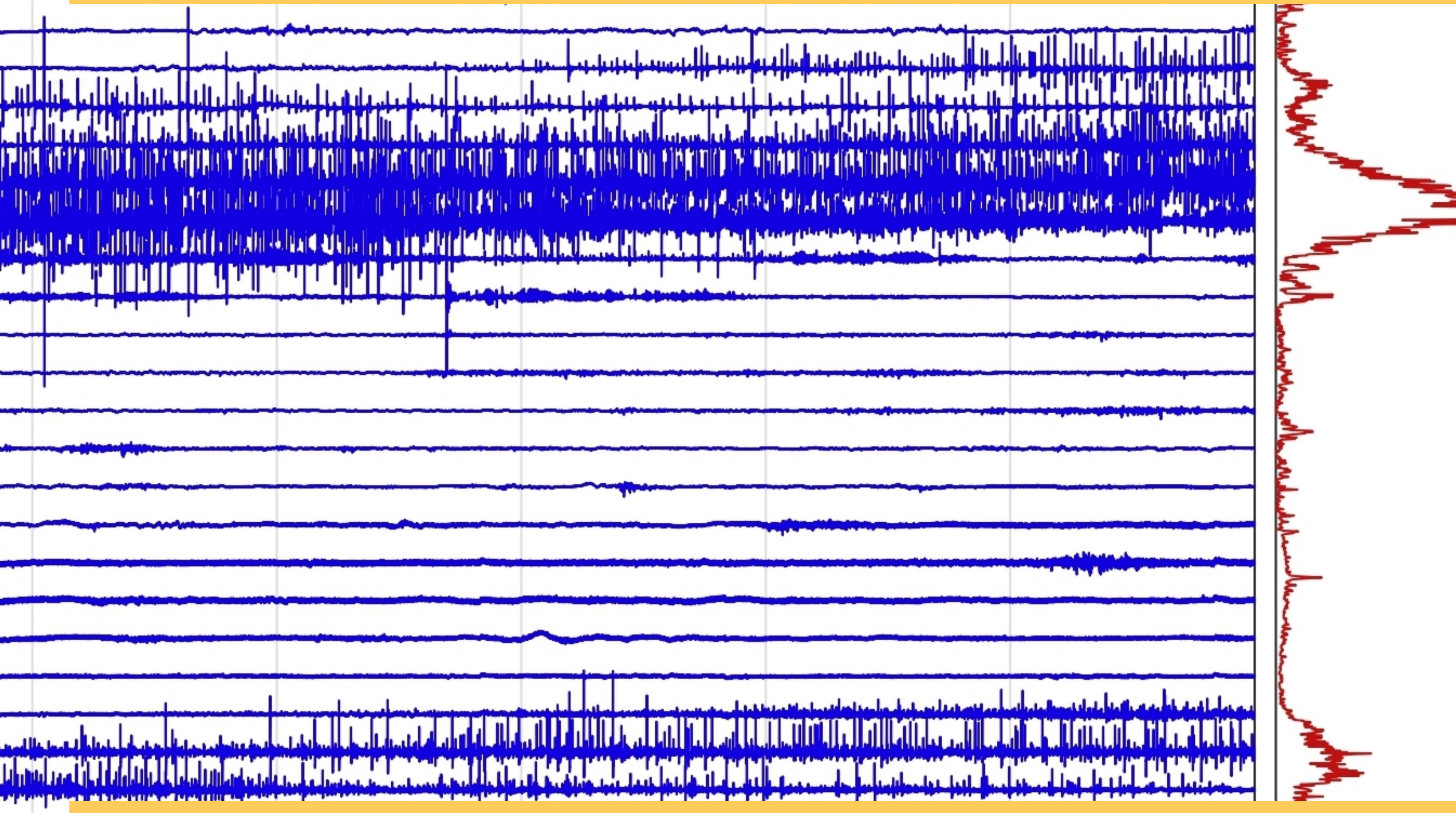
ISSN 2039-7941
anno 2025 numero 490



RAPPORTI TECNICI INGV

Testing infrasound array technology for monitoring eruptive activity at Mt. Etna, Italy

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

490

REGISTRAZIONE AL TRIBUNALE DI ROMA N.174 | 2014, 23 LUGLIO

Sede: Via di Vigna Murata, 605 | Roma

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Testing infrasound array technology for monitoring eruptive activity at Mt. Etna, Italy

Luciano Zuccarello*[1,2], Silvio De Angelis[2,1], Mariangela Sciotto[3], Salvatore Rapisarda[3], Luciano Scuderi[3], Marco Sassano[3], Alessio Rubonello[3], Damiano Biagini[1]

[1]INGV | Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Italy
[2]School of Environmental Sciences, University of Liverpool, 4 Brownlow Street, L69 3GP, Liverpool, UK
[3]INGV | Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Italy

**Corresponding author*

Accepted 12 December 2024 | *Accettato 12 dicembre 2024*
How to cite | *Come citare* Zuccarello L., De Angelis S., Sciotto M., Rapisarda S., Scuderi L., Sassano M., Rubonello A., Biagini D., (2025). Testing infrasound array technology for monitoring eruptive activity at Mt. Etna, Italy. Rapp. Tec. INGV, 490: 1-24, https://doi.org/10.13127/rpt/490

