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# Infrasound detection of meteors

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ABSTRACT

Meteorites that penetrate the atmosphere generate infrasound waves of very low frequency content. These waves can be detected even at large distances. In this study, we analyzed the infrasound waves produced by three meteors.

The October 7, 2008 TC3 meteor fell over the north Sudan Nubian Desert, the February 15, 2013 Russian fireball, and the February 6, 2016 Atlantic meteor near to the Brazil coast.

The signals of these three meteors were detected by the infrasound sensors of the International Monitoring System (IMS) of the Comprehensive Test Ban Treaty Organization (CTBTO). The progressive Multi Channel Technique is applied to the signals in order to locate these infrasound sources. Correlation of the recorded signals in the collocated elements of each array enables to calculate the delays at the different array element relative to a reference one as a way to estimate the azimuth and velocity of the coming infrasound signals. The meteorite infrasound signals show a sudden change in pressure with azimuth due to its track variation at different heights in the atmosphere. Due to movement of the source, a change in azimuth with time occurs. Our deduced locations correlate well with those obtained from the catalogues of the IDC of the CTBTO.



## 1. Introduction

Sound waves in the atmosphere become audible to humans if the frequency is in the range of 20–20,000 Hz, and become inaudible for frequencies higher than 20,000 Hz or lower than 20 Hz. Sound waves are then called infrasound which is usually considered at 0.002 Hz (Evers, 2008). It is analogous to the low frequency light waves which are called infrared and invisible (Gossard and Hooke, 1975). Infrasound signals travel with the speed of sound; 343 m/s at 20 °C in air near to the Earth's surface. This velocity increases at higher temperatures, in a downwind situation, and vice versa. Furthermore, this velocity depends on the fundamental property of the material, which also holds for solids and fluids.

Meteors are considered as an important source of infrasound waves. Most meteors have a low luminosity and occur at high altitudes in the atmosphere. Only a fraction of meteoroids give rise to high luminosity meteors and called fireballs. Large cometary meteors are usually destroyed at very high altitudes over 80 km. Only meteoroids with high strength can give rise to deep penetrating fireballs that can produce explosions when the dynamic pressure is higher than the meteoroid strength. The infrasound signals resulting from these meteors have been recorded by the IMS of the CTBTO. Monitoring meteors is a common use of the huge facilities of this organization other than the verifications of the nuclear explosions. The October 7, 2008 TC3 meteor fell over the north Sudan Nubian Desert, the February 15, 2013 Russian fireball, and the February 6, 2016 Atlantic meteor near to the Brazil coast represent the three studied examples that have been recorded by the infrasound network of the IMS of the CTBTO.

The TC3 meteor which had fallen over the north Sudan in the Nubian Desert had been recorded in a far station; I32 Ke in Kenya. The Russian fireball is considered as the biggest infrasound event which had been recorded by the IMS. The blast was detected at 20 infrasound stations in the CTBTO's network. The Atlantic meteor which had fallen near to the Brazil coast has been recorded in the I27 De station located in the Antarctica at about 5000 km from the source.

In this study, we analyze the infrasound signals of these three meteors using the data recorded by the infrasound stations of

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the IMS in order to find their sources locations. This could be an important input for the evaluation of the atmospheric conditions. Locating infrasound sources represents a key target of the CTBTO. Our deduced locations will be correlated with those obtained from the catalogues of the IDC of the CTBTO.

## 2. Data source

All the waveforms data are obtained from the infrasound network of the IMS of CTBTO. This network consists of 60 infrasound stations distributed all over the world (Fig. 1). The stations list which are used in this study are listed in Table 1.

## 3. Data processing

Progressive multi-channel cross correlation (Cansi, 1995; Cansi and Klinger, 1997) is used to analyze the infrasound waves. It considers these waves as a set of plane waves, as the infrasound station consists of array of sensors. Therefore, the correlation function between the sensors can be computed and also can be used to differentiate between signals and noise.

The correlation function is used to calculate the propagation time of the wave between sensors i and j. For each sub-network (i, j, k), the sum of time delays $\Delta t_{ij} + \Delta t_{jk} + \Delta t_{ki}$ is computed. In case of a planar wave across the array, the closure relation $\Delta t_{ij} + \Delta t_{jk} + \Delta t_{ki} = 0$ should be obtained (Cansi and Klinger, 1997). In the presence of a background noise, the measured delays are the result of random phase combinations and the closure relation given earlier is no longer valid. The consistency of the set of delays obtained using all sensors is then defined as a mean quadratic residual of the closure relation, and detection is declared if the consistency value is below a given threshold (Le Pichon et al., 2010).

**Table 1**
Infrasound stations used in this study.

| Station | Latitude | Longitude | Location |
|---|---|---|---|
| I31 Kz | 50.406970° | 58.034820° | Kazakhstan |
| I43 Ru | 56.721360° | 37.217590° | Russia |
| I32 Ke | −1.242160° | 36.827210° | Kenya |
| I27 De | −70.701100° | −8.302910° | Antarctica |

Some parameters can be computed from correlation; like apparent velocity and azimuth which are very useful to describe the infrasound waves. Apparent velocity can be easily computed using the locations of two sensors and the difference in arrival times between them. Using the delay time between all sensors, the azimuth and the apparent velocity across the array can be computed. The slowness vector which represents the wave propagation direction is obtained by combining the apparent velocity of the waveform signal across the elements of the array and the azimuth.

Assuming a homogeneous elastic medium, the wave front takes the same time to cover the distance between $S_1$ and $S_2$ as between the projection of the two sensors on the ray: $S'_1$ and $S'_2$. So the time difference between the arrivals can be calculated by:

