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Characterisation of the Coherent Infrasound Sources Recorded by the Infrasound International Monitoring System Station I48TN in Tunisia (Mines & Quarries)

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Abstract

The I48TN is one of the 60 International Monitoring System (IMS) stations of the Comprehensive nuclear Test Ban Treaty Organization (CTBTO), characterized by its location in the heart of the IMS Infrasound network. The ability of the International Monitoring System (IMS) infrasound network to detect atmospheric nuclear explosions and other signals of interest is strongly dependent on station-specific ambient noise. This ambient noise, includes both incoherent wind noise and real coherent infrasonic waves. Infrasound analysis software detects tens to hundreds of events per day which consume a lot of time for the Infrasound analysts, to define and categorize events where around 90% of the detections are coherent noise. This study analyzed the importance of the synergy between infrasound and seismic data, and provided the infrasound data analyst with the most important local coherent infrasound sources in the region as recorded by the IMS station I48TN, in order to reduce the workload of the analysts and give them a clear view on the coherent noise affecting this station for better discrimination between events of interest like nuclear explosions and coherent sources. DTK_GPMCC and DIVA software were used to perform this study. Geotool software from the International Data Centre (IDC) was used in analysing seismic data from the Tunisian IMS station KEST. The result of this study allowed the characterization of the most important coherent local infrasound sources (Mines and Quarries) which are considered as coherent noise to I48TN station and correct parameters in some reference events in the Reference Event Database source of the International Data Centre.

Keywords

Mines and Quarries, Infrasound Stations, Infrasound Local Sources, Acoustic Energy

1. Introduction

The Infrasound station I48TN in Tunisia is one of the most important Infrasound stations in the International Monitoring System (IMS) network with its location in the heart of the IMS infrasound network (**Figure 1(a)**). The objective of the IMS infrasound network in the verification regime is to detect nuclear explosion in the atmosphere and the surface of the earth where all other sources are considered as noise. The ambient noise, includes both incoherent wind noise and real coherent infrasonic waves [1] can affect the infrasound analyst work, which can be much easier if he is aware of the ambient coherent infrasound sources, in order to distinguish between the coherent noise and the sources of interest. For this reason, this study focused on one of the 60 IMS infrasound station (I48TN) to define and characterize the mines and quarries sources in the region recorded by the Tunisian station in order to contribute to the ongoing effort of infrasound experts to define and characterize the existing coherent noise which is around 85% to 90% of the detections [2] for all Infrasound IMS network stations, as most of the existing studies focused on some separate events and not for long term observations to define and characterize the coherent Infrasound sources.

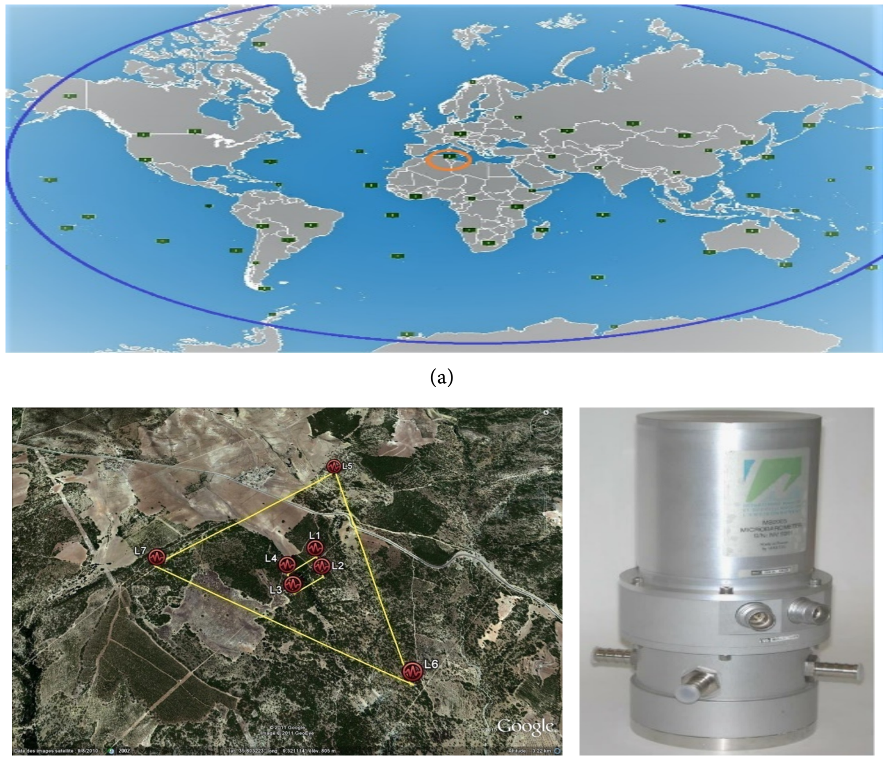
2. Location of the I48TN

I48TN is located in Latitude 35˚.80523 and Longitude 9˚.32302 at 800 m above the sea level in the north west of Tunisia. It is the only infrasound station in North Africa (**Figure 1(a)**) and very close to Europe. Data from I48TN is used for the production of the European Infrasound Bulletin [3].

I48TN is an infrasound array that is composed of seven sites (**Figure 1(b)**) and one meteorological station within the site 1. Each site is equipped with a Microbarometer MB2005 (**Figure 1(c)**) from 2006 to 2017 and MB3a from 2017 up to now. Both sensors were developed by the CEA, France [4], and evaluated by SANDIA laboratory [5].

3. Software and Data Used in This Study

The software used for data analysis in this study are provided by the International Data Centre of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) to the National Data Centres of the state signatories within the



(a)

(b) (c)

Figure 1. (a) IMS infrasound network (© CTBTO); (b) I48TN (© Google, image © 2011 GeoEye); (c) MB2005.

NDC-in-A-Box package. The DTK_GPMCC version 6.3.0 to analyse the infrasound data, DIVA version 3.4.3 [6] [7] (Copyright © 2016, Commissariat à l'energie atomique et aux énergies alternatives (CEA)) to visualize long-term detections and Geotool version 2.3.91 (Copyright © 2015, CTBTO) to analyse the seismic data. Geotool uses Generic Mapping Tools (GMT) to generate maps [8]. The NDC-in-A-Box package software is used by the National Data Centres (NDCs) and for the NDC training cycle in the International Data Centre [9]. The 1/3 octave configuration is used for the Infrasound data processing [10]. The National Data Centre in Madagascar provided the Raytracer software used to perform the raytracing. Eleven years of collected Infrasound data from the I48TN station and some specific periods of time from the seismic station KEST were used for this study. Data are available for authorized users from the state parties of the Comprehensive Nuclear Test Ban Treaty Organization. Also, the data can be available for academic purpose via a virtual Data Exploration Center after signing an agreement with the CTBTO.

4. Propagation of Infrasound Waves

The speed of sound for an ideal gas is given by:

$$C_{ideal} = \sqrt{\gamma_g R_c T_a} \quad (1)$$

where γ_g gives the ratio of the specific heats, R_c is the gas constant and T_a

represents the absolute temperature. This equation applies only when the sound wave is a small perturbation with respect to the ambient pressure. For air at room temperature, the multiplication of γ_g with R_c equals 402.8 $m^2 \cdot s^{-2} \cdot K^{-1}$ and so the speed of sound in air is given by:

$$C_{air} = \sqrt{402.8 T_a} \tag{2}$$

The atmosphere influences infrasound propagation, with the composition, temperature and wind as the important controlling variables. Using equation 1 for C_{ideal} and taking into account this wind effect as well, [11] describe the so-called effective sound:

$$C_{eff} = \sqrt{\gamma_g R_c T_a} + \hat{n}_{xy} \cdot \overline{u} \tag{3}$$

The inner product between the wind speed vector $\overline{u}$ and the unit vector $\hat{n}_{xy}$ gives the contribution of the wind for infrasound waves traveling from source location $\overline{x}$ to receiver location $\overline{y}$. This means that C_{eff} is positively affected by wind vectors having a component in the direction of propagation and negatively affected by winds with a component opposing the propagation direction of the infrasound waves [12]. Refraction of infrasound follows from Snell's law and the bending of infrasound waves towards the earth's surface depends on the combined effect of temperature and the wind. As the temperature and wind vector change when traveling upwards through the atmosphere, so does the effective sound speed.

C_{eff} relates to the square root of the temperature. The combined effect of this temperature effect and the contribution of the wind vector controls the refraction of infrasound waves. In general, due to the temperature increase with altitude in the stratosphere and thermosphere, these two layers have a high potential of acting as a duct for upward traveling infrasound waves [13] [14]. Attenuation of infrasound is frequency dependent. Both, the classical amplitude absorption coefficient and the rotational amplitude absorption co-efficient relate to the square of the frequency [15]. As the total amplitude coefficient is the sum of these two coefficients, the attenuation of infrasound is related to the square of the frequency.

5. General Observation on the Detections at I48TN from 2006 to 2012

The long-term period detection from 2006 to 2012 visualized by DIVA software (**Figure 2**), shows the most coherent sources azimuths in the station I48TN. Most of those sources are repetitive and from different azimuths and will be defined starting from this observation.

6. General Observation on the Detections at I48TN from 2016 to 2019

The observation was continued for the last four years (2016-2019) to confirm the azimuths and all parameters related to the repetitive infrasound sources in the station I48TN. The long-term observation (**Figure 2** and **Figure 3**) shows some

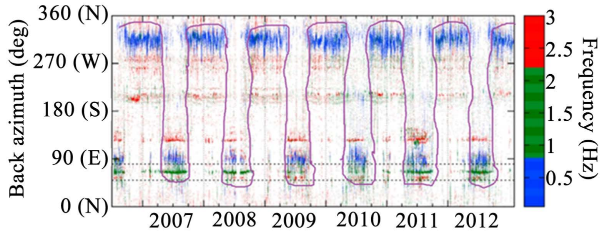


Figure 2. Long-term observation of infrasound detections at I48TN from 2006 to 2012.

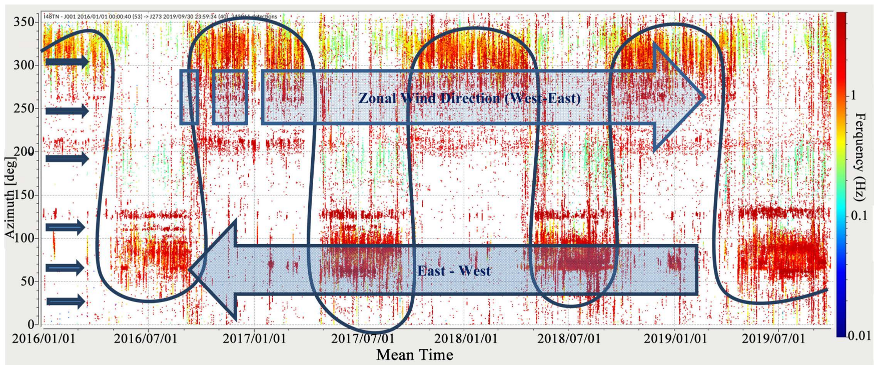


Figure 3. Long-term observation of infrasound detections at I48TN from 2016 to 2019.

repetitive infrasound sources and the influence of the zonal wind on the detections at the station. In Summertime most of the detections are Westward and in wintertime most of the detections are Eastward (**Figure 3**).

7. Repetitive Infrasound Sources (Mines and Quarries) Detected by the I48TN

As shown in **Figure 4**, some known infrasound sources were ignored (black color), as the microbaroms from the Ocean; Mediterranean Sea and the two Volcanos (Etna and Stromboli), in order to focus on the other coherent sources. Most of the sources in red are quarries and mines observed by the IMS station IS48 in the last few years. Most of the coherent infrasound sources in Tunisia are in the South-West and some of them in the neighboring countries like Algeria (**Figure 5**).

The detected infrasound sources (mines and quarries) will be presented one by one; based on the Long-term observation of infrasound detections at I48TN and the Pg and Lg arrivals from the IMS seismic station (KEST) in Tunisia, situated at the Latitude: 35˚.7317 and Longitude: 9˚.346. The IMS station “KEST” is a broadband 3-component primary seismic station, equipped with a seismometer CMG-3TB [16]. The sensor is installed in a 100 m deep borehole.

7.1. Phosphate Mine in Mdhilla, Tunisia

7.1.1. Ground Truth Information

The coordinates in **Table 1** are from Google Earth and are the same used in the Infrasound Reference Event Database source of the International Data Centre [17]. The origin time is based on seismic arrivals at KEST station (**Figure 10**).

