presented in a first report (Gruppo Deformazioni I.I.V., 1976). Starting in 1975 the deformation pattern in the Lipari-Vulcano area was monitored by means of EDM. In the same period, four separate networks were realized on Mt. Etna whose measurements began in 1977 (Neri et al. 2005); finally, in 1979 an EDM network was set up on Pantelleria island (Bonaccorso and Mattia 2000).

EDM measurements, carried out by the IIV deformation workgroup, were performed by using laser Electro-Optical Geodimeters manufactured by the AGA Company in Sweden (Bergstrand 1960; Smith 1998). These instruments have the advantage of using light as the carrier projected between the instrument and the mirror without reflections from ground or from obstructions off the line. In particular, IIV initially used the Geodimeter AGA Model 6BL, one of the first instruments for precise electronic measurements made in 1969, and successively the AGA Model 6000, made in 1987 and used from 1992 to 1993 (Fig. 1). AGA 6000 was able to measure reasonably longer distances (14–22 km) in very good visibility conditions and to show the measurements automatically and immediately on a display (Smith 1998). The precision of both Geodimeters is 5 mm + 1 ppm and the slope distances recorded by the EDM technique need to be corrected for atmospheric conditions, considering temperature and atmospheric pressure values acquired at the measurement points (Rüeger 2012). Distances between each pair of stations of the networks were measured in one direction and the atmospheric corrections were calculated averaging the air temperature and pressure at both ends of the measured lines. Periodic angular measurements were performed with a Kern DKM3 first-order theodolite. It might be worthwhile to mention two other EDM techniques: Savage and Prescott (1973) employed an aircraft to measure the temperature and pressure profile and this reduced the length dependent portion of the error from 1 to 0.2 ppm; Slater and Huggett (1976) used two optical wavelengths which provides a precision of 0.3 mm + 0.1 ppm.

Geodynamic processes, such as increased pressure of a magma source, intrusions, faulting or fracture opening, may cause both lengthening and shortening of the distances between benchmarks. The study of volcanic processes needs an efficient EDM network configuration that includes several

interlocking quadrilaterals for good closure errors estimation, aiming also at an optimal areal coverage and considering the structures and processes to be detected.

A useful representation of the overall deformation is given by the network areal dilatation parameter. It is obtained through the temporal analysis of the components of the uniform strain tensor, considering the distance variations of the baselines and assuming a uniform strain field (e.g., Bonaccorso 2002). This parameter has often been considered a first-order indication of the overall deformation, representing the general contraction or expansion of the surveyed area as the result of a possible inflation or deflation of the volcanic edifice (Neri et al. 2005). To view the displacements of each point of the network, one baseline had to be fixed as a reference frame (Alparone et al. 2013). When zenith angle measurements were available, of course, also the 3D motion of the benchmarks could be calculated with respect to a reference point.

This paper reports the descriptions of EDM networks installed on Sicilian volcanoes; it provides a summary of the main scientific results obtained in these decades for improving the geophysical monitoring and the knowledge of the dynamics of the volcanoes (with some unpublished results for the 2001 and 2002–03 Mt. Etna eruptions) and sharing all the recorded data.

2 The EDM networks on Sicilian volcanoes (methods)

In the following, we report the history, description of the networks, activities, and main results for the different networks at each monitored volcano. The approach adopted for all studied areas was always the same; every baseline was measured always in the same direction, performing every time a set of ten measurements in about 15 min and calculating the mean value and standard deviation. Atmospheric parameters (i.e., temperature, pressure) were measured at both ends of each baselines and the average values were used for correcting the measurements for atmospheric refraction. Besides the common methodology and approach, Sicilian volcanoes (Fig. 1) have very different levels of activity, hence the monitoring approaches and, subsequently, the resulting datasets, time series as well as scientific information and models, also differ. For these reasons, we describe all these aspects separately for each volcano.

2.1 Vulcano (Aeolian Archipelago)

Vulcano (500 m.a.s.l.) is a volcanic edifice located in the southcentral sector of the Aeolian Archipelago (Tyrrhenian Sea, Italy). The island, with Lipari and Salina, is the emerging part of a NW–SE complex volcanic chain (Lipari-Vulcano

Fig. 1 EDM measurement on Stromboli volcano, by using the AGA 6000 model Geodimeter and map of the active Sicilian volcanoes investigated by using EDM

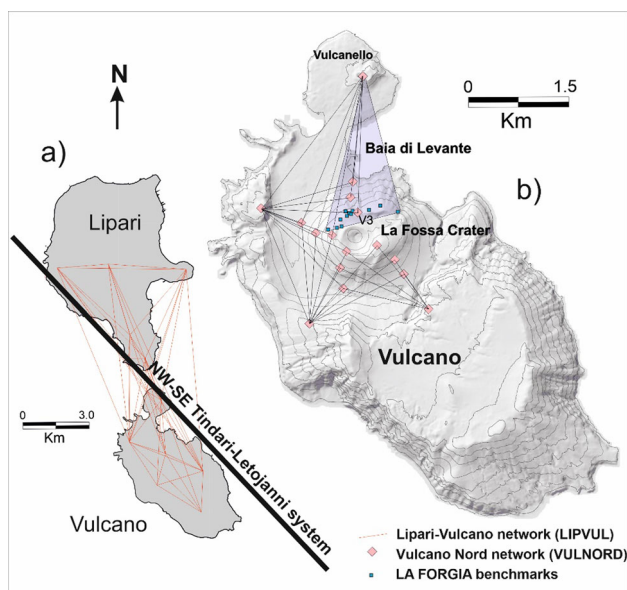


Fig. 2 **a** Geodetic LIPVUL network covering the islands of Lipari and Vulcano. **b** The VULNORD network that covers La Fossa cone area and LA FORGIA one on the northern rim of “La Fossa” (purple area)

Volcanic Complex—LVVC, after Ventura et al. 1999), rising from the seafloor and lying along a lithospheric structure (NW-wards prolongation of the Tindari-Letojanni system), affected by a right-lateral strike slip (Fig. 2a, Mazzuoli et al. 1995).

At present, the volcanic activity at LVVC consists of fumarolic emissions at Vulcano island from La Fossa Cone (391 m high) and along the north-eastern coast between La Fossa and Vulcanello cone (“Baia di Levante” area). The historic activity of La Fossa Cone has been characterized by frequent transitions from phreatomagmatic to minor magmatic activity. The last eruption in 1888–90 saw energetic explosive pulses, defined worldwide as “Vulcanian” activity, taking the name from this island (Selva et al. 2020).

