ACOUSTIC MONITORING OF THE GLOBAL OCEAN FOR THE CTBT

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Abstract

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) provides for monitoring of the whole globe by a network of stations, using various technologies, in order to verify absence of nuclear explosion tests. The hydroacoustic component of this network, which monitors the major world oceans, is currently under construction. When complete it will consist of eleven stations located with an emphasis on the vast ocean areas of the Southern Hemisphere. At mid 2004, eight stations were transmitting data and construction is well advanced on all but one of the remaining stations. The stations transmit real-time continuous data to the CTBT Organization headquarters in Vienna, Austria. The hydroacoustic network uses two different types of stations. One type is based on hydrophones floated from the sea floor to the SOFAR axis depth, arranged horizontally in a triplet configuration. The other type is based on use of seismometers located on small islands to detect hydroacoustic signals after conversion to seismic signals at the flanks of the island. During the time since completing the first stations, many interesting acoustical phenomena have been observed in the data, including earthquakes, volcanoes, oil exploration, whale vocalizations, Antarctic ice bergs. Also, many interesting physical phenomena have been observed, such as reflections of hydroacoustic energy from the sides of continents. Hydroacoustic path lengths of in excess of ten thousand kilometres are routinely observed.

Introduction

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) mandates an International Monitoring System (IMS) to ensure verification of compliance with the Treaty’s prohibition on tests of nuclear weapon explosions [1]. A companion paper at this conference [2] describes the three waveform technologies used to monitor for vibrations caused by nuclear explosions. These three technologies are seismic (monitoring ground vibrations), hydroacoustic (monitoring ocean vibrations) and infrasound (monitoring air vibrations). Also used for CTBT monitoring is the radionuclide technology, which checks for the presence of radioactive products of a nuclear explosion.

This paper focuses on just one of these monitoring technologies, hydroacoustics. A description is provided of the IMS hydroacoustic network, the status of establishment of this network, as well as how this network can achieve the assigned task. Finally, there is a description of some events seen on this network.

The primary purpose of the IMS hydroacoustic network is to provide monitoring coverage of the broad ocean areas of the globe. This network works in synergy with the other IMS networks. The seismic stations are located on land masses and can provide good coverage of all such areas. In addition, the seismic network will also work well in providing monitoring for seas and lakes. However, the 70% of the globe’s surface that is covered by oceans is difficult to adequately cover with land based instruments. Hence the focus of the hydroacoustic network on the broad ocean areas. Since the broad ocean areas are preponderantly in the Southern Hemisphere, the IMS hydroacoustic stations are also predominantly in the Southern Hemisphere.

As is described more fully below, the IMS hydroacoustic network consists of a total of eleven stations; six based on cabled hydrophones and five based on suitably designed seismic stations located on small islands.

Hydroacoustic Propagation

Before describing the IMS hydroacoustic network itself, it is useful to have a short description of some relevant aspects of hydroacoustic propagation. A fuller understanding can be obtained from references [3] and [4].

The ocean is an excellent medium for sound; low frequency hydroacoustic energy propagates for very long distances with little loss of intensity. The reason for this is twofold. Firstly, there just happens to be a very low absorption of hydroacoustic energy (it is much less than in the atmosphere, for example). Secondly, the ocean acts like a waveguide which traps the hydroacoustic energy and minimizes spreading losses.

The ocean is limited above by the sea surface and below by the sea floor, and it thus resembles a waveguide, where energy can be reflected from the boundaries to contain the energy. However, the situation is even more advantageous than that. The spatial variation of the speed of sound (which acts to bend rays of acoustic energy) enhances this waveguide effect. The sound speed is basically horizontally homogeneous, but has a minimum with depth at around 1 km from the surface (due to competing effects of temperature and static pressure). The channel created by the resulting refractive focussing is commonly called SOFAR.

Note that the overall effect of this SOFAR channel is to reduce spreading loss to inverse with distance, rather that inverse with the square of distance as would result from an isotropic environment.

