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Key Points:

- We present unique uncrewed aircraft system (UAS)-based infrasound observations of explosive eruptions
- Vertical infrasound directionality from volcanic jetting was observed even after accounting for the effects of topography
- This successful proof-of-concept study presents a novel UAS-based sensor platform suitable for future volcano infrasound deployments

Supporting Information:

Supporting Information may be found in the online version of this article.

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UAS-Based Observations of Infrasound Directionality at Stromboli Volcano, Italy

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Abstract Infrasound (low frequency sound waves) can be used to monitor and characterize volcanic eruptions. However, infrasound sensors are usually placed on the ground, thus providing a limited sampling of the acoustic radiation pattern that can bias source size estimates. We present observations of explosive eruptions from a novel uncrewed aircraft system (UAS)-based infrasound sensor platform that was strategically hovered near the active vents of Stromboli volcano, Italy. We captured eruption infrasound from short-duration explosions and jetting events. While potential vertical directionality was inconclusive for the short-duration explosion, we find that jetting events exhibit vertical sound directionality that was observed with a UAS close to vertical. This directionality would not have been observed using only traditional deployments of ground-based infrasound sensors, but is consistent with jet noise theory. This proof-of-concept study provides unique information that can improve our ability to characterize and quantify the directionality of volcanic eruptions and their associated hazards.

Plain Language Summary Low frequency sound (infrasound) is emitted from volcanic eruptions and can be used to detect and characterize the event. However, sensors that record infrasound are often placed on the ground, so the data only sample a small fraction of the sound that is radiated in all directions. We present observations of explosive events at Stromboli volcano, Italy, using infrasound sensors tethered to an uncrewed aircraft system (UAS) that was strategically hovered near the eruptions. By having a sensor high above the ground, we find that some explosive eruptions radiate more sound vertically than horizontally. This phenomenon cannot be observed by ground-based sensors alone. This proof-of-concept study provides unique information on infrasound and explosion dynamics using a platform that successfully extends data collection capabilities to previously unreachable locations near active volcanoes and other explosive sources.

1. Introduction

Infrasound, or low frequency acoustic waves below the threshold of human hearing (20 Hz), can be generated by a variety of anthropogenic (e.g., aircraft, mining blasts, and chemical explosions) and natural sources (e.g., mass flow events, earthquakes, tsunamis, and volcanic eruptions) (Bedard & Georges, 2000). Infrasound can be used to detect, locate, and quantify sources from local to remote distances (De Angelis et al., 2019; Fee & Matoza, 2013; Johnson & Ripepe, 2011; Matoza et al., 2019) and is therefore useful for volcano monitoring. While many explosions may be well-described by a simple volumetric source (monopole), sources such as buried chemical explosions (e.g., Blom et al., 2020; Kim et al., 2022), complex volcanic eruptions (e.g., Iezzi et al., 2019; Johnson et al., 2008; Jolly et al., 2016, 2017, 2022; Kim et al., 2012; Matoza et al., 2013; Schmid et al., 2020, 2022; Watson et al., 2021), and mass movements (e.g., Johnson et al., 2021; Marchetti et al., 2019; Ripepe et al., 2010; Toney et al., 2021; Ulivieri et al., 2011) can have a significant directional component. Hazardous ballistic and gas trajectories may be consistent with acoustic directionality (Fitzgerald et al., 2020; Jolly et al., 2017). Identifying the acoustic directional radiation pattern of volcanic eruptions can help determine trajectory, thereby increasing the safety of tourists, scientists, and residents near an active volcano. Additionally, it would increase the understanding of regional and global observations of infrasound from directional sources (e.g., Fee et al., 2013) that are often only modeled using a simple source (e.g., Blom, 2019).

Recorded infrasound data are influenced by the source process, propagation conditions between the source and station, recording instruments, and site effects at the receiver. For simplicity, many infrasound studies assume a simple acoustic source (monopole) that radiates pressure equally in all directions (Fee et al., 2017; Johnson & Miller, 2014; Kim et al., 2015; Pierce, 1989). However, more complex source reconstructions are increasingly being estimated using a combination of monopole sources (dipole, e.g., Iezzi et al., 2019; Johnson et al., 2008; Kim et al., 2012) that better represent the directionality of the source. The term "dipole" refers to the source itself being directional, but topography can also induce directionality that is recorded. For example, topography that is not adequately accounted for can create an "effective dipole" (e.g., Diaz-Moreno et al., 2019; Kim et al., 2012), or the conduit itself can generate directivity in the radiation pattern as a function of the frequency content of the acoustic signal (e.g., Lacanna & Ripepe, 2020). This "induced" or "effective" directionality can be accounted for using techniques such as finite-difference time-domain (FDTD) modeling (Kim & Lees, 2014; Lacanna & Ripepe, 2013, 2020) with an accurate digital elevation model (DEM), allowing for the creation of predicted pressure waveforms at a specified location.

Sensors that record infrasound are usually placed on the ground, thus providing a limited sampling of the acoustic radiation pattern, especially in the vertical direction. This configuration has difficulty characterizing volcanic eruptions with an unknown radiation pattern that may be directional. Consequently, studies commonly assume that infrasound from volcanic eruptions either radiates as a monopole or that there is horizontal, but no vertical, directionality. The lack of clarity on the sources of infrasound signals can create a bias in data interpretation and quantification of source parameters (Iezzi et al., 2022). This may include quantifying the mass flow rate and eruption mass, which are invaluable parameters for volcanic ash dispersal forecasting (e.g., Schwaiger et al., 2012).