After this eruption, La Fossa has been affected by three main unrest episodes characterized by increased fumarolic activity. The first one occurred in 1913–1923, when the maximum temperature of the crater fumaroles increased to 615 °C (Sicardi 1940); the second episode during the 1980’s when fumarole temperature progressively increased to 690 °C (Chiodini et al. 1995) and the third began in September 2021 and is currently underway (Inguaggiato et al. 2022).

Monitoring ground deformation on Vulcano (and Lipari), by using EDM, has been carried out along three networks (namely LIPVUL, VULNORD, La Forgia), which have been surveyed at least yearly (e.g., Bonaccorso et al. 1993a, 1995a, 1995c, 1998a, 2000a) and are described below.

2.1.1 Lipari-Vulcano and Vulcano North network (LIPVUL and VULNORD)

The first pioneering EDM network was the Lipari-Vulcano one (LIPVUL); it was installed in 1975, consisting of 14 concrete pillars connected by 39 baselines (Fig. 2a), covering the entire island of Vulcano and the central-southern part of Lipari (e.g., Falsaperla et al. 1989; Bonaccorso 2002; Bonforte and Guglielmino 2008).

From 1987, a smaller and denser EDM network (VULNORD) was set up on the northern part of Vulcano (Fig. 2b), with the aim of more detailed monitoring of the deformation affecting the active cone of “La Fossa.” This network, surveyed every four months until 1997, comprised 16 benchmarks and 32 lines.

The network comprised four radial profiles each with 3 benchmarks around La Fossa cone (at its base, middle flank and rim), which were measured from two of the four stations (pillars of LIPVUL network) located at high points on the caldera rim surrounding the Fossa cone and on Vulcanello. (Fig. 2b). These measurements, together with the LIPVUL

network, enable connecting the Fossa network to the broader network covering Lipari and Vulcano.

The results of several studies have shown the transpressive kinematics of the NNW–SSE prolongation of the Tindari Letojanni structure that crosses the Lipari-Vulcano Volcanic Complex (Bonforte and Guglielmino 2008; Mattia et al. 2008).

EDM data with GPS, leveling and tilt, revealed processes at different scales ranging from regional tectonics involving the Lipari-Vulcano Volcanic Complex to the volcanic and hydrothermal activity at Vulcano, also inducing an incipient instability of the northern slope of the La Fossa cone (Bonaccorso 2002; Gambino et al. 2007; Gambino and Guglielmino 2008; Harris et al. 2012; Pesci et al. 2013; Alparone et al. 2019). Data provided with this work complete the database of geodetic data published by Esposito et al. (2015) for the entire Aeolian archipelago and by Bonforte et al. (2016) for the rest of Sicilian seismic and volcanic areas.

All geodetic investigations concur in indicating the meaning tectonic dynamics, dominated by a transpressive strain along the regional NNW-SSE lineament, as the main deformation affecting the LVVC. Since 1975, the areal dilatation of the LIPVUL network (Fig. 3) has shown a continuous contraction except during the 1977–1979 and 1984–1986 intervals (Bonaccorso 2002; Alparone et al. 2019). This general trend was then confirmed by the GPS measurements that took the place of EDM on the same network in the late '90 s. EDM-GPS continuity of measurements on the LIPVUL and VULNORD networks (Figs. 4, 8, 10 and 11 in Alparone et al. 2019) makes this time series one of the longest geodetic records available for a volcano, allowing the medium-to-long-term volcano-tectonic dynamics to be investigated.

The general and fairly continuous tectonic spatial trend of deformation is modulated by the volcanic dynamics, whose ground deformation is locally superimposed on the dominating transpressive strain. In the 1990–96 period, in fact, the VULNORD baselines were affected by clear changes; Gambino and Guglielmino (2008) inverted the 1990–1996 EDM and leveling data, finding a deflating ellipsoidal source, centered under La Fossa Crater at about sea level depth. The subsidence recorded at La Fossa Cone in that period has been explained as the fluid loss from the geothermal reservoir in agreement with the strong increase of steam emission and temperature at crater fumaroles. These volcanic dynamics, mostly related to the shallow hydrothermal system, and its relation to the regional one, have been summarized well in Alparone et al. (2019), where the role of the deep feeding system, controlled by the tectonics, in modulating the fluid migration and then the hydrothermal system unrests, has been investigated by linking many decades of observations.

2.1.2 La Forgia network (La Forgia)

In 1990, in order to monitor the local gravitational process of the upper northern flank of the cone (Barberi et al. 1991) an even denser array, composed of 12 benchmarks (F1 to F12), was installed along the northern rim of “La Fossa” crater and measured from the LIPVUL pillar located at the top of Vulcanello, the volcanic edifice constituting the northern promontory of the island (Fig. 2b). These measurements were initially carried out about 3 times per year, and the observations performed between 1990 and 1994 showed a shortening of about 6 to 7 cm of some baselines (F4–F8) measured over a small section of the northern rim (Fig. 4).

In the successive 4 years, these baselines showed an extension of about 3 cm, partially recovering the previous deformation. This suggests that a sliding movement was also responsible for some of the shortening of the baselines.

The resulting interpretation is that only part of these movements was related to a thermal expansion and inflation of the crater rim, induced by the cycle of temperature change (heating–cooling) recorded at the fumaroles (Bonaccorso et al. 2010). Part of the shortening and lengthening of the EDM baselines (about 3 cm) was due to the increasing and decreasing temperature of the rock body lying close to the deforming area that caused a thermal expansion/contraction. The shortening that was not recovered represents a non-elastic deformation, interpreted as ground fracturing for increased fluid pressure and circulation (Harris et al. 2012). Added to an induced instability and downslope movement of the northern flank of the cone facing the main village and the harbor (Bonaccorso et al. 2010), this augments the hazard and prompts the detailed monitoring of this part of the cone.