The IMS Hydroacoustic Network

Design of Hydroacoustic Network

The exceptionally low transmission losses for long range hydroacoustic energy allow a global monitoring network to be established with only eleven stations. This may be compared with the infrasound network which requires sixty stations to achieve global coverage.

The signal generated by an explosion in the water, above water in the low atmosphere, or underground near the ocean, will be detected even at long distances by sensors located in the SOFAR channel.

Six stations of the hydroacoustic network are equipped with hydrophone sensors. The other five stations are located on small steep-sloped islands and make use of seismic sensors to detect waterborne energy, which is converted to a seismic wave on the flanks of the island. This type of propagation has long been known to the seismic community, which calls it T-phase propagation. By analogy these types of monitoring station are called T-Phase. These stations are not as effective as hydrophone stations in detecting and identifying hydroacoustic signals from explosions, but they are considerably less complex and expensive. The mixture of hydrophone and T-phase stations was selected for the IMS hydroacoustic network to provide a cost-effective compromise. The locations of the stations are set out in Figure 1 and Tables 1 and 2.

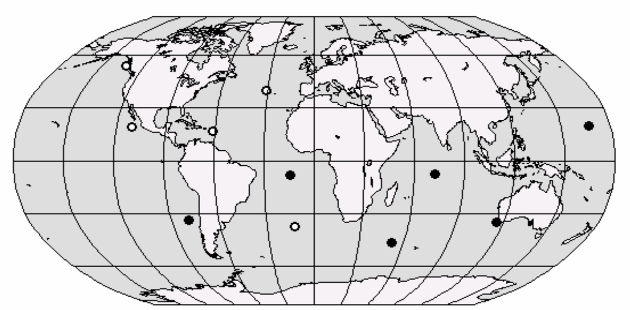

Figure 1. Hydroacoustic network of the IMS.
Filled dots are hydrophone stations.
Open dots are T-Phase stations.

Hydrophone Stations

Table 1. Location of Hydrophone Stations

Code	Site	Latitude	Longitude
HA01	Cape Leeuwin	34.3°S	115.2°E
HA03	Juan Fernandez Is.	33.6°S	78.8°W
HA04	Crozet Island	46.4°S	51.9°E
HA08	Diego Garcia Is.	7.3°S	72.4°E
HA10	Ascension Island	8.0°S	14.4°W
HA11	Wake Island	19.3°N	166.6°E

All hydrophone stations, except for Cape Leeuwin, are located on small islands. They consist of two undersea trunk cables, each with three hydrophone sensors. Cables and sensors are deployed on opposite shores of the island in order to avoid bathymetric blockage by the island. Each hydrophone sensor has an independent wet-end digitizer. The digital signals are transmitted to the shore facility via a non-repeatered fiber optic cable for processing and transmission by satellite to the IDC in Vienna (Figure 2). The IDC is the International Data Centre, which is part of the CTBT Organization headquarters.

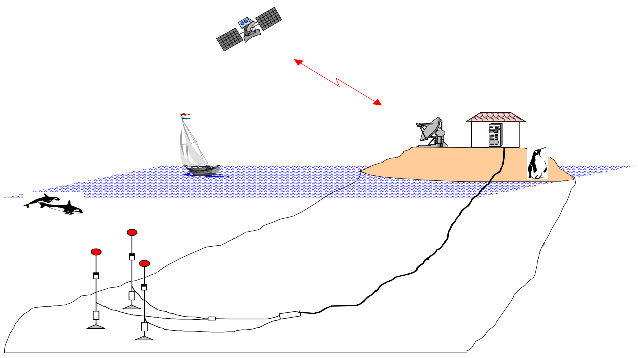

Figure 2. Hydrophone station showing
one triplet of hydrophones,
the shore facility and the satellite antenna.

