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Acoustic characteristics of fish bombing: potential to develop an automated blast detector

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Abstract

The use of explosives to catch fish has caused extensive damage to coral reefs throughout Southeast Asia, but the frequency with which they are used is largely unknown. The aim of this work is to develop a detection system capable of distinguishing underwater explosions from background noise, and locating their origin by triangulation. Blast signals have been recorded over a range of distances and the key features that differentiate them from background noise have been determined. For small charges the effective range of such a detector is more than 12 km and may extend up to 50 km depending on the mass of the charges being used. Such a system would help to determine the scale of the problem, identify areas at greatest risk and quantify the effectiveness of management intervention designed to control destructive fishing practices. It may assist with fisheries enforcement in some areas.

Keywords: Fishery management; Reefs; Noise; Destructive fishing practices; Fish bombing; Underwater explosions

1. Introduction

It is widely acknowledged that destructive fishing practices are among the most serious and immediate threats to coral reefs in Southeast Asia. Fish blasting (also known as 'fish bombing' or 'dynamite fishing') has been reported from almost all countries in the region (McAllister, 1988; Lemay et al., 1991; Gomez et al., 1994; Hair, 1994; Huber, 1994; ICRI, 1995; Pet-Soede and Erdmann, 1998a,b; Oakley et al., 1999) as well as from East Africa (Makoloweka, 1998). Fish blasting at high intensity is particularly destructive because it transforms a reef from a productive and solid structure to an area of mobile rubble that takes years to recover at best, or induces an ecological phase shift that prevents corals from re-colonizing at worst.

Despite the impact of fish blasting on the sustainability of reef fisheries, no quantitative data are available on the frequency or geographic distribution of fish blasting. This lack of data is seen as a key constraint to the management of the problem at both a local and regional level. The long-term goal of this work is to develop a tool for detecting and locating blast events in a quantifiable area. From such data the frequency and distribution of blasting over a range of geographical scales can be determined.

Although the acoustic signal from underwater explosions can be detected at considerable ranges, reliably differentiating weak blast signals from background noise poses significant technical challenges. The purpose of this investigation is to characterize acoustic signals from blasts and sources of background noise to enable a suitable detection algorithm to be developed.

2. Methods and materials

Acoustic signals from blast events in shallow water are complicated by reflections from the water surface and the seabed. In addition, there is considerable variability in the construction and chemical composition of

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the charges being used. Although underwater explosions have been studied for over fifty years, typically shock waves have been generated using standardized charges in deep water (Chapman, 1985). To our knowledge no work has been published on acoustic signals from fish bombs in shallow water.

For this study it was critical to detonate charges under controlled conditions in the field to characterize their blast signals. The variables under control were the distance from the bomb to the detector, the depths of the charge and the detector, and the mass of the charge. Standardized fish bombs were manufactured and detonated using traditional methods and to minimize impacts to the reef and fish, blasts were triggered in water 20–30 m deep in sandy areas.

2.1. Charges

Ammonium nitrate fertilizer was supplied in the form of granules that were mixed with kerosine (fuel oil). Blast fishermen use a well-known recipe for mixing fuel oil with fertilizer to produce the ammonium nitrate/fuel oil (ANFO) explosive. The recipe incorporates the optimum mixing ratio of 94% ammonium nitrate and 6% fuel oil (by mass) that ensures full oxidation of the fuel oil and maximum blast energy (Köhler and Meyer, 1993). A small charge typical of the region consists of a glass bottle (often 625 ml capacity) filled with a 500 g charge. The open end of the bottle was sealed with a plastic foam plug with a slit cut into it to allow a high explosive detonator to be inserted into the charge. The detonator consisted of a thin, hollow aluminium cylinder with one open end, roughly 3 mm in diameter and 30 mm in length. The closed end of the cylinder contained the high explosive detonator charge along about a third of its length. Detonators are widely available over Southeast Asia and account for a significant fraction of the total cost of a fish bomb. One end of a length of fuse wire was inserted into the open end of the detonator and at the other end two safety matches were bound to it with thread to act as a source of ignition. A clear plastic film was tightly wrapped over the match heads and tied as waterproofing. The length of fuse varies and allows the fisherman to control the timing of the detonation, and therefore its depth given a constant rate of sinking. By attaching iron bars or rocks to the charge the rate of sinking can be increased.

2.2. Signal detection

The parameters identified as influencing the energy received by the sensor were the efficiency of mixing of charge ingredients, orientation, depth of the charge and the presence of islands. Charges used in this study were known to have been manufactured in a single batch, which reduced the expected variability in the composition of explosive. Since bottles are asymmetrical it is likely that they behave as shaped charges, producing an asymmetrical shock wave. However, controlling the orientation of the charge until detonation would have been difficult and was not attempted. The depth at which the blast occurred was controlled by attaching a line and float to the charge. Target depths varied between 7 and 12 m. Trials were conducted with and without a land barrier between the detector and the blast.

The investigations required the use of two survey boats, one carrying the detection equipment, the other directing the timing and location of the blasts. Each boat was equipped with a handheld GPS unit to measure the distance from blasts to the detector. A number of trials investigated the effect of distance (which ranged between 150 m to 12 km) on the blast signal. The uncertainty of the position measurements from the GPS was around 15 m.