Recent infrasound studies have attempted to increase coverage of the vertical wavefield using aerostats (tethered balloons, e.g., Iezzi et al., 2019; Jolly et al., 2017; Krishnamoorthy et al., 2018), free-floating balloons (e.g., Bowman & Lees, 2015; Brissaud et al., 2021; Lamb et al., 2018), birds (den Ouden et al., 2021), and leveraging nearby topography (e.g., McKee et al., 2017; Rowell et al., 2014). However, these methods can have logistical challenges and limited flexibility of sensor placement. We overcome some of these challenges and address the issue of limited wavefield sampling by using a novel approach of collecting infrasound data with a sensor tethered to an uncrewed aircraft system (UAS) that can be safely and strategically hovered around the explosion source with precise locations. UASs are becoming common for volcano monitoring and research (James et al., 2020) due to their ability to collect data from otherwise inaccessible areas. UASs are used for the creation of digital elevation models (e.g., Carr et al., 2019; Schmid et al., 2021), optical imaging of volcanic plumes (e.g., Gomez & Kennedy, 2018), thermal mapping of lava flows (e.g., Dietterich et al., 2021), and gas sensor collection of volcanic plumes (e.g., D'Arcy et al., 2018; McGonigle et al., 2008). To our knowledge, there is only one study (not peer-reviewed) that placed an infrasound sensor on a UAS to record signals from a seismo-acoustic hammer (Jones et al., 2015), and no studies have deployed a UAS-mounted infrasound sensor to capture data from volcanic eruptions or characterize infrasound directionality.

This study presents observations of infrasound from volcanic eruptions recorded using a novel approach of sensors tethered to a UAS at Stromboli volcano, Italy. We show examples of multiple event types from short duration explosions to longer duration jetting, including an example where the UAS reached unprecedented inclination angles relative to the jet axis and captured vertical infrasound directionality.

2. Deployment at Stromboli Volcano, Italy

Stromboli volcano, Italy, is a 924 m tall stratocone located in the Aeolian Island arc off the coast of Sicily (Figure 1a, inset). Its activity is characterized by frequent, discrete Strombolian eruptions (Delle Donne & Ripepe, 2012; Ripepe & Marchetti, 2002) along with infrequent major explosions and paroxysms (Métrich et al., 2021; Ripepe et al., 2021) that can generate tsunamigenic pyroclastic density currents along the Sciara del Fuoco on the northwest flank of the volcano (Fornaciai et al., 2019). There are often multiple active vents at Stromboli (e.g., Ripepe et al., 2007; Ripepe & Marchetti, 2002; Witsil & Johnson, 2020) that frequently reshape the geometry of the summit crater (e.g., Harris & Ripepe, 2007; Schmid et al., 2021).

As part of a multidisciplinary study in May 2022, we deployed nine ground-based infrasound sensors (UAF1-9) surrounding the summit crater of Stromboli volcano as well as our novel platform of an infrasound sensor tethered