2.2 Mt. Etna

Mt. Etna, located on the eastern coast of Sicily, is one of the most active volcanoes on Earth. It has grown (3340 m a.s.l.) at the intersection of two regional structural trends, NE–SW striking (Messina fault system) and NNW–SSE-oriented (Malta Escarpment) (Gresta et al. 1998) and consequently, its eastern and southern flanks are unstable and move downslope ESE-wards continuously (e.g., Neri et al. 2007). This mobile sector comprises several active faults, namely the Timpe Fault System, Trecastragni and Tremestieri faults, which dissect the eastern flank in different blocks characterized by inhomogeneous kinematics (Bonforte et al. 2011) and is bordered to the north by the Pernicana Fault System. Mt. Etna volcanic activity comprises a persistent activity with episodic paroxysmal events at the summit craters, and lateral flank eruptions generally preceded by intrusive processes with seismic swarms and ground deformation (e.g., Allard et al. 2006). The 1981, 1983, 1985, 1989, 1991–1993, 2001 and

Fig. 3 Areal dilatation of the LIPVUL network (from Alparone et al. 2019)

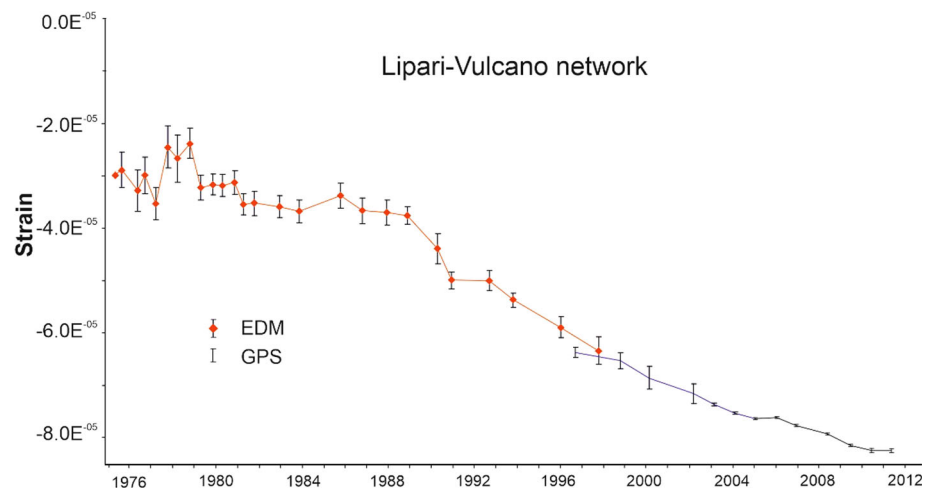
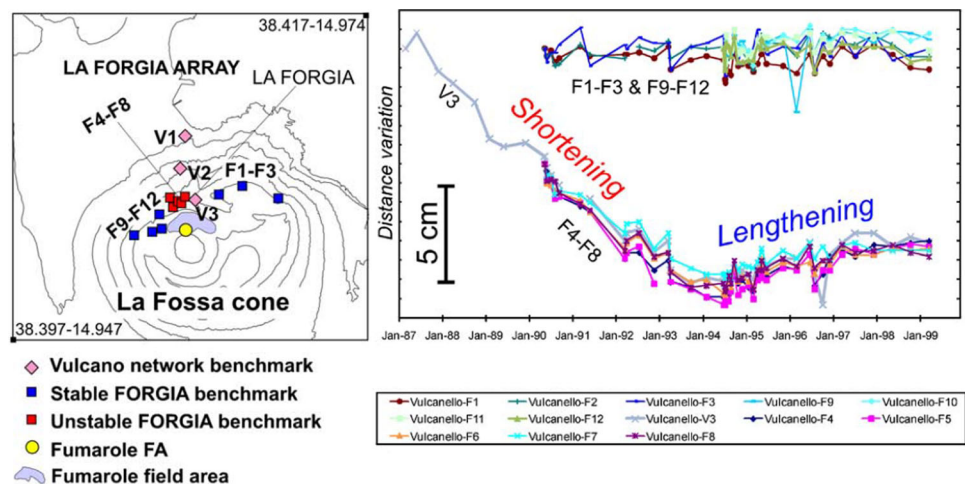


Fig. 4 Map of La Fossa with La Forgia geodetic benchmarks on the northern rim area (left side). Slope distance variations from the Vulcanello benchmark to the Forgia array measured between 1990 and 2000 (right side)



2002 events represent the main lateral eruptions occurring during the EDM monitoring.

The horizontal component of ground deformation at Mt. Etna was measured with EDM techniques between 1977 and 2004 (Bonaccorso et al. 1993b, 1995b, 1995c, 1998b, 2000b; Puglisi et al. 2004). Three separate networks, installed on the northeastern, western and southern flanks, are generally surveyed once a year (Fig. 5). A fourth EDM network (Ionica network) was installed across the lower eastern flank; it was measured for the first time in October 1977 but surveyed only until 1985 (Fig. 5).

The three EDM networks have been strategically placed in areas with the highest eruption probability, closely corresponding to the so-called northeast, south and western rifts. During eruptive activity, the measurements were repeated more frequently to investigate in detail the deformation patterns linked to the ongoing events (Neri et al. 2005).

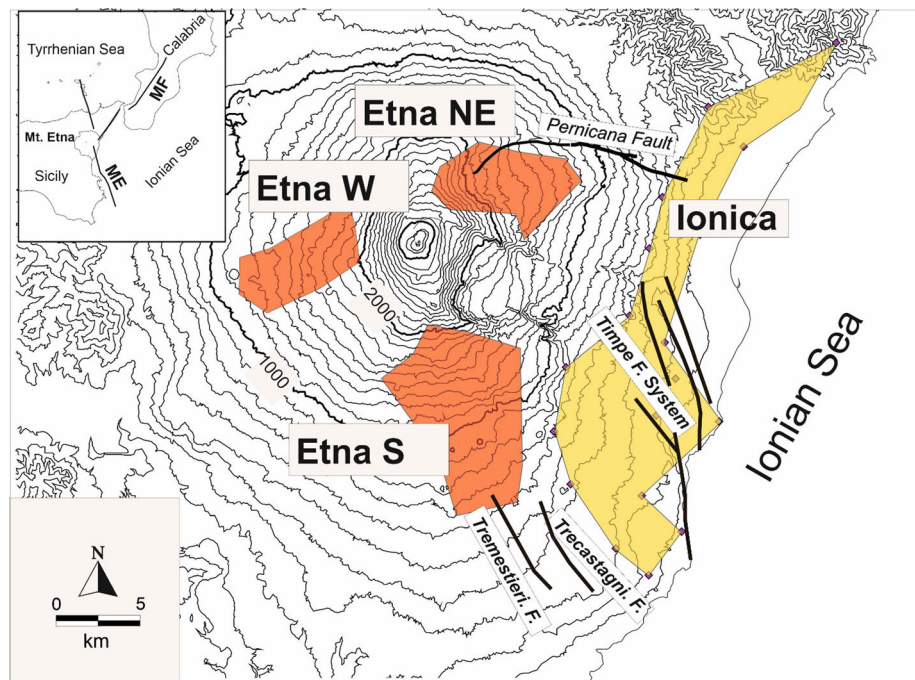
The EDM data immediately showed significant correlations between ground deformation events and eruptive activity since 1978 (e.g., Falzone et al. 1988; Bonaccorso

et al. 1990), the deformation being more pronounced in relation with flank eruptions, providing the very first geodetic evidence for starting volcano-geodesy studies and modeling on Etna and other volcanoes. Indeed, numerical modeling of EDM data on Mt. Etna contributed useful insights into the likely geometry and depth of the deformation sources that characterized the 1981, 1989 and 1991–93 eruptions (Bonaccorso 2001). Pioneering applications of repeated EDM measurements on the highly active Etna volcano sowed the seeds of what is now one of the most important disciplines for geophysical studies and monitoring of volcanoes.

