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The use of a low-cost, small-aperture array as an auxiliary tool to improve infrasound monitoring in the Azores region

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Abstract—The 2022's seismo-volcanic crisis on São Jorge Island of the Azores archipelago has provided an opportunity to deploy a portable infrasound array as a collaborative work between the Research Institute for Volcanology and Risk Assessment (IVAR) of the University of the Azores (UAc) and the University of Florence (UniFI). The four-element array, SJ1, became operational on 2 April 2022. Despite being deployed in a first stage to monitor the activities related to the volcanic unrest on São Jorge Island, SJ1 worked as a supporting tool to the existing IMS infrasound station IS42, located on Graciosa Island at $\sim$ 40 km distance, leading to an enhancement of the infrasonic monitoring network in the region. This work emphasises the importance of low-cost portable infrasound arrays to improve the coverage of infrasound observations for local and regional monitoring purposes in the Azores region. Two events recorded by both arrays are briefly exemplified: a low-magnitude earthquake on São Jorge Island and a fireball which crossed the North Atlantic Ocean. Infrasound data from both arrays are combined to obtain a fast but still accurate source localization of the analysed events.

Keywords: Infrasound, infrasonic monitoring, low-cost array, IMS, seismo-volcanic crisis, fireballs.

1. Introduction

1.1. Infrasound and infrasonic array processing

Infrasound is low frequency (< 20 Hz) sound consisting of longitudinal pressure waves propagating in the atmosphere at the speed of sound (340 m/s at ground level and 25 °C). It is produced by any natural or man-made processes capable of generating a pressure disturbance in the air (Bedard & Georges, 2000). Natural sources can be detected as near-field events, ranging from debris flows (e.g., Belli et al., 2022; Marchetti et al., 2019a), mass movements like snow avalanches (e.g., Havens et al., 2014; Marchetti et al., 2015), pyroclastic density currents (Ripepe et al., 2009; Yamasato, 1997) and collapsing glaciers (e.g., Marchetti et al., 2021). Far-field events like ocean waves (e.g., Garces et al., 2006), severe weather (Bowman & Bedard, 1971), earthquakes (e.g., Johnson et al., 2020; Marchetti et al., 2016), explosive volcanic eruptions (*e.g.*, Johnson & Ripepe, 2011; Gheri et al., 2023) and fireballs (*e.g.*, Le Pichon et al., 2013; Belli et al., 2021) can be detected globally. Man-made sources include, for example ground and air traffic (*e.g.*, Liszka & Waldemark, 1995; Howe, 2003), launching and re-entry of spacecrafts (*e.g.*, Pilger et al., 2021a), chemical (e.g., Pilger et al., 2021b) and nuclear explosions (*e.g.*, Che et al., 2014).

Given the high number of active sources, infrasound is usually recorded using arrays of pressure sensors, from a range of different types of absolute to differential pressure devices (*e.g.*, Ponceau & Bosca, 2010; Nief et al., 2019), rather than single ones. An array allows improvement of the signal-to-noise ratio, to discriminate coherent signal from noise, as well as a more accurate estimate of the wave parameters (*e.g.*, Scott et al., 2007; Christie & Campus, 2010; Johnson, 2019).

Similarly to other detection methods broadly used for infrasound technology, the array processing used in this work operates through a multi-channel cross-correlation analysis performed on subsequent time windows of the signal recorded at all the array elements and is based on the assumption that a signal

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is coherent at all the sensors, differently from noise, which is heavily incoherent (Ulivieri et al., 2011). Once coherent infrasound is identified within each signal window, an infrasonic detection is defined and characterised in terms of wave parameters, including pressure amplitude, back-azimuth and apparent velocity. While the pressure amplitude is computed as the mean recorded infrasonic pressure within the signal window corresponding to each detection identified, the back-azimuth and the apparent velocity are computed based on the differences in the recording times at the different sensors of the array.

In particular, the back-azimuth (clockwise angle between the North and the sensor-to-source direction) represents the planar direction where the infrasonic wave comes from. The apparent velocity (v_a) instead is defined as the speed the infrasonic wave would have if propagated on the same plane of the array, according to (Belli et al., 2021):

$$v_a = \frac{c}{\sin(\gamma)} \tag{1}$$

where c is the sound speed and γ is the take-off angle (measured with respect to the vertical) of the infrasonic ray. For a source located just above the array, $\gamma=0$ and the apparent velocity would tend to the infinite. Once a realistic value is assumed for c, the apparent velocity allows to compute the inclination of the infrasonic ray and, once combined with the computed back-azimuth, to fully reconstruct the 3D direction of the infrasonic wave. Therefore, the array processing provides crucial information that can lead to an estimate of the location of the infrasonic source and thus helps distinguish the signal of interest from the signals generated by the other sources (Belli et al., 2021).

1.2. Local and regional infrasound monitoring: the role of low-cost portable infrasound arrays

Portable infrasound arrays play an important role to study and understand local and regional infrasound observations. These low-cost systems can be used as an auxiliary tool to the existing permanent infrasound arrays of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), for civil and scientific applications, and other non-IMS arrays, as they increase the density of infrasound stations worldwide, and consequently improve the overall detection capability of a myriad of infrasound sources (e.g., Campus et al., 2010; Christie et al., 2006; Le Pichon et al., 2005; Mialle et al., 2010). They contribute to the identification of new infrasound sources at local to global ranges as well as to the improvement of the accuracy and robustness of the atmospheric corrections in the detected signals by several techniques, including the measured azimuth deviations (Le Pichon et al., 2005).

Thanks to being low-cost, lightweight and easy to deploy, portable arrays can be installed in harsh environments or in locations difficult to access. They are of interest for various research domains (McIntire et al., 2017), such as to study the Alpine environments (Belli et al., 2022; Marchetti & Johnson, 2023; Marchetti et al., 2021) or for volcanology research (Fee & Matoza, 2013; Ripepe & Marchetti, 2002). For instance, in the Azores Islands, several sites have already been identified (Jesus, 2023) as possible suitable locations for quick infrasound deployments in case of seismo-volcanic unrests, which are common due to the complex geodynamic setting of the region.