Cover Detail of an example helicorder plots of infrasonic waveforms

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Abstract

Several studies have highlighted that infrasound is a powerful tool for volcano monitoring and holds promise to improve our understanding of volcano unrest and eruptive processes. As such, infrasound sensors are routinely deployed at active volcanoes, typically co-located with seismometer networks. Recent studies have demonstrated the value of deploying infrasound sensors in array configuration (clusters of few sensors at interstation of up a few tens of meters) at distances up to a few kilometers from active volcanic vents. Arrays provide a powerful tool for real-time detection and tracking the time evolution of eruptive activity, and can deliver real-time estimates of eruption intensity. Here, we report the results of extensive testing of a 6-element infrasound array at Mt. Etna, Italy. The key objectives of the deployment were to assess the suitability of the chosen array location and configuration for future operational use at Mt. Etna, and evaluate its ability to provide a real-time assessment of eruption occurrence, location and intensity. The array was deployed between May 2021 and April 2022, during a period of intense activity and continuous eruption, characterized by frequent occurrence of paroxysmal activity. The array was deployed near to a permanent seismic station (EMNC) operated by the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV) at the site *Monte Conca*, approximately 6 km from the South-East crater, the most active during the study period. The installation was optimized for maintenance-free deployment, throughout the snowy winter season, including a custom-made instrument housing and a dedicated solar power system. All data collected were processed with a slowness inversion algorithm; the results of these analyses demonstrated the ability of the array to detect the onset of eruptive activity and track its evolution, and to discriminate multiple active vents within the summit area at Mt. Etna. We conclude that the *Monte Conca* site is suitable for future deployment of a real-time, permanent, infrasound array, and the proposed configuration delivers satisfactory performances in terms of location uncertainty. This temporary deployment was supported by a collaboration between INGV *Sezione di Pisa (PI)* and *Osservatorio Etneo (OE)*, and the University of Liverpool (UK).

Keywords Infrasound array; Volcano monitoring; Etna Volcano

Introduction

Mt. Etna is one of the most active volcanoes on the globe. During the last two decades Etna has shown frequent and vigorous, eruptive activity accompanied by the emplacement of extensive lava flows and vigorous ash emissions. Eruptive activity at Etna is continuously monitored by the OE with a modern instrument network, recording seismic, acoustic, deformation, gas and other ground-based remote sensing data. The frequent activity at Mt. Etna offers an ideal opportunity to investigate the suitability of infrasound arrays for real-time eruption detection and tracking, as well as to test models that link the occurrence of acoustic signals to the injection of volcanic ash in the atmosphere [e.g., De Angelis et al., 2019; 2020; 2021; 2023]. However, testing equipment during temporary, long-term (i.e., several months) instrument deployments at Etna poses challenges, one of these includes limited access for equipment maintenance during the winter months, when the snow cover can reach up to a few meters, thus severely reducing road access to many locations. To overcome this issue, the technical team of OE and PI in collaboration with the University of Liverpool, developed a custom-made instrument housing and solar power system, with the aim to preserve equipment functionality for long-term acquisition. In this report we describe the installation of a 6-element infrasound array at the *Monte Conca* site (CONC, Figure 1a) and show data examples recorded during the 12-months deployment. The array, deployed in proximity to the permanent INGV-OE seismic station EMCN, was operational during a period of continuous eruption and captured several episodes of paroxysmal activity. We demonstrate that the site and configuration chosen for the infrasound array allow continuous detection and location of explosive activity, and can discriminate eruption and degassing from multiple summit vents at Etna [De Angelis et al., 2023].

1. Seismic and infrasound monitoring at Mt. Etna

In recent decades, infrasound has increasingly been used to investigate magma dynamics at active volcanoes, especially at open-vent volcanoes as Mt. Etna and Stromboli [e.g., Braun and Ripepe, 1993; De Angelis et al., 2021; Sciotto et al., 2022]. On 1993, the Department of Earth Sciences of the University of Florence deployed the first infrasound stations at Stromboli [Ripepe and Gordeev, 1999], giving an acceleration towards infrasound Stromboli volcano monitoring. On Etna the first infrasound permanent network of four stations was installed on 2005, joining with the seismic permanent network. Several researchers have demonstrated the benefits of integrating infrasound sensors into local seismic networks installed on the volcano edifice. These infrasound deployments enhance signal beamforming and help to distinguish activity at various volcanic vents from unrelated noise or external infrasound sources [e.g., De Angelis et al., 2023, Cannata et al., 2009a; Cannata et al., 2009b; Marchetti et al., 2009; Montalto et al., 2010; Ripepe and Marchetti, 2002; Ripepe et al., 2007].
Nowadays, Mt. Etna is monitored by OE, by a network of 28 seismometers used to define a level-of-concern color code and transmit eruption warnings to the Italian Civil Aviation Authority and the Department of Civil Protection. A well-calibrated alert system monitors the RMS-amplitude (Root Mean Square) of seismic tremor to pre-alert the authorities of the likely occurrence of paroxysmal activity [e.g. Ripepe et al., 2018]. Long-term monitoring of Mt Etna's volcanic unrest by INGV-OE also makes use of the location of seismic tremor, whose signal characteristics depend on the volcanic activity (degassing, magma migration at depth, effusive and explosive activity [e.g., Di Grazia et al., 2006; Carbone et al., 2008; 2015; Zuccarello et al., 2013; 2022]). Furthermore, INGV-OE operates a network of 10 infrasound sensors, which are installed at some of the seismic stations, allowing automatic detection and location of discrete explosive activity. Since 2015 the *Laboratorio di Geofisica Sperimentale of the University of Firenze* (LGS) also operates two, 4-element, infrasound arrays at Mt. Etna [Ripepe et al., 2018], used to inform a volcano Early Warning System (EWS) adopted by the Italian Civil Protection during eruption response [Alparone et al., 2007].

