University of Brasilia studies explosions occurred in Beirut – Lebanon

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Abstract

The Beirut, Lebanon chemical explosion on August 4, 2020, is one of the largest non-nuclear blasts in history and was recorded by the infrasound and seismic stations of the International Monitoring System (IMS), a global network designated to detect clandestine nuclear explosion in violation to the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The explosion was detected by infrasound and seismic stations located up to 6,000 and 2,400 km from the source, respectively. Data from 5 infrasound and 3 seismic stations of the IMS and stored at IDC-CTBTO was accessed by the Seismological Observatory of the University of Brasilia (SIS-UnB) and used to calculate hypocenter, magnitudes, and explosive yield. An attempt to determine the CMT was made, but it is not shown in this study. This introductory work aims to test the performance of the IMS network in the detection, location and characterization of an explosion and develop authors' skills and capacity to accurately locate events of CTBT interest. Additionally, we intend to share the importance of the CTBT and arouse interest to in the use of IMS data for civil and scientific applications.

Introduction

A devastating chemical explosion occurred at the Beirut harbor on August 4, 2020, at 18:08 (local time) or 12:08 (UTC), killing 207 people, leaving around 7,500 injured, 300,000 homeless and 15 billion dollars loss (Reuters, 2020). Within a radius of 800 meters from the source, almost everything was destroyed: ships anchored at the port were sunk, buildings and houses collapsed, cars destroyed etc. (Fig. 1). The shock waves were felt in Turkey, Syria, and Palestine, and it was heard in Nicosia, Cyprus, more than 240 km away from the source. After the explosion, a large cloud of black smoke washed over the port area.

The explosion was caused by the detonation of 2750 tons of ammonium nitrate that had been stored in a warehouse in the port since 2013. Ammonium nitrate is a fertilizer used in agriculture, but that can burn up when subjected to temperatures of about 300 Celsius. A fire in a neighboring warehouse triggered the first small detonation, which triggered the second big explosion of nitrate. Considering an efficiency of about 50%, this explosion had a yield equivalent to a nuclear explosion with more than 1 kt of TNT, enough to generate seismic waves with energy equivalent to a magnitude 4 earthquake, considering a subsurface explosion, which was not the case. Even so, the USGS estimated a magnitude of 3.3 mb. In this work, we estimated magnitudes equal to 3.3 Mw and 3.6 mb.

Figure 1: Images before and after the explosion at the Beirut Port. As you can see, everything was destroyed in a radius of 400 m from the explosion point.

A big nuclear test, of about hundreds of kilotons, can generate energy capable of spreading throughout the planet, in the form of disturbances detectable by a certain type of geophysical sensors. In this sense, it was designed the International Monitoring System composed by sensors of four technologies, each one suitable for detection in one of three possible environments: atmosphere, subsurface and underwater masses.

The Seismological Observatory of the University of Brasilia (SIS-UnB) collaborates with the United Nations Organization CTBTO (Comprehensive Nuclear-Test-Ban-Treat Organization), based in Vienna - Austria, which aims to verify the compliance with the CTBT. The Brazilian government participates in this organization with data from its IMS stations installed within its borders as well as the result of the data analysis and interpretation obtained by the analysists and experts. Any nuclear explosion, whether underground, underwater or in the atmosphere, with a power equivalent to at least 1 kiloton of TNT (Trinitrotoluene), at any time and place, can be detected by this network.

In this work, we present the Beirut chemical explosion sources parameters (epicentral location, magnitudes and yield) determined using infrasound and seismic data. But before that, we would like briefly present the CTBT Treaty, its verification regime and the seismic and infrasound technologies used. We also aim to arouse interest of Latin American researchers in the use of IMS technologies. However, under a confidentiality clause, the IMS data can be used by all States Parties.

A brief review of the CTBT Treaty and its verification regime

The Comprehensive Nuclear Test-Ban Treaty (CTBT) prohibits nuclear explosions on a global level. The CTBT, although not yet in force, has an International Monitoring System (IMS) based on geophysical sensors, capable of globally detecting any nuclear test with a power equal to or greater than 1 kt of TNT. Data from the IMS network is transmitted to the International Data Centre (IDC), located at the United Nations in Vienna - Austria, where it is processed, analyzed, and interpreted to identify possible signals related to clandestine nuclear explosions, as well as for issuing bulletins and reports on any events of interest in compliance with the Treaty.