1.3. The 2022's seismo-volcanic crisis of São Jorge Island

The Azores Islands are an archipelago of nine volcanic islands located in the middle of the North Atlantic Ocean, around 1400 km west of mainland Portugal. The islands are distributed along a 650 km NW–SE trend. They are geographically disposed in three groups: Western, formed by Flores and Corvo Islands; Central, formed by Graciosa, São Jorge, Terceira, Pico, and Faial Islands; and Eastern, formed by São Miguel and Santa Maria Islands (Fig. 1).

This region is located within a unique and complex geodynamic setting, characterised by the interaction of the boundaries between the Eurasian, Nubian, and North American tectonic plates, well-known as the Azores Triple Junction (*e.g.,* Madeira et al., 2015; Miranda et al., 2015). As a result, significant seismic and volcanic activity have been recorded through the centuries, in particular on the

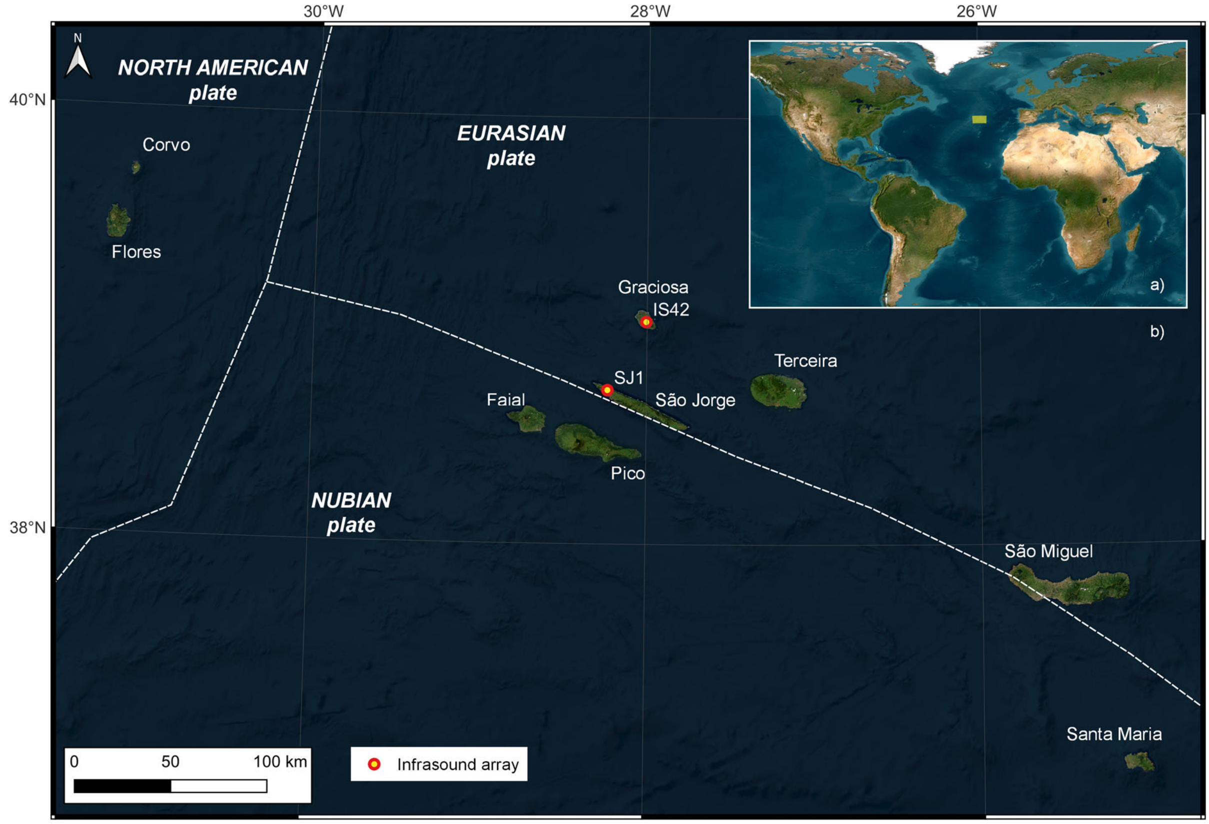


Figure. 1
a Location of the Azores Islands (yellow box); **b** geological setting within the boundaries between the Eurasian, Nubian, and North American tectonic plates (schematic representation), and location of the infrasound arrays IS42 and SJ1 on Graciosa and São Jorge Islands, respectively. Maps a and b were created using the Free and Open Source QGIS, with Esri® World Imagery.

islands of the central and eastern groups. Since the settlement by the Portuguese in the fifteenth century, the Azores Islands were affected by 15 major earthquakes, 16 seismic crises, and 28 volcanic eruptions, of which 15 occurred on land. The biggest earthquake so far occurred close to São Jorge north coast on 9 July 1757, reaching an estimated magnitude of 7.4 ML (Machado, 1949; Silva, 2005). More recently, on 1 January 1980, an earthquake of magnitude 7.2 ML has mostly devastated Terceira Island (Hirn et al., 1980; Silva, 2005). Subaerial volcanic eruptions have ranged from Hawaiian to sub-Plinian style, while submarine ones have been mainly of Surtseyan type (Gaspar et al., 2015a, 2015b).

On 19 March 2022 at 5:05 pm UTC, seismic activity abruptly increased on São Jorge Island. The next two weeks were characterised by a higher hourly frequency of earthquakes releasing energy, generally concentrated along a WNW-ESE orientated range. The daily frequency of recorded earthquakes reached a peak of more than 4500 on 20 March 2022. The correspondent hypocentres were estimated at more than 5 km depth. Since the first day, the Seismo-volcanic Information and Surveillance Centre of the Azores (CIVISA) and the Research Institute for Volcanology and Risk Assessment (IVAR) of the University of the Azores (UAc) deployed a monitoring network on the island composed of several distinct monitoring techniques from various scientific domains, namely seismicity, geodesy, geochemistry (gases), hydrogeology, and infrasound. The integration of data from those monitoring technologies led to the assumption that the Manadas Fissure Volcanic

System was reactivated, with the intrusion of magma in depth at the beginning of this now recognised seismo-volcanic crisis (CIVISA, 2022). The most recent subaerial eruptions on São Jorge Island occurred in this volcanic system in 1580 and 1808 (Madeira, 1998; Wallenstein et al., 2018a; Zanon & Viveiros, 2019). During the next two months, seismicity slowly diminished, sometimes interrupted by short periods of higher hourly frequency of energy release. Still, no other anomalous signs were detected by the mentioned techniques. However, CIVISA and IVAR continue to maintain high monitoring levels and enhance the permanent seismo-volcanic observation network, to detect any eruptive precursor signs (CIVISA, 2022).