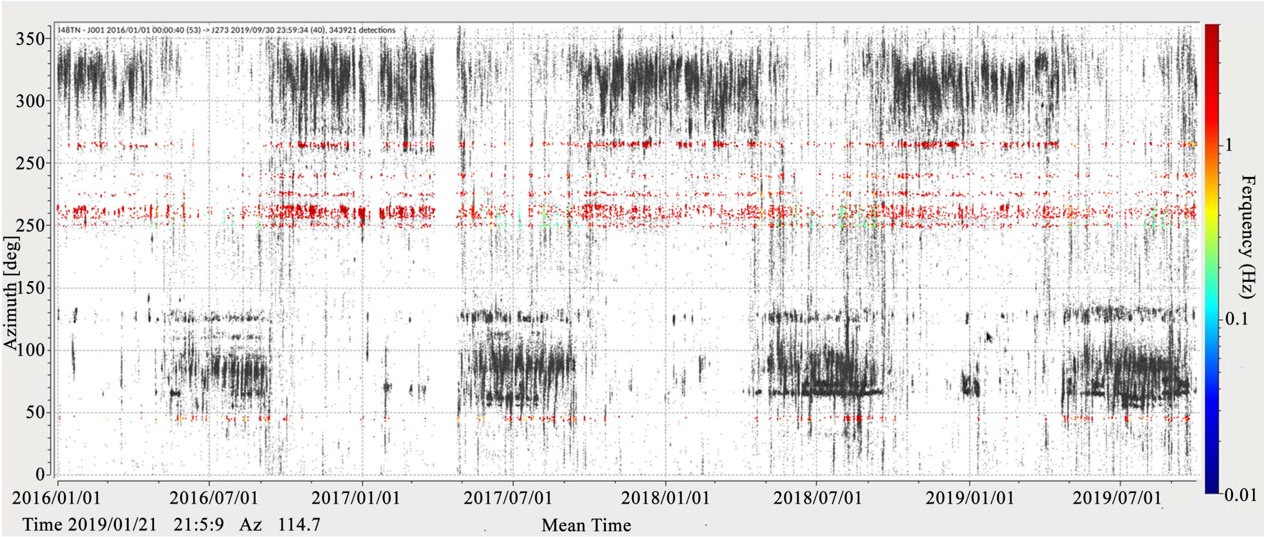


Figure 4. Coherent infrasound sources observed in I48TN.

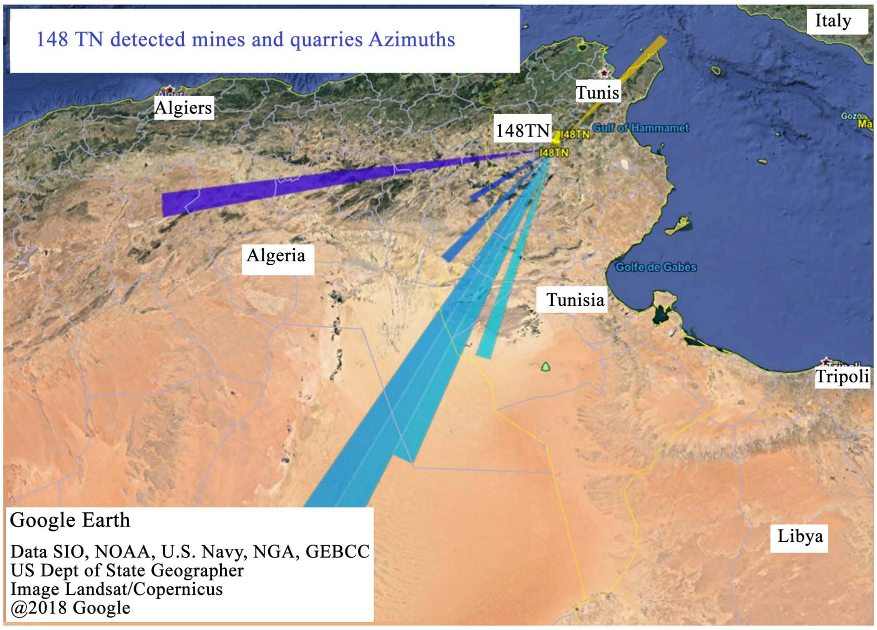


Figure 5. Back azimuths of coherent infrasound sources at I48TN (Map data: Google, Maxer Technologies).

Table 1. Ground truth information of Mdhilla mine in Tunisia.

Category	Mine and Quarry
Origin time	2007-02-14 13:41:35
Latitude	34˚.210
Longitude	8˚.620
Depth (km)	0
Theoretical Back Azimuth from I48TN	200.05
Distance to I48TN	188.26 km

7.1.2. Detection Information

A repetitive infrasound source in the Azimuth ~200˚ in red color was observed with the long-term observation (Figure 6). Based on this long-term observation, this repetitive source is considered as a coherent noise for the I48TN and it is dominant in wintertime of the year following the zonal wind direction as the source is in South-West side of the station.

The result of analysing the IMS data from the infrasound station I48TN for the date of 14th of February 2007 using the latest version of the DTK-GPMCC software (Figure 7) shows the characteristics of the repetitive coherent source coming from the back Azimuth ~200˚ as described in Table 2.

Table 2. Infrasound analysis results from I48TN data.

Station	Time	Phase	BackAz	Speed (m/s)	Frequency
I48TN	2007-02-14 13:53:29	I	**200˚.706**	352	2.197

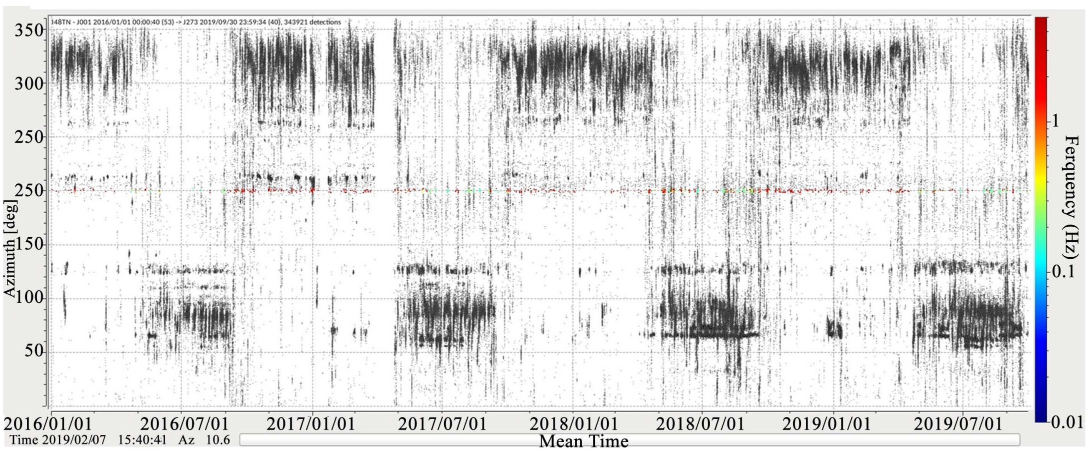
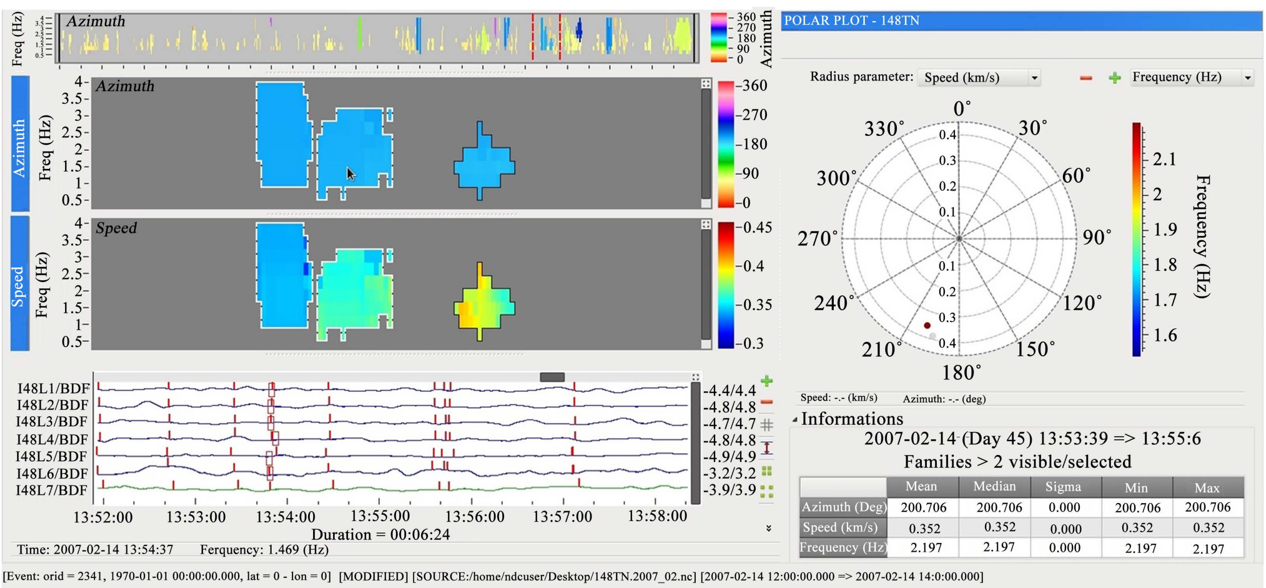


Figure 6. Long-term observation of Mdhilla mine activities.



	Mean	Median	Sigma	Min	Max
Azimuth (Deg)	200.706	200.706	0.000	200.706	200.706
Speed (km/s)	0.352	0.352	0.000	0.352	0.352
Frequency (Hz)	2.197	2.197	0.000	2.197	2.197

Figure 7. I48TN Infrasound detection information from Mdhilla mine on 2007-02-14.

By analysing the seismic data from the IMS station (KEST) in Tunisia for the same period of time by using the Geotool software (**Figure 8**), Pg and Lg arrivals were added and the origin time was defined “13:41:35” as shown in **Figure 10** and described in **Table 3**.

The map in **Figure 9** and the event location in **Figure 10** are the results of picking the Pg and Lg seismic phases with Geotool software in the data collected from KEST seismic station and by adding the infrasound I phases observed with DTK-GPMCC on the infrasound data from the I48TN (**Table 2**).

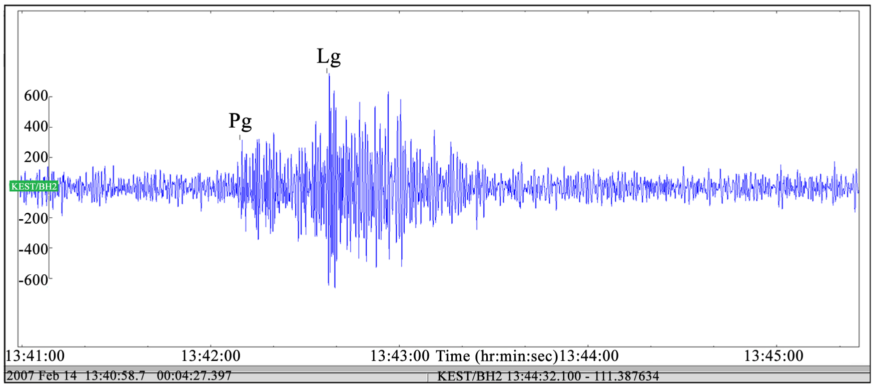


Figure 8. KEST Seismic detection information from Mdhilla mine on 2007-02-14.

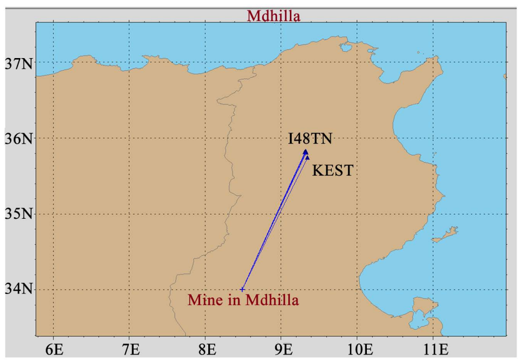


Figure 9. Geotool map for the event using GMT [8].

orid	lat	lon	depth	time	sdepth
-68	34.0027	8.4903	0.0000	2007Feb14 13:41:35	-1.0000

P	T	A	S	sta	P-68	timeres-68	time
Pg	d	n	n	KEST	Pg	0.61	2007Feb14 13:42:08
Lg	d	n	n	KEST	Lg	-0.48	2007Feb14 13:42:36
I	d	n	n	I48L6	I	13.69	2007Feb14 13:53:49
I	d	n	n	I48L7	I	14.15	2007Feb14 13:53:50
I	d	n	n	I48L3	I	12.93	2007Feb14 13:53:49
I	d	n	n	I48L4	I	12.69	2007Feb14 13:53:50
I	d	n	n	I48L2	I	12.43	2007Feb14 13:53:50
I	d	n	n	I48L1	I	11.88	2007Feb14 13:53:50
I	d	n	n	I48L5	I	8.65	2007Feb14 13:53:50

Figure 10. Event location using Geotool software.