The hydrophone sensors are placed at or near the axis of the SOFAR channel, using a subsurface float and an ocean-bottom anchor. To provide the station with directional capabilities, the three hydrophones are placed in a triangular configuration and each sensor is separated horizontally by approximately two kilometers. The frequency band of the hydrophone station is from 1 to 100 Hz.

The principal threats to long and reliable operation of hydrophone stations are possible damage to the cables at the land-sea interface and possible cable breakage caused by anchoring and trawling activities. The station design uses well-developed techniques for cable laying and protection, including cable burial at the surf zone, armoring of the cable, and split pipe protection. These techniques all serve to enhance the potential lifetime of the stations.

T-Phase Stations

Table 2. Location of T-Phase Stations

Code	Site	Latitude	Longitude
HA02	Queen Charlotte Is.	53.3°N	132.5°W
HA05	Guadeloupe Is.	16.3°N	61.1°W
HA06	Socorro Island	18.7°N	110.9°W
HA07	Flores Island	39.4°N	31.2°W
HA09	Tristan da Cunha Is.	37.1°S	12.3°W

A T-phase station uses seismometers to detect seismic waves generated by the coupling of waterborne energy at the flanks of the island. As in the case of the hydrophone stations, the data are formatted and transmitted by satellite in real time to the IDC. Figure 3 is a schema of a typical T-Phase Station showing the seismic and hydroacoustic signal paths from an underwater event, the shore facility (containing the seismometers and the associated data acquisition system) as well as the satellite link to the IDC.

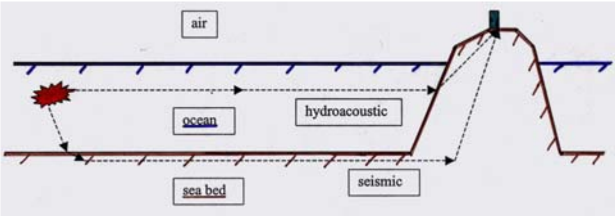

Figure 3. T-Phase station, showing T-Phase path through ocean, converting to seismic energy at island flank.

The absorption rate of acoustic energy in the ocean is very small, compared to the absorption rate of seismic energy propagating through the Earth itself (in which there is high absorption of the higher frequencies). Hence the T-phase signals will have considerably more energy at the higher frequencies than do regular seismic signals. As a consequence, T-phase stations are designed to operate in the frequency band from 0.5 to 40 Hz, which is higher than the normal range used for long distance seismic monitoring.

The T-Phase stations each use seismometers arranged to provide measures of motion in three orthogonal directions (vertical, north-south and east-west). Further, up to three seismometer locations are used, in order to achieve a good azimuthal coverage by the station.

Station Establishment

The implementation of the IMS network is performed in four phases: site survey; manufacture and installation; certification; and finally operations and maintenance.

A site survey is carried out to assess the suitability of the site for hosting a station and to identify any specific conditions that would impact the station design. The results of the site survey are used to determine the exact sensor locations.

The CTBT Organization has required standards that a station must meet in order to be certified as a valid station within the IMS network. Careful review is made of all aspects of each station to ensure that it meets these required standards. Once the station is certified, operations and maintenance agreements are established between the CTBT Organization and a station operator. Long term quality monitoring is then undertaken to ensure high standards of data quality, data availability, and station performance.

The status of completion of the IMS Hydroacoustic network, by mid 2004, was as follows. All of the site surveys had been completed. Work had commenced on all stations but one hydrophone station (Wake Island). One further hydrophone station (Ascension Island) was not yet installed and one T-Phase station (Flores Island) was not yet installed. Three hydrophone stations and one T-Phase station were certified as fully meeting the requirements of the CTBT Organization.

Signals at Hydrophone Triplets

As mentioned above, rather than using a single hydrophone, a triplet of hydrophones is used arranged in a triangular configuration. The purpose of this arrangement is to obtain some directional information on the source of the signal. This is useful in order to facilitate automatic assignment of detection of signals on one IMS station with the signals received on other IMS stations, originating from the same event. Due to the long travel times involved and the high number of natural events, lack of such directional information from stations would make automatic processing much more difficult, if not impossible.

