Infrasound technology applied to the discrimination of small magnitudes earthquakes and quarry blasts in southeast Brazil

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Abstract

Discriminating natural events (tectonic) from artificial events (explosions) is not an easy and straightforward task, especially when both sources are small and very close to each other. Recently, we have faced this problem in more than one place where there are quarries for rock blasting and tectonic seismic sources, probably triggered by the stress released from rock removal. This raises a great deal of doubt about the origin and nature of these co-located events.

There are several known discriminants and, even using them, doubt can persist. The strictest forward is to use information on the origin time, explosive charge and delay time of the detonations, but this is not always provided by mine companies. Other concerns are related to the polarity of the first P-wave arrival, which, for explosions, must be impulsive and upward. This is not always observed. The signal frequency content is also used to determine the signal complexity. The explosions, being generally shallow, generate surface waves with a high energy. However, this also happens in the case of shallow natural earthquakes, which is almost always observed in intraplate regions, especially for triggered earthquakes.

In this work, we make an attempt to present an useful straightforward method to help discriminate these two types of events, using an infrasound and a seismic co-located stations to monitor blasting in quarries and natural events at close sites. The records obtained from these stations show that low-magnitude tectonic events do not generate infrasonic signals.

Introduction

Mine companies often do not provide crucial information about the origin time, explosive charge, and delay time of detonations. This lack of information can hinder accurate event analysis and classification.

Various methods have been employed to differentiate between quarry blasts and shallow micro-earthquakes in seismic recordings. These methods include spectral analysis (Postema, 1996; Korrat et al., 2023), maximum P/S amplitude ratios in various frequency bands (Hissely, 2022; Wang et al., 2020), analysis and measurement of seismic source parameters such as corner frequency and seismic moment (Saadalla et al., 2023), and comparing magnitude measurements for seismic events recorded locally, such as local magnitude and coda wave magnitude. By utilizing these methods, researchers can determine whether an event is a small earthquake or a single-fire buried chemical explosion (Seismological Society of America, 2020).

Researches have demonstrated that mining blasts generate infrasonic signals and these can assist in differentiating between small earthquakes and mining blasts (ReVelle et al., 2004; Che et al., 2010; Czanik, 2021). In a study conducted in Romania, seismo-acoustic analysis was used to distinguish between quarry blasts and local earthquakes (Ghica et al., 2016).

Our research began by utilizing data from two IMS stations in Brazil: the I09BR infrasound station, which consists of a 4-element array with a 2 km aperture, and the BDFB primary seismic station. These stations were used to monitor detonations in mines located within a radius of approximately 28 km, near the Brasilia National Park (PNB), where the stations are located (**Fig. 1**). In addition, we used a temporary station (RFFB5), which consisted of a short period (SP) seismic component and an acoustic sensor, co-located at the BDFB station (inserted on Fig. 1). This temporary station remained operating for 20 days and it was used to compare its data with that of the I09BR and BDFB stations, for the same events recorded at all of these stations (**Fig. 2**). Several explosions were detected during this period, and no natural events were recorded.

The PNB vicinities are devoid of natural events, whose prevent to achieve the objective of this study, which is to develop a method for distinguishing between natural events and explosions. To address this limitation, we have selected Sete Lagoas city as our research location, as it experiences both low-magnitude earthquakes and man-made events in its vicinity.

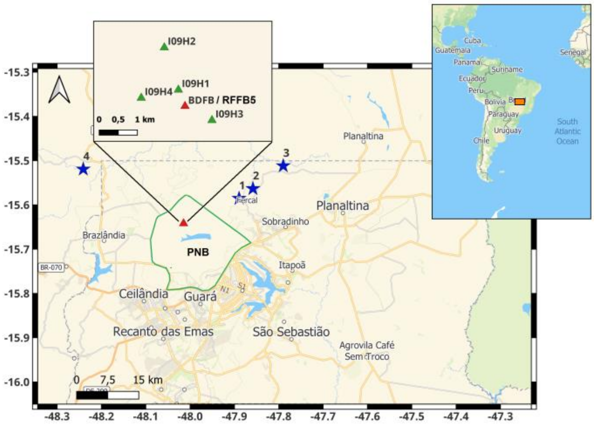

Fig. 1 – Location of the I09BR infrasound station's four elements (H1, H2, H3 and H4 - green triangles) and the BDFB seismic station (red triangle), where it was co-located the RFFB5 station temporary. The blue stars indicate the location of four blasting mines within a radius of up to 28 km from the BDFB station. The inserted figure details the 4 elements array and BDFB station, as well as RFFB5.