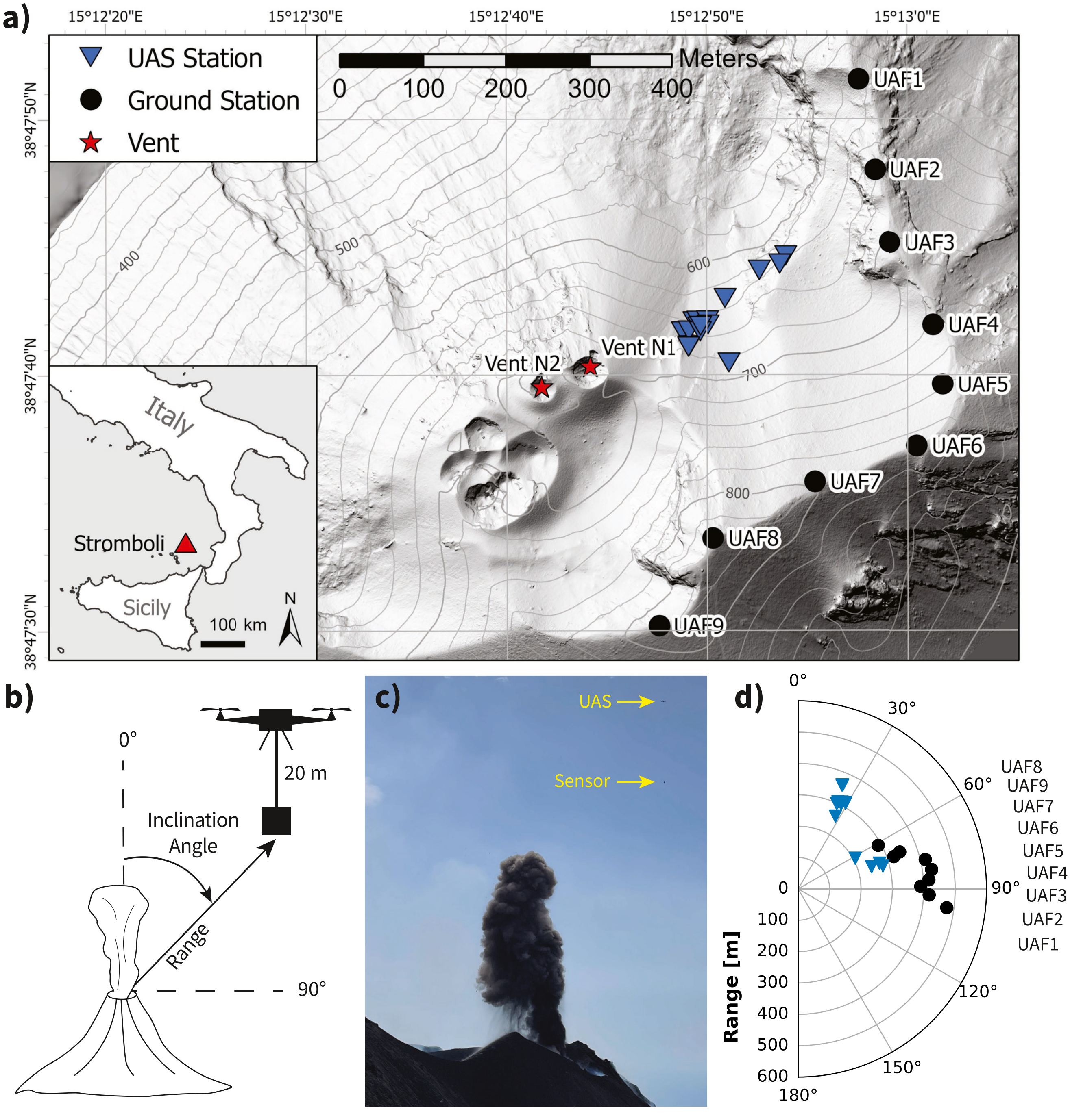

Figure 1. Study area map. (a) Map showing the locations of the active vents discussed in this study (red stars), ground-based infrasound stations (black circles) and stationary locations of the uncrewed aircraft system (UAS) sensors (blue inverted triangles). Contours are at 20 m intervals above ellipsoid. Inset shows the location of Stromboli (red triangle) in southern Italy. (b) Sketch showing the UAS-based sensor platform along with inclination angle (degrees from vertical jet axis) and range (slant distance from vent). (c) Photo of the UAS-based sensor platform during an eruptive event from vent N1. (d) Vertical inclination of ground- and UAS-based sensors with range from the source. Ground-based stations are listed in order from smallest inclination (UAF8) to greatest inclination (UAF1) from vertical.

to a UAS (Figure 1) to complement the permanent monitoring network. All stations consisted of a single Chaparral Physics Model 60 sensor (all UHP, except UAF1,2 that were Vx2) sampled at a rate of 400 Hz on DiGOS DATA-CUBE digitizers. A DJI Matrice 600 Pro was used for the aerial deployment. The infrasound sensor package was suspended 20 m below the UAS to reduce rotor noise affecting the sensor (Figures 1b and 1c, with further details on engineering and testing in Text S1 and Figures S1, S2 in Supporting Information S1). Following the conventions of aeroacoustics research and Matoza et al. (2013), we define the inclination to be the angle from the jet axis, with 0° pointing vertically upward and 90° pointing horizontal (Figure 1b). The UAS-based sensor was deployed from May 10 to May 13, with four flights per day for a total of 16 stationary loiter positions (Figure 1a). The UAS was launched from the helipad and shelter area next to station UAF6 (Figure 1a) for most flights and remained in the stationary position for an average of 10 min per flight. The location error for the UAS is within a few meters (see Text S2 in Supporting Information S1). The ground stations spanned azimuths of 43.0°–165.1° (Figure 1a), inclinations from 97.2° to 61.4° from vertical (Figure 1d), and ranges of 290–477 m relative to vent N1 (Figure 1a). We note that the range of ground station inclinations is greater than would be possible at many other volcanoes due to the unique topography of the Stromboli summit. The UAS-based sensor was deployed roughly in the same azimuth as UAF3 at ranges of 206–360 m, but reached inclinations of 74.7°–22.8° from vertical (Figure 1d) relative to vent N1. It is able to observe the vent within line-of-sight, unlike the ground-based sensors that have topography in the path between the source and receiver (Figure S3 in Supporting Information S1). This technique greatly increases the ability to sample the infrasonic wavefield in the vertical and allows for sensors to be placed closer to the vents without increased risk to the field team.

3. Observations Using UAS-Based Infrasound Data

Activity during the deployment was relatively low for Stromboli, with eruptions occurring on average every 15 min, mainly from the north crater (vents N1 and N2, discussed in this study). The UAS-based sensor captured infrasound from multiple active vents with a variety of eruptive styles (similar to the types described by Goto et al. (2014), Leduc et al. (2015), and Patrick (2007)) during times when the UAS-mounted infrasound sensor was strategically hovered near the eruptions. Vent N1 produced jetting events that lasted for tens of seconds (e.g., Figures 2a and 2b), while vent N2 produced short-duration explosions (e.g., Figures 2c and 2d).

We compare the data recorded by the ground-based and UAS-based sensors. For many events, the UAS-based sensor (Figures 2a and 2c) had slightly higher noise levels than the ground-based sensors (Figures 2b and 2d). These higher noise levels were especially evident in the low frequencies (Figure 2, Figure S1 in Supporting Information S1), and the UAS-based sensor also had a continuous noise source at approximately 110 Hz that was observed on the spectrograms (Figures 2a and 2c) and is likely a result of the UAS (e.g., rotor noise). The frequency band used for our analyses (2–50 Hz) was chosen to mitigate these issues while highlighting the eruptive signals. Regardless, most events were easily observed with high signal-to-noise ratio (SNR) on all stations, including the UAS-based sensor. The field crew noted eruptive events that occurred, and all six of those clearly visible on the ground-based data were also observed on the UAS sensor when it was stationary (Figure S4 in Supporting Information S1). In Sections 3.1 and 3.2, we analyze an example explosive event of both the short-duration and jetting types that had the clearest signal on the UAS-based sensor, with a focus on the UAS-based data and its ability to observe potential vertical directionality.