The directional information that is obtained from the triplet of hydrophones is obtained by examining the relative time of arrival at the three hydrophones. One way of performing such an examination is by using a pair-wise correlation of the hydrophone signals. An example the results of such a process is given in Figure 4, which shows the useful coherence of these signals even after travelling 16,000 km.

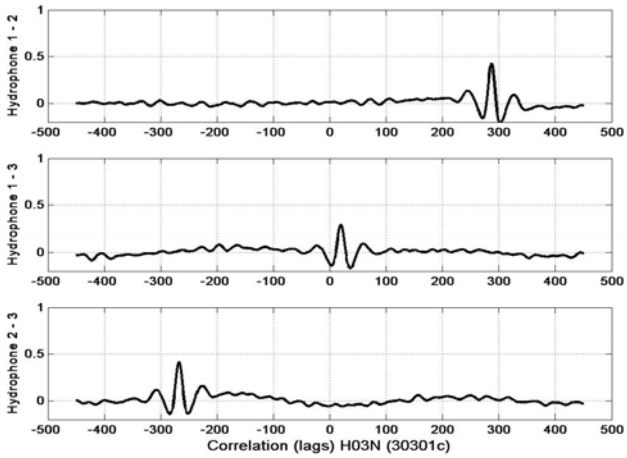

Figure 4. Pair-wise correlation of signals received on H03N from an earthquake in the Kurile Islands on 23 March 2003, a range of 16,000 km. Correlation coefficient is plotted against time lags (each sample is 4 ms).

Interestingly, this technique can be used to improve the knowledge of the relative positions of the hydrophones. At time of installation of the station, careful measurement is made of the hydrophone locations. However, due to the hydrophones being far beneath the ocean surface, this process is not highly accurate. Later, using the signals from a single earthquake, a comparison can be made between the directions to the source event determined (i) from the measured relative hydrophone positions and (ii) by the CTBT International Data Centre using data from other stations. By repeating this process using a large number of earthquakes, from a range of azimuths, an inverse method can be used to minimize the azimuthal errors. The minimum is achieved by adjusting the assumed relative positions of the three hydrophones. By using this technique the relative hydrophone locations have been corrected by typically 100 m resulting in maximum directional errors falling by about a factor of four.

Station Coverage

By examining signals from a number of events (mostly undersea earthquakes) a picture may be built up which illustrates the coverage by a single IMS hydrophone station. An example of this is given in Figure 5.

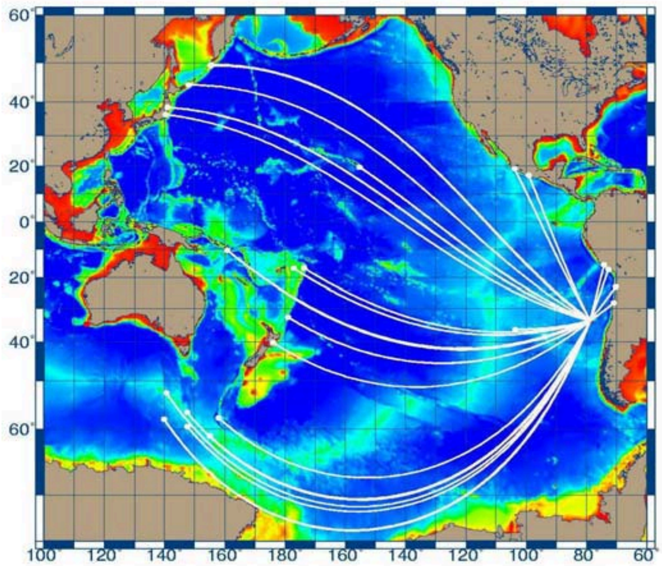

Figure 5. Great circle paths from various events (earthquakes) observed at the Juan Fernandez station, both on the north and south hydrophones.