Method

In our study, we employ a co-located seismic and infrasound station to monitor both local natural and man-made events in Sete Lagoas city vicinities. The central focus of our investigation is to examine the detection of infrasonic signals, specifically associated with low-magnitudes earthquakes.

Mutschlecner and Whitaker (2005) have shown that the absence of acoustic waves can be possible explained the nature of the event. Their research demonstrates that small-magnitudes earthquakes do not produce infrasonic signals, as the atmospheric infrasound generation requires a minimum peak surface acceleration threshold between 10 and 20 cm s-2.

Arrowsmith et al. (2011) show that low-magnitudes earthquakes appear to be relatively poor infrasound sources and that infrasound should be used as a source-type discriminant.

RFFB5 Data Comparation

The RFFB5 station, using RS&Boom (Raspberry Shake), was co-located at the BDFB station, before of the beginning works at Sete Lagoas city. RFFB5 recorded events during a period of 20 days in this site. **Fig. 2** shows the records of the event, from a detonation occurred in a mine (Mine #2), located about 19 km from BDFB, on 12/08/2022, at 20:16 UTC, detected by I09BR, by BDFB and by RFFB5. Notably, the seismic and acoustic signals recorded by RFFB5 are similar to the correlated signals recorded by I09BR and BDFB. It is essential to highlight that I09BR utilized an effective mechanical filter to decrease wind noise, whereas RFFB5 did not employ any mechanical filter. Furthermore, the BDFB seismometer is a broad-band device that is installed at a depth of 100 meters in a borehole.

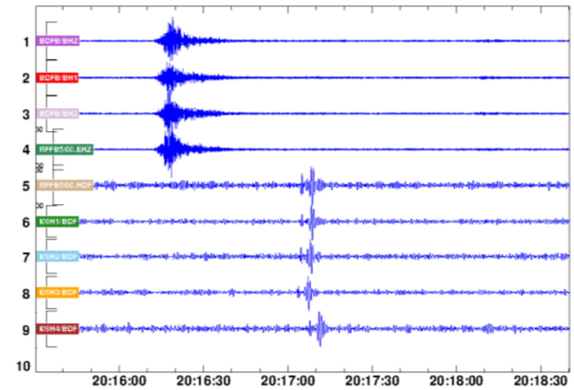

Fig. 2 – Artificial event occurred on 12/08/2022, at 20:16:12.6 UTC, recorded by: BDFB (traces 1, 2 and 3); RFFB5 (co-located at BDFB site), trace 4 (seismic signal) and trace 5 (acoustic signal); and I09BR (traces 6, 7, 8 and 9). It was used a 4th order Butterworth Filter for the seismic signals (3 - 12Hz) and the acoustic signals (1 - 3 Hz).

Sete Lagoas Case

Sete Lagoas (SL) is a city located in the southeast region of Brazil, in the State of Minas Gerais. In the vicinity of SL, there are ten active blasting mines that have been in operation for several decades. Recently, residents of Sete Lagoas have reported feeling and hearing disturbances that differ from the typical vibrations and sounds produced by mine detonations. These disturbances have longer durations and are different in nature from what they are accustomed to experiencing.

In September 2022, we started to monitor the local events using the RFFB5 station. The station was located in the middle area between the mines and close to the epicenters of events that have occurred over the years, as shown in **Fig. 3**. The largest event documented in the region was a magnitude 3.5 earthquake occurred in 1931. It is important to note that all the events plotted on the map took place prior to the installation of the RFFB5 station. The monitoring period lasted approximately two months, during which the RFFB5 station recorded 25 local events.