2. Temporary infrasound array at Monte Conca

The infrasound array installed at the CONC site (*Monte Conca*) was the first deployed by INGV to monitor activity at Mt. Etna; the objective of this deployment was conducting an extensive test of this technology before its adoption by OE as part of their volcano monitoring mission.
A 5-element array was initially deployed at the CONC site (Figure 1a) on Mt. Etna on May 19, 2021, by a pool of technicians and researchers from PI and OE, and the University of Liverpool (UK), within the framework of project SINFONIA (*Progetto Bando Ricerca Libera 2021- Delibera 214/2021-INGV*) [1]. On July 16, the installation of the sixth array element completed the planned 6-element configuration shown in Figure 1b.

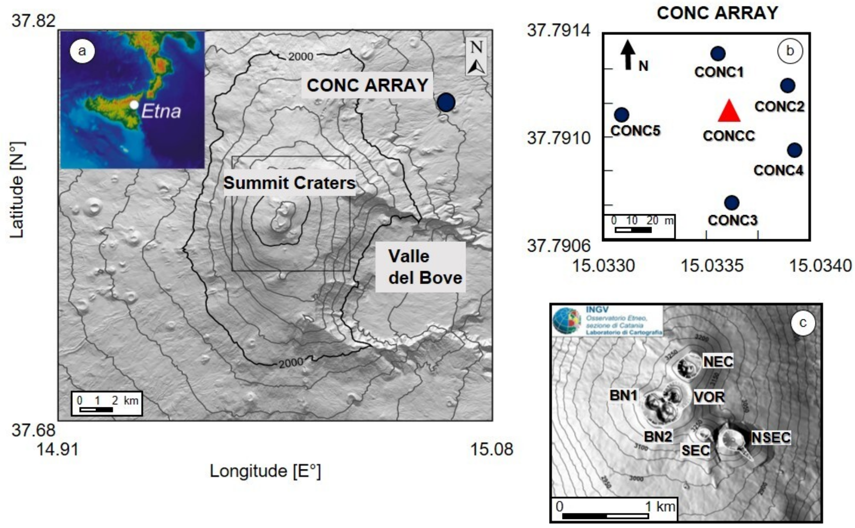

Figure 1 a) Map of Mt. Etna showing the location of infrasound array CONC. The left upper corner shows the location of the Mt. Etna National park, Italy. b) Configuration of the infrasound array; each dot represents the location of one infrasound sensor. The red triangle symbolizes the central node of the array. c) Detail of the summit craters at Etna.

The geometry of the array consisted of a central element, installed at the seismic station EMCN (OE), surrounded by 5 sensors positioned approximately at the vertices of a pentagon, with an aperture of approximately 70 meters (Figure 1b). The location of the array and of each individual node were chosen according to three main criteria: i) site accessibility and safety of personnel; ii) minimizing differences in elevation between sensors within the array; iii) optimizing the detection and discrimination of activity from all summit craters. Table 1 provides the locations for all elements of the CONC array.

Array Monte Conca	Latitude (°)	Longitude (°)	Altitude (m)
CONC1	37.79131	15.03355	1869
CONC2	37.79119	15.03388	1864
CONC3	37.79073	15.03362	1883
CONC4	37.79095	15.03392	1875
CONC5	37.79108	15.03307	1876
CONCC	37.79109	15.03358	1865

Table 1 Geographical coordinates of the infrasonic sensors deployed at *Monte Conca* array site.

Array methods are based on a common waveform model of the signal [e.g., Aki e Richards, 1980]. All array elements should record the same waveform with the exception of a delay time related to the acoustic wavefield propagation across the array and very small variations linked to site-specific noise conditions. The quality of the output of array analysis depends on the number of array nodes, the array aperture and configuration, and the contribution of spatial aliasing. The array response function is a theoretical tool to assess the frequency range in which the results of the analysis can be considered reliable. Consequently, we evaluated the so-called array response function using a modified version of the Beam Pattern relationship [Capon, 1969]:

$$B(S,w) = \frac{1}{M}\sum_{i=1}^{M} e^{iw\mathrm{Sx}_i}. \qquad (1)$$

For a given slowness and angular frequency, the function B (S, w) depends on only the node positions, and it returns the array response of a monochromatic plane wave with a central peak of unit amplitude and many secondary peaks at different locations in the slowness space. When the amplitude of the secondary peaks is much smaller than the central one, the spatial aliasing is negligible. Results indicated the contribution of spatial aliasing in the array response

(Figure 2) at frequencies higher than 5 Hz, outside the dominant range of frequencies of interest at Mt. Etna (i.e., 0.5-5 Hz).