Hydroacoustic Signals

Hydroacoustic signals are changes in the water pressure generated by sound waves. Due to the efficient transmission of sound in the ocean, low-amplitude signals are detectable at very long distances. The primary operational objectives of the IMS hydroacoustic network are the detection, location and characterization of impulsive signals from nuclear explosions. Acoustic signals are also produced by human activities such as seismic profiling for oil exploration or military exercises, as well as by natural sources such as earthquakes or volcanic eruptions.

An understanding of the characteristics of these signals as received at hydrophone and T-phase stations are important for sensor placement as well as for signal processing to enhance the detection of events, and the extraction of information to identify, characterize and locate the event. These characterizations and various interesting signals are illustrated below.

Earthquakes

A common type of event seen on the IMS hydroacoustic stations is the earthquake. Undersea earthquakes are seen, in which case the energy travels from the site of the earthquake to nearby sea floor where there is conversion from seismic to hydroacoustic energy, which finally travels through the ocean to the hydroacoustic station. Also detected are earthquakes that occur in land masses but not too distant from the ocean (distances up to some hundreds of kilometres). In this latter case, the seismic path through the land is normally longer than for the undersea earthquakes.

The spectra from hydroacoustic signals generated by earthquakes have a number of typical characteristics. The upper frequency where the signal can be seen above ambient noise is normally less than 30 Hz. This is in contrast with signals from underwater explosions in which energy is observed up to the maximum frequency (100 Hz) available from the IMS hydroacoustic system. Also the time span of the signals from an earthquake is longer than for an explosion. Figure 6 presents an example time series from an earthquake.

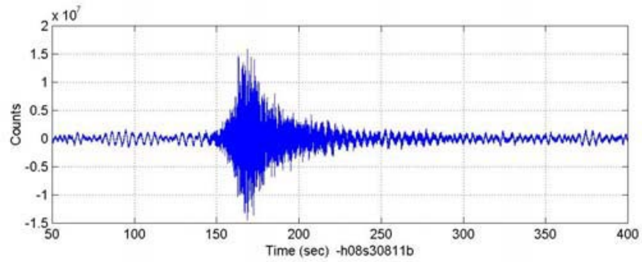

Figure 6. Hydroacoustic time series from earthquake near Macquarie Island recorded at Diego Garcia station on the south hydrophones.

Volcanoes

Undersea volcanic activity tends to last for long periods. Periods of activity last for many minutes, days or even months. The periods of activity also recur, sometimes for years. An example of the hydroacoustic signals generated are shown in Figure 7.

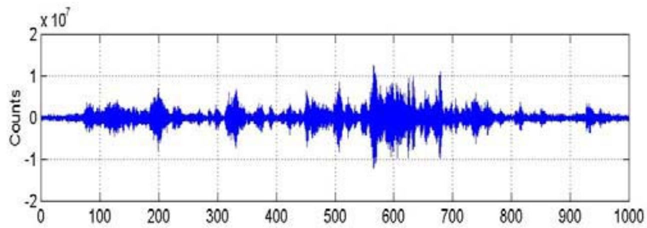

Figure 7. Hydroacoustic time series from volcano located in the Western Pacific Ocean recorded at Juan Fernandez station on the north hydrophones. The abscissa is in seconds.

Whales

Marine mammals are known to vocalize, both for communication purposes and to locate objects by echoes.

Much of this acoustic activity lies above the frequency band of the IMS hydroacoustic stations. It is only the larger whales that produce sounds below 100 Hz. However, these whales produce very loud sounds, quite often. These sounds are routinely detected over ranges of hundreds of kilometres. The most frequent whale noises seen on the IMS hydrophone stations are from blue and fin whales (see Figure 8 for an example).