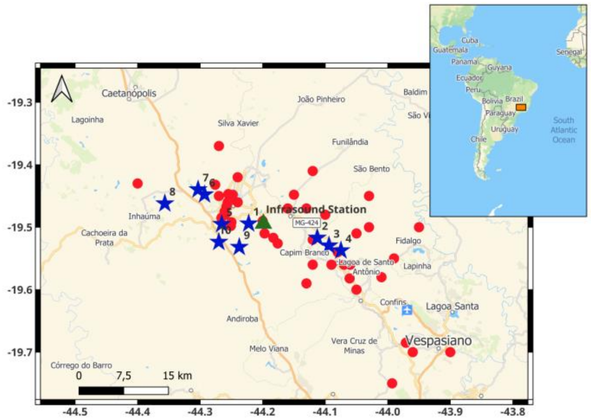

Fig. 3 – *Map of Sete Lagoas study area. The green triangle represents the acoustic and seismic vertical short period (SP) co-located station, denominated RFFB5. The blue stars represent the blasting mines in operation. The red circles indicate the epicenters of natural events from 1931 to 2022 (IAG-USP and SIS-UnB catalogues).*

Data

During the monitoring period at the Sete Lagoas site, the RFFB5 station recorded 25 local events (Δ < 40 km), Table 1. From this total, the station detected both seismic and acoustic signals in 16 events. For the remaining 9 events, the station detected only seismic signals.

Table 1 – *Local events detected by the RFFB5 station in Sete Lagoas site. In yellow are the nine events clearly related to micro earthquakes.*

#	A	B	C	D	E	F	G
1	03/10/2022	18:13:46	yes	yes	1.41	26.40	27.80
2	03/10/2022	18:15:06	yes	yes	1.32	24.60	25.79
3	04/10/2022	20:14:35	yes	yes	0.93	20.50	17.07
4	07/10/2022	12:59:06	yes	no	0.81	-	14.38
5	07/10/2022	20:11:17	yes	no	0.82	-	14.61
6	10/10/2022	14:07:40	yes	yes	0.46	6.90	6.55
7	11/10/2022	14:45:17	yes	yes	1.03	19.10	19.30
8	14/10/2022	16:33:30	yes	yes	1.54	30.00	30.71
9	16/10/2022	12:18:22	yes	no	1.3	-	25.34
10	17/10/2022	18:27:36	yes	yes	1.30	26.10	25.34
11	19/10/2022	14:16:51	yes	yes	0.46	7.00	6.55
12	20/10/2022	21:57:14	yes	no	1.30	-	26.34
13	20/10/2022	22:08:47	yes	no	1.30	-	26.34
14	20/10/2022	22:43:17	yes	no	1.30	-	26.34
15	21/10/2022	14:46:09	yes	yes	0.97	19.20	17.96
16	21/10/2022	16:30:39	yes	yes	1.42	29.80	28.03
17	29/10/2022	14:15:27	yes	yes	1.00	19.30	18.63
18	29/10/2022	14:25:54	yes	yes	1.10	19.50	20.87
19	31/10/2022	14:14:07	yes	yes	0.64	6.60	10.58
20	18/11/2022	03:30:38	yes	no	1.29	-	25.12
21	21/11/2022	19:08:44	yes	yes	1.38	25.80	27.13
22	22/11/2022	03:34:02	yes	no	0.84	-	15.05
23	24/11/2022	02:02:37	yes	no	0.75	-	13.04
24	28/11/2022	16:04:46	yes	yes	1.20	24.50	23.11
25	29/11/2022	20:21:48	yes	yes	1.10	21.00	20.87

A) Date; B) Time Seismic Signal (hh:mm:ss UTC); C) Seismic Signal; D) Acoustic Signal; E) S-P Seismic phases (sec); F) Observed Acoustic Signal Arrival After P (sec); G) Theoric Acoustic Signal Arrival After P (sec).