As soon as the crisis started, the Infrasound Scientific and Operational Unit of IVAR/CIVISA, in collaboration with the University of Florence (UniFI), deployed the portable infrasound array SJ1 (Fig. 1) about 4 km from the main epicentral area of the seismo-volcanic crises on São Jorge Island. In the context of monitoring the seismic activity and precursor signs of a possible eruption, the data analysis from SJ1 and the infrasound station IS42 of the IMS, which is also operated by IVAR and located on Graciosa Island at around 40 km distance from São Jorge Island (Fig. 1), were utilised at first to detect infrasound-generated signals from seismo-volcanic activity (e.g., Arrowsmith et al., 2010; Hale et al., 2010; Ichihara et al., 2012; McNutt et al., 2015; Thelen et al., 2022). In the eventuality of an eruption, both infrasound arrays, SJ1 and IS42, would be already operational to record respectively near-field and middle-field detections (e.g., Campus et al., 2013) of volcano infrasound from an open-vent (e.g., Ripepe & Marchetti., 2002; McNutt et al., 2015; Johnson, 2019; Matoza et al., 2019; Marchetti et al., 2019b).

Since the crisis started, for the first time an infrasound monitoring network of two arrays is currently fully operating in the region (Fig. 1), showing great value in assisting the other seismo-volcanic monitoring techniques implemented in the region, in particular the seismic monitoring network of CIVISA.

Moreover, the combined data analysis from the SJ1 array and the IMS IS42 station has been showing great improvements in localising and characterising infrasound sources in the region as described by the two examples in Sect. 3. It supports how valuable it is to implement portable, small-aperture, low-cost infrasound arrays for local and regional monitoring.

2. *The Azorean infrasound monitoring network*

2.1. *The IS42 infrasound station of the IMS*

Operating and certified since 2 December 2010, the IS42 infrasound station is one of the 60 planned infrasound stations of the IMS, a worldwide network comprising a total of 337 facilities of four complementary monitoring technologies (seismic, hydroacoustic, infrasound, and radionuclide) that supports the verification regime of the Comprehensive Nuclear Test-Ban Treaty (CTBT) by detecting events that might indicate violations of the Treaty (CTBTO, 2024). It is located on Graciosa Island, the northernmost island of the Central group of the Azores archipelago. The management, operation and maintenance of the station are assured locally by IVAR on behalf of the CTBTO (Wallenstein & Campus, 2018; Wallenstein et al., 2011a, 2011b, 2011c, 2013).

The strategic location of IS42 in the North Atlantic not only completes the coverage of other Atlantic infrasound stations (IS51 - Bermuda; IS11 - Cape Verde Islands; IS50 - Ascension Island and IS49 - Tristan da Cunha) for CTBTO monitoring purposes, but it also brings value for scientific and civil monitoring applications, particularly, in detecting long-range infrasound from explosive volcanic activity in the Mediterranean and Atlantic areas (Campus et al., 2013; Matos et al., 2023a; Wallenstein & Campus, 2018; Wallenstein et al., 2013). This data has been applied for conducting preliminary tests on developing a local early warning detection algorithm adapted to global observations (e.g., Gheri et al., 2023; Marchetti et al., 2019b).

2.1.1 *Location background*

Graciosa Island has an area of 60.7 km^2 and a maximum altitude of 402 m above sea level. Its geological history comprises more than

600,000 years and the last volcanic episode occurred less than 2,000 years ago (Gaspar, 1996). The infrasonic station IS42 is installed in a heavily forested area (Fig. 2a), part of the UNESCO (United Nations Educational, Scientific and Cultural Organization) Biosphere Reserve, that grew over the mentioned recent (< 2,000 years ago) basaltic lava flow in the SE sector of the central part of Graciosa Island.

2.1.2 Technical specifications

Following the IMS infrasound network specifications (Marty, 2019), the IS42 station array is composed of eight data acquisition elements (named H1 to H8) and one central facility (CF), where data are collected before transmission to the International Data Centre (IDC) in Vienna. The geometry of the array is arranged on a 1 km aperture pentagonal outer sub-array and a 200 m inner triangular sub-array (Fig. 2b). At each array element, a wind-noise-reducing system (WNRS) of four rosette-pipes with 20 m diameter and 96 ports is connected to the inlets of the absolute pressure sensor, a MARTEC CEA MB2005 microbarometer, inside the vault. Infrasonic signals are recorded with a sampling rate of 20 Hz using a Nanometrics Europa T digitizer and transmitted to the CF via a Telesto optical fibre modem. Time synchronisation is performed by a GPS receiver. Additionally, the air temperature and the wind velocity are also collected by a meteorological station at H1 element. Each element is provided of 230 V independent power supply from the public grid and all elements are linked to the CF by optical fibre to guarantee reliability, robustness, and high performance, as demonstrated by the high data availability (around 100%) and detections since the time of its certification (Wallenstein et al., 2011a, 2011b, 2018b). Some photos from the station are shown in Fig. 2.

