CONTRIBUTION OF THE IMS GLOBAL NETWORK OF HYDROACOUSTIC STATIONS FOR MONITORING THE CTBT

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The International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Preparatory Commission, in Vienna operates a global network of 321 monitoring stations and 16 radionuclide laboratories that monitors the earth for evidence of nuclear explosions within the atmosphere, underwater and underground. The IMS uses a network of four verification technologies: seismic, hydroacoustic, infrasound and radionuclide. All the data recorded by the IMS network are transmitted to the International Data Centre (IDC) of the CTBTO in Vienna. The data are then received, processed, resulting data and products distributed and archived by the IDC. This study will give an overview of the contribution of the IMS hydroacoustic network and will highlight that for areas not well covered with the seismic network this part of the IMS can be very valuable for detecting events, improving the location obtained from the seismic network and providing information about the nature of sources.

INTRODUCTION

The CTBT bans all nuclear test explosions. A globally distributed network of seismic, hydrophone, infrasound and radionuclide facilities, called the IMS, has been established as one of elements of this treaty verification.

The IDC based in Vienna supports the IMS by receiving, collecting, processing, analysing, reporting on and archiving data from the IMS facilities. Both automatic processing and later human interactive analysis are carried out on raw IMS data in order to produce and archive standard IDC products. One group of products produced automatically are Standard Event Lists (SELs). The final SEL, published typically 12 hours after the real time, contains data from all waveform technology stations. This is the best bulletin provided automatically and is interactively reviewed and modified by analysts. All events that have passed analyst

inspection and quality check are published in the Reviewed Event Bulletin (REB). Location of almost all REB events results from signals detected within the seismic network. However, signals detected at hydroacoustic stations are associated to many REB events. This paper will focus on signals recorded by the IMS hydroacoustic network and their contribution for monitoring the CTBT.

1. HYDROACOUSTIC NETWORK OF THE INTERNATIONAL MONITORING SYSTEM

Due to the presence of the deep sound channel called the SOFAR channel (Sound Fixing and Ranging), signals can propagate great distances with low transmission loss. It is therefore possible to record underwater signals at distant stations (several thousand kilometres away) from a source of relatively small strength if the propagation path is not blocked by a mass of land. It was therefore possible to design a relatively small network of hydroacoustic stations to monitor huge area of oceans.

The IMS hydroacoustic network uses two different types of hydroacoustic station: 6 hydrophone stations and 5 T-phase stations [2]. See fig.1. for distribution of hydroacoustic stations.