$$\Delta T_{12} = T_2 - T_1 = \frac{\overline{S'_1 S'_2}}{v_a}, \quad (1)$$

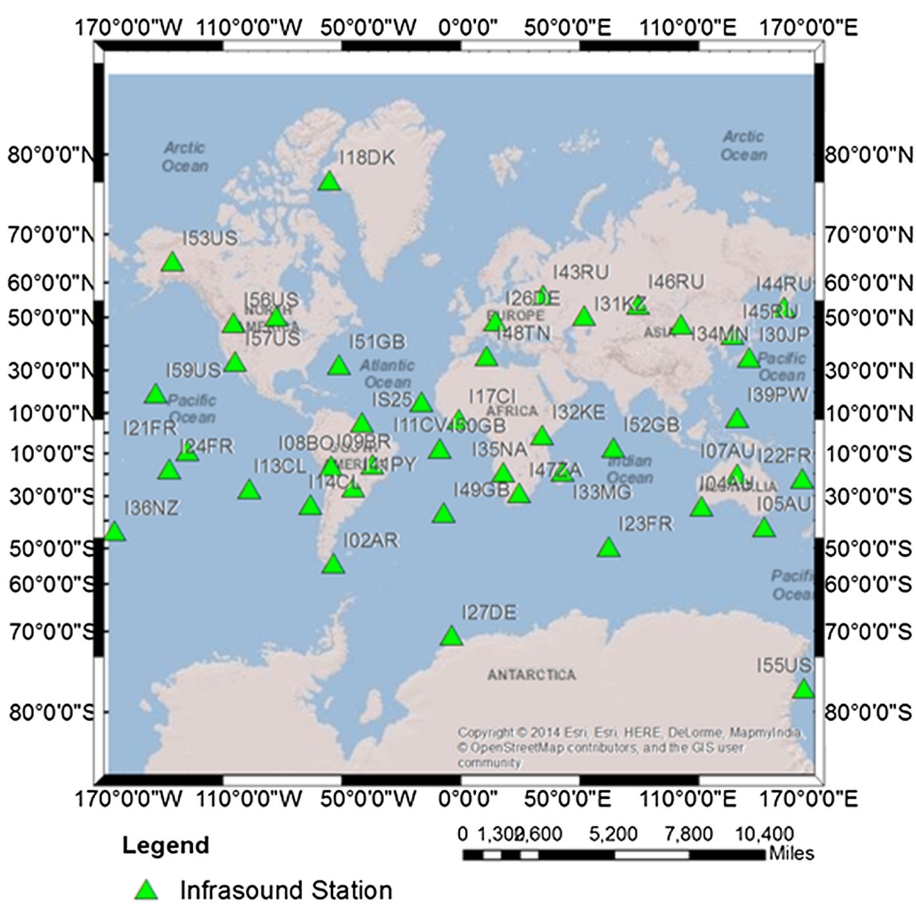


**Fig. 1.** The infrasound stations of International Monitoring System.

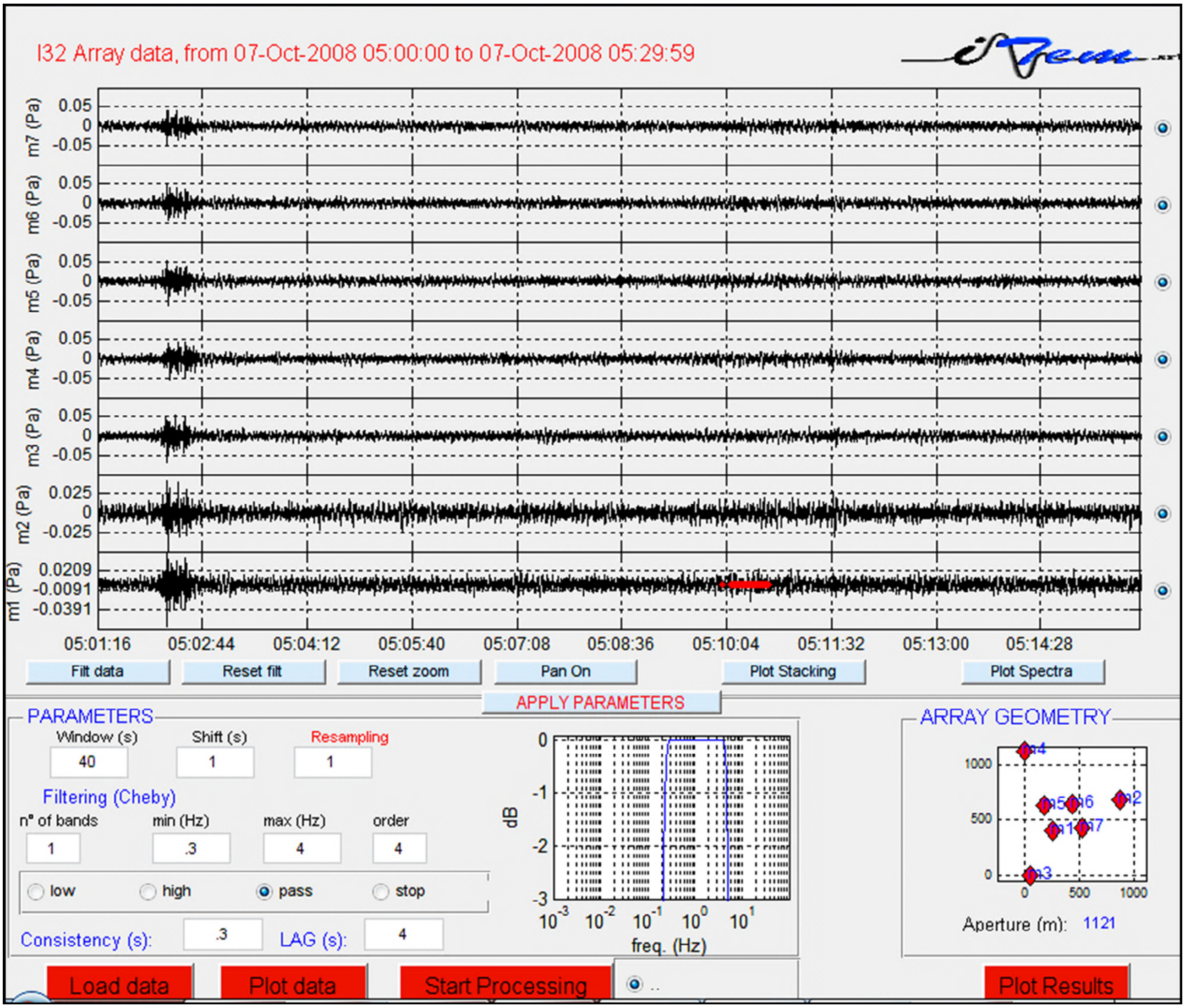


**Fig. 2.** The recorded infrasound signals from TC3 Meteor on the element of I32 Ke station.

where $v_a$ is the apparent velocity of the wave front. By simple plane geometry, Eq. (1) can be written as a function of the sensor coordinates and the event's azimuth:

$$\Delta T_{12} = \frac{(y_2 - y_1)\cos\varphi + (x_2 - x_1)\sin\varphi}{v_a} \quad (2)$$