2.2. The portable infrasound array SJ1

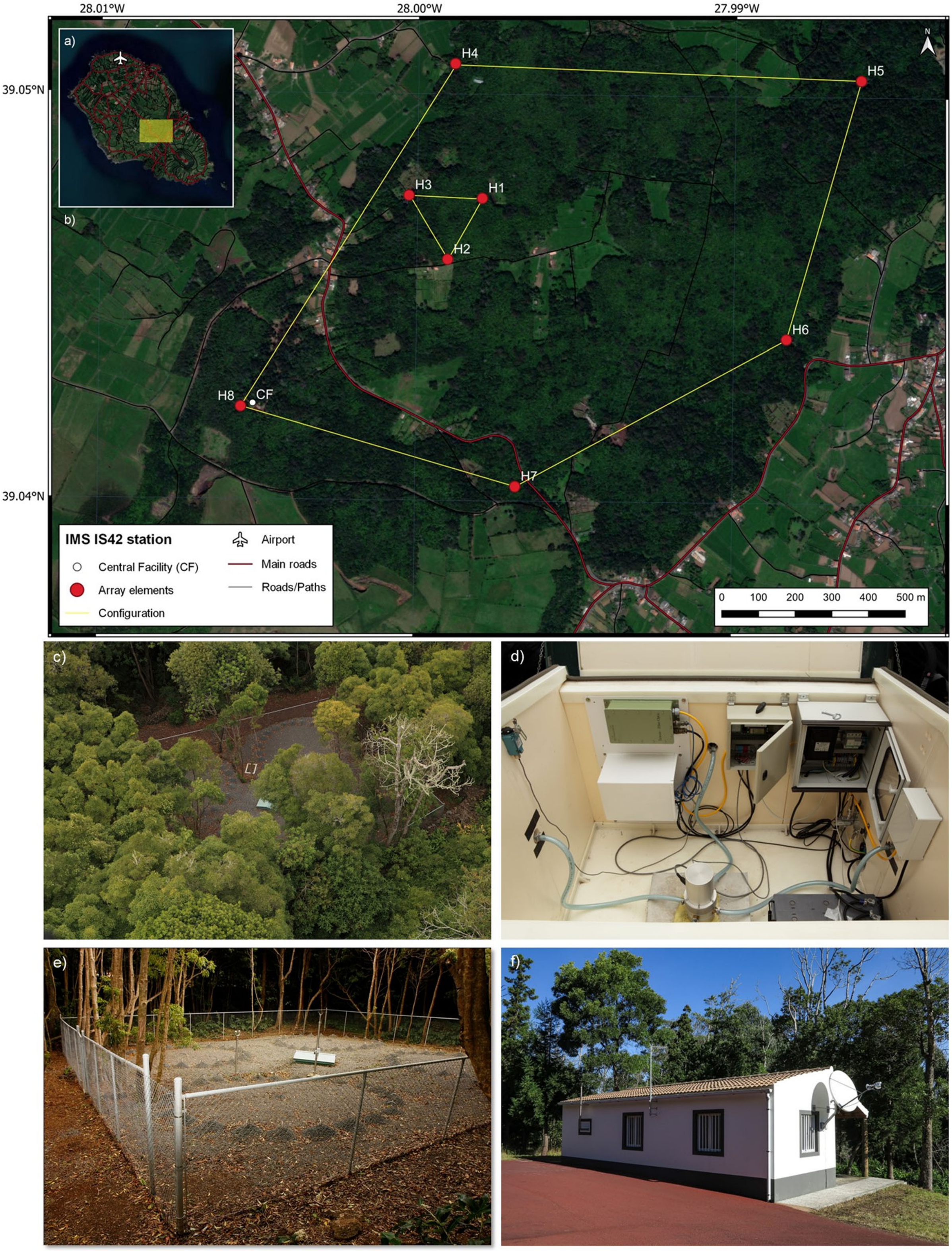
A four-element low-cost portable small-aperture infrasound array (SJ1) was deployed on São Jorge Island (Fig. 3a) around 4 km from the main epicentral area of the ongoing seismic activity, becoming operational on 2 April 2022.

2.2.1 Location background

São Jorge Island has an area of about 246 km^2 and a maximum altitude of 1053 m above sea level. With a long (54 km) and narrow (7 km) rugged and steep terrain, with extremely high cliffs around 300 m above sea level (Madeira, 1998), the island is the result of a WNW-ESE trending fissure volcanic system, unique in the region, and its geological history comprises more than 1 million years (Hildenbrand et al., 2008; Madeira et al., 2015). In the last 5000 years, its most recent volcanic fissure system (Manadas Fissure Volcanic System) has been one of the most active in the Azores archipelago.

2.2.2 Technical specifications

SJ1 consists of four differential pressure transducers, with a sensitivity of 400 mV/Pa in the frequency band 0.01–200 Hz, each connected by 100 m electrical cables to a 24-bit Güralp GDM-DM24 digitizer. Data is sampled at 100 Hz, GPS time stamped and transmitted in near-real time via a GSM modem to the UniFI webserver. Power is supplied by two lead-acid rechargeable batteries connected to solar panels. To reduce wind noise the array is installed in a dense, flat forested area (Fig. 3d) and each sensor is deployed inside a barrel buried 20 cm below the ground (Fig. 3e). An additional 50-cm rubber hose, connecting the barrel with the outside, is used as a rudimental WNRS. The array was first deployed in a diamond geometry with an aperture of $\sim$ 115 m (Fig. 3b) and later rearranged into a centred triangular design, in order to improve the coherence of signal and response resemblance between the four sensors and extend the aperture up to $\sim$ 130 m (Fig. 3c) (Jesus, 2023; Jesus et al., 2023). Photos from the array are presented in Fig. 3.


28.01°W
28.00°W
27.99°W
39.05°N
39.04°N
N
a)
b)
H1
H2
H3
H4
H5
H6
H7
H8
CF
IMS IS42 station
Central Facility (CF)
Array elements
Configuration
Airport
Main roads
Roads/Paths
0 100 200 300 400 500 m
c)
d)
e)
f)

◀Figure. 2
a Overview of Graciosa Island orthophoto map with IS42 location (yellow box); **b** array geometry of IS42; **c** aerial view of H7 element; **d** equipment inside the vault; **e** disposition of H1 element, illustrating the pipe-rosette system (WNRS) and the vault in the middle; **f** Central Facility (CF). Maps a and b were created using the Free and Open Source QGIS, with Esri® World Imagery.