Table 3. Seismic analysis results from KEST data.

Origin Time			2007-02-14 13:41:35		
Station	Time	Phase	Latitude	Longitude	Depth (km)
KEST	2007-02-14 13:42:08	Pg	34˚.0027	8˚.4903	0
KEST	2007-02-14 13:42:36	Lg			

7.2. Phosphate Mine in Metlaoui, Tunisia

7.2.1. Ground Truth Information

The coordinates in Table 4 are from google earth and are the same used in the Infrasound Reference Event Database source of the IDC [17]. The origin time is based on seismic arrivals at KEST (Figure 15).

7.2.2. Detection Information

A repetitive infrasound source in the Azimuth ~207˚ in red color was observed with the long-term observation (Figure 11). Based on this long-term observation, this repetitive source is considered as a coherent noise for the I48TN and it is dominant in wintertime of the year following the zonal wind direction as the source is in South-West side of the station.

The result of analysing the IMS data from the infrasound station I48TN for the date of 14th of February 2007 using the latest version of the DTK-GPMCC software (Figure 12) shows the characteristics of the repetitive coherent source coming from the back Azimuth ~207˚ as described below in Table 5.

By analysing the seismic data from the IMS station (KEST) in Tunisia for the same period of time by using the Geotool software (Figure 13), Pg and Lg arrivals were added and the origin time was defined "13:12:30" as shown in (Figure 15) and described in Table 6.

The map in Figure 14 and the event location in Figure 15 are the results of picking the Pg and Lg seismic phases with Geotool software in the data collected from KEST seismic station (Table 6) and by adding the infrasound I phases observed with DTK_GPMCC on the infrasound data from the I48TN (Table 5).

7.3. Phosphate Mine in Redeyef, Tunisia

7.3.1. Ground Truth Information

The coordinates in Table 7 are from google earth and are the same used in the Infrasound Reference Event Database source of the IDC [17]. The origin time is based on seismic arrivals at KEST station (Figure 20).

7.3.2. Detection Information

A repetitive infrasound source in the Azimuth ~212˚ in red color was observed with the long-term observation (Figure 16). Based on this long-term observation, this repetitive source is considered as a coherent noise for the I48TN and it is dominant in wintertime of the year following the zonal wind direction as the source is in the South-West side of the station.

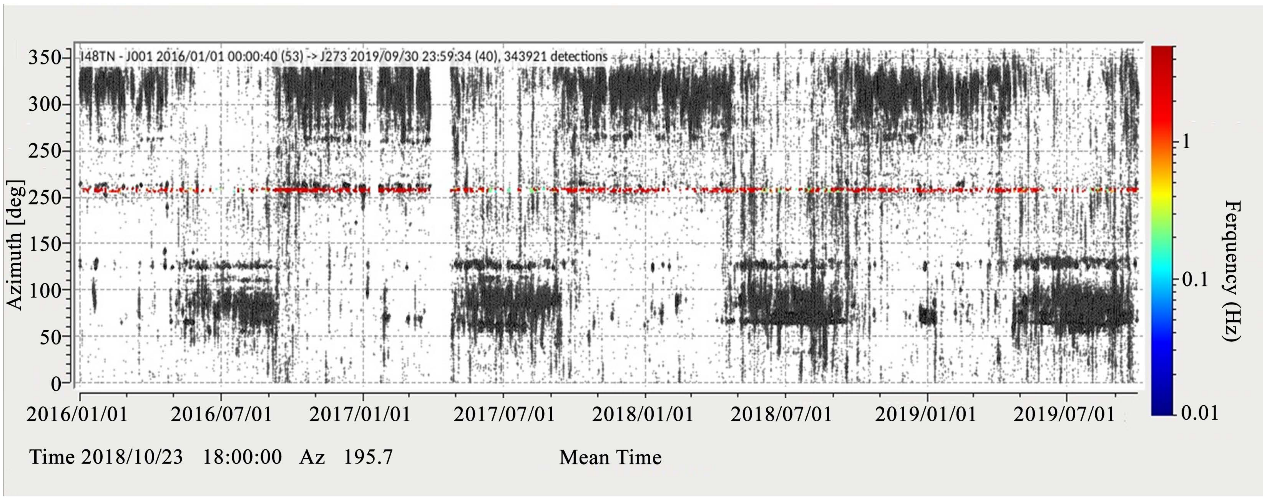


Figure 11. Long-term observation of Metlaoui mine activities.

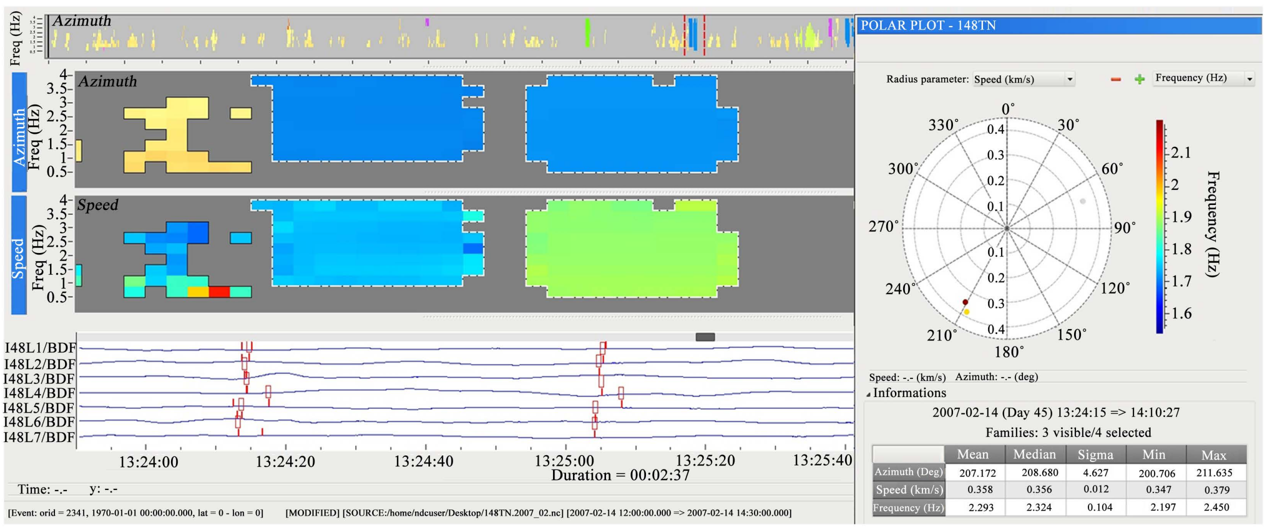


Figure 12. I48TN Infrasound detection information from Metlaoui mine on 2007-02-14.

Table 4. Ground truth information of Metlaoui mine in Tunisia.

Category	Mine and Quarry
Origin time	2007-02-14 13:12:30
Latitude	34˚.380
Longitude	8˚.450
Depth (km)	0
Theoretical Back Azimuth from I48TN	206.87
Distance to I48TN	177.04 Km

Table 5. Infrasound analysis results from I48TN data.

Station	Time	Phase	BackAz	Speed (m/s)	Frequency
I48TN	2007-02-14 13:24:15	I	**207˚.172**	358	2.293

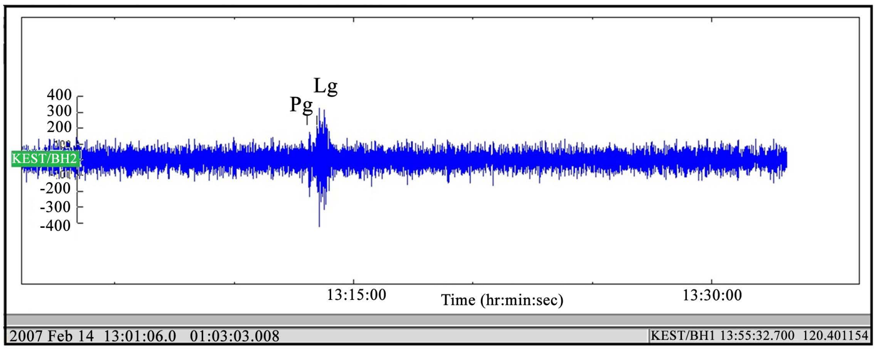


Figure 13. KEST Seismic detection information from Metlaoui mine on 2007-02-14.

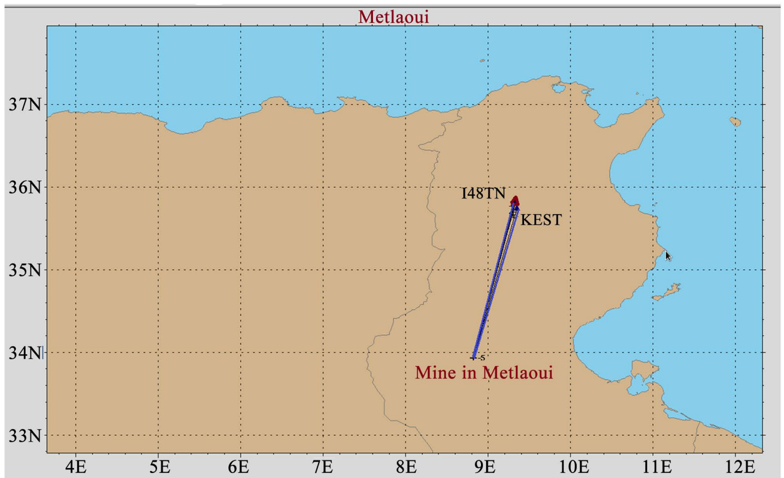
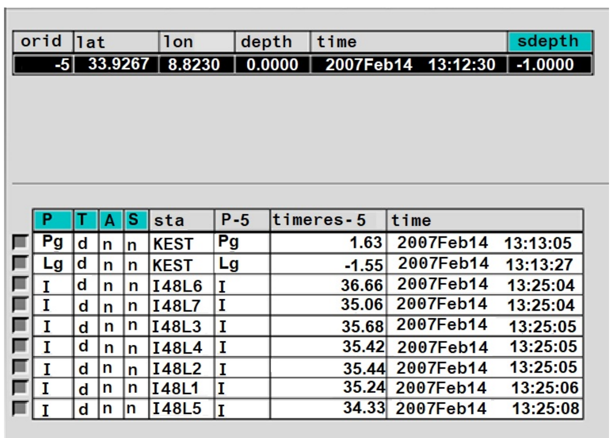


Figure 14. Geotool map for the event using GMT [8].



orid	lat	lon	depth	time	sdepth
-5	33.9267	8.8230	0.0000	2007Feb14 13:12:30	-1.0000

P	T	A	S	sta	P-5	timeres-5	time
Pg	d	n	n	KEST	Pg	1.63	2007Feb14 13:13:05
Lg	d	n	n	KEST	Lg	-1.55	2007Feb14 13:13:27
I	d	n	n	I48L6	I	36.66	2007Feb14 13:25:04
I	d	n	n	I48L7	I	35.06	2007Feb14 13:25:04
I	d	n	n	I48L3	I	35.68	2007Feb14 13:25:05
I	d	n	n	I48L4	I	35.42	2007Feb14 13:25:05
I	d	n	n	I48L2	I	35.44	2007Feb14 13:25:05
I	d	n	n	I48L1	I	35.24	2007Feb14 13:25:06
I	d	n	n	I48L5	I	34.33	2007Feb14 13:25:08

Figure 15. Event location using Geotool software.

Table 6. Seismic analysis results from KEST data.