2.2.1 North-East network (Etna NE)

EDM measurements on the north-eastern sector of the volcano started in 1979 through two separated networks of benchmarks: the first one installed at altitudes between 1500 and 2750 m a.s.l. (Etna Beta) and a second network (Etna Citelli) at lower elevation range. During 1982, the two networks were connected into the unique northeastern network,

Fig. 5 Schematic map of four EDM networks installed on Mt. Etna



consisting of 14 benchmarks and 38 baselines and occupying an area between 1250 and 2750 m elevation. Figure 6A shows the dilatation after these two networks were joined.

Early EDM (and leveling) data recorded during the 17–23 March 1981 eruption were inverted by Bonaccorso (1999) who modeled two sources: a vertical intrusion in the summit area and a final shallow intrusion elongating radially toward NNW.

Later on, the network showed no particular changes between 82 and 91 and a significant contraction associated with the 1991–93 eruption and. Immediately after the eruption, the NE areal dilatation started to show a general expanding trend interrupted only by two modest phases of contraction in June 1998–June 2000 and in May–July 2001 (Fig. 6a), the latter in correspondence with the 2001 eruption (Neri et al. 2005). Successively the 2002–2003 eruption, involving also the upper NE flank of the volcano, produced a marked extension of this network.

For the 1991–93 eruption, one of the longest eruptions to occur over the last 300 years, Bonaccorso (1996) by using EDM (together with GPS and tilt) modeled a 1.2 km b.s.l. planar source 0.8 km wide, 3.6 long and with 2.8 m of opening kinematics.

In Alparone et al. (2013) presented EDM data recorded from the end of 1970s to 2003, highlighting marked changes in the 1984–1987 period. In particular, they noted that lines with E–W direction were affected by marked elongation as the result of an acceleration of the eastern flank dynamics toward the sea (Fig. 7).

Bonforte et al., (2007) considered the baseline changes in the northeastern sector in order to show the Mt. Etna dynamics just before the onset of the 2002–2003 eruption, that also involved the NE rift of the volcano.

Finally, during the eruptive phases of July 2001 (onset of 2001 eruption) and of October 2002 (onset of the 2002–03 eruption), EDM measurements were recorded more frequently (daily) on some specific baselines, in order to have more continuous monitoring of the ongoing phenomena and check the propagation of the dyke intrusion. This network proved especially useful during the 2002–2003 eruption that affected the NE rift and produced a marked acceleration of the NE flank of the volcano (Fig. 6A). Frequent repetition of EDM measures on the upper part of the rift, in fact, allowed monitoring the possible propagation of the intrusion along the NE rift; on the other hand, the lava flow produced by this eruption interrupted the inter-visibility of some benchmarks, preventing the repetition of some baselines. These data are part of the database published with this paper (Table 1).

2.2.2 Southern network (Etna S)

Installed in November 1983, the southern EDM network (Etna S) consists of 16 benchmarks connected by 47 baselines and lies between about 650 and 2100 m elevation (Fig. 5).

Over time, the overall network area showed a contraction until 1991 and later, after the 1991–1993 eruption, a slow expanding trend (Fig. 6c). Large deformation has affected this network during several flank eruptions, in particular during the 1985 and 1989 ones, with a visible contraction; the

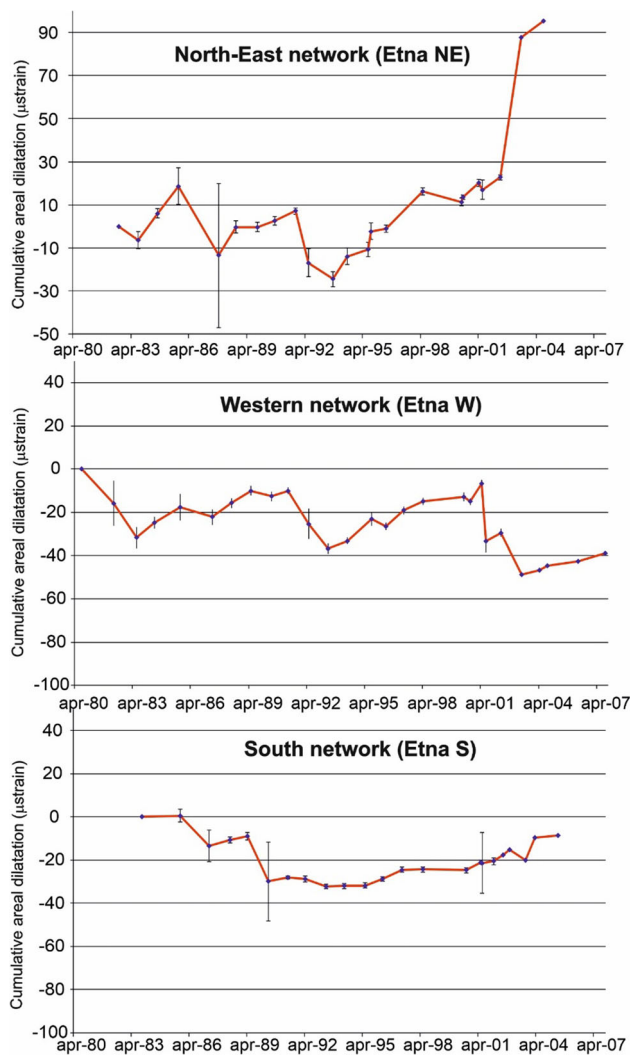


Fig. 6 Areal dilatation on the three Mt. Etna EDM networks

2001 eruption, which affected the upper part of the network, produced a complex deformation, visible only as a large error bar in the plot, due to the nonuniform variation of the baseline lengths.

During the 1989 eruption of Mt. Etna, a NNW-SSE fracture system, starting from the SE Crater on September 24, opened on the upper SE flank of the volcano for a length of 7 km without eruptive phenomena. The southern branch of this fracture lies on the northern border of the South Network that measured, in a few days, variations of tens of centimeters on several baselines; these data were used to calculate a dislocation model, related to the 1989 potential dyke intrusion in the southeastern flank (Bonaccorso and Davis 1993).