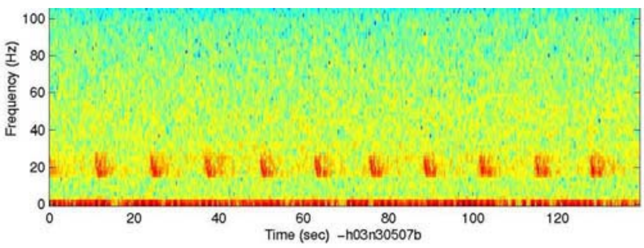

Figure 8. Spectrogram of fin whale calls at H03N, the north hydrophones at Juan Fernandez. The whale calls are roughly from 18 to 27 Hz.

Ambient Noise

The hydrophone-based IMS hydroacoustic stations are well calibrated systems designed to measure down to levels below the ambient noise of the ocean. Thus variations in ambient noise with time and location are readily apparent. There are obvious long-term differences in the ambient noise from one station to another (Figure 9). Also more transitory effects, such as due to storm action, can be readily observed.

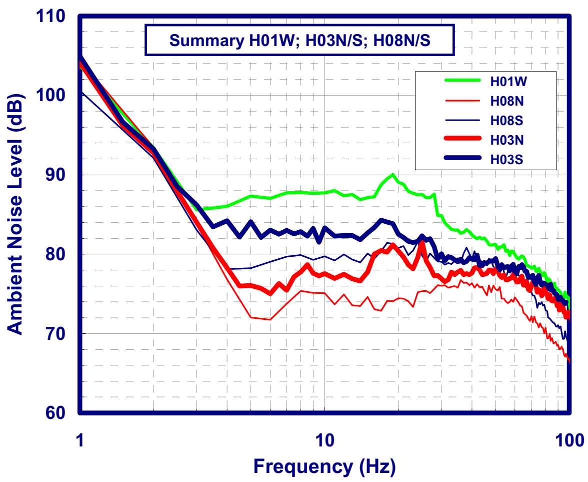

Figure 9. Ambient noise spectra measured at hydrophone-based IMS hydroacoustic stations.

Figure 9 shows the ambient noise spectra, averaged over one year, at three different IMS hydroacoustic stations. In two cases spectra are provided from both the north and south of the island. The suffixes N, S and W in Figure 9 refer to the geographical location (north, south and west) of the hydrophones with respect to the station facility (which is usually on a small island). The noisiest station is H01W at Cape Leeuwin, the quietest is H08N on the north side of the island of Diego Garcia. In general, the noisiest stations are those facing the Southern Ocean, with proximity to the Southern Ocean also corresponding to increased noise levels. This is not surprising since the Southern Ocean is a place of great storm activity and the SOFAR channel shoals in the region allowing surface generated noises to couple very efficiently into the SOFAR channel.

An interesting feature evident in Figure 9 is the hump in the spectrum from 18 to 27 Hz. This corresponds to the noise generated by fin whales. Evidently the fin whale population is so noisy for so much time that they are the predominant noise source in this frequency band when averaged over a year, at both the Cape Leeuwin station and also at the Juan Fernandez station.

Conclusions

It is evident that a global ocean acoustic observatory is currently under construction and is already providing high quality data. This data is collected continuously, with high data availability. The data collection will continue into the future and all of the data is archived in a robust manner.

The data set being accumulated is valuable for CTBT monitoring purposes, the intended use of the data. However, it is clear that this data set will have scientific applications as well.

The IMS data are collected by the CTBTO at its headquarters in Vienna. From here it is made available to the National Authorities of all State Signatories to the CTBT.

References

[1] "Comprehensive Nuclear-Test-Ban Treaty", adopted by the General Assembly of the United Nations on 10 September 1996, resolution 50/245.

[2] Lawrence M W, "Global Monitoring of the Earth, Ocean and Atmosphere for the CTBT", Acoustics 2004, Gold Coast Australia, November 2004.

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[4] Urick R J, *Principles of Underwater Sound*, 3rd ed. McGraw-Hill, New York, 1983.