3.1. Short-Duration Explosion

Here we focus on a short-duration explosion on 10 May 2022 at 13:40:47 UTC from vent N2 with a signal dominated by a single high-amplitude pressure increase and compare the observed and predicted amplitudes. We use FDTD modeling of a monopole source represented by a Blackman-Harris window function. To obtain synthetic waveforms for each station, this source is propagated across a DEM made during the field campaign from structure-from-motion techniques of UAS imagery (see Text S3 in Supporting Information S1). Infrasound data are bandpass filtered (causal) between 2 and 50 Hz. The amplitudes of the FDTD predicted waveforms and observed data are normalized to the peak amplitude at station UAF3 (most similar azimuth to the UAS sensor), respectively, so the predictions and observations can be compared (Figure 3a). Using the relative amplitudes of the synthetic waveforms instead of the simpler $1/r$ (where r is range) amplitude correction (e.g., Johnson & Ripepe, 2011) incorporates both the impact of topography on the amplitude predictions at each station as well as the amplitude decay with distance from the source. The normalized peak amplitudes of the FDTD predictions and observations for each station are compared and plotted as a function of azimuth (Figure 3b) and inclination angle (Figure 3c). When normalized to UAF3, the percent error between the predicted and observed peak amplitudes of the ground stations have an average of 5.0% and median of 5.3%, while the UAS sensor has a percent error of 2.4%. While the observed amplitudes of the ground sensor closest to vertical (UAF8) is slightly higher than predicted (Figures 3b and 3c) (12.6%) relative to the other stations, the overall waveform features and amplitudes

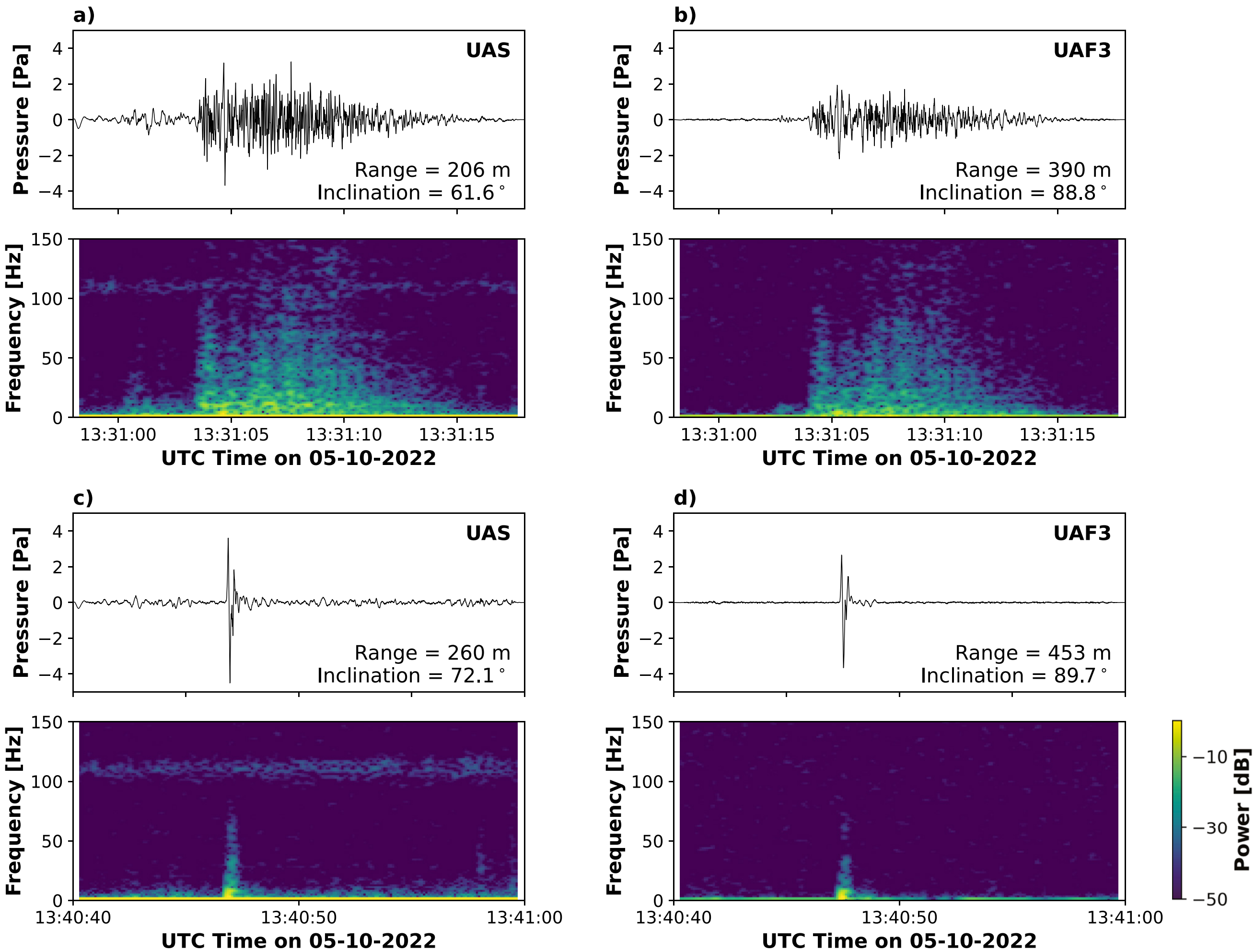

Figure 2. General observations of uncrewed aircraft system (UAS)- and ground-based infrasound sensors. Time series (bandpass filtered, 2–50 Hz) and spectrograms (unfiltered) for two eruptive events on the (a, c) UAS- and (b, d) ground-based sensors. (a, b) Jetting event from N1 on 10 May 2022 at 13:31:03 UTC. (c, d) Simple explosion from N2 on 10 May 2022 at 13:40:47 UTC.