The IMS Network is a global nuclear test surveillance system composed of 337 installations with four technologies distributed to guarantee a global surveillance against nuclear tests. More than 90% of the IMS Network are already in operation. Since we will use data only from the seismic and infrasound technologies (Fig. 2), we will briefly describe both.

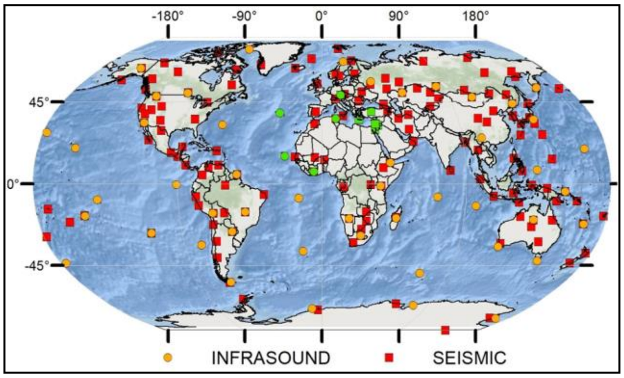

Figure 2: IMS seismic network. Primary (50 red squares), auxiliary seismic stations (120 yellow squares) and infrasound stations (60 yellow circles). The green symbols indicate the stations that have detected the explosion.

Seismic technology

A subsurface explosion generates, like an earthquake, seismic waves that can be detected by seismographic stations over long distances. The IMS seismographic network was designed to detect mainly subsurface nuclear explosions. It consists of 170 stations: 50 primary stations and 120 auxiliary stations (Fig. 2). There are two types of seismic stations: array stations, a set of seismic sensors spatially distributed with a given geometry, usually in the form of concentric rings, and three-component stations (3C), which detect ground motion caused by the passage of seismic waves in three tri-orthogonal directions (one vertical and two horizontals). The sensors, at these stations, are usually installed in deep wells, 100 meters or more in depth. Seismographic array has the advantage of enhancing the signal-to-noise ratio (SNR) by data signal processing like beamforming technique, hence, they can detect small signals.

Infrasound technology

Sound waves are variations in air pressure or acoustic disturbances, which can be detected by microbarometers. Nuclear explosions in the atmosphere generate variations in air pressure (infrasound) that, depending on the temperature and wind speed, travel long distances. The infrasound stations, installed for monitoring the planet, can detect very low frequency, non-audible sound waves, in the range of 0.001 Hz to 16 Hz, emitted by natural or artificial sources, such as volcanic eruptions, storms, nuclear explosions, supersonic airplanes, among others. Due to their low frequency, infrasonic waves propagate through the atmosphere over long distances, suffering low attenuation. In this sense, infrasound technology is suitable for detecting nuclear tests in the atmosphere (Le Pichon et al., 2010).

An infrasound station is an array of microbarographs usually installed at the vertices of an equilateral triangle, with a central sensor. This is the most common configuration, but there are other possible configurations, according to the number and the spatial arrangement of the elements. The determination of azimuth (direction of the wavefront) is based on the difference in the arrival times of infrasound waves in each element of the array (Le Pichon et al., 2010). The IMS infrasound network is made of 60 stations (Chistie et al., 2010) (Fig.2).

Hydroacoustic and radionuclide technologies

The Beirut chemical explosion was not detected by IMS hydroacoustic and radionuclide stations. Hydroacoustic technology was developed to detect signals resulting from changes in water pressure, generated by sound waves in the seas and/or oceans. These waves can be caused by a variety of natural or man-made sources, such as marine seismic survey explosions, gust fishing and nuclear explosions (artificial sources); noise caused by icebergs, whales, and earthquakes (natural sources). This monitoring technology is used to detect underwater nuclear explosions or nuclear explosions close to the surface or on the coast, which was the case of the Beirut harbor explosion. Given its effectiveness, only 11 stations are sufficient to monitor the conduct of clandestine nuclear explosions in aquatic environments across the planet. The radionuclides monitoring is carried out by a network of 80 stations globally distributed, which allows a continuous worldwide observation of aerosol samples of radionuclides or radionuclide particles. To increase the efficiency of radionuclide monitoring, half of these stations are equipped with technology for monitoring noble gases generated by nuclear explosions. Sixteen radionuclide laboratories complement this global network. In the city of Rio de Janeiro, there is a radionuclide station and one of the 16 radionuclide laboratories at IMS, operated by the Institute of Radiometry and Dosimetry (IRD).