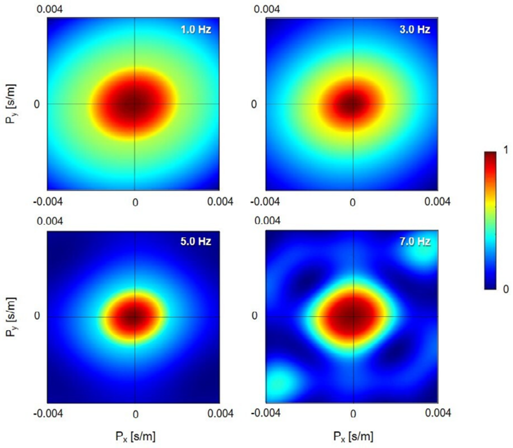

Figure 2 Array response functions at 1.0, 3.0, 5.0 and 7.0 Hz; the colorbar on the right-hand side refers to the normalized values of the Beam Pattern function.

3. Instrument characteristics and technical validation

The CONC array was equipped with 6 IST-2018 broadband infrasound sensors manufactured by ISTerre, Université Savoie Mont Blanc, France. These sensors are optimized for detection and analysis of the infrasound wavefield recorded on volcanoes. Their compact dimensions (26 mm x 45 mm x 80 mm) and their low weight (100 g) make these infrasound sensors easy to deploy and to handle. In addition, the low power consumption of 42 mW (3.5mA at 12V), allows deployment even with a relatively basic solar power system. The IST-2018 technology is based on a robust and low-cost micro-electromechanical differential pressure transducer (MEMS). Once an atmospheric perturbation, characterized by noise level less than 0.05 Pa at frequency values higher than 60 mHz, triggers the infrasound sensors, this pressure variation produces changes in the piezo-electric elements of the MEMS, inducing an electrical variation measured by a "Wheatstone bridge" inside the electronic circuit [Grangeon and Lesage, 2019]. Figure 3 shows the amplitude frequency response of the infrasound sensor (Figure 3a) and an image of the infrasound sensor (Figure 3b); Table 2 summarizes the technical characteristics of the IST-2018 sensor.

These sensors are already calibrated by the manufacturer, but before deployment at Mt. Etna, they were additionally tested in the field versus high-quality infrasound sensors. The manufacturer calibrates all sensors using a comparative approach to obtain both the transfer function and the sensitivity of the IST-2018; a vibrating platform is used to compare the IST-2018 sensors with a reference Martec MB2005 micro-barometer at lower frequencies, and a GRAS 40AE-sensor at higher frequencies. The details of the calibration procedures are reported in Grangeon and Lesage [2019]. The University of Liverpool and the manufacturer have additionally tested the instrument during a field experiment at Sabancava Volcano, Peru alongside Chaparral Model 60 UHP sensors, with exceptional conformity between the two in terms of waveforms, signal amplitudes and spectra [Grangeon and Lesage, 2019].

The output of the CONC infrasound sensor was sampled at 100 Hz using DIGOS DATA-CUBE[3] (Figure 4) digital data recorders [2]. DATA-CUBE[3] recorders have an effective resolution of 22.4 bit (at 100 Hz), and a GPS timing accuracy of 1 µs. Some of the technical characteristics of the DATA-CUBE[3] digitizers are reported in Table 3. We have chosen this type of instrument for its low self-noise, and power consumption and the advantageous cost-value ratio. The stations were designed to work in extreme environmental conditions [3].

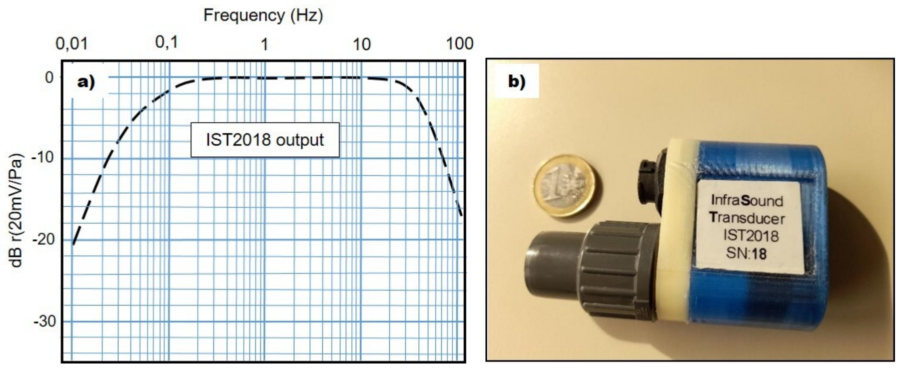

Figure 3 a) IST2018 Amplitude frequency response and b) photograph of an IST2018 infrasound transducer used for the CONC array.

IS output	
Frequency range	60 mHz – 40 Hz
Sensitivity	20 mVPa^{-1}
Dynamic range	> 80 dB
Amplitude range	± 240 Pa
Background noise (0.06-40 Hz)	< 0.05 Pa RMS

Table 2 Technical features of the IST-2018 infrasound transducer.

Figure 4 The digital data recorders DATA-CUBE³ [2].

DIGOS DATA-CUBE³	
Data Storage	Buffered Mode
Channel	3 channels
Sample Rate (Hz)	100
Storage	Compact Flash 32 GB
Nominal Sensitivity (cnt / µV)	1 (with gain = 1)
Hardware and Software Gain (ch 1,2,3)	1
Digitizer Resolution (bit)	24
Input Range (Vref)	16 Vpp
Dynamic Range	> 138 dB (at 100 Hz)
Input Impedance (kΩ)	43.07 (low impedance)

Table 3 Datasheet of the main technical specification of the DATA-CUBE³.