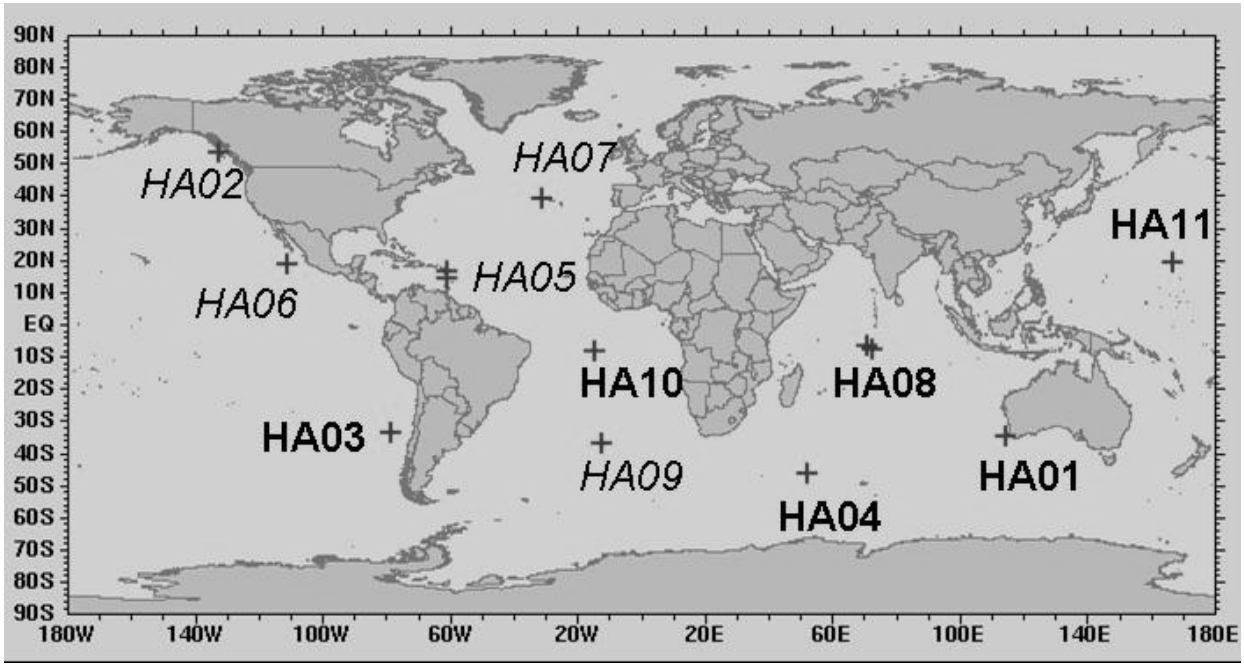

Fig.1 Hydroacoustic network within the International Monitoring System; stations are numbered from 01 to 11; hydrophone stations are marked with bold, T-phase stations with italic

The hydrophone stations consist of hydrophones floated in the SOFAR channel above an anchor on the sea floor with a cable to nearby land for data and power transmission. Hydrophones are grouped in triplets to provide stations with directional capabilities. The separation between the hydrophones in a triplet is approx. 2 km, the frequency band of hydrophone stations is 1-100 Hz (the Nyquist frequency is 125 Hz). T-phase stations are seismic stations placed in coastal regions and they record seismic waves generated by conversion of underwater signals at the coast slope. They are situated close to the shore where depth is increasing fast to minimize signal attenuation. T-phase stations are not configured to

provide information about the signal azimuth. Their frequency band covers 0.5-45 Hz due to attenuation of higher frequencies in the solid earth. Almost all hydroacoustic stations are placed close to or on small islands. Therefore, except HA01, they are equipped with two or three sensor locations to avoid bathymetric blockage by the host island.

Hydrophone stations are much more sensitive than T-phase stations; they have directional capability and record broader signal spectra. However, hydrophone stations are quite difficult to maintain and very expensive to install. Once there is a failure of any underwater part it takes a great effort to repair it, especially if the fault is close to the sensor. Therefore, the IMS hydroacoustic network is a compromise between cost and efficiency.

Some parts of the oceans are not covered by the hydroacoustic network, but onshore seismic arrays should provide enough information about events in those locations.

2. SIGNALS RECORDED AT HYDROACOUSTIC STATIONS AND ASSOCIATED TO EVENTS SAVED IN THE REVIEWED EVENT BULLETIN

Continuous seismic, hydroacoustic and infrasound data arriving at the IDC are first automatically processed in various stages. Automatic processing methods such as automatic detection, measurement and identification of signals, are applied to the data to extract a set of standard signal parameters. The list of signal parameters may include arrival time, amplitude, period, azimuth and slowness. The signal detected is then characterized depending on its parameters. Following this automatic process, hydroacoustic signals are identified as one of the following three categories: H-phases, T-phases or noise (N). H-phases are signals generated by explosive sources. Their entire propagation path is in water. T-phases are generated underground and converted to underwater acoustic signals close to their sources.

Hydroacoustic stations of the IMS are also capable of recording seismic signals, generated and propagated underground. Observation of our data shows primary (P) and secondary (S) body waves recorded in both hydrophone and T-phase stations. So far they have not been automatically recognized. However, analysts can perform a proper identification if needed and in the current development the automatic processing software will also be able to recognize seismic signals at hydroacoustic stations [3].

For hydroacoustic stations only arrival times of H-phases and seismic phases recorded at T-phase stations are currently contributing to the location of events saved in the REB. T-phases are only associated to events located from arrival times of seismic signals.

3. REVIEW OF HYDROACOUSTIC SIGNALS

Under normal operation there are at least 40 detections recorded daily at each hydroacoustic station, providing a big set of data to analyse.

Two approaches of reviewing hydroacoustic signals were followed.

(1) Routine SEL3 review. The SEL3 is the final output of the automatic processing. It contains candidate events built from data from all waveform technology stations to be interactively reviewed and modified by analysts to produce the REB. In addition to analysis of SEL3 events, analysts look for events missed by the automatic system. The vast majority of events represent earthquakes; therefore analysts are mainly associating T-phases.

(2) Systematic review of detections. This exercise is time consuming and is not routinely performed. We will provide some results of observation of one data day at stations belonging to a subnetwork which covers the Indian Ocean.