Each CTBT verification technology is suitable for detecting nuclear explosions in one of the three possible environments: atmosphere, subsoil and underwater. The radionuclides technology is used to confirm if a suspect event has a radioactive origin source. However, it is possible to have synergy between the four technologies, that is, more than one technology can contribute to the validation of a nuclear test. For example, underground nuclear tests can be detected by seismic, infrasonic and radionuclide technologies, with seismic being the main technology. Atmospheric nuclear tests can also be detected by infrasonic, seismic and radionuclide technologies, with infrasound being the most appropriate technology. The synergy is occurring because the same event can be detected by different technologies and, thus, the analysis is complementary (Barros et al., 2020). The explosion in Beirut was detected by two technologies: seismic and infrasonic.

Brazilian stations belonging to the IMS network

Brazil, which has already signed (on September 26, 1996) and ratified (on July 24, 199) the CTBT, contributes with data from three technologies: Seismic, Infrasound and Radionuclides. The Seismological Observatory of the University of Brasilia contributes with data from two stations, one primary seismic station and one infrasound array, both installed inside the Brasilia National Park (PNB). The data from these stations are transmitted to the SIS - UnB, where they are recorded, analyzed, and retransmitted to the IDC in Vienna. The other IMS stations in Brazil are: two auxiliary seismic stations, located in the States of Rio Grande do Norte and Amazonas; two radionuclide stations, located in Rio de Janeiro and Recife (this last one not yet deployed), and a radionuclide laboratory, located at the Institute of Radioprotection and Dosimetry (IRD), also in the city of Rio de Janeiro (Fig. 3).

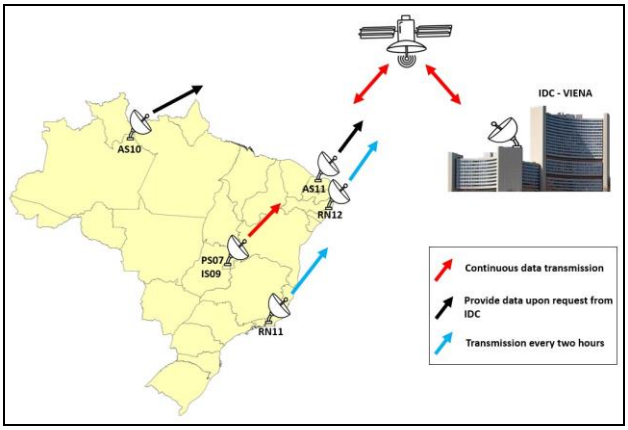

Figure 3: Locations of Brazilian IMS stations and way of transmitting data to the IDC in Vienna - Austria. AS10 and AS11 are auxiliary seismic stations, RN11 and RN12 are radionuclide stations, PS07 and IS09 are primary seismic stations and infrasound stations.

Data analysis

We analyzed infrasound and seismic data using software tools developed by PTS - CTBTO and released as the package NDC-in-a Box: Geotool for seismic analysis, PMCC - Progressive Multichannel Correlation (Cansi, 1995); Cansi and Klinger (1997) and Diva for infrasound data analysis (CEA/DASE, 2016). Due to the long distance (~10,000 km) and energy dissipation, the Beirut explosion was not recorded by IMS stations located in South America. Here we used IMS data (five infrasound arrays and three seismic stations) and four seismic open data for source parameters estimation.