3. Detected events: examples of natural infrasound sources from the Azores region

We identified two different infrasound sources of natural origin that were detected by both the IS42 and SJ1 arrays. The first one was a local detection of a low-magnitude earthquake related to the seismo-volcanic crisis on São Jorge Island, with direct propagation of infrasound waves from the epicentre. The second source, later identified as a fireball crossing the atmosphere, represents a regional detection (> 300 km from the receiver). Since both signals were recorded at both arrays, we performed a grid search to locate the source of the recorded events, performing the cross-bearing of back-azimuth determined at IS42 and SJ1 (Figs. 4e and 5e), similarly to the approaches described in several studies (Arrowsmith et al., 2008; Walker et al., 2010; Matoza et al., 2017; Sanderson et al., 2020). The location is obtained by minimising the product of:

$$\left|Ba_{ij} - Ba_{obs}\right|_{SJ1} \times \left|Ba_{ij} - Ba_{obs}\right|_{IS42}, \qquad (2)$$

where Ba_{ij} represents the theoretical back-azimuth expected at the SJ1 and IS42 arrays, computed for each node of the grid, while Ba_{obs} is the observed back-azimuth corresponding to the maximum amplitude recorded at both arrays. The source location is determined by identifying the grid node with the minimum difference between the calculated and observed values.

Both events confirm the capability of the two arrays of the Azorean Infrasound Monitoring Network to detect local and regional infrasound sources.

3.1. Volcano-tectonic earthquake of 5 April 2022

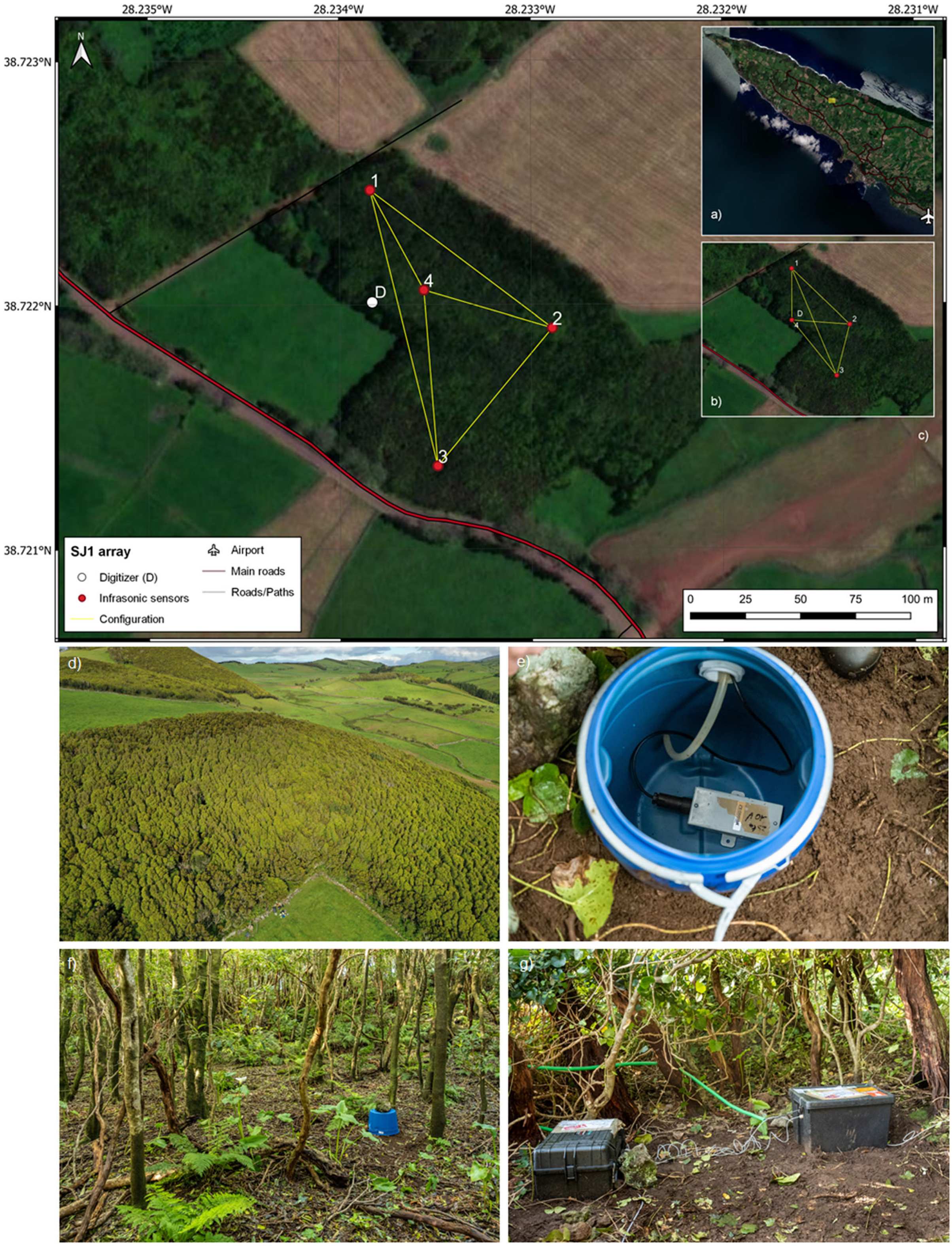
During the 2022 seismo-volcanic crisis on São Jorge Island, an infrasonic event was recorded at both IS42 and SJ1 arrays on 5 April 2022 (Matos et al., 2023b).

Seven operational sensors of IS42 detected an infrasonic signal at 21:25:30 UTC (Fig. 4a, left), with a frequency content concentrated between 1 and 5 Hz. The signal was processed with array processing techniques applying the methods previously described (Sect. 1.1; Belli et al., 2021; Ulivieri et al., 2011) on 1–8 Hz filtered data, using subsequent 5-s-long windows of data with 98% of overlap. The obtained infrasonic detections were characterised by an infrasonic amplitude peak of ~ 0.02 Pa, calculated as the average of pressure peaks recorded at all sensors within the time window of analysis (Fig. 4b, left), a mean back-azimuth of 203°N (Fig. 4c, left) and a mean speed of 350 m/s (Fig. 4d, left).