$\Delta T_{13}$ can be expressed in the same way. $\Delta T_{12}$ and $\Delta T_{13}$ are observed quantities, so the ratio between the two equations defines the azimuth of the event:

$$\tan\varphi = \frac{\Delta T_{12}(y_3 - y_1) - \Delta T_{13}(y_2 - y_1)}{\Delta T_{12}(x_3 - x_1) - \Delta T_{13}(x_2 - x_1)} \quad (3)$$

Once the azimuth has been calculated, it is possible to define the apparent velocity of the wave through Eq. (4) according to (Pignatelli et al., 2008):

$$v_a = \frac{(y_2 - y_1)\cos\varphi + (x_2 - x_1)\sin\varphi}{\Delta T_{12}} \quad (4)$$

In this work, MCCA (Multi-channel cross correlation) program is used in the analysis of infrasound data to get the coherency between the data from all sensors for every event and also to compute the difference in differential pressure, azimuth and the apparent velocity.

### *3.1. TC3 2008*

On October 7, 2008, a small asteroid named 2008 $TC_3$ was detected in space about 19 h prior to its impact on the Earth. Numerous worldwide observations of this object; while still in space allowed a very precise determination of its impact area on the Nubian Desert of northern Sudan, Africa. But the meteorite was not big enough to survive the ground and it was exploded at estimated height of 37 Kilometer above the ground.

The infrasound signals were recorded at I32 Ke station in Kenya. Infrasound signals are very clear in this station. A multi cross correlation technique using the MCCA program was applied to the waveform data extracted from the IDC for this event. Fig. 2 shows the waveform data from the different elements of the I32 Ke station. The azimuth and coherency between the data from each element of the station are calculated.

Fig. 3A shows that there is no change in the pressure across the array; 0.02 Pa. Fig. 3B shows that there is continuity in the coherency of the infrasound waves from this meteor. A band-pass filter between 0.3 and 4 Hz is applied to the signals before correlation in order to remove noise and improve the detectability of the source. The apparent velocity from one element to the next in the array is shown in Fig. 3D. This figure reflects a clear change in the trace

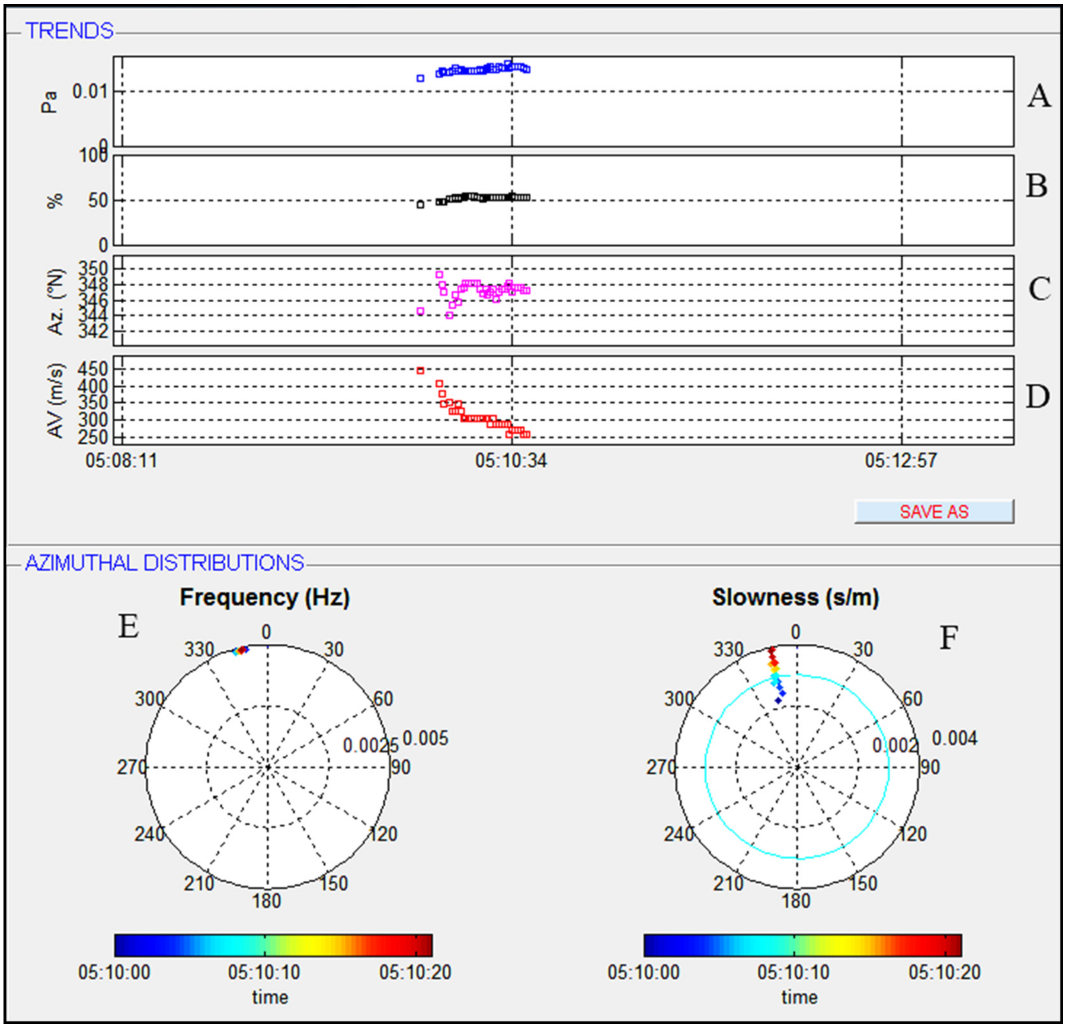


**Fig. 3.** Array analysis of the data recorded by I32 Ke.

velocity within the estimated azimuth range due to the change in incident angles of infrasound waves to the station. The direction to the maximum correlation (azimuth) reflects the continuation of the arrivals from 346° to 348° (Fig. 3C and E). Fig. 3F shows that the slowness has similar values in the direction of the signal arrivals. The azimuth estimated direction from I32 Ke infrasound station refers to the location of the meteorite explosion which had been located by IDC (as shown in Fig. 4). The azimuth obtained in this study is well comparable with that estimated in infrasound reference database events by the IDC.