Strong deformation related to the 2001 eruption (Jun–Jul 2001 period) was also recorded by the network (Gambino 2004), showing a general contraction (Fig. 6c), mainly along a NNE–SSW direction (Neri et al. 2005). A very small

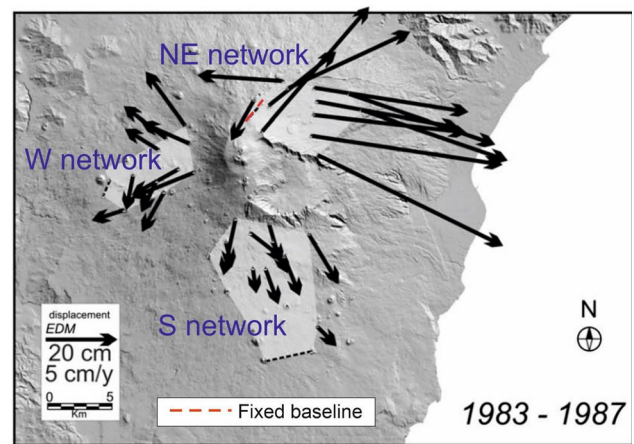


Fig. 7 Relative displacements from 1983 to 1987 calculated on EDM networks with respect to a fixed baseline for each network (dashed lines); in this case, the uppermost baseline (DAG-B09, in red) has been chosen for the NE network. Fixing this baseline, located at the westernmost side of the network and whose distance does not vary significantly in time, the relative motion toward the east is accurately traced (Redrawn from Alparone et al. 2013)

deformation (essentially NW–SE contraction) was recorded during the 2002–2003 eruption (Neri et al. 2005).

Also for the Etna S network, during the 2001 and 2002–03 eruptions, EDM measurements have been repeated more frequently (daily) on some baselines and these data are part of the published database (Table 1). In particular, the unpublished measurements carried out in July 2001, were very useful during the initial phases of the 2001 eruption (Bonforte et al. 2009) since they started to show significant variations between 12 and 13 July 2001 and in the following days up to the 17th, when the eruptive fractures finally began to open on the ground (Fig. 8). These daily updates were routinely sent to the Italian Civil Protection Authorities for continuous updates on the volcanic activity, including a first estimation of the possible uprising dyke position, hence the most probable eruption site. The EDM measurements were in fact able to provide immediate and reliable information about the ongoing intrusion, its depth and magnitude. A clear and unpublished example is the evolution of the ground deformation pattern on the sub-network that was routinely measured during the days of intrusion and related seismic swarm, here reported, for the first time, in Fig. 8. It was interesting to note how an outstanding extension (up to 12 cm), accompanied by a N–S contraction, immediately affected, from the very first hours of the seismic swarm, the lower baselines of the network, on July 12 2001. This trend of deformation slowly continued to accumulate extension (and contraction on N–S baselines), but only on July 17, did a sudden and even stronger extension (up to 20 cm) solely affect the uppermost baselines.

Fig. 8 Measured benchmarks of the northern part of Etna S network between 12 and 20 July 2001 (A). Green baselines are those affected by changes since the first hours of the seismic swarm, the blue ones are the baselines that recorded stronger variations on July 17. The red line is the 2001 dyke position modeled by Bonforte et al. (2009). Baseline trends measured during the first phase of the 2001 eruption characterized by the beginning of a strong seismic swarm until the ground fracturing and lava emission (B)

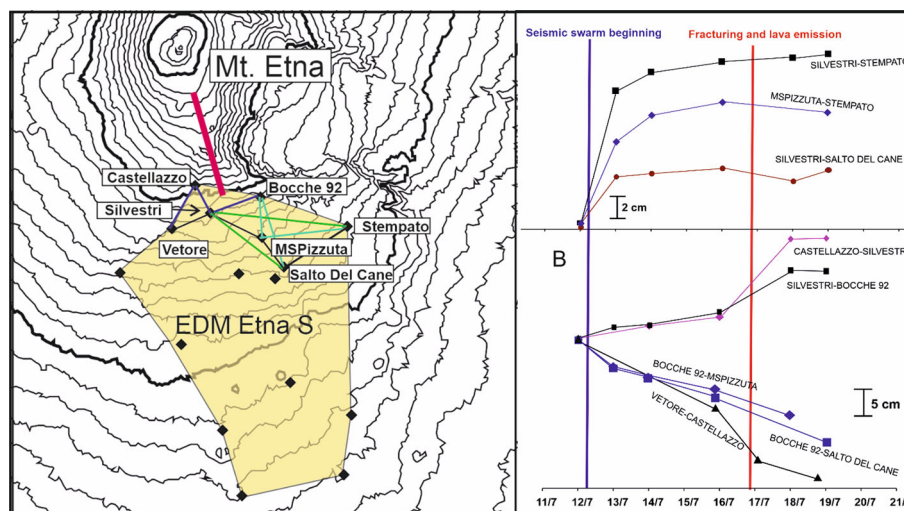


Table 1 EDM networks, measured periods and data file names

Area	Network	Measurement Period	Data file name	Coordinates file name
Eolie	Lipari-Vulcano	Apr. 1975–Dec. 1997	Vulcano LIPVUL.xls	VULNORD & LIPVUL Coord.xls
	Vulcano Nord	Mar. 1987–Dec. 1997	Vulcano VULNORD.xls	VULNORD & LIPVUL Coord.xls
	La Forgia	May 1990–May 2009	Vulcano La Forgia.xls	La Forgia Coord.xls
	Stromboli	2003	Stromboli.xls	Stromboli Coord.xls
Etna	North-East	Sept. 1977–Sept. 2004	Etna North-East.xls	Etna North-East Coord.xls
	South-West	Sept. 1980–Oct. 2007	Etna South-West.xls	Etna South-West Coord.xls
	South	Nov 1983–June 2005	Etna South.xls	Etna South Coord.xls
	North-East 2001 2002	2001 and 2002	Etna North-East 2001 2002.xls	Etna North-East Coord.xls
	South 2001 2002	2001 and 2002	Etna South 2001 2002.xls	Etna South Coord.xls
	Ionica	Oct. 1977–Mar. 1985	Etna Ionica.xls	Etna Ionica Coord.xls
Pantelleria	Pantelleria	Oct. 1979–Sept. 1997	Pantelleria.xls	Pantelleria Coord.xls

A significant contraction affected the upper westernmost baseline on the same day. This was interpreted as clear evidence that the dyke was very shallow and approaching the surface, also allowing to define the most probable position for the eruptive fissure. The eruption started later on the same day with a fissure crossing those extending baselines and eastwards of the shortening one.

2.2.3 Western network (Etna W)

The Western network (Etna W in Fig. 5), consisting of 16 benchmarks connected by 36 baselines, lies approximately between 1100 and 2000 m elevation and was first measured in September 1980.