By utilizing the average propagation speed of acoustic waves in the atmosphere, inferred from the acoustic signals of recorded events (as shown in Table 1), and employing the mathematical function $y = 22.369x - 3.7368$, derived from the linear regression analysis below, it becomes feasible to predict the arrival time of acoustic waves at the RFFB5 station under similar weather conditions and distances. This method allows for the identification of a specific time window corresponding to the expected arrival time in the acoustic traces of events where no acoustic signals were recorded. The duration of the time window is determined based on the average differences observed between the calculated and observed acoustic signal arrival times, which amount to approximately 15%. **Fig. 4** displays the arrival time of the acoustic signal in seconds relative to the S-P time difference, following the P seismic phase.

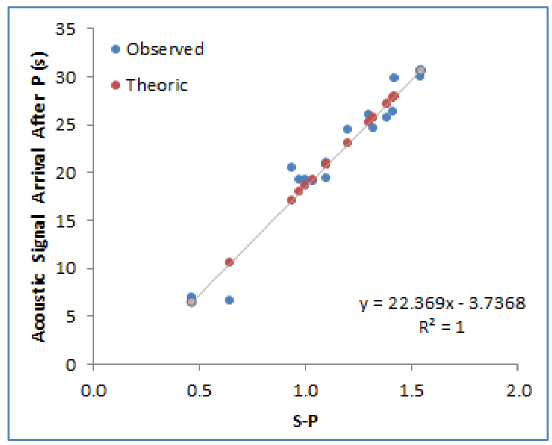

Fig. 4 – *Acoustic signal arrival time after P seismic phase, in seconds, regarding to S-P time difference.*

Results

During the monitoring period at the Sete Lagoas site, the RFFB5 station recorded seismic signals from nine possible local natural events that did not produce any acoustic signals.

However, we will only consider three of these events**, Figs. 5, 6,** and **7** (Events #20, 22, and 23 in Table 1), because they occurred outside of working hours, when detonations in mines are not typically performed. Additionally, their S-P distances are consistent with mines. Sete Lagoas local time is UTC minus three hours. The first event occurred on November 18, 2022, at 03:30 UTC, with an S-P time difference of 1.29 seconds. The second event occurred on November 22, 2022, at 03:34 UTC, with an S-P time difference of 0.84 seconds. The last event was recorded on November 24, 2022, at 02:02 UTC, with an S-P time difference of 0.75 seconds. Besides these events did not produce a detectable acoustic signal, their S-P time difference indicates that they occurred at distances consistent with mines. We do not have the exact locations of these events yet.

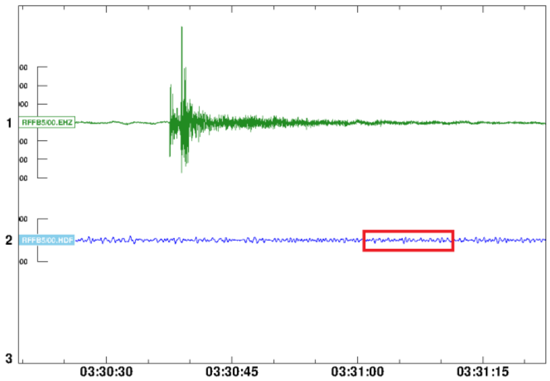

Fig. 5 – *Event recorded on November 18, 2022, at 03:30 UTC, by the RFFB5 station. The green trace (up trace) represents the seismic vertical component, while the blue trace (down trace) represents the acoustic component. The S-P time difference is 1.29 seconds (Event #20 Table 1). The red window denotes the expected record time of the acoustic signals. It was used a 4th order Butterworth Filter for the acoustic signals (1 - 3 Hz).*