### *3.2. Chelyabinsk meteor*

This is the largest ever infrasound event recorded by the CTBTO's IMS stations. The blast was detected by 20 infrasound stations of the CTBTO's network. The farthest station recorded signals was 15,000 km away in Antarctica. The origin time of the low frequency sound waves from the blast was estimated at 03:22 GMT on 15th Feb. 2013 (Le Pichon et al., 2013). Seismic signals from the meteor were also detected at several Kazakh stations close to the explosion and the impact area.

The Russian fireball was automatically detected by the International Data Center (IDC) of CTBTO in Vienna. The reviewed analysis carried out in the hours following the event provided an extended list of infrasound signals associated with this meteor as well as a refined source location (Le Pichon et al., 2013). Both I31Kz and I43Ru stations recorded clear infrasound signals from it. The Kazakhestan I31 Kz infrasound station is the nearest station (about 531 km) to the event. The infrasound waves recorded at this station were retrieved from the IDC data base as shown in Fig. 5.

Fig. 6A shows that there is a clear change in the pressure across the array (1–6 Pa). A multi cross correlation technique is applied to the signals detected by the elements of the array of this station in order to determine the azimuth to the signal maximum cross correlation within a moving time window of 40 s (Fig. 6B). This figure shows that there is continuity in the coherency of the infrasound waves from the fireball. This figure reflects a little change in the trace velocity with a slight increase at the time 3:56:05 and a clear increase near 4:02. The direction to the maximum correlation (azimuth) reflects the continuation of the arrivals from 20° to 34° (Fig. 6C and E). Variation in the azimuth is related to the propagation path where the meteor enters the atmosphere over Oral Mountain and fall over Chelyabinsk. A band-pass filter between 0.1 and 4 Hz was applied to the signal before correlation in order to remove noise and improve the detectability of the source. The apparent velocity which is a measure of the travelling signal from one element to the next in the array is shown in Fig. 6D. Fig. 6F shows that the slowness has similar values in the direction of the signal arrival.


**Fig. 4.** The location of TC3 using I32 Ke infrasound station.

The I43 Ru is another infrasound station which is at about 1500 km in Russia has recorded the same event.

The multi cross correlation technique is applied to the data extracted from the IDC using the MCCA program. The azimuth and the coherency between the data from each element of the station are calculated. The recorded infrasound waveform data are shown in Fig. 7.

Fig. 8A shows that there is a clear change in the pressure across the array (0–0.5 Pa). The signal maximum cross correlation within a moving time window of 40 s is shown in Fig. 8B. This figure shows coherency of the infrasound waves from the fireball at intermittent time intervals. A band-pass filter between 0.1 and 4 Hz was applied to the signals before correlation in order to remove noise and improve the detectability of the source. The apparent velocity from one element to the next in the array is shown in Fig. 8D. The direction to the maximum correlation (azimuth) reflects the continuation of the arrivals from 80 to 90° (Fig. 8C). Variation in the azimuth is related to the propagation path where the meteor entered the atmosphere over Oral Mountain and fall over Chelyabinsk. Fig. 8F shows that the slowness has similar values in the direction of the signal arrivals.

By plotting the azimuth estimated from the two stations we can get the intersection between these two directions and a better location of the event can be obtained as shown in Fig. 9. Comparing the estimated results with those obtained from infrasound reference database events by the IDC indicates a good agreement between them.

### 3.3. Atlantic fireball

On February 6th, 2016 at 14:00 UTC a huge fireball crashed into the Atlantic, and went almost unseen. This meteor has exploded in the air at about 1000 km off the coast of Brazil. Its infrasound signals were recorded clearly in I27 De station (Fig. 10) which is located in Antarctica at about 5000 km from the event.

Fig. 11A shows that there is a clear change in the pressure across the array (0–0.7 Pa). Fig. 11B shows that there is coherence stability at a certain time interval for the infrasound waves from the fireball. This figure reflects a change in the trace velocity ranging from 300 to 380 m/s. The direction to the maximum correlation (azimuth) reflects the continuation of the arrivals from 334° to 336° (Fig. 11C and E). A band-pass filter between 0.1 and 4 Hz was applied to the signals before correlation in order to remove noise and improve the detectability of the source. The apparent velocity from one element to the next in the array is shown in Fig. 11D. Fig. 11F shows that the slowness has similar values in the direction of the signal arrivals. The azimuth estimated from I27 De infrasound station refers to the location of the event is obtained which announced from National Aeronautics and Space Administration (NASA) (Fig. 12).