are consistent with the predictions for most stations. Therefore, this event appears to be adequately modeled by a simple monopole source represented by a Blackman-Harris window function with the given station configuration. The UAS station had an inclination similar to some of the ground-based stations for this event (72.1°), so there is no evidence for or against vertical directionality for this explosion.

3.2. Jetting Event With Vertical Infrasound Directionality

Next we analyze a jetting event at 12:04:25 UTC on 11 May 2022 from vent N1, similar to the event shown in Figure 1c. The jetting that lasted over 20 s visually had multiple pulses, appeared to be inclined slightly from vertical, and was relatively tephra-poor with few bombs. The UAS-based sensor was at an inclination of 27.1°, which is less than half the inclination of the highest ground-based station (UAF8). This event was notable because it was detected clearly on the UAS-based sensor with a high signal-to-noise ratio (SNR), but had low SNR or was not evident in most of the ground-based stations (Figure 4a). We investigate the potential impact of wind noise on the ground stations (Text S4 and Figure S5 in Supporting Information S1) using the low frequencies (0.01–0.5 Hz) as a proxy for wind noise, finding that the stations with lower SNR for this event (UAF1,2,5) corresponded to higher amplitude values in the low frequency band at the time of the explosion. This analysis shows that these stations likely suffered from increased wind noise interacting with the topography at the time of the event which obscured the low amplitude jetting event. This event illustrates how a UAS-suspended sensor