Before deployment, all infrasound stations were simultaneously tested (huddle test) at INGV-OE in Catania (Figure 5a) to ensure their correct operation mode, and the consistency of the instrument responses, using a custom-made structure that exploits the movement of the lab door to create pressure variations. In Figure 5b we show an example of the waveforms recorded during these tests using a calibrated impulsive source.

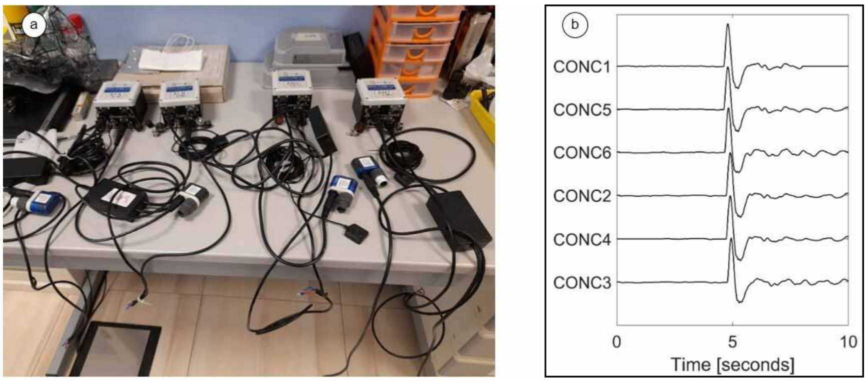

Figure 5 a) DATA-CUBE[3] equipped with IST2018 infrasound sensor during the huddle test of the equipment in the INGV laboratory. b) Example of waveforms (normalize amplitude) recorded by all the IST2018 infrasound sensors during the laboratory test.

4. Description of the custom-made instrument housing

The main challenge of our deployment was to implement a prototype of installation that allowed the instruments to operate continuously during the winter season. To guarantee array operation, the technical team at INGV-OE and the University of Liverpool designed a custom-made equipment housing. The installation consisted of a hard plastic box containing a sensor, a digitizer and a 12V/52Ah, battery (Figures 6 and 7); one 80W solar panel was positioned on top of the box (Figures 7 and 8) to maintain battery voltage above the required 9V to power the station. At each node, the infrasound sensor was positioned inside the box and equipped with a mechanical filter system (Figure 7) to reduce wind noise. The waterproof, hard-plastic box was thermally insulated using 5cm-thick sheets of polystyrene (Figure 7). To protect the infrasonic sensors, stainless steel mesh guards were employed, secured with specialized adhesive to ensure a proper hermetic seal, connecting to the box and the sensor via PVC tubing. Inside each steel guard, an open-cell polyurethane wind filter was placed; this foam cover protects the microphone from wind interference and humidity, maintaining cleanliness and efficiency in the frequency range of the infrasonic signals being measured. Taking into account the energy needs for each infrasonic station, it was determined to power them with a 12 V/52 Ah battery and an 80 W solar panel. Each panel was secured to the station box using two steel springs, providing effective damping against oscillations during strong winds. This setup ensured adequate power throughout the winter months and minimized the stations' visibility, thereby reducing their environmental impact in the mountainous region. Additionally, it made them less conspicuous from a distance, deterring any potential vandalism.

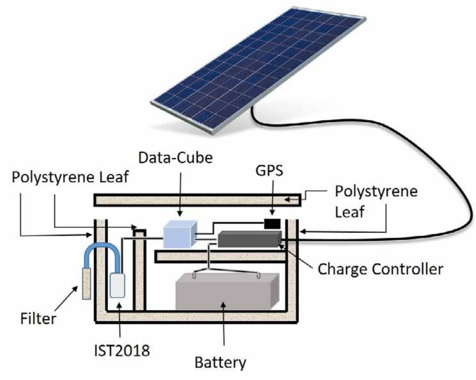

Figure 6 Cartoon of the custom-made box designed for infrasound installation at Mt. Etna.

Figure 7 Images of the custom-made housing for instrument deployment. Note the housing thermal insulation and spring anchoring system of the solar panels to the box.

Figure 8 Images of the stations under the snow during the array decommissioning at the end of March 2022. The two central photos show the solar panel (CONC5 station) damaged by the snow load during the winter.

5. Overall dataset quality and availability

Here, we illustrate the data recovery statistics (Figure 9) and the satisfactory performances of the CONC multi-channel array deployment. The array was operational from May 19, 2021 to April 02, 2022, when the thick snow cover prevented correct functioning of the power supply (Figure 8). Data recovery for this time period was 100% at all array elements but the CONC2 node, which was periodically affected by datalogger malfunctioning (Figure 8), and CONC5 that operated until the first week of February 2022, when the snow damaged the solar panel, cutting off the station’s power supply (Figure 8). All other minor data gaps visible in Figure 8 correspond to periods of equipment maintenance (i.e, periodic data download). The complete dataset recovered, including the continuous raw waveform data and station metadata, will be available through community data repositories [Zuccarello and De Angelis, 2019; Zuccarello et al., 2021] such as (i) the Incorporated Research Institutions for Seismology Data Management Center and the (ii) Zenodo and/or FigShare free access remote data products repositories [4] [5] [6].

In addition, all processing results and products obtained, will be available to the scientific community according to the protocols described in *"Principi della Politica dei Dati INGV"* (delibera CDA n. 651/2018; Allegato U al Verbale n. 05 I 2018) [7].