3.1. RESULTS OF THE ROUTINE SEL3 REVIEW

Normally analysts review a large number of SEL3 events which contain hydroacoustic signals. For example 30% out of about 8000 REB events recorded during the first 100 days of 2008 were detected by at least one hydroacoustic station. The correct association of a hydroacoustic phase is achieved considering the predicted arrival time, signal azimuth and signal characteristics. Review of SEL3 events makes it is easy to identify an event to which an observed signal belongs but covers only a small percentage of all hydroacoustic detections.

The systematic review of SEL3 events has shown the importance of synergy between seismic and hydroacoustic technologies. Three areas of contribution of hydroacoustic network to detecting and locating events were identified:

- increasing analyst's confidence about the reality of an event

  Some events are detected by only a few seismic stations and are poorly located. However, if an event took place in a coastal or remote oceanic area and hydroacoustic signals were generated, their signal to noise ratios (SNR) may be higher than those of seismic signals. Also, observations of seismic signals recorded both at T-phase and hydrophone stations may be included in the REB solution. Presence of signals recorded at hydroacoustic stations increases the analyst's confidence about reality of an event and results in it being saved into the REB.

- improving location of an event

  If seismic waves are observed for events located close to hydroacoustic stations it is possible to improve their location by using arrival times of P and S phases.

- confirming location of an event

  A seismic event detected by only a few seismic stations may be poorly located, even if there is no doubt about the correct association of seismic detections. However, if it is possible to associate a T-phase, a small difference between observed and predicted arrival time and azimuth values confirms the location of an event.

The following example illustrates the points which were mentioned above. An event from the Leeward Islands automatically detected by only 2 seismic stations was poorly located near the coast of Venezuela and saved in the SEL3 bulletin. Following analyst review this event was relocated by adding 2 hydroacoustic stations HA05 (Guadeloupe/Martinique, East Atlantic Ocean) and HA10 (Ascension Island, Central Atlantic Ocean). Seismic signals of the highest SNR were observed at HA05 which was the closest station at 170 km from the epicentre. Also, T-phases recorded at HA10 had higher SNR than signals recorded at seismic stations. Arrival times of P and S phases recorded at HA05 improved location of the event. Moreover arrival time and azimuths residuals at HA10, which are the difference between predicted and observed values, were very small - 12 sec. and 0.3 deg respectively. Data from hydroacoustic stations also increased the confidence that the event was not bogus. It was possible to manually add detections at two more seismic stations and to save this event into the REB.

Signals from both hydroacoustic stations are shown in the fig.2. All traces have been filtered with a band pass filter 3-6 Hz and represent almost 9 min. of data. Traces have been aligned on the predicted T phase arrival time.

The location of the event, and of the two hydroacoustic stations, is shown in the fig.3.