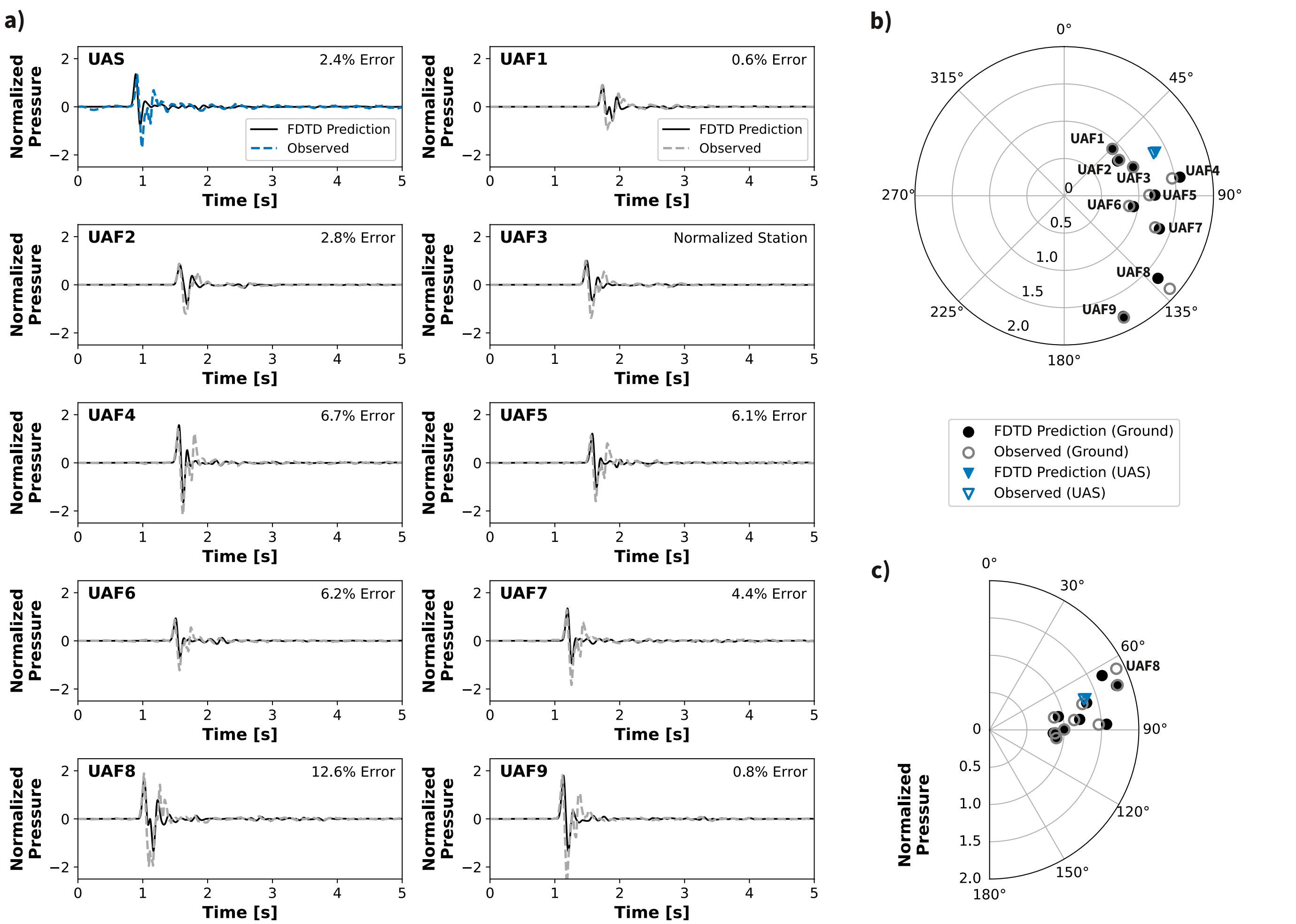

Figure 3. Short-duration explosive event at 13:40:42 UTC on 10 May 2022 from vent N2 comparison with finite-difference time-domain (FDTD) predictions. (a) Bandpass filtered data (2–50 Hz) for the event compared with FDTD prediction waveforms, both amplitudes are normalized to the peak amplitude at UAF3. Normalized peak amplitudes are shown by (b) azimuth from the vent and (c) inclination from vertical.

package can sometimes have a lower noise profile compared to ground-based sensors by being farther from interactions of wind with the topography, likely due to the turbulence and mean shear interaction described in Raspet et al. (2006).

In addition to having a higher SNR in the 2–50 Hz passband than the ground-based stations for this event, the UAS-based sensor also had a larger amplitude than expected based on source-receiver distance, relative to the other stations. For the next phase of analysis, we exclude the stations where the event could not be observed clearly (UAF1,2,5). The event duration is extended compared to the explosion in Section 3.1 where we could simply compare the peak amplitude of the observations with the peak amplitude of the predictions using a simple source. Therefore, we calculate the root-mean-square (RMS) amplitude and sum the amplitude for the first 15 s of the jetting event to create a measure of observed amplitude for each station. We compare this with the peak amplitude of the FDTD monopole prediction for each station, both normalized relative to the value at station UAF3 (Figures 4b and 4c). When normalized to UAF3, the percent error between the predicted and observed normalized RMS sum of the ground stations is low with an average of 10.8% and median of 3.2%, while the UAS sensor has a percent error of 75.4%, nearly double that of the prediction. An analysis of the time-dependence of the directionality is performed (Figure 4d, Text S5 in Supporting Information S1, Movie S1), where it is shown that the directionality is higher for the first part of the event and decreases through time before being close to the prediction at 15 s. This high UAS-based infrasound amplitude relative to all other stations indicates that the source is not well-fit by a monopole-only source, as it clearly does not match the same amplitude pattern as the