Infrasound data analysis

To locate the explosion, we used data from the infrasound stations indicated by green circles in Fig. 4. The stations in Germany (I26DE, 2,500 km), Tunisia (I48TN, 2,400 km), Côte d'Ivoire (I17CI, 5,000 km), Azores – Portugal (I42PT, 5,600 km) and (I11CV Cape Verde 6,136 km), recorded clear infrasound families, with low variation in the back azimuth of the event. Azimuthal rays of each station point to the source of infrasound waves. In Figure 5 is showing PMCC family from the I48TN station.

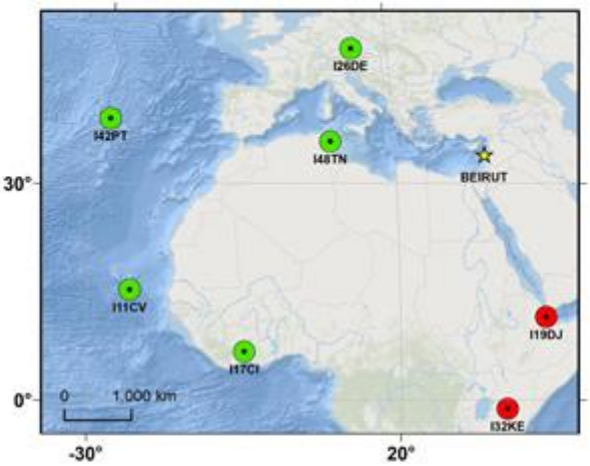

Figure 4: IMS infrasound stations that detected the event (green).

Despite the long distances from the stations, the orientation calculated by the PMCC algorithm is satisfactory. This analysis, performed with only five infrasound stations, will be improved using data from seismic stations. Table 1 indicates the results of the output parameters computed by PMCC. The epicenter location is Lat 33.864º N ± 204 km, Long 34.311º E ± 315 km. The Origin Time is 15:03:32.351 and depth is equal

Table 1: Data of the infrasound stations that registered the event (Fig. 5).

Station	Country	Dist (km)	Hour	Azimuth	Speed (km/s)	Duration	Freq (Hz)	Correlation	Consistency (s)	Max Amp (Pa)	RMS Amp (Pa)	Family size	N E
I11CV	Cape Verde	6206	20:44:31	60,58°	0,359	680,0	0,815	0,4712	0,1133	0,2915	0,0722	218	8
I17CI	Ivory Coast	5128	19:44:32	47,11°	0,342	808,4	0,375	0,6188	0,0800	0,1324	0,0223	949	4
I26DE	Germany	2450	17:12:21	125,6°	0,346	926,9	0,548	0,6471	0,0657	0,1329	0,0155	1929	8
I42PT	Portugal	5625	20:20:37	79,73°	0,338	69,0	0,623	0,3286	0,1500	0,0259	0,0087	42	8
I42PT	Portugal	5625	20:23:56	80,17°	0,349	50,6	0,909	0,2676	0,1285	0,0184	0,0046	44	8
I48TN	Tunisia	2400	17:06:41	87,17°	0,364	63,3	2,448	0,3250	0,0537	0,0272	0,0043	241	7
I48TN	Tunisia	2400	17:08:20	88,67°	0,359	395,6	2,541	0,3935	0,0642	0,1026	0,0146	2000	7
I48TN	Tunisia	2400	17:14:54	88,32°	0,357	318,6	2,551	0,4290	0,0617	0,1873	0,0295	2000	7
I48TN	Tunisia	2400	17:19:47	88,62°	0,354	278,3	2,563	0,5136	0,0521	0,4817	0,0710	2000	7
I48TN	Tunisia	2400	17:24:33	89,35°	0,353	203,6	2,532	0,3984	0,0665	0,1147	0,0254	958	7

to 0 km (Fig. 6). As will be seen, the obtained location from the infrasound data is not as accurate as the location from the seismic data. However, this kind of event generally is jointly studied by both technologies.

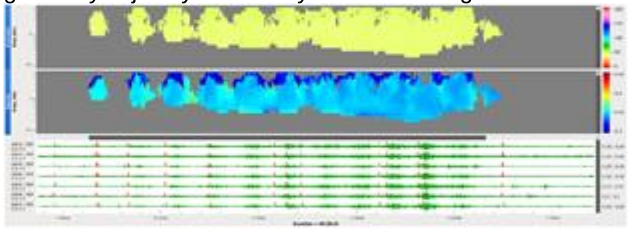

Figure 5: PMCC family from the I48TN station.