The SJ1 array, still arranged on the initial diamond geometry at that time, registered a ~ 30-s-long infrasonic signal starting at 21:23:35 UTC (~ 2 min before) (Fig. 4a, right), with a frequency content peaking between 1 and 5 Hz. Similarly to what was done for IS42, data were processed with array techniques on 1–10 Hz filtered data, considering subsequent 5-s-long windows of data with 98% overlap. Results revealed a signal with a peak amplitude of 0.2 Pa (Fig. 4b, right) and a back-azimuth ranging between ~ 110°N and 130°N (Fig. 4c, right). In this case, the apparent velocity exhibits a particular pattern, with the initial ~ 5-s-long cluster of infrasonic detections around 1000–1500 m/s, and the ~ 25-s remaining part of the signal showing an apparent velocity of ~ 340 m/s (Fig. 4d, right).

The grid-search analysis, as described above, was executed considering a resolution of 1 km and assuming direct infrasound wave propagation at constant velocity (340 m/s). The analysis allowed us to locate the source of the recorded signal on São Jorge Island, ~ 6 km southeast of SJ1.

The obtained localisation, as well as the recording times of the infrasonic signals, are consistent with the timing and location of a 2.1 ML earthquake associated with the seismo-volcanic crisis on São Jorge recorded by the CIVISA seismic monitoring network on 5 April 2022, at 21:23:32 (UTC). The analysis of the recorded seismic data allowed CIVISA to locate the hypocentre on the NW part of São Jorge Island at


28.235°W
28.234°W
28.233°W
28.232°W
28.231°W
38.723°N
38.722°N
38.721°N
N
1
2
3
4
D
a)
b)
c)
SJ1 array
Digitizer (D)
Infrasonic sensors
Configuration
Airport
Main roads
Roads/Paths
0
25
50
75
100 m
d)
e)
f)
g)

◀Figure. 3
a Overview of the western part of São Jorge Island orthophoto map with SJ1 location (yellow box); **b** previous array geometry of SJ1 (diamond shape design); **c** current array geometry of SJ1 (centred-triangular design); **d** aerial view of the site; **e** deployment of one sensor inside a barrel; **f** disposition of one element inside the woods; **g** plastic boxes hosting the digitizer (left) and the batteries (right). Maps a, b, and c were created using the Free and Open Source QGIS, with Esri® World Imagery.

a depth of ~ 0 km (Matos et al., 2023b). The reconstructed epicentre is within 1 km from the localisation obtained with infrasound data (Fig. 4e), while the temporal shift between the earthquake and the recording times at the arrays is in excellent agreement with the source-to-receiver distances (~ 6 km for SJ1, ~ 40 km for IS42), considering the ~ 340 m/s speed of the sound in the air. We can therefore state with certainty that the recorded signals correspond to the acoustic waves generated by the earthquake itself. Accordingly, the ground motion associated with the earthquake coupled with the atmosphere (Marchetti et al., 2016), allowing the transmission of the seismic wave into the air in the form of infrasound wave (Ichiara et al., 2012), was recorded at IS42 and SJ1.

Our interpretation of the source process also explains the high apparent velocity values identified at the beginning of the event recorded at SJ1: this phase corresponds to the signal component generated by the arrival of the seismic waves at the recording site, which produced a shaking of the sensors, recorded as pressure oscillations marked by an apparent velocity, reflecting the local speed of the incident seismic waves (Marchetti et al., 2016).

3.2. *Unreported fireball of 29 June 2022*

On 29 June 2022, both IS42 and SJ1 recorded an infrasonic event around 02:17 (UTC) (Fig. 5). To investigate the source, the 1–8 Hz bandpass filtered signal was analysed by applying the array processing described above, considering 5-s time windows with 98% overlap. At the time of this event, SJ1 was already arranged on the final centred-triangular geometry (Fig. 3c). At both arrays, the recorded signals were composed of three clusters of detections, the first two characterised by a higher amplitude (maximum pressure of 0.3 Pa and 0.75 Pa at IS42 and SJ1, respectively) and the third one with a significantly smaller amplitude (~ 0.01 Pa) (Fig. 5b, black circles). At IS42, the array processing highlighted a back-azimuth of ~ 110°N for the first two clusters of detections, and of ~ 120°N for the third one of smaller amplitude (Fig. 5c, left). At SJ1, a back-azimuth of ~ 100°N and 110°N is determined for the first two clusters and the third one respectively (Fig. 5c, right). The apparent velocity ranges between ~ 350 m/s and ~ 380 m/s at IS42, and between ~ 310 m/s and ~ 350 m/s at SJ1 (Fig. 5d). Given the small array aperture (~ 130 m), the apparent velocity estimates at SJ1 are less accurate compared to IS42.

These infrasonic signals have been studied in previous work by Hicks et al. (2023), where the authors, analysing data from a dense seismic network in the Azores, complemented by the IS42 and SJ1 infrasonic arrays, managed to attribute the recorded signals to an unreported fireball event occurred in the Atlantic Ocean on 29 June 2022. The analysis performed by Hicks et al. (2023), based on a 3D ray-tracing of the infrasonic waves (Belli et al., 2021; Blom & Waxler, 2012), allowed to locate the source ~ 60 km NE of São Miguel Island, at ~ 40 km altitude, accurately matching with the location of an unidentified flash captured by the Geostationary Lightning Mapper (GLM) on 29 June 2022 at 02:02:10 (UTC). The ray tracing analysis also explained the three clusters of detections recorded at IS42 and SJ1 as the result of multipathing of the signal generated by a single fragmentation episode of the meteoroid, generating both stratospheric and thermospheric arrivals.