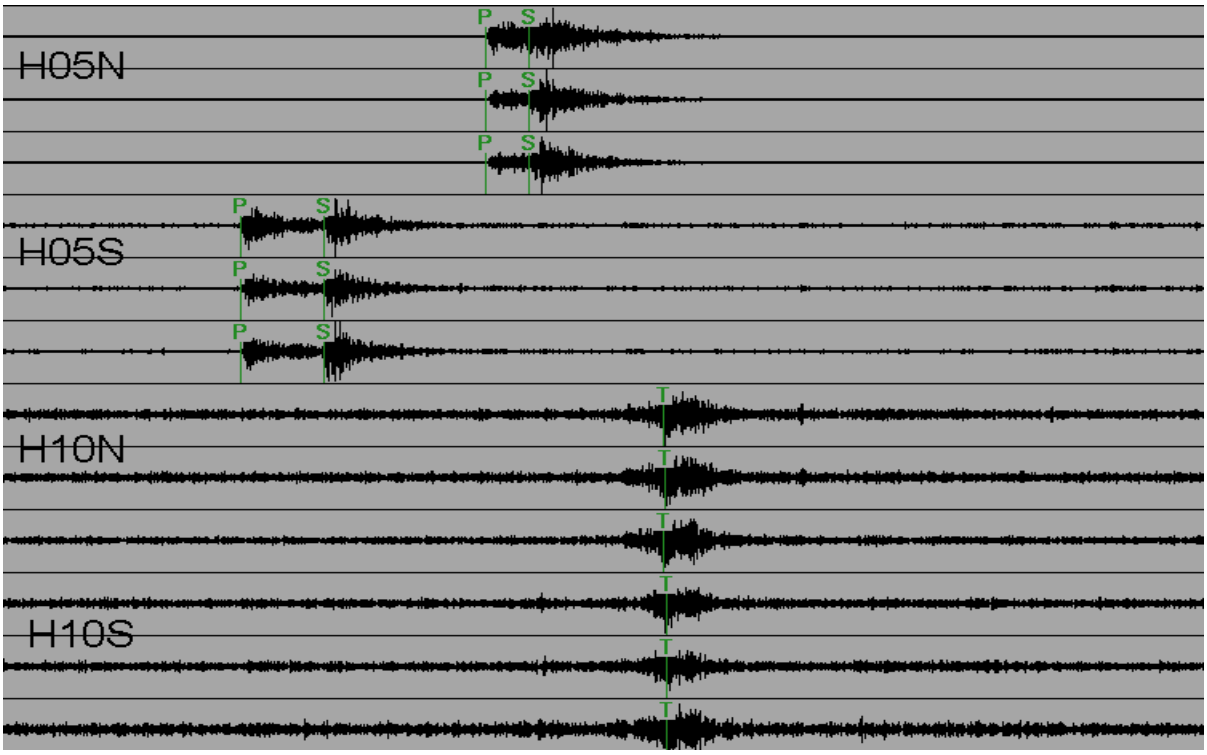

Fig.2 Waveforms recorded at two hydroacoustic stations. Signals are aligned on the predicted T phase arrival time. Only seismic signals are visible at HA05

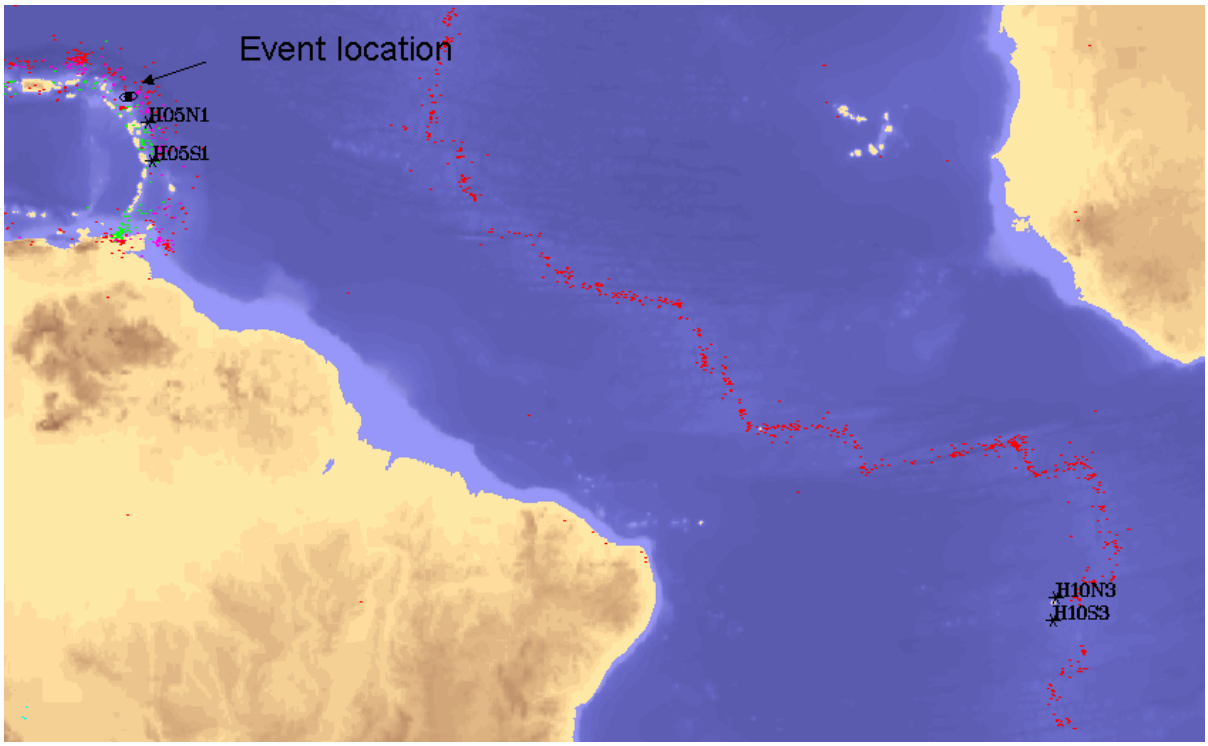

Fig.3 Location of a source which generated signals shown in the fig.2. and four elements of detecting stations

3.2. RESULTS OF SYSTEMATIC REVIEW OF DETECTIONS

Another method of investigating hydroacoustic signals is to look at all hydroacoustic detections recorded within a certain period. This activity, although time consuming, allowed us to identify non-earthquake sources of hydroacoustic detections. The systematic review was done for the data provided by a subnetwork covering the Indian Ocean basin.