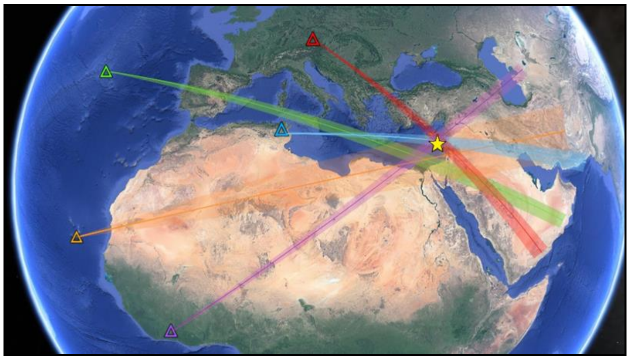

Figure 6: Location of the explosion (yellow star). The triangles indicate the infrasound stations. Colored rays from stations I26DE (Germany), I48TN (Tunisia), I17CI (Côte d'Ivoire), I42PT (Azores, Portugal) I11CV (Cabo Verde – Portugal), point in the direction of the source (Beirut). The dispersion around the azimuth radius represents the deviation from the estimated average azimuth value, that is, the greater the distance the greater the error in the location.

This explosion was recorded by infrasound stations so far away due to the explosive charge (USGS - United States Geological Survey estimated a magnitude of 3.3 ml) and low frequency of infrasound waves. The wind propagation direction helped in the propagation of the infrasound waves over great distances. The stations on the east side did not register this event, indicating that the wind movement was from east to west (Fig. 4).

The energy released by the explosion was greater than the released by a magnitude 3.3 earthquake, because earthquakes occur underground, converting most of its energy into seismic waves. The same does not occur for explosions on the surface.

Seismic data analysis

We analyzed data from 7 seismic stations, 3 belonging to IMS and 4 belonging to IRIS (Incorporated Research Institutions for Seismology) (Fig. 7). For hypocenter location, we used 26 stations, 2 from IMS and 24 from IRIS.

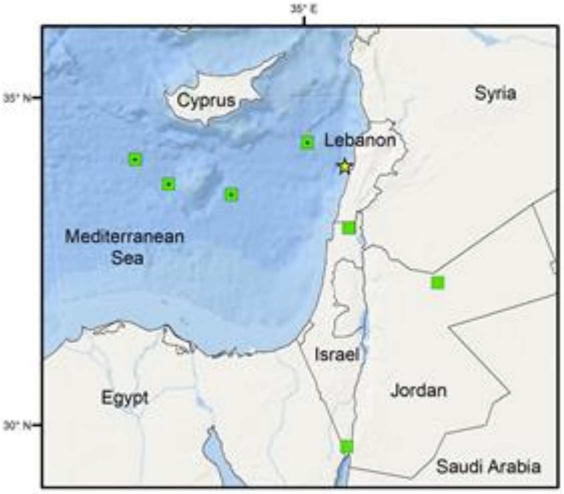

Figure 7: Seismic stations used for hypocentral location.

The location is: lat. 33.793º N ± 7.251 km, Long. 35.295º E ± 9.843 km, fixed depth (0 km), Origin Time 15:08:21.1 and body wave magnitude 3.6 mb. Azimuthal gap = 189, Minimum distance = 85 km, Maximum distance = 450 km. Figure 8 shows the seismic waveforms. Figure 9 shows the locations using infrasound data, seismic data and IDC location

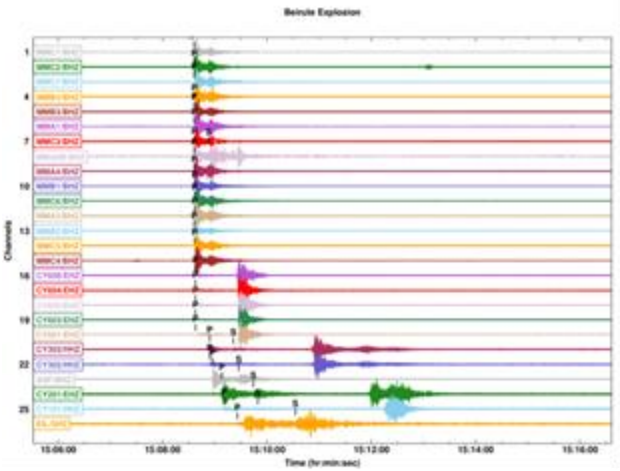

Figure 8: Seismic waveforms, vertical components of the explosion register.