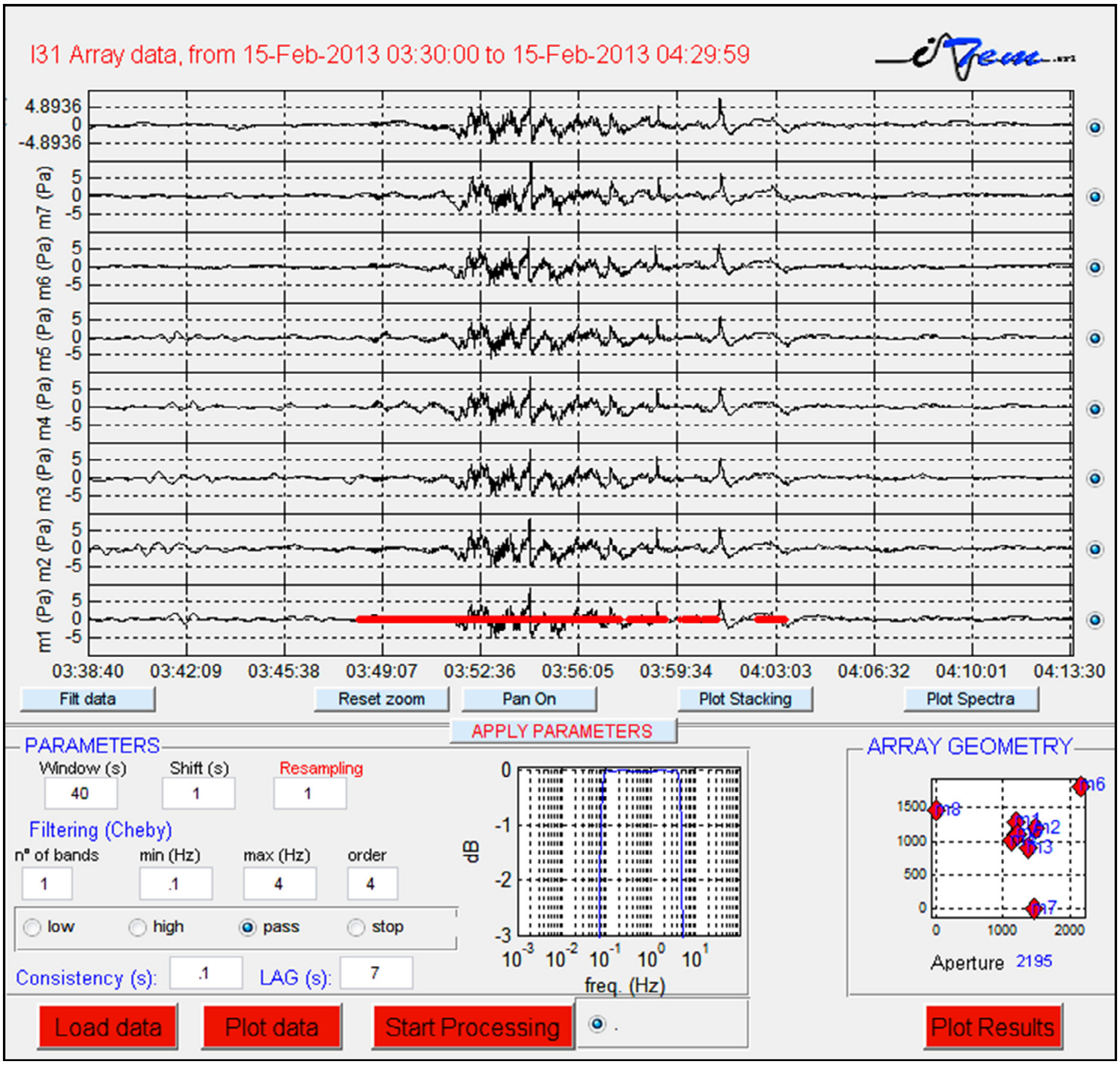


**Fig. 5.** The recorded infrasound signal from the Russian fireball on the elements of I31 Kz station.

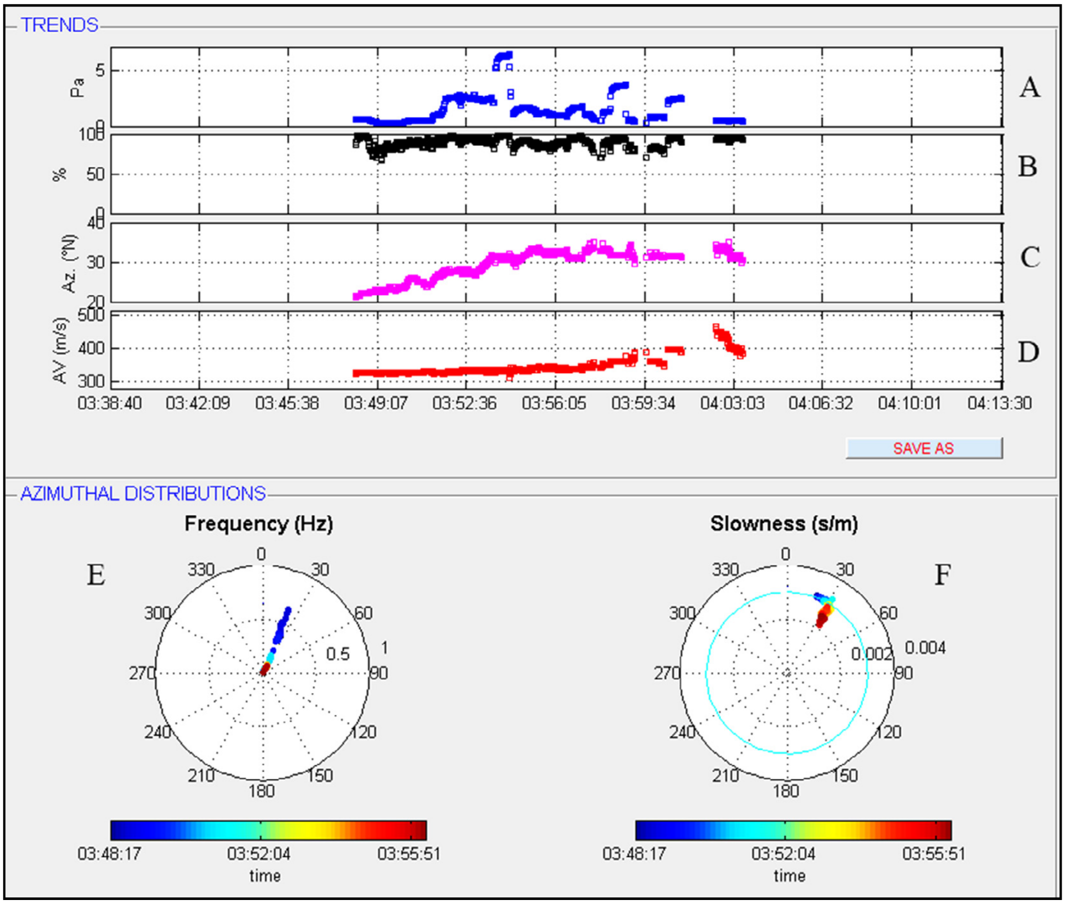


**Fig. 6.** Array analysis of I31 KZ station.

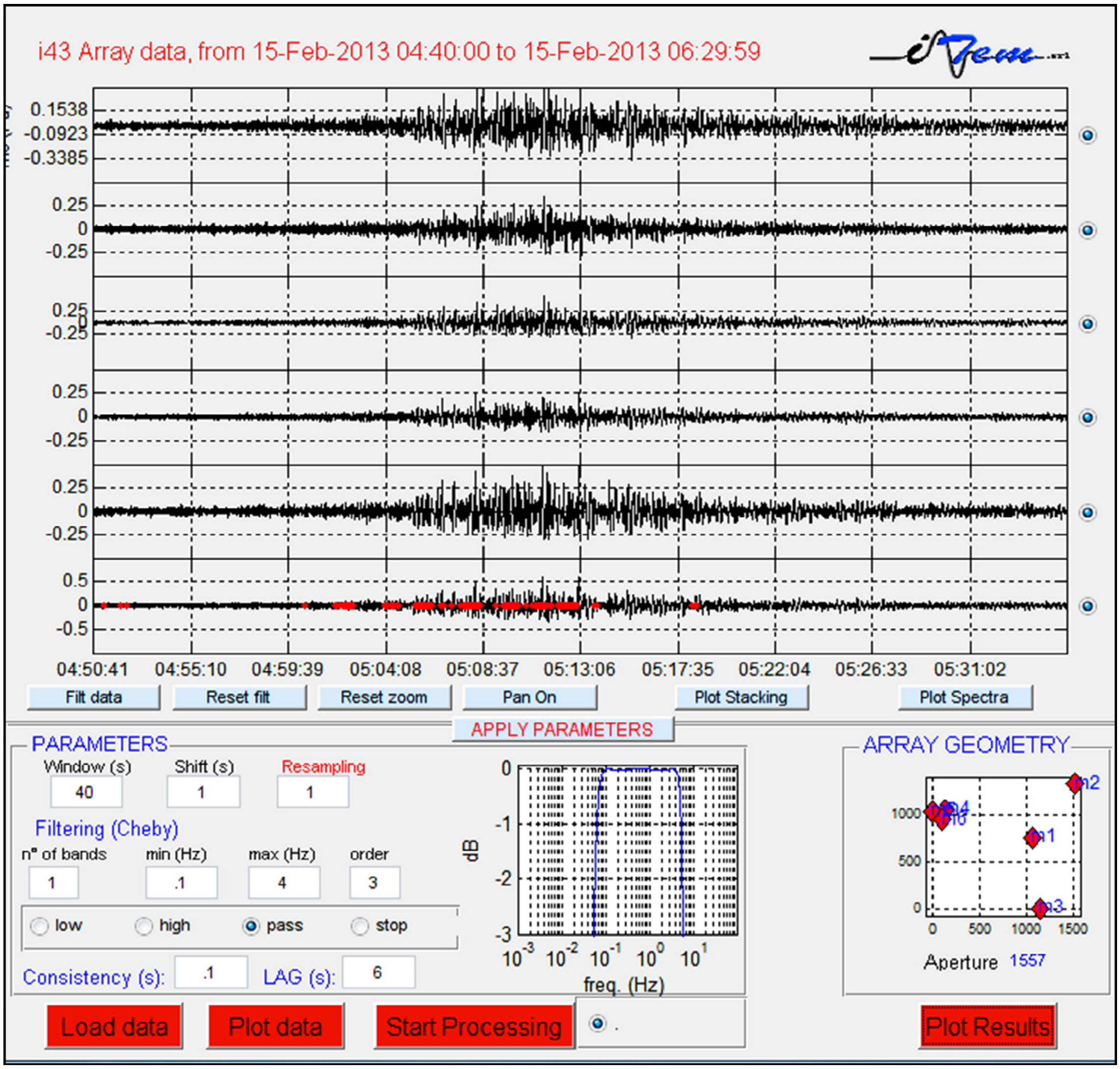