Origin Time			2007-02-14 13:12:30		
Station	Time	Phase	Latitude	Longitude	Depth (km)
KEST	2007-02-14 13:13:05	Pg	33˚.9267	8˚.823	0
KEST	2007-02-14 13:13:27	Lg			

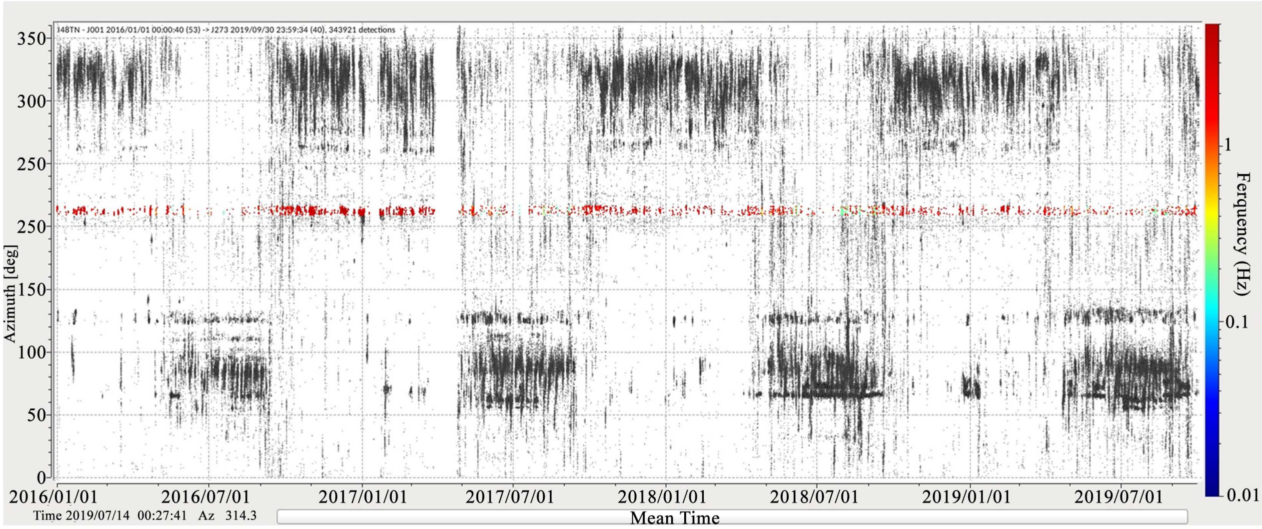


Figure 16. Long-term observation of Redeyef mine activities.

Table 7. Ground truth information of Redeyef mine in Tunisia.

Category	Mine and Quarry
Origin time	2007-02-16 12:21:13
Latitude	34˚.390
Longitude	8˚.240
Depth (km)	0
Theoretical Back Azimuth from I48TN	212˚.36
Distance to I48TN	185.49 Km

The result of analysing the IMS data from the infrasound station I48TN for the date of 16th of February 2007 using the latest version of the DTK-GPMCC software (Figure 17) shows the characteristics of the repetitive coherent source coming from the back Azimuth ~212˚ as described below in Table 8.

By analysing the seismic data from the IMS station (KEST) in Tunisia for the same period of time by using the Geotool software (Figure 18), Pg and Lg arrivals were added and the origin time was defined "12:21:13" as shown in (Figure 20) and described in Table 9.

The map in Figure 19 and the event location in Figure 20 are the results of picking the Pg and Lg seismic phases with Geotool software in the data collected from KEST seismic station (Table 9) and by adding the infrasound I phases observed with DTK_GPMCC on the infrasound data from the I48TN (Table 8).

7.4. Phosphate Mine in Djebel Onk, Algeria

7.4.1. Ground Truth Information

The coordinates in Table 10 are from google earth and are the same used in the Infrasound Reference Event Database source of the International Data Centre [17]. The origin time is based on seismic arrivals at KEST station (Figure 25).

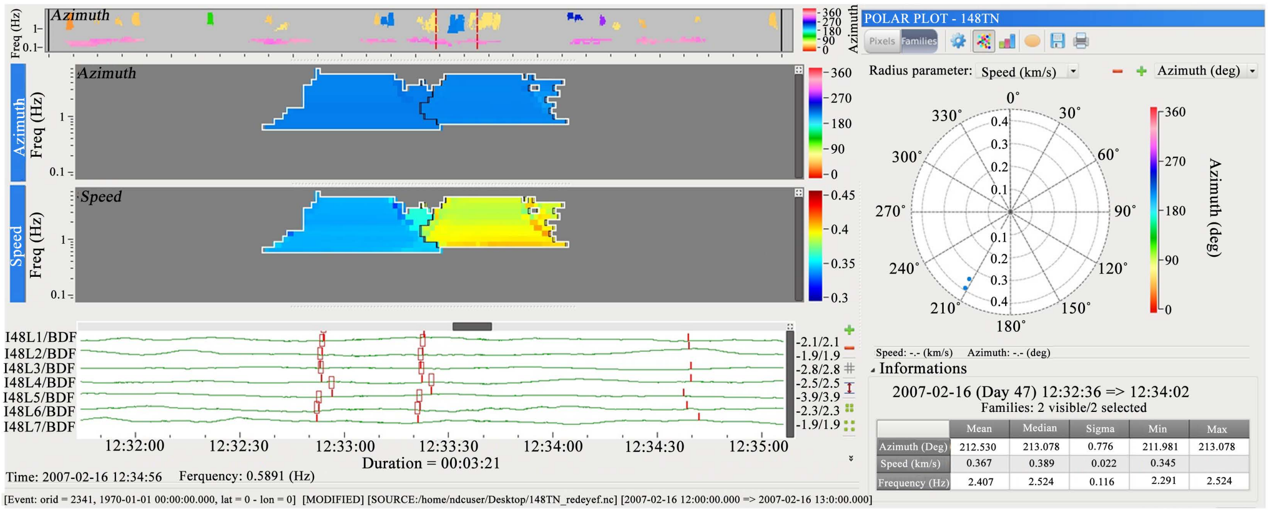


Figure 17. I48TN Infrasound detection information from Redeyef mine on 2007-02-16.

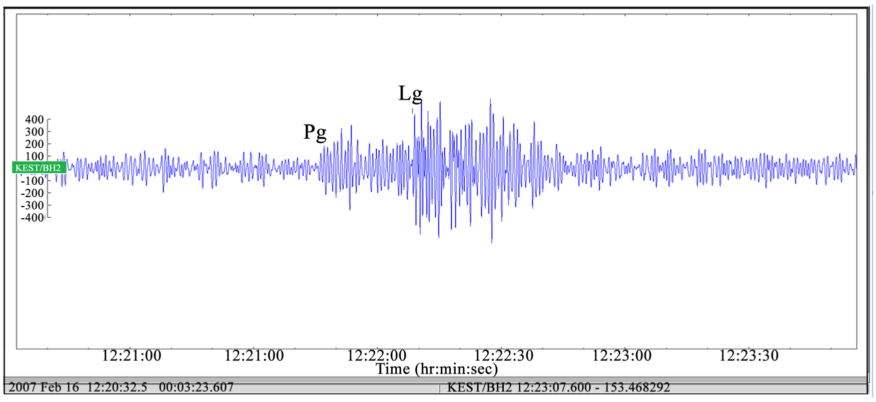


Figure 18. KEST Seismic detection information from Redeyef mine on 2007-02-16.

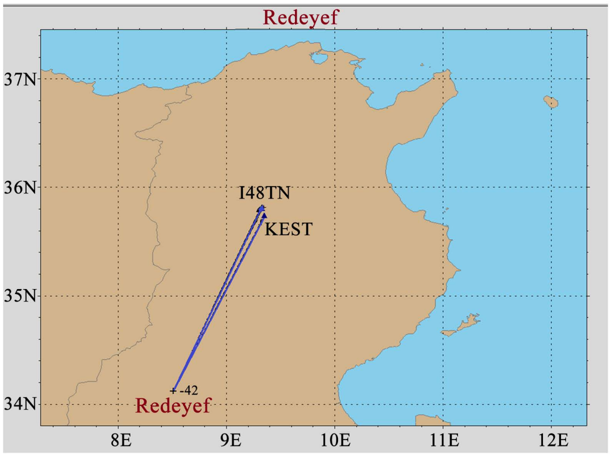


Figure 19. Geotool map for the event using GMT [8].

Table 8. Infrasound analysis results from I48TN data.

Station	Time	Phase	BackAz	Speed (m/s)	Frequency
I48TN	2007-02-16 12:32:36	I	**212˚.530**	367	2.407

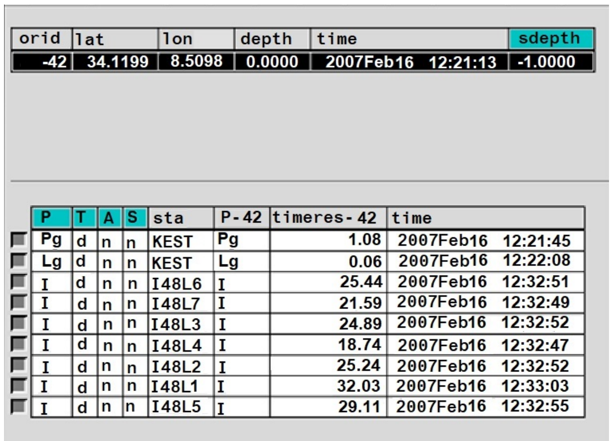


Figure 20. Event location using Geotool software

Table 9. Seismic analysis results from KEST data.

Origin Time			**2007-02-16 12:21:13**		
Station	Time	Phase	Latitude	Longitude	Depth (km)
KEST	2007-02-16 12:21:45	Pg	34˚.119	8˚.509	0
KEST	2007-02-16 12:22:08	Lg			

Table 10. Ground truth information of Djebel Onk mine in Algeria.

Category	Mine and Quarry
Origin time	2007-02-25 12:11:25
Latitude	34˚.700
Longitude	8˚.000
Depth (km)	0
Theoretical Back Azimuth from I48TN	224˚.73
Distance to I48TN	171.84 Km

7.4.2. Detection Information

A repetitive infrasound source in the Azimuth ~224˚ in red color was observed with the long-term observation (**Figure 21**). Based on this long-term observation, this repetitive source is considered as a coherent noise for the I48TN and it is dominant in wintertime of the year following the zonal wind direction as the source is in South-West side of the station.

The result of analysing the IMS data from the infrasound station I48TN for the date of 25th of February 2007 using the latest version of the DTK-GPMCC software (**Figure 22**) shows the characteristics of the repetitive coherent source coming from the back Azimuth ~224˚ as described in **Table 11**.

By analysing the seismic data from the IMS station (KEST) in Tunisia for the same period of time by using the Geotool software (**Figure 23**), Pg and Lg arrivals were added and the origin time was defined "12:11:25" as shown in (**Figure 25**) and described in **Table 12**.

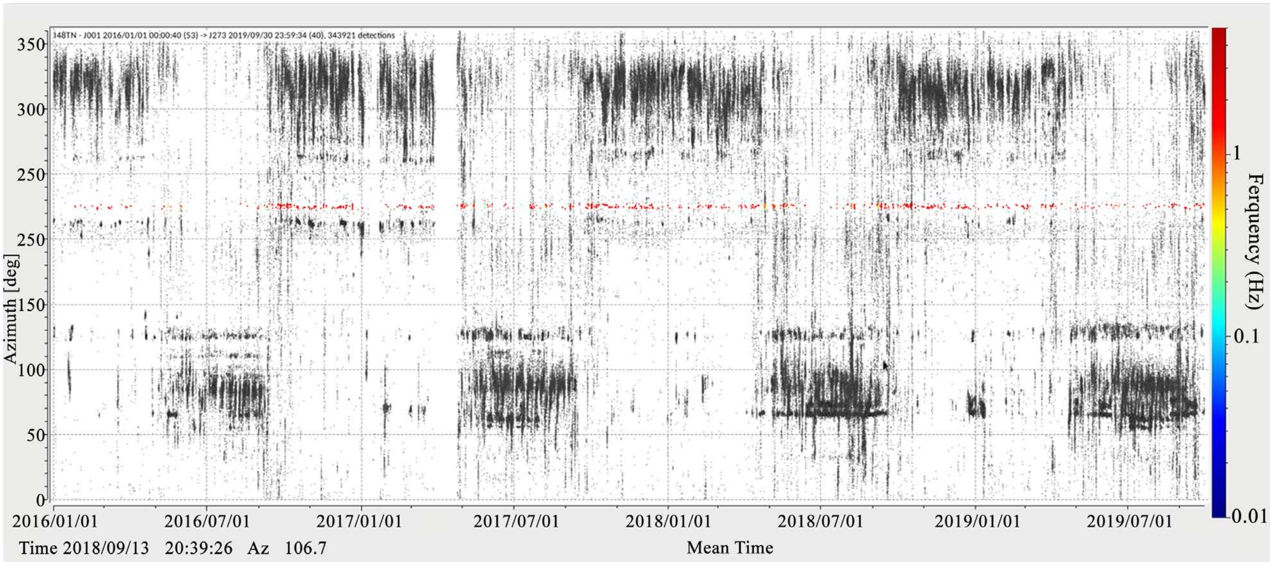


Figure 21. Long-term observation of Djebel Onk mine activities.