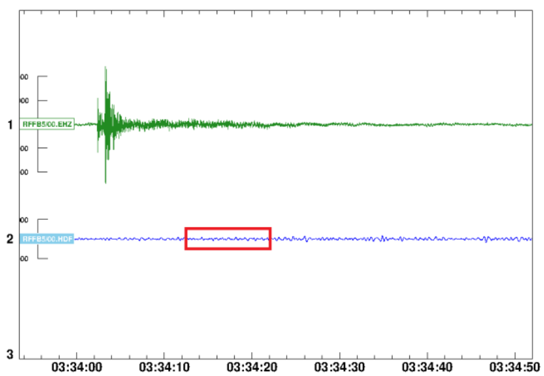

Fig. 6 – *Event recorded on November 22, 2022, at 03:34 UTC, by the RFFB5 station. The green trace (up trace) represents the seismic vertical component, while the blue trace (down trace) represents the acoustic component. The S-P time difference is 0.84 seconds (Event #22 Table 1). The red window denotes the expected record time of the acoustic signals. It was used a 4th order Butterworth Filter for the acoustic signals (1 - 3 Hz).*

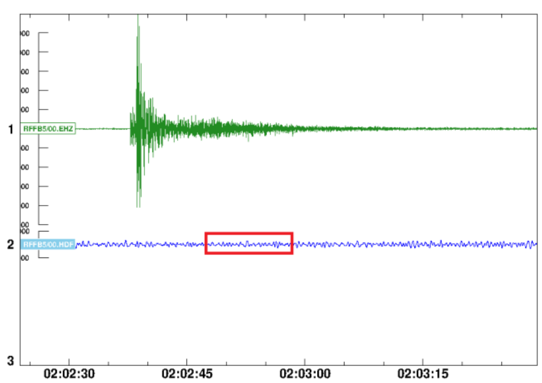

Fig. 7 – *Event recorded on November 24, 2022, at 02:02 UTC, by the RFFB5 station. The green trace (up trace) represents the seismic vertical component, while the blue trace (down trace) represents the acoustic component. The S-P time difference is 0.75 seconds (Event #23 Table 1). The red window denotes the expected record time of the acoustic signals. It was used a 4th order Butterworth Filter for the acoustic signals (1 - 3 Hz).*

Figs. 8, 9 and **10** show three examples of events that generated both seismic and acoustic signals, namely events #11, 17, and 19 from Table 1. All three events were detonations in mines that occurred at times consistent with quarry blasting.

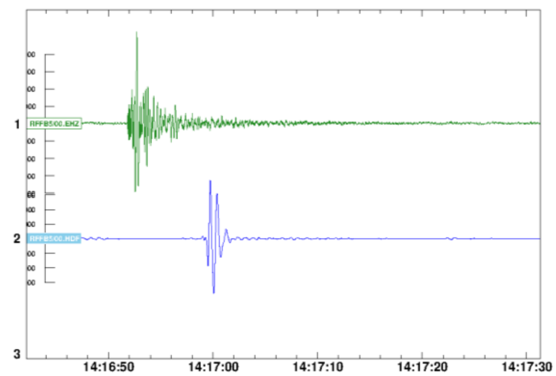

Fig. 8 – *Event recorded on October 19, 2022, at 14:16 UTC, by the RFFB5 station. The green trace (up trace) represents the seismic vertical component, while the blue trace (down trace) represents the acoustic component. The S-P time difference is 0.46 seconds, and the time difference between the P phase and the first arrival of the acoustic signal is 7.0 seconds (Event #11 in Table 1). It was used a 4th order Butterworth Filter for the acoustic signals (1 - 3 Hz).*