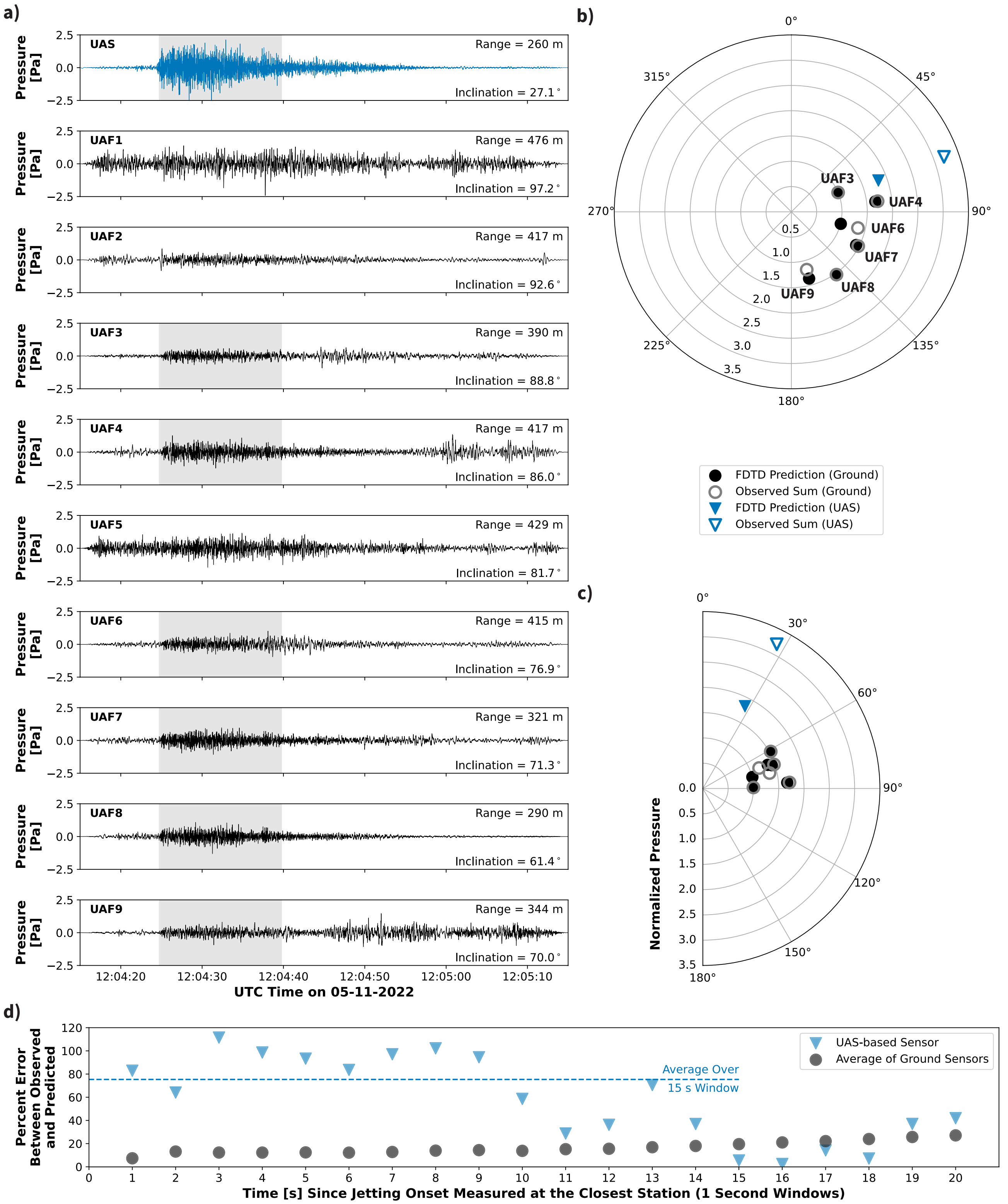

Figure 4. Infrasonic waveforms and comparison to simulations for the jetting event at 12:04:25 UTC on 11 May 2022 from vent N1. (a) Bandpass filtered data (2–50 Hz) for the event. The gray boxes indicate the period used for the RMS sum in (b, c). Comparison between the FDTD prediction (solid markers, normalized to the peak amplitude at UAF3) with the root-mean-square (RMS) sum over the first 15 s of the event (open markers, normalized to the sum of the RMS amplitude at UAF3) are shown by (b) azimuth from the vent and (c) inclination from vertical. (d) Summary of percent error between observed and predicted results in one-second windows through the 15 s of (b, c). The UAS-based sensor is shown in blue, while ground-based stations are shown in black.

ground-based network. This result differs from the previous example (Figure 3) and therefore suggests vertical directionality for this jetting event that is not detected by the ground-based network.

4. Discussion

We present unique observations of explosive volcanic eruptions using infrasound sensors tethered to a UAS and explore its potential for improving the understanding of the acoustic radiation pattern from potentially directional sources. The UAS-based sensor successfully recorded high-quality eruption data from previously inaccessible inclination angles and can serve as a prototype for future deployments. The attachment apparatus was engineered to reduce the impact of the rotor noise on the infrasound data by placing the sensor on a 20 m tether suspended below the UAS while still being relatively easy to maneuver in flight. In some cases, the UAS-based sensor had a higher SNR than the ground-based stations (Figure 4a), likely due to being away from the interaction of wind with the topography, which nearly obscured some events from being evident in the ground-based data. Thus, using a sensor tethered to a UAS may increase the number of events detected and included in an eruption catalog, especially for low amplitude events such as those at Stromboli during the deployment.

Two events (one short-duration and one jetting) were investigated in detail. For the short-duration explosion from vent N2, there is no clear evidence for or against vertical directionality for this explosion since the UAS station had a relatively large inclination for this event (72.1°), similar to some of the ground-based stations. Therefore, there may also be vertical directionality present for this event that we are not recording due to the relatively low height of the UAS for this eruption. This event does serve as a validation that the UAS-based sensor was recording properly from a sensor response perspective, as the amplitudes are consistent with the ground-based sensors at similar inclination angles (Figure 3 and Figure S6a in Supporting Information S1). We do note that the observed amplitude of station UAF8 is slightly higher than predicted (Figures 3b and 3c), so there could be a small amount of directionality toward that station that remains unresolved. In contrast, there is strong evidence supporting vertical infrasound directionality for the jetting event in which the UAS was placed at an inclination angle of 27.1° (Figure 4 and Figure S6b in Supporting Information S1). We find that the event is more directional at the onset, and the directionality drops off gradually throughout the event. By the 14–15 s time window (after onset at the closest station) in Figure 4d, the UAS observation is in alignment with its FDTD prediction, indicating that at this time the event may be well approximated by a monopole source at the vent. An interpretation is that at the beginning of the event, the directional jetting and sustained finite extended source produces a directional acoustic wavefield. Then, as the jet flow decelerates (signal amplitude decreases), the extended/directional source effects correspondingly diminish and the infrasound source is mostly localized at the vent. The same station (UAF8) that was showing possible directionality for the short-duration event does not show that same trend for the jetting event (Figures 4b and 4c). Therefore, we find that there is more evidence that the jetting event could have more vertical infrasound directionality than the simple explosion.

Because infrasound sensors are traditionally placed on the ground, vertical directionality such as that illuminated using aerostats (Iezzi et al., 2019; Jolly et al., 2017) or UASs (this study) are unresolved and a simple source that radiates equally in all directions is assumed. The lack of clarity on directional sources of infrasound can create a bias in data interpretation due to only using data recorded on the ground (Iezzi et al., 2022), such as underestimating mass flow rate of an eruption. Additionally, we show that jetting events should be treated differently than simple transient explosions, and that a monopole is not a good estimation for the modeling jetting events. By including aerial infrasound observations in deployments, we find a clear example of how source characteristics (e.g., yield, size, mass flow rates) may be underestimated due to limitations of typical ground-based infrasound deployments that do not capture the full infrasound wavefield radiation pattern and thus may assume an incorrect source representation. Jet noise (e.g., Matoza et al., 2013) and the relationship between conduit radius and frequency (e.g., Lacanna & Ripepe, 2020) have been predicted to be highly directional, but to our knowledge this is the first observation confirming this hypothesis in the vertical direction for volcanic jets. Vertical and slanted dipole components are not well-constrained by the available station geometry and could be addressed in future work using more aerial sensors.