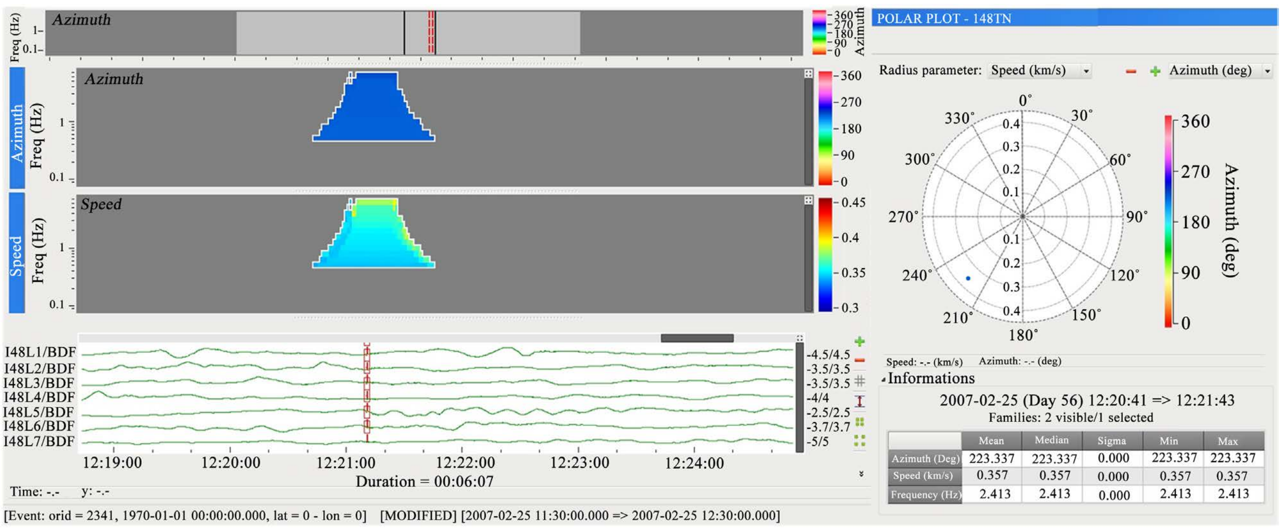


Figure 22. I48TN Infrasound detection information from Djebel Onk mine on 2007-02-25.

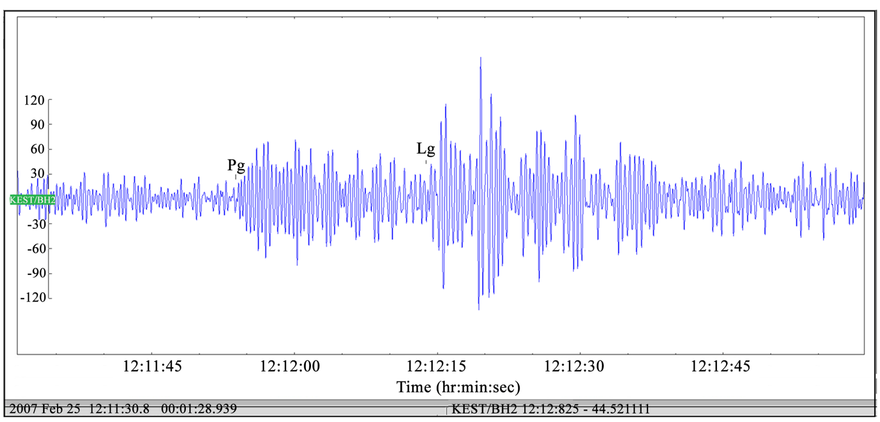


Figure 23. KEST Seismic detection information from Djebel Onk mine on 2007-02-25.

Table 11. Infrasound analysis results from I48TN data.

Station	Time	Phase	BackAz	Speed (m/s)	Frequency
I48TN	2007-02-25 12:20:41	I	**223˚.337**	357	2.413

Table 12. Seismic analysis results from KEST data.

Origin Time			**2007-02-25 12:11:25**		
Station	Time	Phase	Latitude	Longitude	Depth (km)
KEST	2007-02-25 12:11:53	Pg	34˚.566	8˚.129	0
KEST	2007-02-25 12:12:13	Lg			

The map of event in **Figure 24** and the event location in **Figure 25** are the results of picking the Pg and Lg seismic phases with Geotool software in the data collected from KEST seismic station (**Table 12**) and by adding the infrasound I phases observed with DTK_GPMCC on the infrasound data from the I48TN (**Table 11**).

7.5. Mine in Mechtat Ouled Saad, Algeria

7.5.1. Ground Truth Information

The coordinates in **Table 13** are from google earth and are the same used in the Infrasound Reference Event Database source of the International Data Centre [17]. The origin time is based on seismic arrivals at KEST (**Figure 30**).

7.5.2. Detection Information

A repetitive infrasound source in the Azimuth ~239˚ in red color was observed with the long-term observation (**Figure 26**). Based on this long-term observation, this repetitive source is considered as a coherent noise for the I48TN and it is dominant in wintertime of the year following the zonal wind direction as the source is in South-West side of the station.

The result of analysing the IMS data from the infrasound station I48TN for the date of 21st of February 2007 using the latest version of the DTK-GPMCC software (**Figure 27**) shows the characteristics of the repetitive coherent source coming from the back Azimuth ~239˚ as described in **Table 14**.

By analysing the seismic data from the IMS station (KEST) in Tunisia for the same period of time by using the Geotool software (**Figure 28**), Pg and Lg arrivals were added and the origin time was defined "12:57:31" as shown in (**Figure 30**) and described in **Table 15**.

The map of event in **Figure 29** and the event location in **Figure 30** are the results of picking the Pg and Lg seismic phases with Geotool software in the data collected from KEST seismic station (**Table 15**) and by adding the infrasound I phases observed with DTK_GPMCC on the infrasound data from the I48TN (**Table 14**).

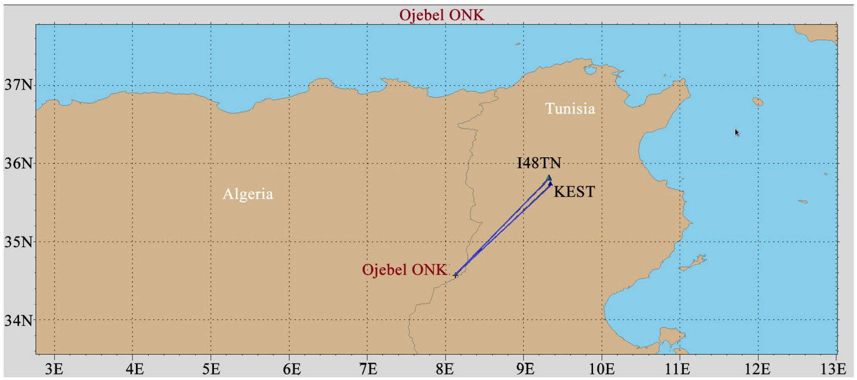
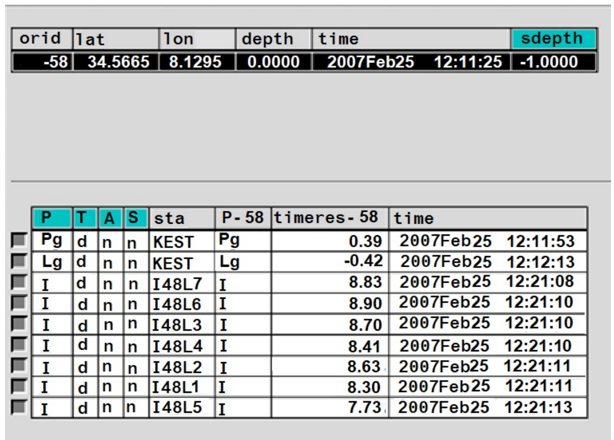


Figure 24. Geotool map for the event using GMT [8].



orid	lat	lon	depth	time	sdepth
-58	34.5665	8.1295	0.0000	2007Feb25 12:11:25	-1.0000

P	T	A	S	sta	P-58	timeres-58	time
Pg	d	n	n	KEST	Pg	0.39	2007Feb25 12:11:53
Lg	d	n	n	KEST	Lg	-0.42	2007Feb25 12:12:13
I	d	n	n	I48L7	I	8.83	2007Feb25 12:21:08
I	d	n	n	I48L6	I	8.90	2007Feb25 12:21:10
I	d	n	n	I48L3	I	8.70	2007Feb25 12:21:10
I	d	n	n	I48L4	I	8.41	2007Feb25 12:21:10
I	d	n	n	I48L2	I	8.63	2007Feb25 12:21:11
I	d	n	n	I48L1	I	8.30	2007Feb25 12:21:11
I	d	n	n	I48L5	I	7.73	2007Feb25 12:21:13

Figure 25. Event location using Geotool software.

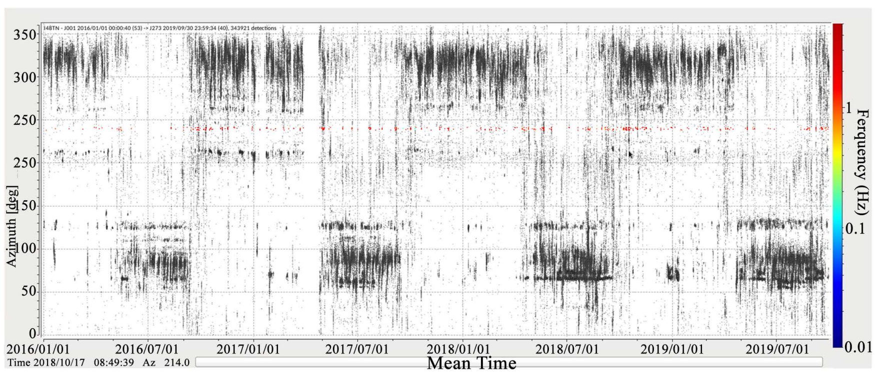


Figure 26. Long-term observation of Mechtat Ouled Saad mine activities.

Table 13. Ground truth information of Mechtat Ouled Saad mine in Algeria.

Category	Mine and Quarry
Origin time	2007-02-21 12:57:31
Latitude	35˚.230
Longitude	8˚.180
Depth (km)	0
Theoretical Back Azimuth from I48TN	238˚.60
Distance to I48TN	121.75 Km

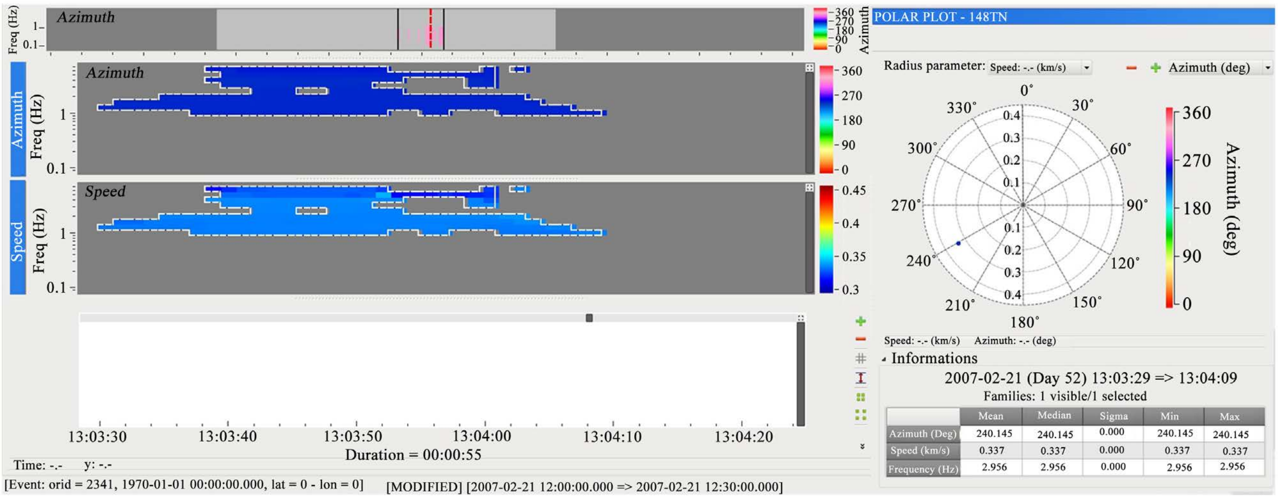


Figure 27. I48TN Infrasound detection information from Mechtat Ouled Saad mine on 2007-02-21.