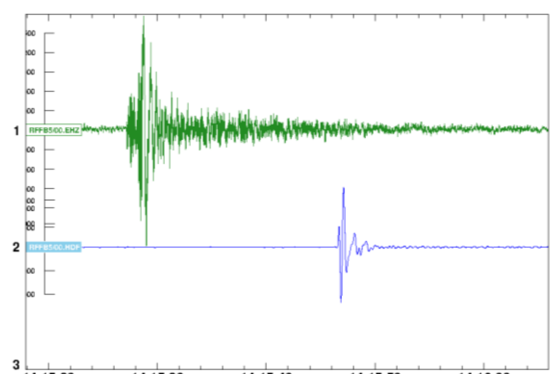

Fig. 9 – *Event recorded on October 29, 2022, at 14:15 UTC, by the RFFB5 station. The green trace (up trace) is the seismic vertical component and the blue trace (down trace) is the acoustic component. The S-P is 1.0 seconds. The time difference between the P phase and the first arrival of acoustic signal is 19.3 seconds (Event # 17 Table 1). It was used a 4th order Butterworth Filter for the acoustic signals (1 - 3 Hz).*

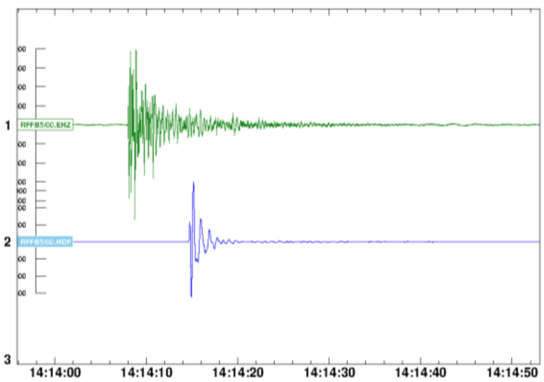

Fig. 10 – *Event recorded on October 31, 2022, at 14:14 UTC, by the RFFB5 station. The seismic vertical component is depicted in green (up trace) and the acoustic component is shown in blue (down trace). The S-P interval is 0.64 seconds, and the time difference between the P phase and the first arrival of the acoustic signal is 6.6 seconds (Event #19 in Table 1). It was used a 4th order Butterworth Filter for the acoustic signals (1 - 3 Hz).*

Discussion

The text point out some methods employed for differentiating between quarry blasts and shallow micro-earthquakes in seismic recordings. Additionally, it introduces an alternative approach utilizing co-located seismic and infrasound station to monitor local natural and man-made events with epicenters close to each other. It is raised the lack of crucial information provided by mine companies, such as the origin time, explosive charge, and delay time of detonations. This lack of information can hinder accurate event analysis and classification.

Explosions in mines generate both seismic and acoustic signals that can be detected by infrasound stations. The detectability of these signals depends on various factors such as distance, explosive charge, and meteorological conditions. Infrasound stations can serve as effective tools for detecting events, particularly when it comes to distinguishing between natural events triggered by mines and other types of events.

The text emphasizes three events that did not produce any acoustic signals. These events can be considered as discriminants, suggesting that they were natural events occurring inside the mine. This highlights the potential of using the absence of acoustic signals as an indicator for categorizing events.

Infrasound stations prove valuable in situations where there is uncertainty surrounding the nature of an event. They can provide reliable information and contribute to accurate event characterization, especially in cases where crucial data is not provided by the mine companies.

Conclusions

The utilization of a co-located seismic and infrasound station presents an effective method for monitoring both local natural and man-made events. The absence of detectable acoustic signals in local events serves as a useful discriminator, allowing for the classification of events either as natural occurrences or triggered by the mine when they take place within the pit. Infrasound stations have proven to be reliable sources of information, particularly in situations where uncertainty exists regarding the nature of an event.

It is important to note that the detectability of seismo-acoustic signals is influenced by various factors, including event magnitude, distance, and meteorological conditions. The case study conducted in Sete Lagoas revealed that low-magnitudes earthquakes did not produce detectable acoustic signals, even with an infrasound station close to the source (~5 km). Therefore, while the co-located seismic and infrasound station offers significant advantages, it is necessary to consider additional factors and account for variations in event characteristics and signal detectability. The way to manage these factors is to deploy one or two 4-elements infrasound array in the vicinities of the mines under investigating, in order to locate the source.

Overall, the combination of seismic and infrasound monitoring provides a comprehensive and reliable approach to monitoring events. It enhances our understanding of both natural and man-made events by contributing to event classification.

Acknowledgments

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