About 70 detections recorded at HA08 and HA01 were taken into consideration. These data were recorded on 21/02/2006. Unfortunately the third hydrophone station situated in the Indian Ocean basin - HA04 was not operational for the investigated period.

After looking into the duration and frequency content of signals, the detections were, where possible, identified and labelled accordingly. Although, some signals, like T phases belonging to the REB events could be easily classified, there was a big group of detections which needed more investigation to identify their source.

Signals generated by events saved in the REB had T phase characteristics. An example of a spectrogram of signal associated an event in Chagos Archipelago region is shown in fig.4. This signal is characterized by a long duration (about 100 s) and energy concentrated below 50 Hz [1].

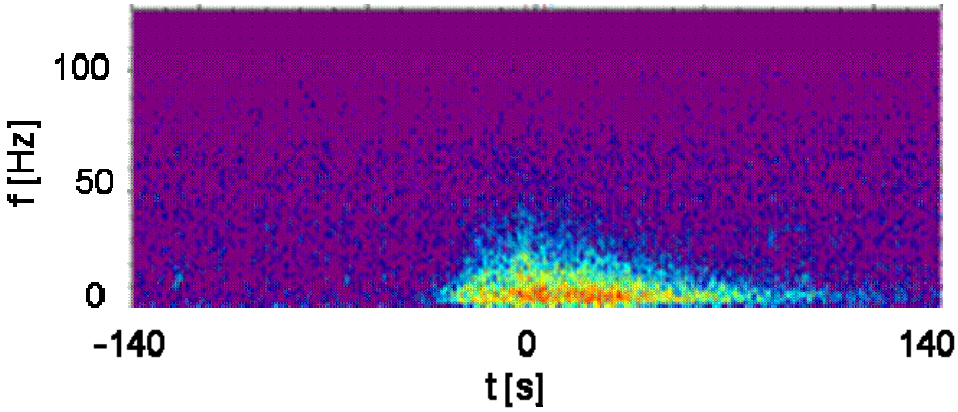

Fig.4 Spectrogram of a T phase generated by an event from Chagos Archipelago region and recorded at a hydrophone station 500 km away from the event

We also tried to locate events using only signals detected at hydroacoustic stations. First, we decided to use REB event locations that had T phases associated to them as a reference. We relocated the same events using only the associated T phases and compared the results with the REB solution. This exercise showed us how reliable the hydro-based solution is compared to the seismic-based one. The next step was to locate some events, which did not have an REB location. Signals recorded by two or more stations were identified as belonging to the same event if their frequency content and duration was similar. Also azimuth and time difference of signal detections should have given a reasonable location solution. In practice it was possible to group detections from the southern site of HA08 – H08S and the only site of HA01 – H01W. Due to the bathymetrical blockage of the island at which HA08 is situated it was difficult to build non REB events from data recorded at H08N.

For the investigated data day there were five REB events which could be located basing on arrival time of associated T phases. The greatest difference (9.4 degrees) was observed for

the Chagos Archipelago event due to the small difference in measured azimuths from H01W and H08S, where the range could not be constrained. In other cases, the difference between REB and the hydro location was smaller than 1.5 deg.

While looking at all detections it was possible to see signals presumably generated by other sources than earthquakes. These events did not belong to the REB and only hydroacoustic data contributed to their location. One type of source generated signals thorough the recorded frequency range (1-100 Hz) and with relatively short duration. We were able to locate the sources close to the Mid Indian ridge. Signal characteristics together with the location of its source may suggest a volcanic origin [1]. An example of these signals is shown in fig.5.