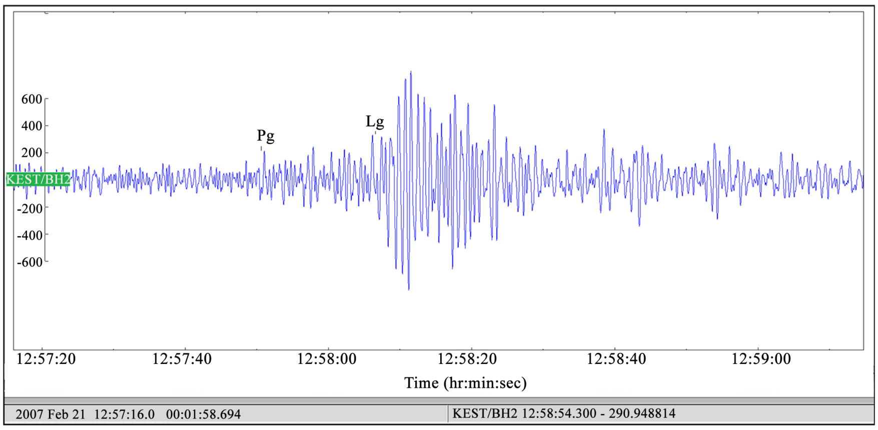


Figure 28. KEST Seismic detection information from Mechtat Ouled Saad mine on 2007-02-21.

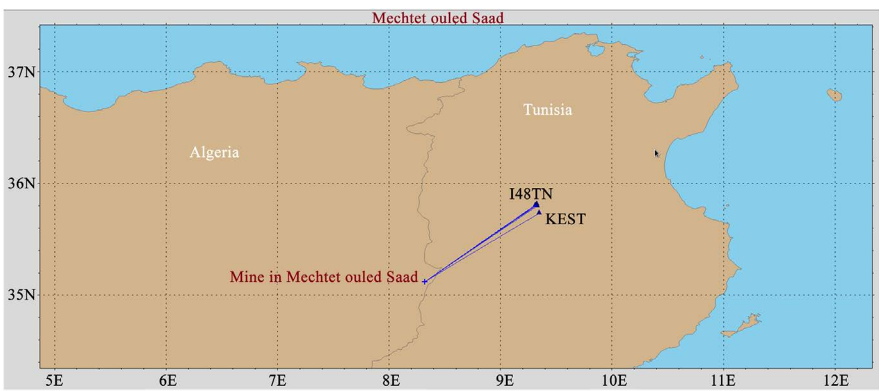
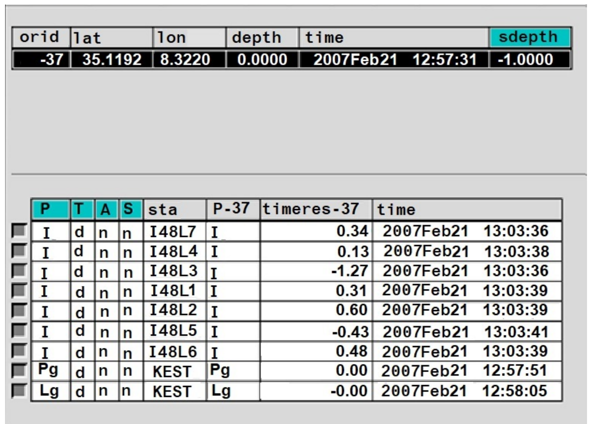


Figure 29. Geotool map for the event using GMT [8].

Table 14. Infrasound analysis results from I48TN data.

Station	Time	Phase	BackAz	Speed (m/s)	Frequency
I48TN	2007-02-21 13:03:29	I	**240˚.145**	337	2.956



orid	lat	lon	depth	time	sdepth
-37	35.1192	8.3220	0.0000	2007Feb21 12:57:31	-1.0000

P	T	A	S	sta	P-37	timeres-37	time
I	d	n	n	I48L7	I	0.34	2007Feb21 13:03:36
I	d	n	n	I48L4	I	0.13	2007Feb21 13:03:38
I	d	n	n	I48L3	I	-1.27	2007Feb21 13:03:36
I	d	n	n	I48L1	I	0.31	2007Feb21 13:03:39
I	d	n	n	I48L2	I	0.60	2007Feb21 13:03:39
I	d	n	n	I48L5	I	-0.43	2007Feb21 13:03:41
I	d	n	n	I48L6	I	0.48	2007Feb21 13:03:39
Pg	d	n	n	KEST	Pg	0.00	2007Feb21 12:57:51
Lg	d	n	n	KEST	Lg	-0.00	2007Feb21 12:58:05

Figure 30. Event location using Geotool software.

Table 15. Seismic analysis results from KEST data.

Origin Time			2007-02-21 12:57:31		
Station	Time	Phase	Latitude	Longitude	Depth (km)
KEST	2007-02-21 12:57:51	Pg	35˚.119	8˚.322	0
KEST	2007-02-21 12:58:05	Lg			

7.6. Iron Mine in Bou Khadra, Algeria

7.6.1. Ground Truth Information

The coordinates in Table 16 are from google earth and are the same used in the Infrasound Reference Event Database source of the International Data Centre [17]. The origin time is based on seismic arrivals at KEST station (Figure 35).

7.6.2. Detection Information

A repetitive infrasound source in the Azimuth ~267˚ in red color was observed with the long-term observation (Figure 31). Based on this long-term observation, this repetitive source is considered as a coherent noise for the I48TN and it is dominant in wintertime of the year following the zonal wind direction as the source is in West side of the station.

The result of analysing the IMS data from the infrasound station I48TN for the date of 18th of February 2007 using the latest version of the DTK-GPMCC software (Figure 32) shows the characteristics of the repetitive coherent source coming from the back Azimuth ~267˚ as described in Table 17.

By analysing the seismic data from the IMS station (KEST) in Tunisia for the same period of time by using the Geotool software (Figure 33), Pg and Lg arrivals were added and the origin time was defined "12:04:29" as shown in (Figure 35) and described in Table 18.

The map of event in Figure 34 and the event location in Figure 35 are the results of picking the Pg and Lg seismic phases with Geotool software in the data collected from KEST seismic station (Table 18) and by adding the infrasound I phases observed with DTK_GPMCC on the infrasound data from the I48TN (Table 17).

Table 16. Ground truth information of Bou Khadra mine in Algeria.

Category	Mine and Quarry
Origin time	2007-02-18 12:04:29
Latitude	35˚.750
Longitude	8˚.050
Depth (km)	0
Theoretical Back Azimuth from I48TN	267˚.31
Distance to I48TN	115.26 Km

Table 17. Infrasound analysis results from I48TN data.

Station	Time	Phase	BackAz	Speed (m/s)	Frequency
I48TN	2007-02-18 12:09:52	I	**268˚.397**	341	3.492

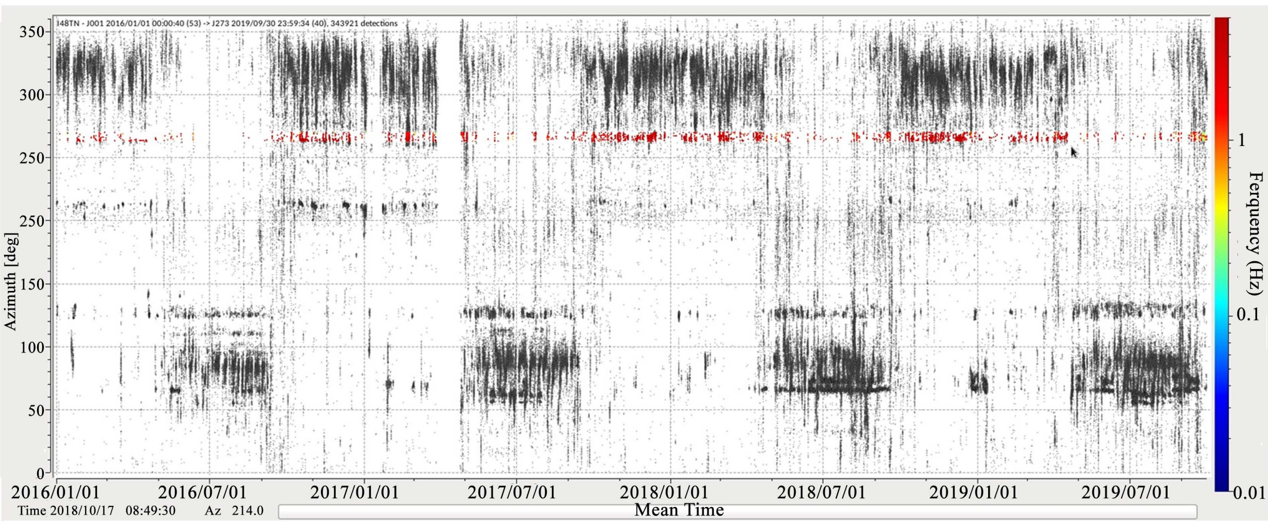


Figure 31. Long-term observation of Bou Khadra mine activities.

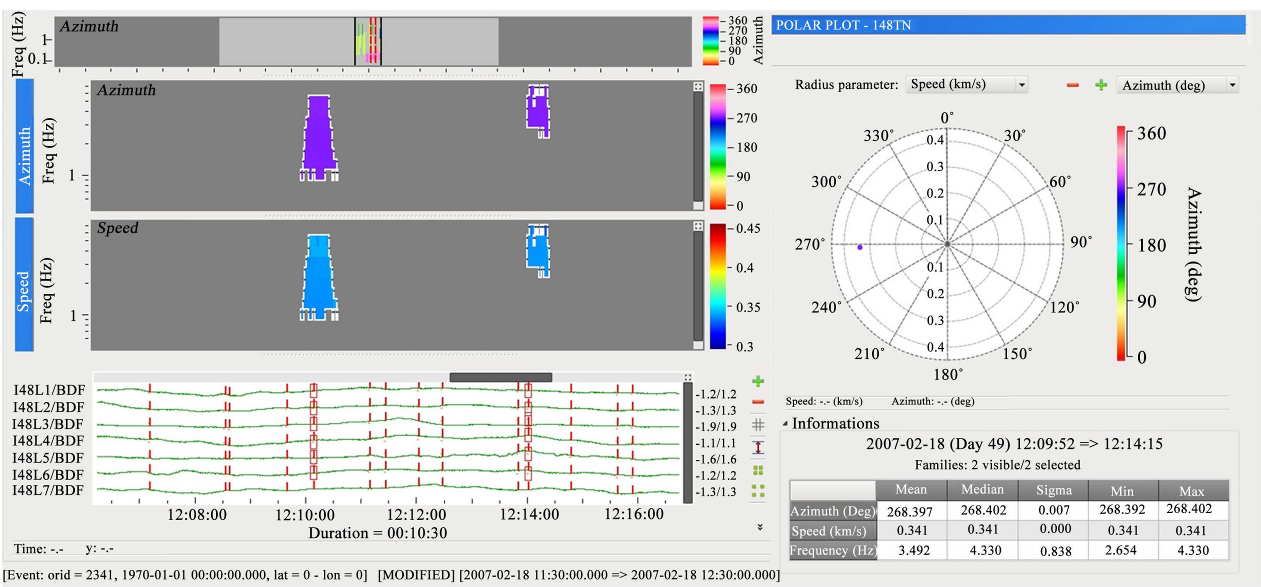


Figure 32. I48TN Infrasound detection information from Bou Khadra mine on 2007-02-18.

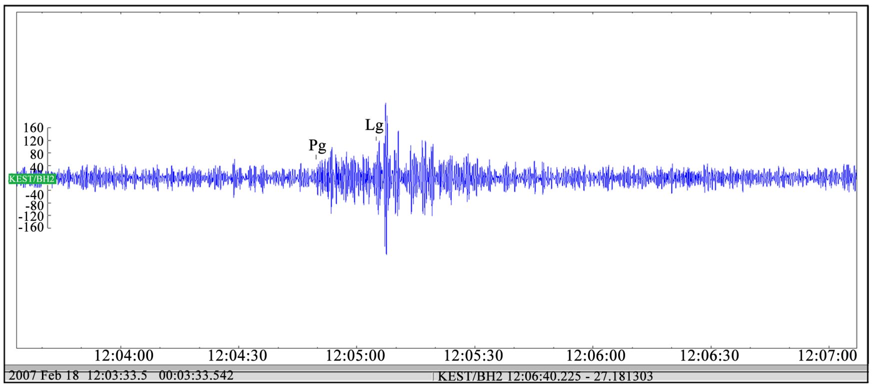


Figure 33. KEST Seismic detection information from Bou Khadra mine on 2007-02-18.