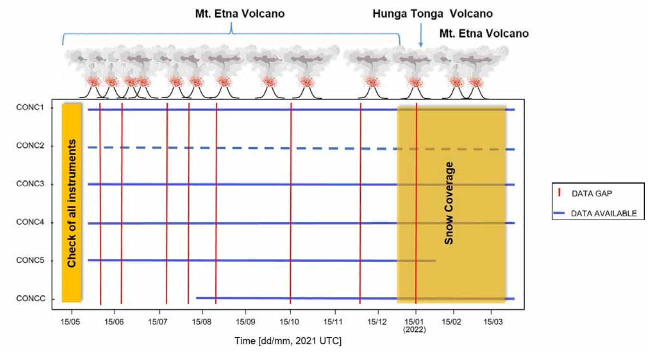

Figure 9 Scheme of infrasonic data availability for the CONC array.

6. Activity at Mt. Etna between 2020-2022

Mt. Etna is one of the most active volcanoes on the globe, exhibiting persistent degassing activity from its summit craters and frequent summit and flank eruptions [e.g., Andronico et al., 2021; Corsaro et al., 2017 and references therein]. In recent years volcanic activity at Etna has occurred across several craters in the summit area. The summit area of Mt. Etna includes five craters (Figure 1c): the Southeast Crater (SEC), the New Southeast Crater (NSEC), Bocca Nuova (BN), Voragine (VOR), and the Northeast Crater (NEC). The period under investigation was characterized by both explosive (i.e., Strombolian and lava fountain) and effusive activity occurring between BN and SEC/NSEC. A new period of intense eruptive activity at Mt. Etna had started in November 2020, with variable Strombolian activity, discontinuous ash emissions and degassing activity across the summit craters. Eruptive activity intensified on 13 December, 2020, when a period of more than 60 paroxysms started. The Mt. Etna, monitoring service identified a recurring pattern for the paroxysmal eruptions. The initial stage of each paroxysm was usually marked by the occurrence of discrete Strombolian activity, later evolving into sustained lava fountaining with associated ash plumes; some of the ash plumes reached up to 10 km elevation above the vent and spread across tens of km affecting numerous towns in the East direction. The end of paroxysmal activity was typically marked by a gradual waning of the lava fountaining activity and a transition to passive degassing, at times accompanied by lava flows [8]. During the deployment of the CONC infrasound array, we recorded more than 30 paroxysms. In addition, the array recorded pressure waves associated with the large submarine eruption that occurred on Hunga Tonga (Tonga Island) on January 14, 2022. In table 4 we report a schematic report of the eruptive activity that occurred during the period in which the array was installed.

Number of Paroxysm	Date of the Paroxysmal event	Start activity (hh:mm) UTC	End of activity (hh:mm) UTC
20	19 May	01:15	05:15
21	21 May	01:05	02:55
22	22 May	20:40	22:40
23	24 May	20:25	03:00 (25/05)
24	25 May	18:20	19:35
25	26 May	01:55	03:50
26	26 May	10:35	11:30
27	27 May	no data	no data
28	28 May	06:47	07:25
29	28 May	15:40	16:15
30	28 May	20:07	20:50
31	30 May	04:40	05:45
32	02 June	08:30	10:45
33	04 June	16:05	17:30
34	12 June	13:50	23:15
35	14 June	21:35	22:45
36	16 June	11:50	12:50
37	17–18 June	20:20 (17/06)	00:10 (18/06)
38	19 June	18:30	20:20
39	20–21 June	22:15 (20/06)	00:15 (21/06)
40	22 June	02:55	04:15
41	23 June	02:15	03:20
42	23 June	18:00	19:00
43	24 June	09:55	10:45
44	25 June	01:00	01:50
45	25 June	18:25	19:15
46	26 June	15:50	17:00
47	27 June	08:25	09:48
48	28 June	15:00	15:30
49	01–02 July	22:50 (01/07)	00:50 (02/07)
50	04 July	15:25	17:00
51	06–07 July	22:30 (06-07)	00:20 (07/07)
52	08 July	20:45	22:50
53	14 July	10:40	12:30
54	20 July	05:50	08:48
55	31 July	19:15	23:30
56	08–09 August	23:10 (08/08)	04:00 (09/08)
57	29 August	15:45	20:40
58	21 September	07:55	09:30
59	23 October	08:45	10:20
60	10 February (2022)	03:30	22:00
61	21 February	10:40	18:00

Table 4 Summary of part of the main Mt. Etna paroxysms between May 2021 and April 2022. Data available from Bollettini INGV-OE [2021; 2022], and from Proietti et al. [2023].

7. Examples of infrasound signals in the dataset

During the first week of array operation, we performed initial quality control analyses to confirm the correct operation of our deployment. The data showed the occurrence of continuous infrasonic tremor with varying characteristics. Acoustic tremor could be separated into two types: 1) continuous non-eruptive, with generally small amplitudes, and 2) pre- and syn-eruptive, associated with paroxysmal activity, typically made up of several overlapping events (discrete explosion signals) eventually coalescing into a continuous waveform with increasing amplitude over the duration of a paroxysm (Figure 10). In Figure 10b we show the Root Mean Square (RMS) amplitude of the infrasonic signal calculated from filtered data (0.5-5Hz, Butterworth, 2-pole) over 10-minute non-overlapping windows. The largest RMS values were achieved during Strombolian explosions and lava fountain activity in the SEC/NSEC area as also confirmed by INGV-OE official activity reports [8].