Yeild stimation

Rapid and accurate assessment of the yield of a major urban explosion is important for implementing emergency response plans, estimating areas of major and minor risk, as well as providing policy makers and the general public with more information about the event (Rigby et al., 2020). The yield of an explosion gives information on its potential for damage. Different methods have been developed to make this estimate. For example, Giterman and Hofstetter (2020), in a GT0 calibration experiment, utilized high-pressure gauges to record air-blast for evaluate the efficiency of the charge design, energy generation to provide a reliable estimation of the actual explosion yield.

Kim at all (2009) used the ratio of the Pn and Pg displacement amplitude spectra between nearly co-located two North Korea UNEs (Undeground Nuclear Explosion) recorded at the same seismic stations by eliminating the path effect. Goldstein (2020) used the crater dimensions to estimate the yield of Beirut 2020, August 4th explosion and found to be equivalent to approximately 1.4 kt of TNT with a lower bound of about 0.7 kt. The crater-size based yield estimates are estimated on crater radius measurements from satellite imagery, empirical curves and data for scaled crater radius from past chemical and nuclear explosions.

An underground explosion, when well-conditioned, is expected to have a high isotropic component, i.e., low percentage of Double Couple (DC%). Gaebler et al (2019) showed that the waveform inversion for the seismic moment tensor of the September 3, 2017, Korean nuclear explosion has presented a dominant isotropic component, showing the explosive character of the event. Analysis of the source mechanism of a tremor that occurred about 8 minutes after the test in the vicinity of the test site, suggested that it was a collapse of the cavity.

In this work, the waveforms inversion for the moment tensor (Zahradnik and Sokos, 2018), using only the IMS seismic stations did not produce any satisfactory result. Less bad results were obtained with open access seismic ocean bottom stations located in Mediterranean Sea. It was found a magnitude 3.3 Mw and a small isotropic component of only 8%. This should be because the Beirut explosion was superficial and almost all the energy was emitted to the space. The most used parameter to estimate an explosion yield is based in the seismic body wave magnitude (mb).

Widely used in underground nuclear test monitoring but can also be used to provide a lower limit of a surface explosive source (Pilger et al., 2020). In this case, different empirical relationships must be developed for different areas. These empirical formulas are of the type mb = a + b log (Y), where Y is the explosion equivalent yield in kt of TNT. The constants *a* and *b* are dependents of the test location. Murphy (1981) has determined the constant values for Nevada Test. mb = 3.92+0.81 log(Y). For mb = 3.6 Yield = 0.4027 kt TNT. This value is the lower limit of the Beirut explosion Yield, as it was exploded on the surface.

Discussion and conclusions

One of the objectives of this work was to test the performance of the IMS Network in the detection, location, and characterization of an explosion similar to a clandestine nuclear explosion of power equivalent to 1 kt of TNT, as well as to develop the skills and improve the capability of the group to locate accuracy events of interest to CTBT. Only with the data from the IMS network it was not possible to make an accurate study of the event. However, by adding data from the IRIS local/regional stations, the results were improved substantially.

Given the introductory nature of the work, we approached fundamental requirements for understanding the Treaty CTBT and its verification system, as a way of disseminating the Treaty and showing the scope of the verification technologies and attracting the interest of researchers for the importance of the infrasound data in the scientific and social areas.