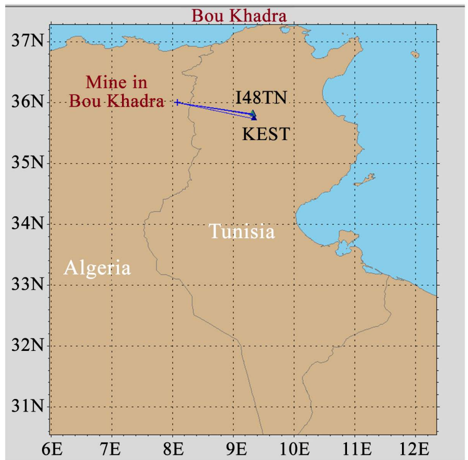
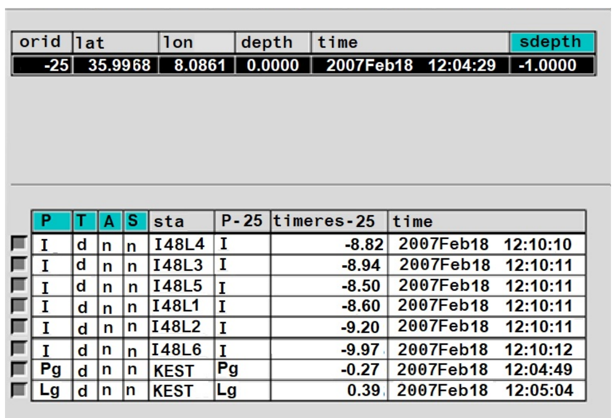


Figure 34. Geotool map for the event using GMT [8].



orid	lat	lon	depth	time	sdepth
-25	35.9968	8.0861	0.0000	2007Feb18 12:04:29	-1.0000

P	T	A	S	sta	P-25	timeres-25	time
I	d	n	n	I48L4	I	-8.82	2007Feb18 12:10:10
I	d	n	n	I48L3	I	-8.94	2007Feb18 12:10:11
I	d	n	n	I48L5	I	-8.50	2007Feb18 12:10:11
I	d	n	n	I48L1	I	-8.60	2007Feb18 12:10:11
I	d	n	n	I48L2	I	-9.20	2007Feb18 12:10:11
I	d	n	n	I48L6	I	-9.97	2007Feb18 12:10:12
Pg	d	n	n	KEST	Pg	-0.27	2007Feb18 12:04:49
Lg	d	n	n	KEST	Lg	0.39	2007Feb18 12:05:04

Figure 35. Event location using Geotool software.

Table 18. Seismic analysis results from KEST data.

Origin Time			**2007-02-18 12:04:29**		
Station	Time	Phase	Latitude	Longitude	Depth (km)
KEST	2007-02-18 12:04:49	Pg	35˚.996	8˚.086	0
KEST	2007-02-18 12:05:04	Lg			

7.7. Quarry in Jebel Ressas, Tunisia

7.7.1. Ground Truth Information

The coordinates in Table 19 are from google earth and are the same used in the Infrasound Reference Event Database source of the International Data Centre [17]. The origin time is based on seismic arrivals at KEST (Figure 40).

7.7.2. Detection Information

A repetitive infrasound source in the Azimuth ~45˚ in red color was observed with the long-term observation (Figure 36). Based on this long-term observation, this repetitive source is considered as a coherent noise for the I48TN and it is dominant in summertime of the year following the zonal wind direction as the source is in the East-North side of the station.

The result of analysing the IMS data from the infrasound station I48TN for the date of 16th of February 2007 using the latest version of the DTK-GPMCC software (Figure 37) shows the characteristics of the repetitive coherent source coming from the back Azimuth ~45˚ as described in Table 20.

By analysing the seismic data from the IMS station (KEST) in Tunisia for the same period of time by using the Geotool software (Figure 38), Pg and Lg arrivals were added and the origin time was defined "16:46:37" as shown in Figure 40 and described in Table 21.

Table 19. Ground truth information of Jebel Ressas Quarry in Tunisia.

Category	Mine and Quarry
Origin time	2007-02-16 16:46:37
Latitude	36˚.600
Longitude	10˚.330
Depth (km)	0
Theoretical Back Azimuth from I48TN	45˚.50
Distance to I48TN	126.41 Km

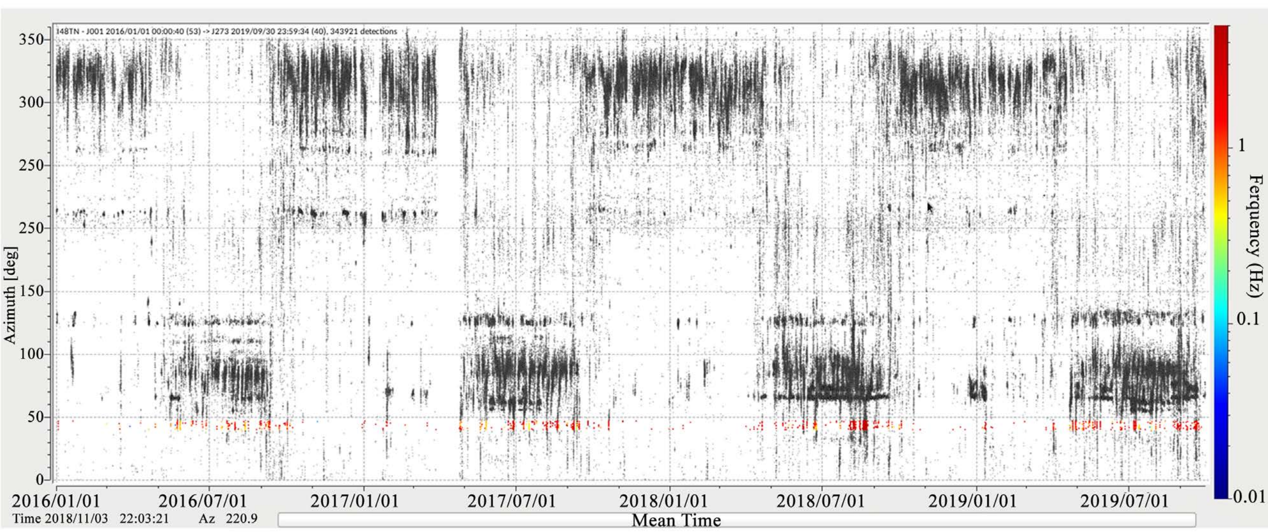


Figure 36. Long-term observation of Jebel Ressas Quarry activities.

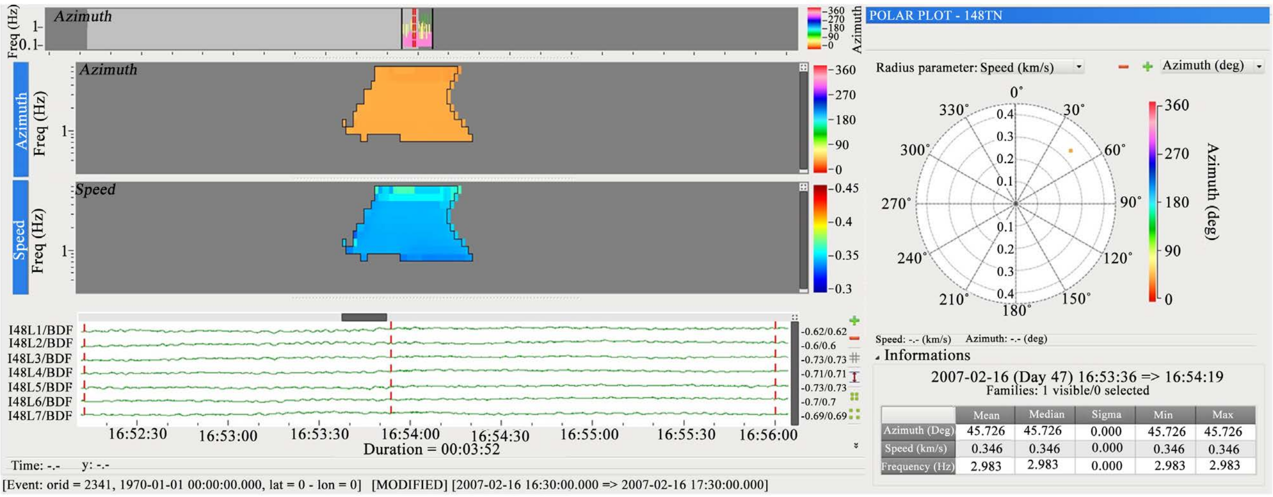


Figure 37. I48TN Infrasound detection information from Jebel Ressas Quarry on 2007-02-16.

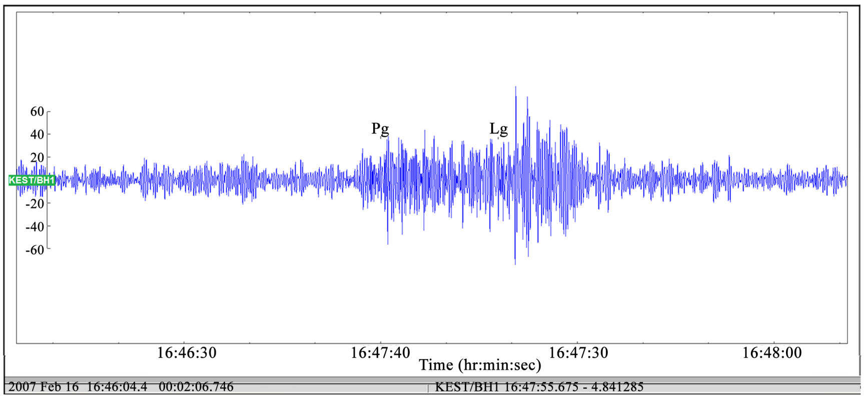


Figure 38. KEST Seismic detection information from Jebel Ressas Quarry on 2007-02-16.

Table 20. Infrasound analysis results from I48TN data.

Station	Time	Phase	BackAz	Speed (m/s)	Frequency
I48TN	2007-02-16 16:53:36	I	**45˚.726**	346	2.983

Table 21. Seismic analysis results from KEST data.

Origin Time			2007-02-16 16:46:37		
Station	Time	Phase	Latitude	Longitude	Depth (km)
KEST	2007-02-16 16:47:00	Pg	36˚.608	10˚.350	0
KEST	2007-02-16 16:47:17	Lg			

The map in **Figure 39** and the event location in **Figure 40** are the results of picking the Pg and Lg seismic phases with Geotool software in the data collected from KEST seismic station (**Table 21**) and by adding the infrasound I phases observed with DTK_GPMCC on the infrasound data from the I48TN (**Table 20**).

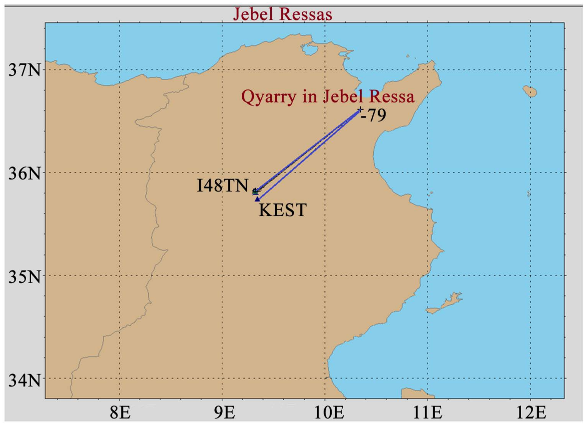
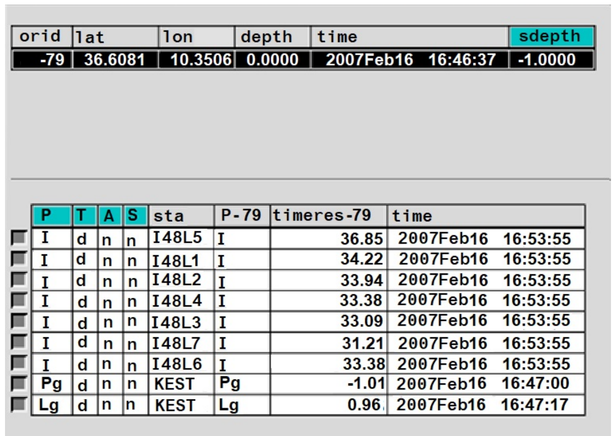


Figure 39. Geotool map for the event using GMT [8].



orid	lat	lon	depth	time	sdepth
-79	36.6081	10.3506	0.0000	2007Feb16 16:46:37	-1.0000

P	T	A	S	sta	P-79	timeres-79	time
I	d	n	n	I48L5	I	36.85	2007Feb16 16:53:55
I	d	n	n	I48L1	I	34.22	2007Feb16 16:53:55
I	d	n	n	I48L2	I	33.94	2007Feb16 16:53:55
I	d	n	n	I48L4	I	33.38	2007Feb16 16:53:55
I	d	n	n	I48L3	I	33.09	2007Feb16 16:53:55
I	d	n	n	I48L7	I	31.21	2007Feb16 16:53:55
I	d	n	n	I48L6	I	33.38	2007Feb16 16:53:55
Pg	d	n	n	KEST	Pg	-1.01	2007Feb16 16:47:00
Lg	d	n	n	KEST	Lg	0.96	2007Feb16 16:47:17

Figure 40. Event location using Geotool software.