The analyses presented here show promise for using UAS-based infrasound sensors to characterize vertical infrasound directionality of volcanic eruptions, but have a few potential uncertainties and limitations that should be addressed. The events at Stromboli during the field deployment were relatively infrequent and lower amplitude than events at Stromboli have been in the past (e.g., Taddeucci et al., 2013). Coupled with the UAS flight time limitations (discussed below), this meant we were only able to capture a few eruptive events on the UAS-based sensor over the 4 day deployment. This small subset of events limits our ability to broaden the interpretation of our results to more generally characterize the eruptions at Stromboli. The location error for the UAS is small (within a few meters, see Text S2 in Supporting Information S1) but the infrasound sensor was suspended by a 20 m tether which could cause a few meters of location uncertainty due to swinging, especially near times when the UAS was in motion. We note that winds were light during times of UAS flights. Reviewing data on the UAS-based sensor has a few more challenges than ground-based data, as takeoffs, landings, and flying to the loiter point can lead to transients that may contaminate natural signals, rendering data uninterpretable. Consequently, simple event detectors such as short-term average long-term average cannot be used on these data. Therefore, diligent notes of the UAS flight times and location through time, as well as having other datasets to confirm eruptions, are critical. We note that the high-resolution DEM that was used for FDTD modeling to obtain predicted waveforms at each station may have small inaccuracies due to the high rate of explosions at Stromboli changing the topography in the vent area over short time scales (though no major explosions occurred during that time).

Higher inclination observations of volcanic events to improve the vertical coverage of an infrasound deployment have been performed at a local scale (<15 km) using aerostats (tethered balloons), leveraging nearby topography, and now using UASs. Each of these methods have strengths and weaknesses that should be considered while planning future field campaigns. Studies that leverage nearby topography require no extra equipment, and can therefore be easily implemented. However, this is limited to very specific topographic environments and sensor placement is dictated by the topography so it is not as flexible as desired for research purposes. Both aerostats and UAS platforms are limited by wind conditions, since the aerostat requires light winds and neither can be used in higher wind conditions. Both are also limited by eruption vigor in order to obtain the vertical directionality observations, as eruptions have to be small enough where a UAS or aerostat can be placed near or above the eruption and maintain line-of-sight with the pilot. Using an aerostat (e.g., Jolly et al., 2017) allows for the aerial infrasound to be collected over hours, thus having a good chance of capturing many explosions at frequently active volcanoes. Some weaknesses of aerostats are that they require the shipment of helium (which can cause logistical challenges), station locations are determined by locations where a tether can be attached to the ground, the aerostat to some extent floats with the prevailing winds so it cannot be placed precisely where needed, and the deployment requires multiple people. Using UASs overcomes some of these challenges by allowing for sensors to be placed with precision (within a few meters) at any inclination and azimuth around the source and can be performed with 1–2 field crew members. Automated takeoff, landing, and flight paths along with auto-stabilization technology make it easy for field personnel to successfully pilot multi-rotor UASs. However, batteries are the limiting factor because they have shipping restrictions and must be recharged. The UAS's flight time is also limited by short battery life, and UASs can only be flown for tens of minutes at a time. Additionally, there can be limitations imposed by civil aviation authorities. These limitations constrain potential field locations to those that are likely to erupt frequently and with high temporal predictability.

5. Conclusions and Future Directions

We present novel observations of explosive volcanic eruptions using infrasound sensors tethered to an uncrewed aerial system (UAS) platform, which sampled up to unprecedented inclination angles of 22.8° from vertical (a difference of 38.6° from ground-based deployments possible at Stromboli). During the field campaign, we observed multiple eruption styles from a few active vents, including simple short-duration explosions and jetting events that last tens of seconds. Analysis of the data shows that the short-duration explosion from vent N2 may have had a more uniform energy radiation pattern, though our UAS-based sensor was close in inclination to that of some of the ground-based sensors. In contrast, the more complex jetting event from vent N1 likely has a vertical directional source component observed with our small inclination (27.1° from vertical) UAS-based sensor that was not evident in the ground-based data alone. Our UAS-based sensor platform serves as a proof-of-concept that can provide unique information on explosion dynamics that successfully extends data collection capabilities to previously unreachable locations near active volcanoes.

This study, and that of Iezzi et al. (2019), illustrate that one aerial station is enough to show that vertical infrasound directionality exists, but future studies can push the science further by deploying multiple simultaneous aerial stations in order to uniquely constrain the multipole source mechanism using techniques such as infrasound waveform inversion. Multidisciplinary observations, such as video recordings from multiple angles, can be used to connect vertical infrasound directionality to overall eruption directionality, which may include increased ballistic hazards in certain directions around the vent (Fitzgerald et al., 2020; Jolly et al., 2017). We propose that mounting infrasound sensors to UASs will allow for greater ability to place sensors in inaccessible areas for eruptions where observatories would not necessarily want people to deploy instruments but would benefit from the data collected. Our proof-of-concept study suggests UAS deployments may be feasible for larger eruptions that pose great threat to society by increasing the ability to understand eruption directionality.

Data Availability Statement

Infrasound data are available on IRIS with temporary network code "ZV" (Fee et al., 2022, https://www.fdsn.org/networks/detail/ZV_2022/). The UAS-based sensors are archived as stations R2D2 and BB81, with the exact sensor locations for the stationary loiter positions stated in the associated metadata document on IRIS (https://ds.iris.edu/data/reports/ZV_2022_2022/).

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