The accurate source localisation performed by Hicks et al. (2023) was possible thanks to the timing of the event provided by the GLM flash (Belli et al., 2021). A simpler and faster localisation is however still possible using only the infrasonic data recorded at IS42 and SJ1, without any information about the source. Following the approach described in Sect. 3, we performed a grid search using estimated back-azimuth considering a 3 km mesh, leading to a coarser resolution compared to the previous case (Sect. 3.1), due to the greater source-receiver

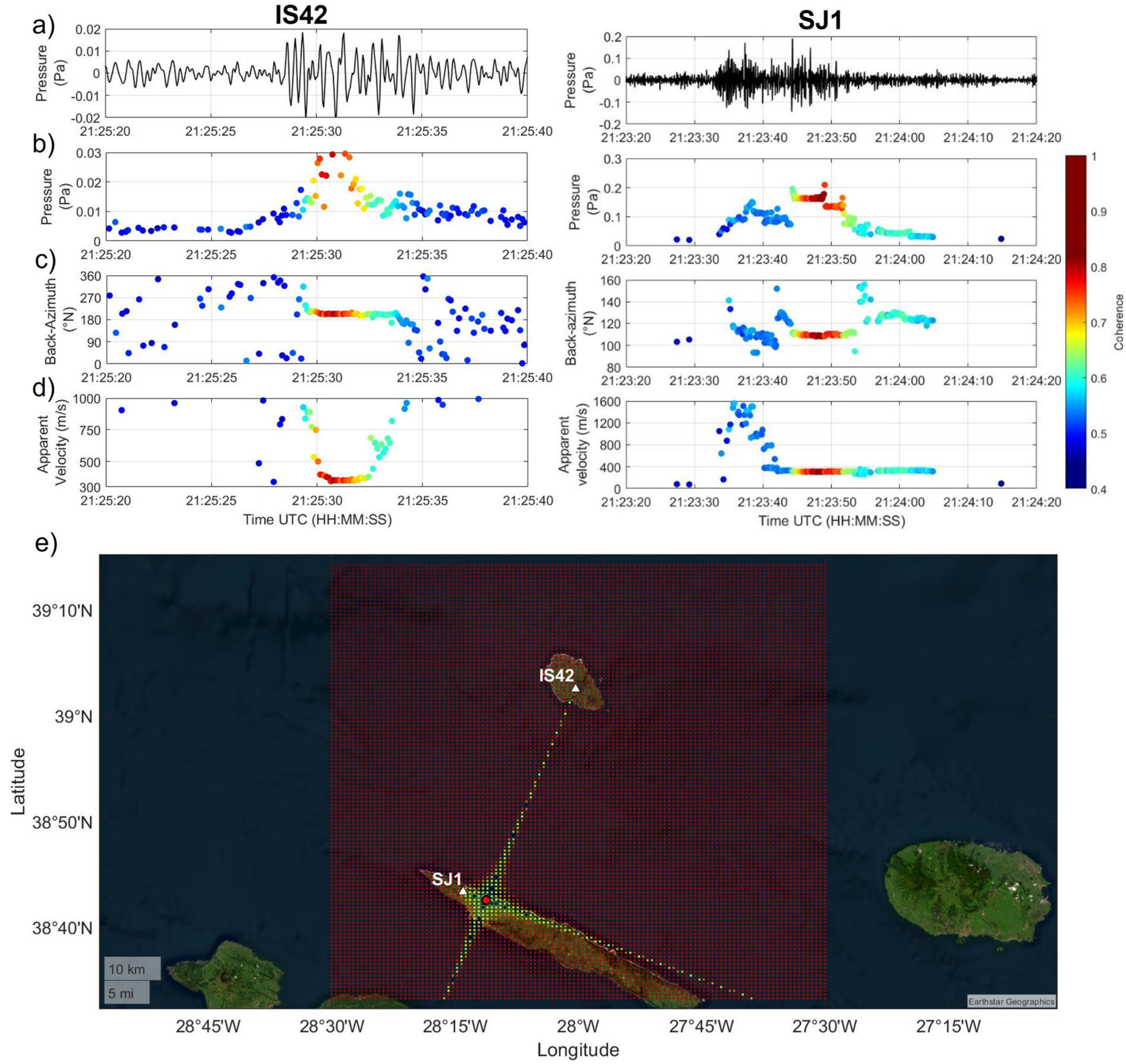


Figure. 4
Infrasonic tracks and array processing results at IS42 (left) and SJ1 (right) for the earthquake recorded at São Jorge on 5 April 2022: **a** filtered infrasound signal; **b** pressure (Pa); **c** back-azimuth (°N); **d** apparent velocity (m/s); each point in b, c and d represents an infrasonic detection defined with the array processing; **e** grid search analysis, with a resolution of 1 km and representation of the real earthquake's epicentre (red dot). Dark blue nodes in the grid represent the best fitting reconstructed source locations

distance ($\sim$ 300 km). When applied for long source-to-receiver distances (hundreds of kilometres), our simple back-azimuth based localisation method is affected by greater uncertainty, as the infrasonic waves are affected by atmospheric winds along its propagation, leading to systematic errors in the recorded back-azimuth (Le Pichon et al., 2005). This is true, especially for the third arrival of the signal, which can be explained by refraction in the thermosphere (Hicks et al., 2023). Due to a stronger wind deflection, the back-azimuth values recorded for the third arrival differ by $\sim$ 10° from values observed for the previous detection clusters (Fig. 5c). Nevertheless, the reconstructed source location is within