8. Comparison of the Analysis Results in This Study with the IDC Results

Table 22 shows that the results of analysing infrasound and seismic data for the defined coherent sources are very close to the results in the Infrasound Reference Event Database source of the International Data Centre [17]. Only for the source in Mechtat ouled Saad where the origin time in the International Data Centre results doesn't much with the IDC Pg arrival time. In our study, Pg arrival is 12:57:51 and in the IDC results is 12:57:52 with 1s difference which is acceptable but the correct time origin in our results is 12:57:31 which is acceptable as the difference between Pg arrival and the origin time is 20 seconds, but for the IDC results is 12:09:18 which cannot be correct as the difference between Pg arrival and the origin time is more than 48 minutes.

9. Ray Tracing of Signals from Some of the Mine Explosions Above

In Figures 41-43, some examples of the ray tracing of three mine explosions in Bou Kadhra, Djebel Onk and Mechtat Ouled Saad shows the low atmosphere propagation under 1km from the sources to the I48TN station.

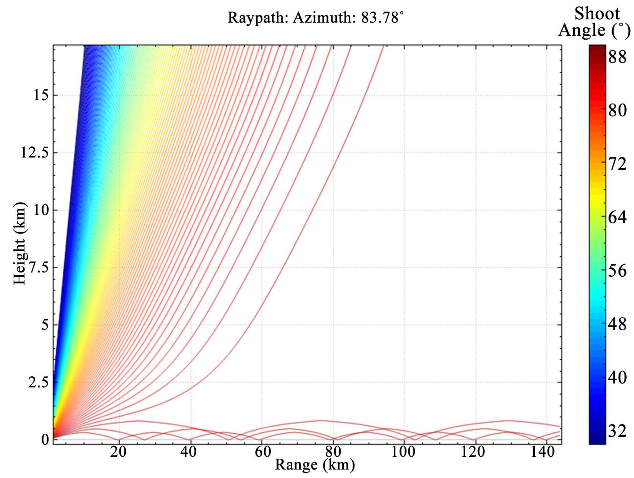


Figure 41. Ray tracing of Bou Kadhra event.

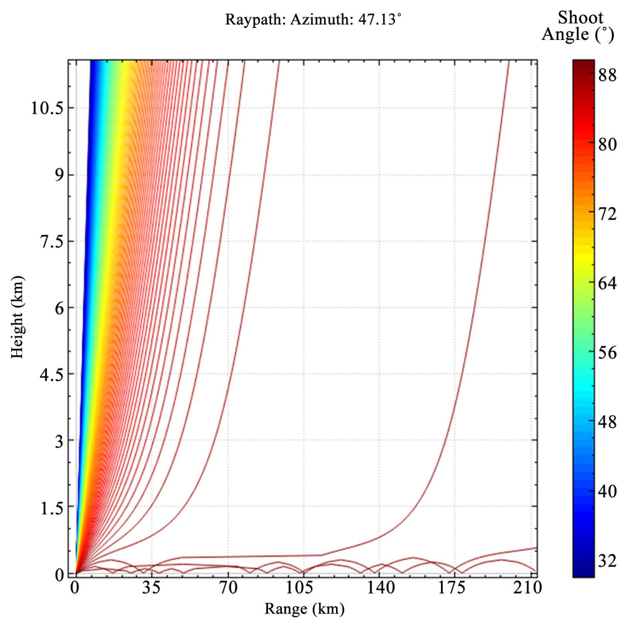


Figure 42. Ray tracing of Djebel Onk event.

Table 22. Analysis results comparison with the IDC results.

Source	Results of Infrasound and seismic data analysis					International Data Centre results				
	Origin Time	Pg	BackAz (°) I48TN	Speed m/s	Freq Hz	Origin Time	Pg	BackAz (°) I48TN	Speed m/s	Freq Hz
Mdhilla	2007-02-14 13:41:35	13:42:08	200.7	352	2.19	2007-02-14 13:41:00	13:42:09	198.6	363	1.71
Metlaoui	2007-02-14 13:12:30	13:13:05	207.1	358	2.29	2007-02-14 13:12:33	13:58:07	207.6	379	1.72
Redeyef	2007-02-16 12:21:13	12:21:45	212.5	367	2.40	2007-02-16 12:21:15	12:21:46	213.4	345	1.68
Djebel Onk	2007-02-25 12:11:25	12:11:53	223.3	357	2.41	2007-02-25 12:11:28	12:11:54	222.8	365	1.42
Mechtat ouled Saad	2007-02-21 12:57:31	12:57:51	240.1	337	2.95	2007-02-21 12:09:18	12:57:52	239.9	338	1.57
Bou Khadra	2007-02-18 12:04:29	12:04:49	268.3	341	3.49	2007-02-18 12:04:27	12:04:49	268.3	341	1.86
Jebel Ressas	2007-02-16 16:46:37	16:47:00	45.7	346	2.98	2007-02-16 16:46:39	16:47:00	45.5	346	1.87

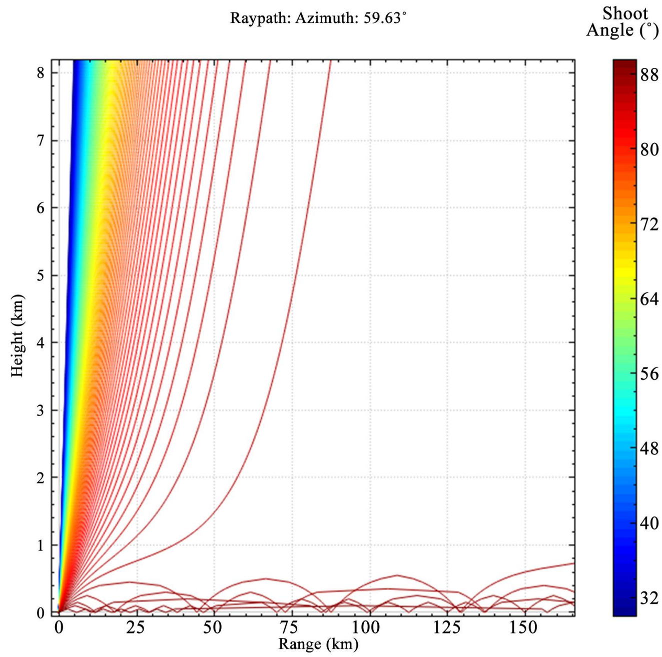


Figure 43. Ray tracing of Mechtat ouled Saad event.

As shown in **Figure 44**, there is a high speed of wind from 10 m/s to 30 m/s between 5 km to 20 km. This low altitude high speed wind and the ground is the wave guide that allows the low propagation possible. Attenuation at low altitude is less than 0.001 dB/km for 1 Hz. Thus, possibility of propagation [18] [19].

10. Discussion

The results show the most important local coherent infrasound sources in the region (mines and Quarries) as recorded by the IMS station I48TN, which are considered as coherent noise to the Tunisian infrasound station (**Table 23** and **Figure 45**). The Progressive Multi-Channel Correlation (PMCC) results include information on the Back azimuth (BackAz), speed and frequency of the coherent signals which typically exhibit systematic seasonal variations [20]. The influence of the zonal wind is very clear on the I48TN station detectability as the dominant detections are coming from West side of the station in Winter and the sources in the East side are dominant in summertime of the year as shown in the long term observations presented in this study.

The origin times of the events were based on the seismic arrivals at KEST station and the Back Azimuths from I48TN were very important to distinguish the right source from different sources in the same region as for the three mines in Mdhilla, Metlaoui and Redeyef.

The comparison of the study results to the International Data Centre results of the analysed events and which are included into the Infrasound Reference Event Database source of the International Data Centre (IRED) shows an arrival time error for the event detected in Mechtat ouled Saad. In our study Pg arrival is 12:57:51 and in the IDC results is 12:57:52 with 1s difference which is acceptable,

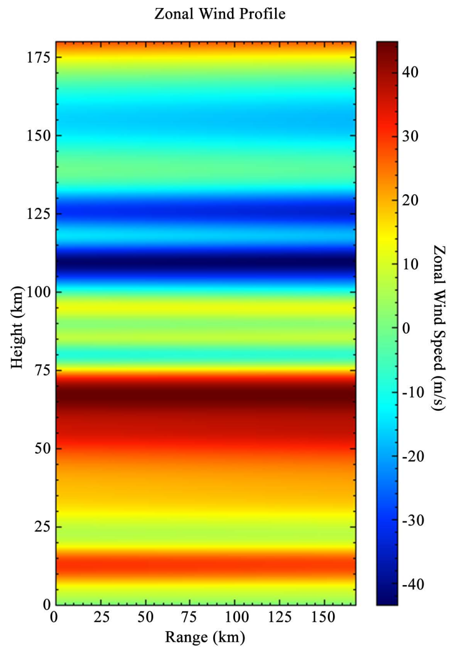


Figure 44. Zonal wind profile.

Figure 45. Infrasound Detections Back Azimuths to I48TN (Map data: Google, Maxer Technologies).

Table 23. Back Azimuths of mines & quarries at I48TN.

Source	Back Azimuth (˚) I48TN
Mdhilla, Tunisia	200.7
Metlaoui, Tunisia	207.1
Redeyef, Tunisia	212.5
Djebel Onk, Algeria	223.3
Mechtat ouled Saad, Algeria	240.1
Bou Khadra, Algeria	268.3
Jebel Ressas, Tunisia	45.7

but the time origin in our results is 12:57:31 which is acceptable as the difference between Pg arrival and the origin time is 20 s while for the IDC results is 12:09:18 which cannot be correct as the difference between Pg arrival and the origin time is more than 48 minutes.

The low altitude high speed wind from 10 m/s to 30 m/s between 5 km to 20 km and the ground is the wave guide that allows the low propagation possible as shown for the three mines explosions in Bou Kadhra, Djebel Onk and Mechtat ouled Saad. Six Infrasound coherent sources defined in the South-West of the I48TN station are considered as the main ambient noise to the station from that side.

11. Conclusions

Several conclusions can be drawn from this study. This will help the infrasound analysts to distinguish between the coherent noise and the events of interest. The synergy between infrasound and seismic data is very important to distinguish the right mine or quarry source from a couple of sources in the same region, especially when there is a low seismic network coverage. However, there is a software limitation in data fusion between Infrasound and Seismic data and this needs to be addressed by software engineering and waveform experts to work more on the existing tools to address this limitation.

Six Infrasound coherent sources defined in the South-West of the I48TN station will help the Infrasound data analyst to better monitor the station and distinguish between the coherent sources and any other event of interest from the South-West region for I48TN.

The Infrasound Reference Event Database source in the International Data Centre (IRED) needs to be updated according to this study regarding the origin time of the event in Mechtat Ouled Saad. The historical Infrasound Reference Event Database needs to be revisited [21].

More studies on the other observed coherent sources in the region as microbaroms from the oceans and the Mediterranean Sea, Etna and Stromboli volcanos and airports, will help the infrasound analyst in focusing more on the events of interest and can distinguish them from coherent noise to the station, as the main goal for the International Monitoring System is to detect nuclear explosions.

The result of this study can be transformed into a script to allow the infrasound analyst to automatically categorize the predefined coherent sources to the I48TN station. Cataloging the coherent infrasound sources for each Infrasound station will improve the monitoring of the earth for any nuclear explosions in the atmosphere and the surface of the earth.

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Data Availability

CTBTO IMS data, IDC products and software package used for this article are available to CTBTO member states. For academic purposes, Infrasound data can be requested at the CTBTO International Data Center (IDC) via the virtual Data Exploration Center.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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