Among the three areas covered by the EDM networks, this sector is the most stable and for this reason the most representative of the undisturbed recharge and discharge phases of the volcano, since it is not often affected by dyke intrusion (the last one was in 1974) and no eruption occurred here during

the years of EDM monitoring. Furthermore, the area covered by this network is not involved in the large-scale flank instability that affects the E and SE flanks (e.g., Bonaccorso et al. 2004; Bonforte et al. 2011). Inflation/deflation phases of Mt. Etna edifice are well-reflected in the deformation response of the western flank. Many studies have highlighted how the Mt. Etna eruptive phases were preceded by the recharge characterized by inflation and accompanied by deflation during the eruptions. These dynamics were soon observed from baseline changes and areal dilatation trends detected on Etna W EDM network (Bonaccorso and Aloisi 2021 and related references therein). Inflation/deflation cycles are the results of arrival and accumulation of new magma at depth, which allows inferring the deformation sources and their approximate locations of the storage, followed by its discharge during the eruptions.

The overall areal dilatation shows (Fig. 6b) the two inflation periods before the 1991–93 and 2001 eruptions and the

successive deflation periods, on occasion of the 1991–1993, 2001 and 2002–2003 flank eruptions.

2.2.4 Ionica network

The Ionica network was set up along the eastern edge of the volcano, over an elongated area extending from Catania to Taormina, at low altitude (between 700 m and sea level); it consisted of 19 benchmarks and 43 lines (Fig. 5), which were measured yearly from 1977 to May 1980. In this period the changes observed are generally within the instrumental error though a trend is detectable for several lines (Cannavò et al. 2016).

The aim of this network was to verify the possible relationships between the tectonic activity, highly evident in this area with the presence of numerous structures, and the volcanic activity. After the Zafferana and Fleri 1984 earthquakes, four measurement surveys were carried out in the period October 1984–March 1985 on the portion of the network covering the area affected by the events. Cannavò et al. (2016), by inverting these EDM data, found that in the period May 1980–October 1984, the Fiandaca Fault was affected by a strike-slip and normal dip-slip of about 20.4 and 12.7 cm, respectively. This result is consistent with field observations of the kinematics of the coseismic ground ruptures along the fault, but it is notably large compared to displacements estimated by seismicity, therefore suggesting that most of the slip over the fault plane was aseismic. Later on, in the 1990s, this network was partially included in a new one, surveyed by GPS technique (Puglisi et al. 2004; Bonforte and Puglisi 2006).

2.3 Stromboli

Stromboli is a composite active volcano rising 924 m a.s.l. and almost 3000 m above the seafloor, forming the northernmost island of the Aeolian Archipelago. It has a pyramidal shape and features a large depression, the Sciara del Fuoco, that marks its northwestern flank.

Three active craters are aligned along a SW–NE trend, not on the summit but on the upper part of the Sciara del Fuoco (SdF) slope, at about 750 m a.s.l.; their activity is characterized by an almost regular and continuous mild explosive activity, defined and known worldwide in volcanology as “Strombolian” activity, following the name of this volcano. One of the main volcanic hazards of Stromboli is due to the strongest paroxysmal episodes whose ballistic ejecta reach and destroy buildings in the villages lying on the E and W corners of the island, with incandescent scoria that also induce fires and can cause severe damage. Occasionally, flank eruptions start from vents opening on the outer side of the Crater Terrace, within the Sciara del Fuoco, and produce lava flows

that reach the sea, running down the slope as on December 28 2002.

On that occasion, two days after the onset of the eruption, on December 30 2002, two landslides also occurred on the northern part of the SdF. The landslides mobilized a mass in the order of tens of millions of cubic meters, both above and below sea level, also generating a tsunami with significant damage to the eastern coast of the island (Bonaccorso et al. 2009).

In order to evaluate the hazard of further or even larger slope failures of the SdF, during the initial days of the volcanic crisis some EDM arrays were set-up, installing three groups of benchmarks in different sectors of the SdF (Puglisi et al. 2005). The first was in the “Fossa” area, the part of Crater Terrace (Fig. 9), and consisted of five reflectors (identified as red stars); the second was a sub-network consisting of six reflectors (yellow stars), placed in the area of the niche of the December 30th landslide (“Sotto Bastimento”) on the upper part of the SdF and the third one, with eight reflectors, downwards along the SdF northern slope (cyan stars).

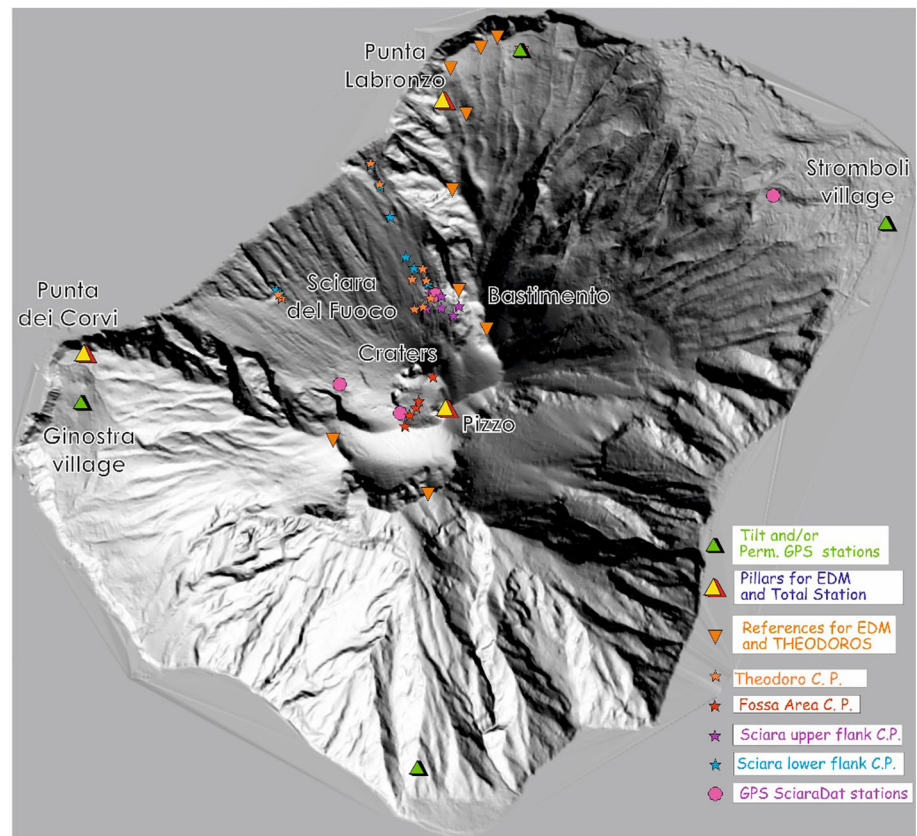
At the same time, four reflectors (BAST, SLF, FORT and VANC) were installed on the upper part of the volcano outside and around the upper part of the SdF area, on sites considered stable (Fig. 9), as control points for checking the stability of the measurements.