**Fig. 7.** The recorded infrasound signals from the Russian fireball on the elements of the I43 Ru station.

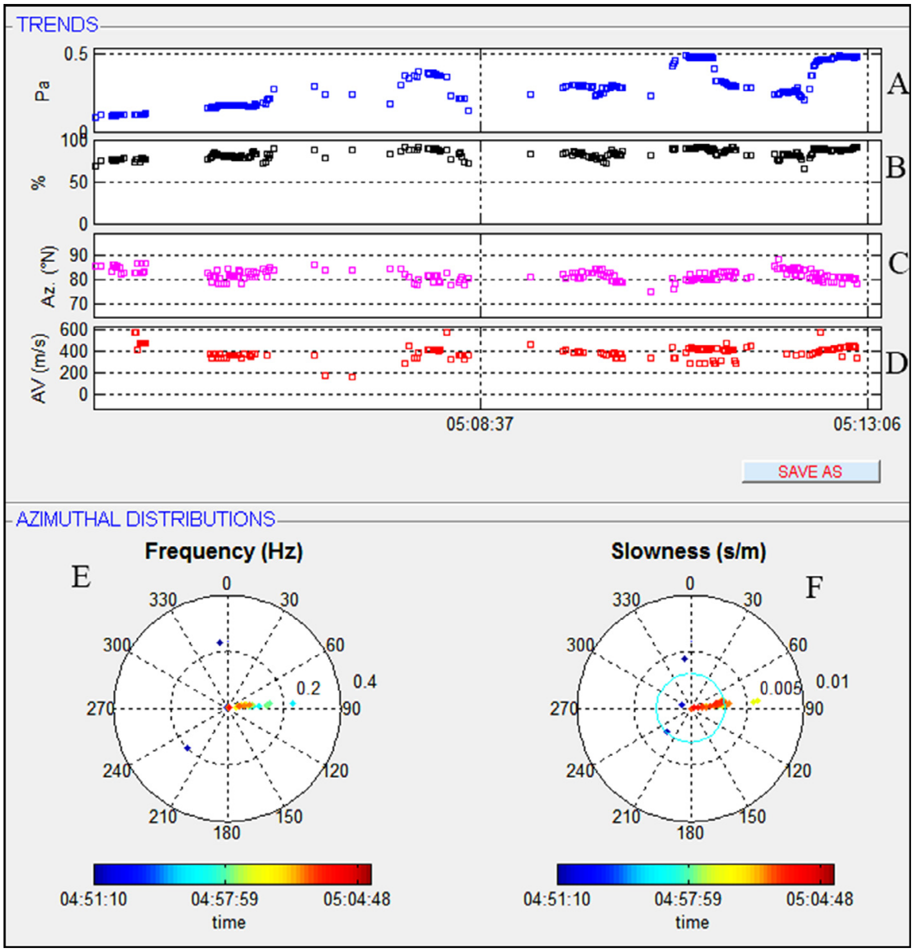


**Fig. 8.** The array analysis of the data recorded by I43 Ru station.