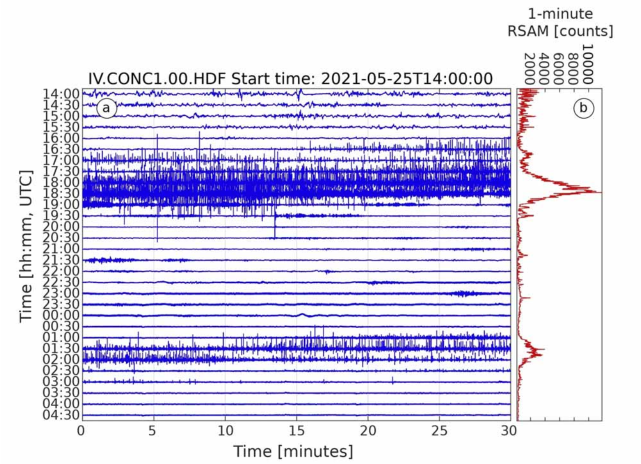

Figure 10 An example helicorder plots of infrasonic waveforms at CONC array, during a lava fountain episode occurred on May 25, 2021. Root Mean Square amplitude of the infrasonic waveform acquired at CONC1 array node, during lava fountain episode occurred on May 25, 2021.

In Figure 11 we show an example of a sequence of infrasound event waveforms recorded at CONC1 station associated with discrete Strombolian explosions.

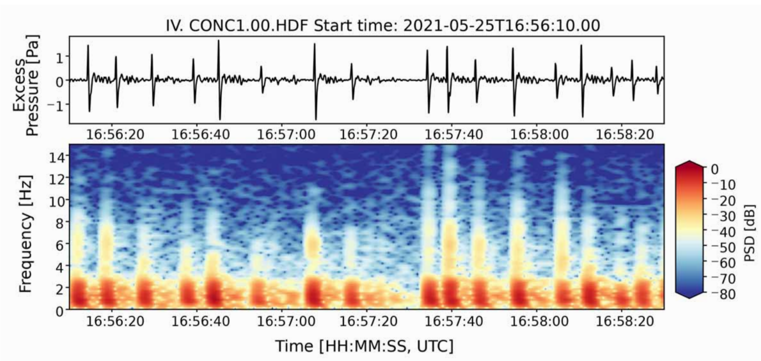

Figure 11 Spectrogram (top panel) and waveform (bottom panel) associated with a sequence of strombolian explosions on May 25, 2021.

Finally, to evaluate the capably of the array to constrain the source(s) location of infrasonic tremor, array processing was conducted to generate time series of Direction of Arrival (DOA, or the so-called" backazimuth") through slowness inversion [e.g., De Angelis et al., 2020; Zuccarello

et al., 2022], utilizing the Fast Least Trimmed Square (FLTS) estimator outlined in Bishop et al. [2020]. This algorithm was selected for its capability to handle anomalous travel-time observations within the array, particularly when deviations from the assumption of a planar wavefront occurred. The infrasonic data were pre-processed in 10-minute intervals, applying a 10% cosine taper and a Butterworth band-pass filter (2-pole) in the frequency range of 1.0 to 3.0 Hz. This frequency range was chosen to capture the predominant energy of tremor (Figure 2b) while reducing aliasing effects from the array response at higher frequencies (see chapter 2). Slowness inversion was executed for each 10-minute segment over 20-second windows with a 50% overlap. Only locations with a maximum multi-channel cross-correlation of 0.75 were plotted (Figure 12a).
Array processing revealed multiple, spatially distinct, sources. Based on the DOA time series (Figure l2c) we identified two different sources in the BN/VOR and SEC/NSEC areas.

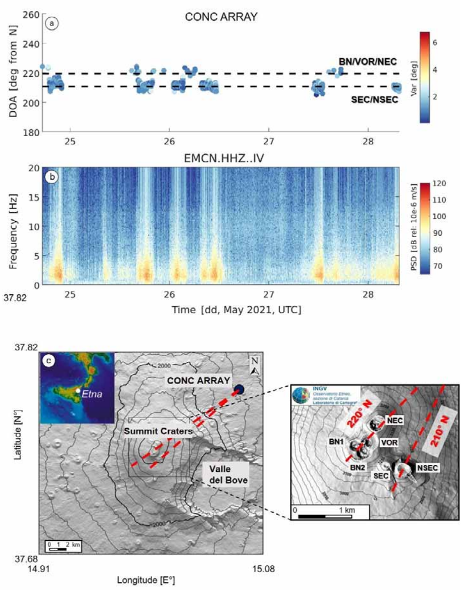

Figure 12 a) Infrasound array locations and b) spectrogram of the infrasound record at the *Monte Conca* site; c) location of the CONC array with respect to the summit of Mt. Etna and directions (red dotted lines) to the different summit craters.