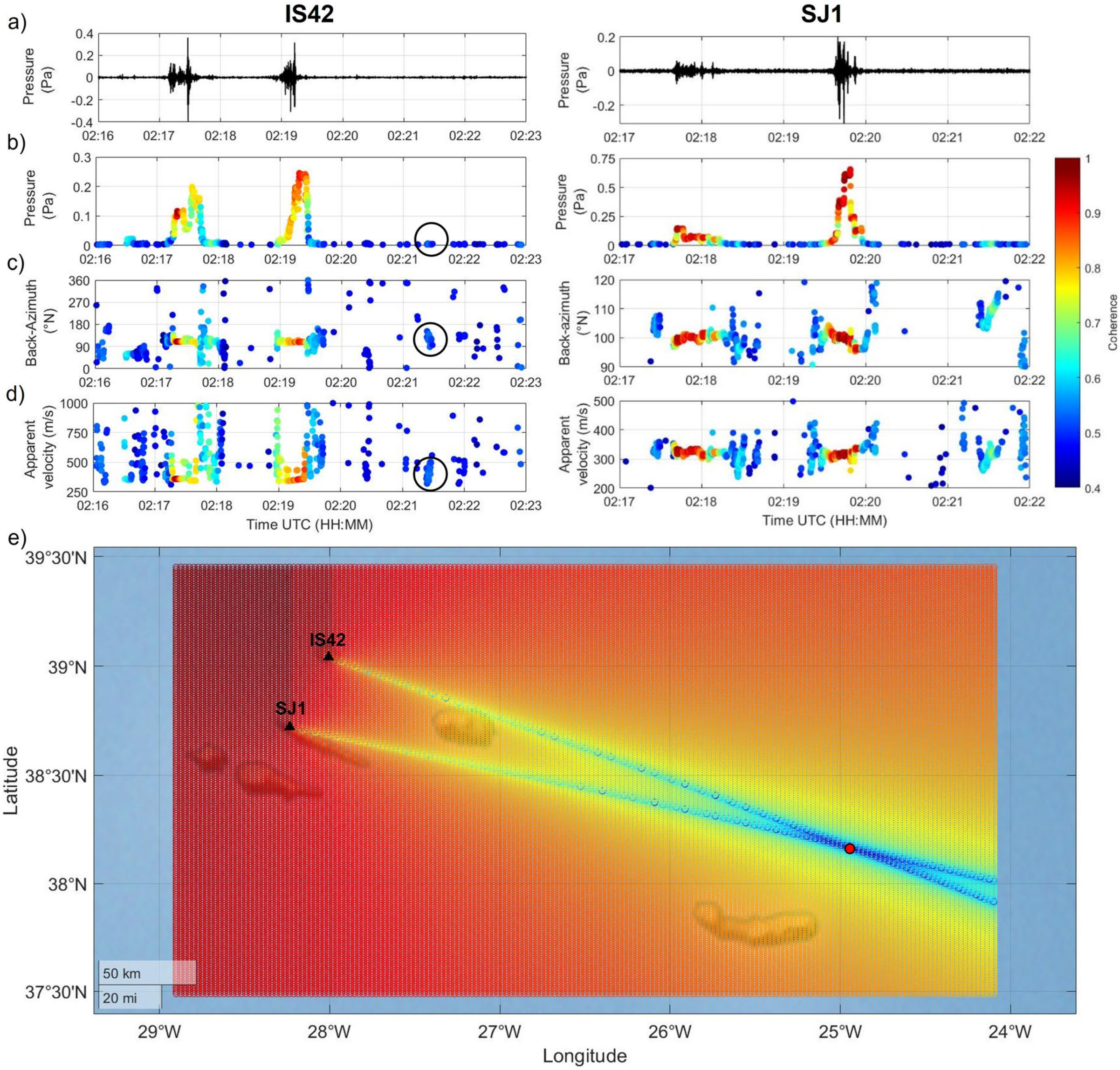


Figure. 5

Infrasonic tracks and array processing results at IS42 (left) and SJ1 (right) for the fireball event in the Atlantic Ocean on 29 June 2022: **a** filtered infrasound signal; **b** pressure (Pa); back-azimuth (°N); **d** apparent velocity (m/s); **e** grid search analysis, with a resolution of 3 km: the red dot indicates the location of the source as reconstructed from the GLM flash (Hicks et al., 2023). Dark blue nodes in the grid represent the best fitting reconstructed source locations

10 km of the position of the GLM flash presented in Hicks et al. (2023) (Fig. 5e), and only 12 km from the ray-tracing based localisation by Hicks et al. (2023), which demonstrates the good accuracy of our analysis. This further highlights the potential of using a regional network of at least two infrasonic arrays to characterise and locate unknown infrasound sources in the Azores.

4. Final considerations

Local-to-global infrasound monitoring is still challenging, due to the abundance of both natural and man-made infrasound-generating processes active on the Earth's surface and in the atmosphere (*e.g.*, Campus & Christie, 2010), often preventing univocal identification of the source of a specific recorded signal. The use of infrasonic arrays provides opportunities to expand signal characterisation, which has been improving the process of classification of the recorded signals (Gheri et al., 2023; Le Pichon et al., 2013; Matoza et al., 2017). Therefore, the scientific progress of array-based infrasound monitoring systems to detect and classify unknown processes in the atmosphere has contributed to the implementation of the IMS infrasound network in the last decades for monitoring nuclear tests worldwide (Christie & Campus, 2010). The distribution of the planned 60 infrasound arrays of the IMS network was designed to detect any explosion with a yield > 1 kt occurring anywhere on the Earth's surface with at least two different stations (Le Pichon et al., 2009). Despite exceeding the planned expectations, the IMS network is not able to provide a complete characterisation of smaller sources at any location on Earth. Such sources generate signals detectable at local to regional scale and are often recorded at most by a single IMS station (Pásztor et al., 2023). For this aim, the use of low-cost, small-aperture, portable infrasonic arrays can complement the monitoring coverage of the existing IMS network, allowing a finer signal characterisation at a smaller scale. Despite the different technical specifications, a portable small-aperture array requires significantly lower deployment and maintenance efforts, offering a cheaper and more ductile solution for specific applications (Belli et al., 2022; Havens et al., 2014; Marchetti & Johnson, 2023; Ulivieri et al., 2013). In this context, our work offers a clear example of how a portable array could be used as an auxiliary tool for an IMS station to identify infrasonic sources, here applied to the Azores region. The SJ1 portable array allowed to classify the source of two different natural infrasonic signals, generated by a low-magnitude earthquake and a fireball, recorded also by the IMS IS42 array, providing additional constraints for event localisation and categorisation at local and regional distances.

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Data availability

Infrasound data from the SJ1 array related to the fireball event are available from Belli (2023). Infrasound from the SJ1 array related to the earthquake event can be available on request to authors. IMS data for the IS42 infrasound array are available on request from the CTBTO Preparatory Commission for scientific purposes through the virtual Data Exploitation Centre (vDEC).

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose.

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