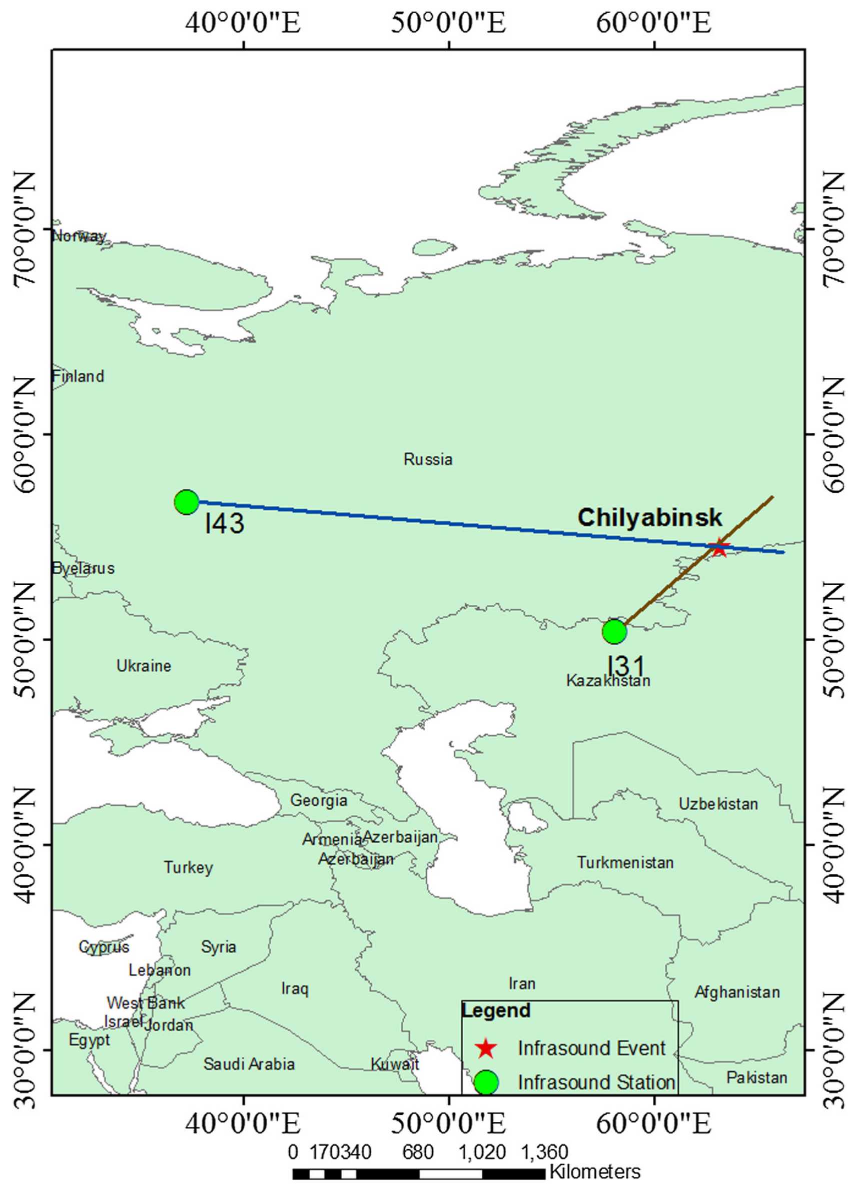


**Fig. 9.** The location of Russian fireball using I43 Ru and I13 Kz infrasound stations.

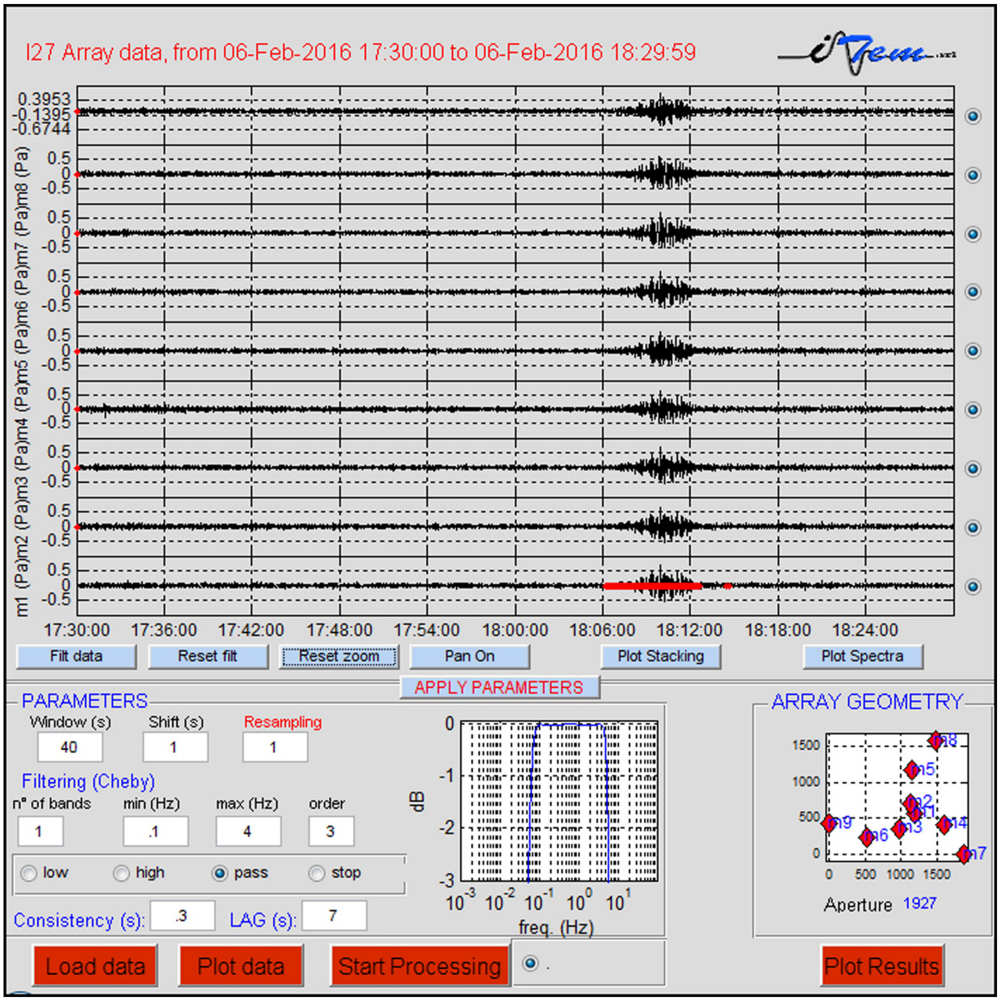


Fig. 10. Array analysis of infrasound data from I27 De station.