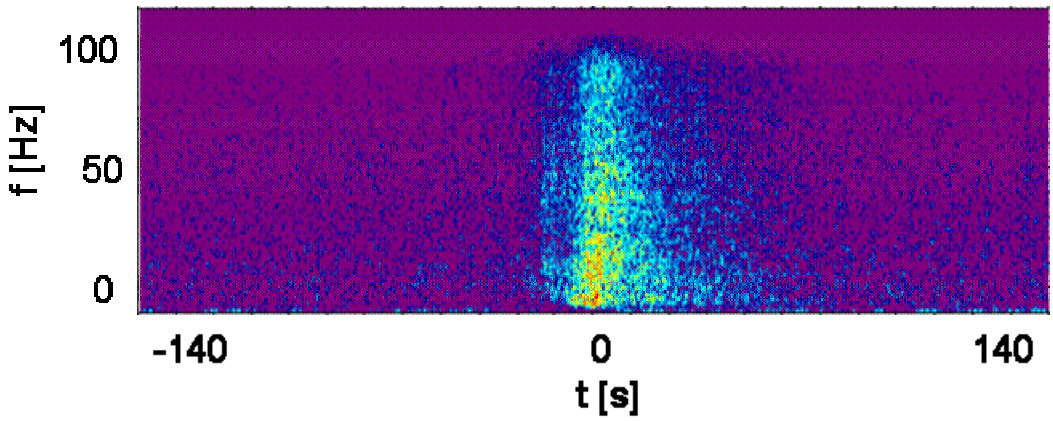

Fig.5 Spectrogram of signal generated by a source at the Mid-Indian Ridge region

Some sources were located close to Antarctica and associated with iceberg activity. An example of spectrogram is shown in fig.6. As visible, these signals have a wide frequency range and varying duration. At least two separate peaks can be distinguished in this example, which indicates a complex source function.

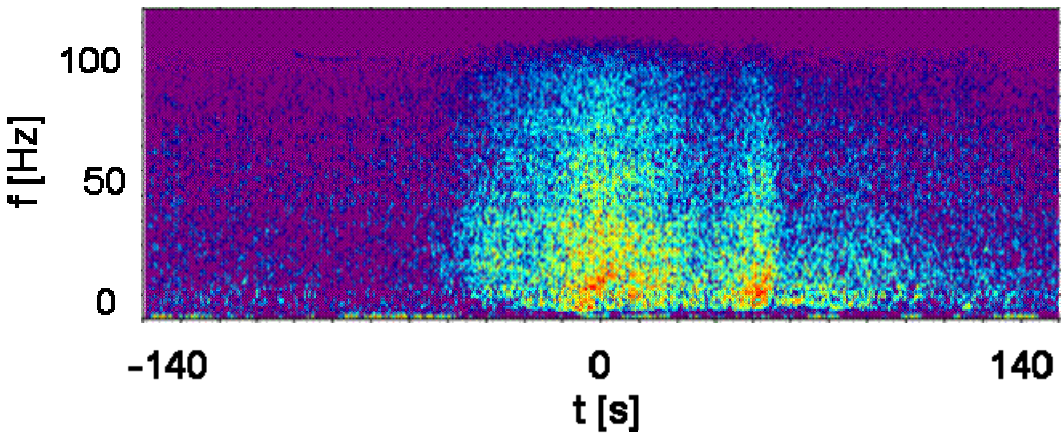

Fig.6 Spectrogram of signal generated by a source close to Antarctica

It can be seen that spectral signatures of signals recorded at hydroacoustic stations belonging to the IMS can provide valuable information about the nature of the source.

During analysis of one day of data from H01W and H08S we were able to locate and identify sources of only 13% of detected signals. Other signals were observed at only one hydraocoustic station.

4. CONCLUSIONS

As a result of the geographical distribution of the IMS hydroacoustic network, it is not always easy to build events based on hydroacoustic detections only. A very limited number of hydrophone stations, which provide an azimuth estimate and signal of good quality, makes this task more difficult than in case of the seismic technology.

Routine analysis of REB events draws analyst attention to hydroacoustic signals generated by earthquakes. It was noticed that although only seismic signals contribute to location of most of REB events, hydroacoustic stations can play an important role in increasing analyst confidence about the reality of an event and its location, if the event was recorded by only a few seismic stations. The hydroacoustic network is also capable of detecting seismic signals which can constrain location solutions for close events. Analysis of signal spectrograms may provide valuable information about the source nature.

During investigation of all hydroacoustic detections for one day of data we noticed that it was difficult to identify a source of a high percentage of the hydroacoustic signals.

DISCLAIMER

The views expressed herein are those of the authors and do not necessarily reflect the views of the CTBTO

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