The benchmarks were measured (Table 1) from three different pillar points (Dark blue triangles in Fig. 9). In particular, the reflectors on the crater terrace were visible only from STR pillar above the craters; those on the SdF slope were visible from PLB as well as all those on “Sotto Bastimento”. Only a couple of benchmarks of this latter group were visible and measured from both STR and PLB pillars.

Daily monitoring of these networks allowed a prompt detection of any anomaly affecting the summit craters and SdF slope. Indeed, an irregular subsidence of the entire crater terrace was detected, accelerated by some deflation episodes accompanying the increase of lava effusion from the lateral vent or the opening of new vents (Aloisi et al. 2008). Results of measurements were in fact immediately communicated to civil protection authorities in order to take the most appropriate actions for hazard estimation and prevention. This was the case, for example, of a new vent opening that significantly displaced some reflectors on the Sotto Bastimento area. The dynamics of this phenomenon was accurately followed by EDM measurements, whose areal deformation pattern enabled excluding the failure of the SdF and clearly detected the location of the new intruding dyke (Bonforte et al. 2008).

Successively, a robotic monitoring system named THEODOROS (Bonforte et al. 2016) was installed, in order to routinely measure the motion of benchmarks.

Fig. 9 Ground deformation monitoring systems in the Sciara del Fuoco triangles mark the pillars where measurements were carried out and the benchmarks used as reference frames; stars mark the control points (C.P.) installed to monitor movements. The control points belonging to the different subnetworks are distinguished with different colors (from Puglisi et al. 2005)



THEODOROS was based on a remotely controlled robotized Total Station installed near Punta Labronzo, capable of routinely measuring horizontal and vertical angles and distances for each reflector in order to obtain 3D positions and displacements at each point. After 2003, the THEODOROS system was able to monitor with high temporal resolution the motion of the benchmarks along the SdF. This new automated system, in fact, performed routinely cycles of measurements on the reference stable benchmarks outside the Sciara del Fuoco every hour for calculating the atmospheric refractivity and every 30 min for defining the position and orientation of the instrument; every 20 min it measured the far stable Control Points for checking the stability of the measurements and every 10 min it measured the Monitoring Points inside the Sciara del Fuoco allowing a detailed reconstruction of the dynamics of this slope (Bonaccorso et al. 2009; Bonforte et al. 2016). From 2007, this automatic monitoring re-started with a new network configuration, because of the destruction of all the reflectors in the lower SdF after the lava flow erupted during the 2007 eruption (those on the crater terrace had been already destroyed by the paroxysm at the end of the 2002–2003 eruption, on April 5, 2003). After the 2007 eruption, a new array of benchmarks was installed on the lava fan formed by the flow entering the

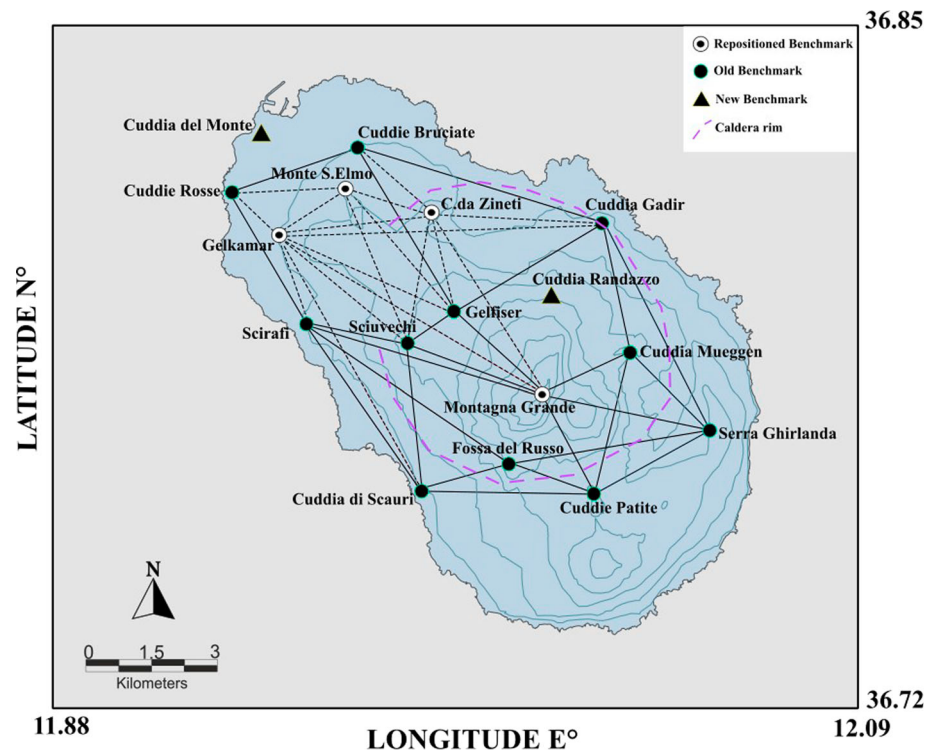
sea at the northern base of the SdF. This fan formed a huge bulge of lava lying on the very steep and incoherent slope of the SdF; the THEODOROS system continuously monitored the motion and deformation of this morphological element, allowing to detect the thermal contraction of the lava flow as its slow seaward movement. Details and results of the robotized monitoring system are reported in Puglisi et al. (2005), Bonaccorso et al. (2009) and Bonforte et al. (2016). Then, in 2014 a new eruption destroyed again the monitoring array in the Sciara del Fuoco and the system has not been re-deployed.

2.4 Pantelleria

Pantelleria island is the emerging part of a large Quaternary volcanic structure located along a tectonic trench (Pantelleria Graben) which extends in a NW–SE direction along the Sicily Channel (Rotolo et al. 2006) between Sicily and Tunisia.

The two most recent underwater eruptions (1831 eruption at Banco di Graham between Pantelleria and Sicily; eruption of the Foerstener volcano a few km NW of the island, 1891), together with the presence of thermal springs and fumaroles on the island, indicate that the magmatic system is still active.