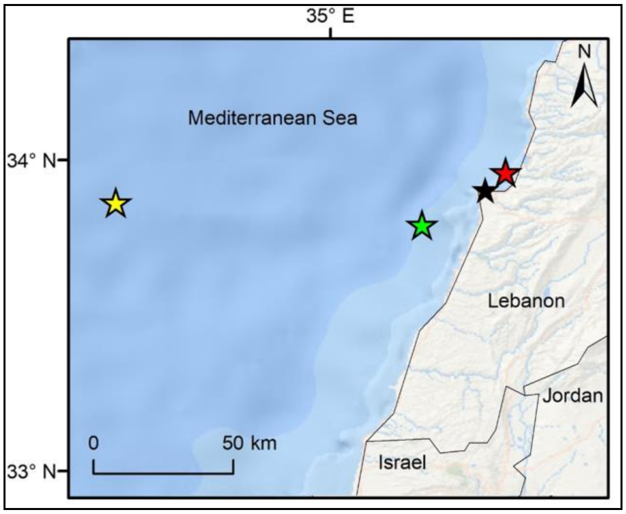

Figure 9: Beirut explosion locations: true location (black star), IDC (red star); SIS-UnB (seismic green star and infrasound yellow star).

References

Barros, L. V., Neri, B. L., Carvalho, J. M and Fontenele, D. P., 2020. A particpação brasileira na verificalçao do Tratado de Proibição Total dos Testes Nucleares.

Cansi, Y. (1995). An automatic seismic event processing for detection and location: The P.M.C.C. Method. Geophysical Research Letters, 22(9), 1021–1024. https://doi.org/10.1029/95GL00468

Cansi, Yves, & Klinger, Y. (1997). An automated data processing method for mini-arrays. News Lett, 11.

Christie DR, Campus P (2010) The IMS infrasound network: design and establishment of infrasound

stations. This volume, pp. 27–72Gattermann, Y and R. Hofstetter, R. 2012. GT0 Explosion Sources for IMS Infrasound Calibration: Charge Design and Yield Estimation from Near-source Observations Pure Appl.

Figure 8: Explosion location: True location – black star; IDC location – red star; SIS – UnB seismic location – green star and SIS – UnB seismic location – yellow star.

Kim, T. S., I.-B. Kang, and G.-Y. Kim (2009), Yield ratio estimates using regional Pn and Pg from North Korea's underground nuclear explosions, Geophys. Res. Lett., 36, L22302, doi:10.1029/2009GL040495.

Goldstein, P., 2020. Beirut Explosion Yield and Mushroom Cloud Height – Effects of the Near Source Environment, Lawrence Livermore National Laboratory - LLNL-TR-815803.

Gaebler, P., Lars Ceranna, Nooshiri, N., Andreas Barth, Simone Cesca, Michaela Frei, Ilona Grünberg, Gernot Hartmann, Karl Koch, Christoph Pilger, J. Ole Ross1, and Torsten Dahm, 2019. A multi-technology analysis of the

2017 North Korean nuclear test. Solid Earth, 10, 59–78, 2019 https://doi.org/10.5194/se-10-59-2019.

Rigby, S. E., Lodge, T. J., · Alotaibi, S., Barr, A., Clarke, S.D., Langdon, G.S. and Tyas, A., 2020. Preliminary yield estimation of the 2020 Beirut explosion using video footage from social media. ShockWaves (2020) 30:671–675 https://doi.org/10.1007/s00193-020-00970-z.

D'Amico, S. (Ed.). (2018). Moment Tensor Solutions. Springer International Publishing. https://doi.org/10.1007/978-3-319-77359-9

Reuters. 30 aug. 2020. Disponível em: <https://www.reuters.com/article/us-lebanon-crisis-blast-casualties-idUSKBN25Q08H

Pichon, A. Le, Matoza, R., Brachet, N., & Cansi, Y. (2010). RECENT ENHANCEMENTS OF THE PMCC INFRASOUND SIGNAL DETECTOR Frequency-dependent parameters Application to IMS data. 26, 5–8.

Pilger,C., Gaebler, P., Patrick Hupe, P., Kalia, A. C., Schneider, F., Steinberg, A., Sudhaus, H. and Lars Ceranna, 2020. Yield estimation of the 2020 Beirut explosion using open access waveform and remote sensing data.

Murphy, J. R., 1981. Identification of Seismic Sources — Earthquake or Underground Explosion, chap. P Wave Coupling of Underground Explosions in Various Geologic Media, 1201–205 (Springer Netherlands, Dordrecht, 1981).