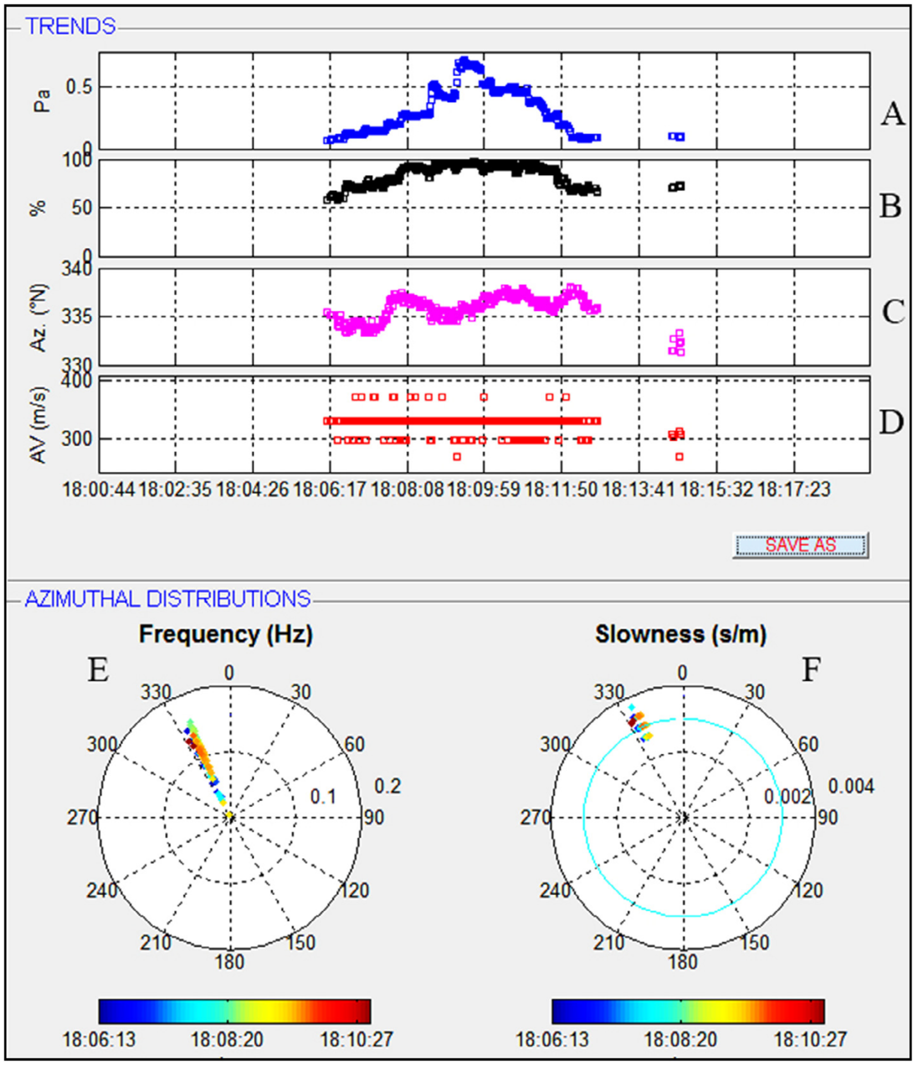


**Fig. 11.** Array analysis of the infrasound data by I27 De station.

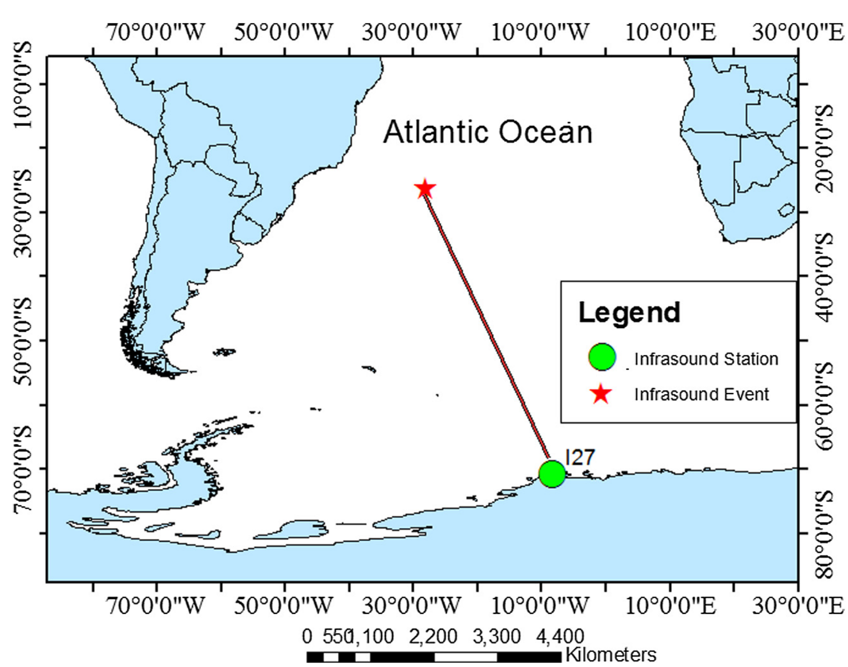


**Fig. 12.** The location of the fallen meteor using the I27 De infrasound station.

## 4. Conclusions

Meteorites and bolides are source of infrasound signals. The IMS of the CTBTO have recorded several events from meteoritic sources. Analyzing infrasound waves from such events provides a location and in some cases estimate of the origin time of the source.

MCCA program has proven a stable processing software compared to results of the International Data Center IDC certified software. It is of utmost importance to characterize the meteoritic sources of infrasound in order to discriminate it from a violation to CTBT. The signals recorded from meteorites is characterized by a changing wave azimuth with time due to the movement of the source. The apparent velocity becomes large as the meteor accelerate while approaching the Earth, sometimes exceeds the sound speed. The observed clear change in the trace velocity within the estimated azimuth range is due to changes in the incident angles of infrasound waves to the station. The abrupt changes in the pressure with the azimuths are expected due to path variation at different heights in the atmosphere. Comparing the results of this study with the locations of the infrasound sources calculated by the IDC shows a good agreement and proves that it is possible to use a limited number of array stations to locate the infrasound sources.

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