8. Conclusive remarks

In this report we have presented the result of a proof-of-concept infrasound array experiment at Mt. Etna. The objective of the deployment was to test the feasibility and characteristics of infrasound array deployments at Mt. Etna to detect and track background and eruptive activity at the volcano. We successfully installed a 6-element infrasound array at about 1800 m a.s.l. recovering a rich dataset during periods of paroxysmal activity at Mt. Etna in 2021. The deployment was successful even in adverse weather conditions, in particular during winter period, a particularly challenging season for temporary installations owing to persistent high wind and snow coverage. The simple and robust style of installation allowed retrieving continuous infrasound data during May 2021-April 2022, and provided an unprecedented record to allow further investigation of degassing and eruptive activity at Mt. Etna.
This experiment allowed to successfully test the performance of infrasound array processing workflows to inform and optimize future deployments of acoustic sensor arrays for real-time volcano monitoring by OE. At the time of this writing, OE is completing the installation of a new 4-element infrasound array at the site *Monte Serra Pizzuta Galvarina* (southern flank of Etna). The initial deployment is being tested with the same methodology explored during our experiment and we envision implementing our processing algorithms into the real-time data processing workflow in collaboration with OE.

Acknowledgments

L. Zuccarello, S. De Angelis, M. Sciotto and S. Rapisarda are supported by the project SINFONIA, progetto Bando Ricerca Libera 2021- Delibera 214/2021-INGV, and by grant "Progetto INGV Pianeta Dinamico" - Sub-project VT_DYNAMO 2023 - code CUP D53J19000170001 - funded by Italian Ministry MIUR ("Fondo Finalizzato al rilancio degli investimenti delle amministrazioni centrali dello Stato e allo sviluppo del Paese", legge 145/2018). S. De Angelis is supported by NERC grant NE/W004771/1.

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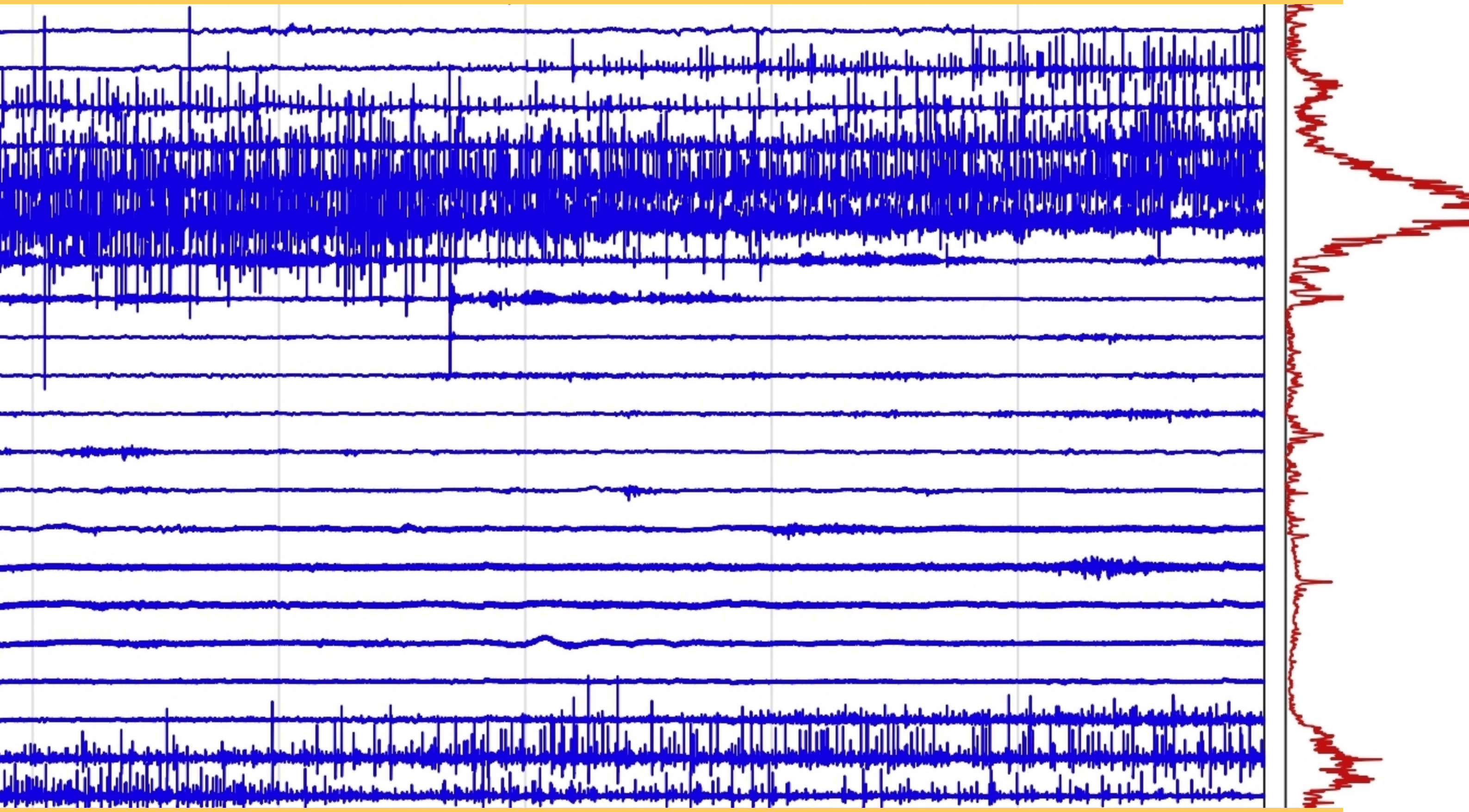

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