Fig. 10 Pantelleria EDM network as installed and measured in 1979. The dashed lines were not re-measured in 1995 because of the lack of some benchmarks. The new repositioned benchmarks are also indicated (from Bonaccorso and Mattia 2000)



2.4.1 Pantelleria network

On Pantelleria Island, an EDM geodetic network (Fig. 10) was installed and measured in 1979 (Bonaccorso and Mattia 2000; Behncke et al. 2006). Originally, the network comprised 15 benchmarks connected to each other by 42 baselines and this configuration was re-measured in October 1980 and April 1982. The measurements revealed a contraction ranging between 1 and 2 cm, measured on most of the baselines. After more than a decade, the network was re-measured in 1995; at that time, some benchmarks were destroyed or covered by new man-made structures. The network was measured in this reduced configuration, with the 12 remaining benchmarks connected by 21 lines. On average, also this new survey revealed consistent contractions of between 3 and 10 cm, with respect to the initial measurements in 1979 (Bonaccorso and Mattia 2000).

The network was then updated with the reinstallation of the missing benchmarks, locating them nearby their former positions, and with the addition of two new benchmarks placed on the northern-western corner and in the central-eastern part of the island, respectively, which brought the configuration number up to 17 benchmarks, linked to each other by 48 connecting lines. In 1996, the GPS surveys began and replaced EDM measurements (Mattia et al. 2007).

By using EDM, leveling, GPS, and differential interferometry synthetic aperture radar data to constrain the inter-eruptive deformation pattern, Mattia et al. (2007) observed

subsidence affecting the main caldera of Pantelleria, in the central southern sector of the island. Subsidence was interpreted as mainly related to hydrothermal cooling and/or fluid withdrawal from a shallow (4 km below sea level) magma chamber located beneath the caldera.

Other studies based on the inverse correlation between the gravity and altimetric variations suggest that Pantelleria is kinematically divided in two blocks, the first to the north subsided and the second to the south uplifted and tilted toward NW, strongly influenced by the geodynamics of the Sicily Channel (Berrino and Capuano 1995; Berrino 1997, 1998). Moreover, integration of gravity and EDM data leads to conclude that the volcanism on the island is also probably closely influenced by the geodynamics of the Sicily Channel, and future eruptions are most likely to occur at the structural boundary separating the two blocks (Behncke et al. 2006).

3 Discussion and conclusions

Electronic distance measurements (EDM) technique is one of the first methods used to precisely measure ground deformation on volcanoes; repetition of leveling measurements enabled (and still does) the most precise detection of vertical deformation along routes, while EDM allowed measuring horizontal deformation over wide areas covered by geodetic networks and, coupled with triangulation, also to measure 3D displacements. Several networks have been realized on tens

of volcanic areas throughout the world, and the bibliography reports examples of detecting, monitoring and studying volume changes in magmatic (e.g., Ramirez-Ruiz et al. 2002; Stiros et al. 2003) and hydrothermal systems (Nakaboh et al. 2003), dome growth (Ratdomopurbo et al. 2013; Aoyama et al. 2009), magma conduit pressure changes (Jackson et al. 1998) or volcanic quiescence (Pingue et al. 2000).

On Sicilian volcanoes, EDM measurements have been performed since the early 1970s, collecting about 8,000 measurements covering the 1975–2009 period. EDM signals at Sicilian volcanoes have enabled monitoring and studying a broad spectrum of processes from quiescent to very active volcanoes. These include, for instance, measuring the edifice inflation/deflation and modeling relative to magmatic and hydrothermal sources (e.g., Bonaccorso and Aloisi 2021; Bonaccorso and Mattia 2000; Gambino and Guglielmino 2008), magma dyke intrusion (e.g., Bonaccorso 1999), fracture opening (e.g., Bonaccorso and Davis 1993), flank sliding processes (e.g., Alparone et al. 2013), crater rim thermal expansion and instability (Bonaccorso et al. 2010), volcano-tectonics (Alparone et al. 2013) or fault dynamics (e.g., Cannavò et al. 2016).

Many results have been obtained by modeling the EDM data or coupling EDM with other data (GNSS, tilt, InSAR, leveling), which have provided insights into the geometry and depth of ground deformation sources.

Even though measurements were generally repeated yearly, during emergency periods their frequency was also increased to daily; in several cases, EDM data have been crucial in defining the evolution of the volcanic activity, for instance during the 1989 and July 2001 eruptions on Mt. Etna, and to monitor the hazard evolution during the unrest of Vulcano in the 1990s and of the dynamics of the Sciara Del Fuoco during the Stromboli 2002–03 eruption.

This kind of experience has opened the way for the volcano-geodesy method for studying and imaging the volcanic systems and structures. Now, thanks also to these pioneering applications, volcano-geodesy is currently one of the main disciplines for volcano monitoring, also for forecasting eruptions. Recent examples include the 2018 eruption on Kilauea, as well as the 2014 Bardarbunga eruption and the 2021 and 2022 eruptions in the Reykjanes peninsula in Iceland (Patrick et al. 2020; Sigmundsson et al. 2022), whose dyke intrusions leading to the eruptions were accurately imaged and followed by ground deformation data. In this work, we also reported the early cases of the unpublished data for the 2001 eruption on Etna and the 2003 event at Stromboli volcano, well-detected and followed by EDM measurements.

In conclusion, this paper summarizes and publishes all EDM data recorded on Sicilian volcanoes and summarizes the experiences gained in the 1970s to early 2000s, which are the basis of subsequent developments through the use

of the most recent and advanced monitoring and analyses techniques.

Appendix: Data records description

Data collected and described in this work and now made publicly available on the Zenodo Repository (<https://doi.org/10.5281/zenodo.7024686>) include thousands of electronic distance measurements collected from 1975 to 2009. These measurements have been organized on Microsoft Excel files and each file reports the network name (Table 1). Inside each file, there are two sheets, the first reporting all measured distances, the second associated errors. Rows show the measurement date, the instrument model and recorded values; in the first column, the pairs of benchmarks considered are reported.

The location of each benchmark is reported on specific coordinate network files (Table 1). All the coordinates have been obtained by using GPS technique, except for the Ionica network where they have been derived from printed maps (1:10,000) and therefore with a certain approximation.

The networks Etna S and Etna NE have additional sheets, reporting the most frequent measurements taken during the eruptive crises of July 2001 (onset of 2001 eruption) and of October 2002 (onset of the 2002–03 eruption). All these data are reported in specific files (Table 1).

Almost all networks were measured using both the AGA6BL and the AGA 6000 Geodimeters. Inside the tables, the surveys in which the transition from one instrument to the other took place are highlighted; in those surveys, measurements were performed with both instruments in order to maintain the time-series continuity. Furthermore, 'double' measurements in the tables related also to reflectors changes or new benchmarks have been observed.

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Author contribution A.B. and R.V. participated in the data collection in the field, data processing and interpretation; A.B. was the responsible for the surveys in the last years; S.G. and L.P. organized the data for this work; all authors contributed to the writing of the manuscript.

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Data availability Data provided along with this work are made publicly available to the scientific community as supplementary material.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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