Further trials were made recording the blast signals on two similar detectors to explore the effects of detector depth and the distance to the blast on the time delay between the signals. The detectors were mounted on a rig that consisted of a top section supported on the sea surface by floats and a submerged weighted framework. The orientation of the rig was controlled manually so that one detector was ≈ 1 m closer to the blast. The depth of water at the detection location was 9 m over a gently sloping reef therefore reflections were expected to complicate the signal shape.

Background noises from two sources were also investigated. These were snapping shrimp (Alphaeidae) and outboard engine and propeller noise.

Pressure signals were recorded using one or two Brüel and Kjaer Type 8103 high-frequency response hydrophones with a Nexus conditioning amplifier. These hydrophones are suitable for recording the signals from underwater explosions. The gain of this amplifier can be adjusted from 10 $\mu\mathrm{V\,Pa^{-1}}$ over a range of 15 decades with 2 preset values per decade. The signals were digitized (with 12 bit resolution) at a rate of 100 or 200 kHz using a National Instruments data acquisition card (DAQCard–AI–16E–4) and a laptop computer. The digitized signals were streamed onto an 18 GB hard disk and then analyzed using a system developed with Labview software (supplied by National Instruments). The signals were also recorded on storage oscilloscope with 8-bit resolution (model type THS720P manufactured by Tektronix) at a data acquisition rate between 500 kHz to 1.25 MHz.

One hour of recording one hydrophone at a sampling rate of 200 kHz or two hydrophones at 100 kHz generates 1.4 GB of data. Blasts signals were roughly located in these large files by using the logged time of the event recorded by an observer. To precisely locate the signal in the file required a search for a pressure value above a certain threshold level. Other events were found in these files by similar techniques; matching file times with the written records produced by observers equipped with headphones, and performing searches for pressure values over a chosen threshold level.

3. Results

3.1. Variability of blast signals

Shock wave peak pressures are highly reproducible with carefully controlled charges (Chapman, 1985). However, the standard deviation of peak shock pressures for the homemade charges used in this study was ≈20% of the average maximum peak pressure. Fig. 1 shows the peak pressures of eight repeated blasts recorded at a distance of 390 m. The low resolution in digitization in this trial contributed to the large errors. However similar variability in peak pressures was observed at all ranges where shock fronts were distinct. Differences in mixing of the charge ingredients and charge asymmetry are the most likely sources of this variability.

3.2. Peak pressure of shock fronts vs distance

At less than 2 km from the blast a well-defined shock wave is observed, the signal showing a characteristic, almost vertical leading edge (Fig. 2). At ranges greater than 2 km the steep leading edge decays rapidly and at 3 km the shock front is either small or absent. At these larger distances maximum pressure peak often occurs in the main body of the signal rather than the front (e.g. Figs. 3 and 6).

3.3. Surface reflections

Reflections from the air–water surface arrive soon after the directly propagated pulse complicating the signal. These reflections invert the pressure signal, (Medwin and Clay, 1998) leading to significant negative pressures. Large negative pressures produced by surface reflections close to the blast are likely to be a major cause of fish mortality as they result in rupturing of gas filled cavities such as swim bladders (Lewis, 1996).

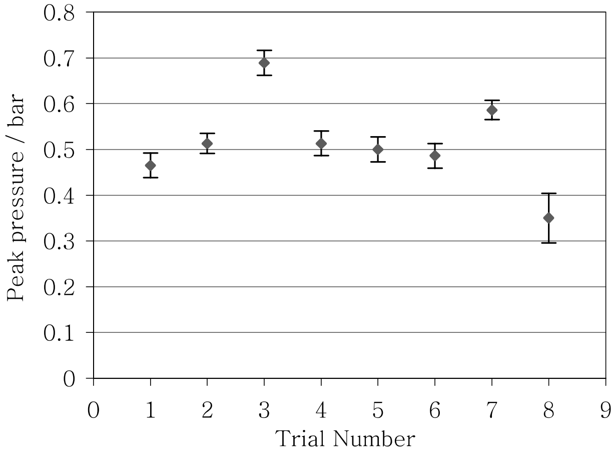

Fig. 1. Peak pressure of repeated blasts at around 390 m distance.

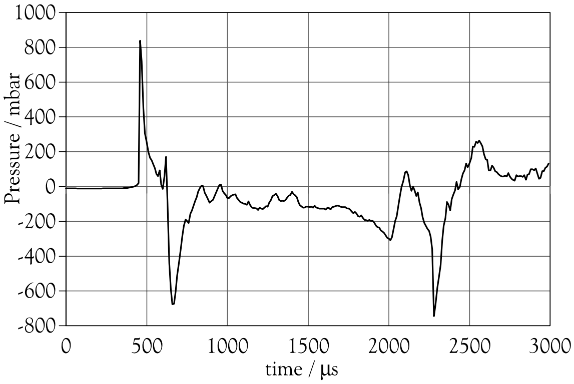

Fig. 2. Blast signal at 250 m.

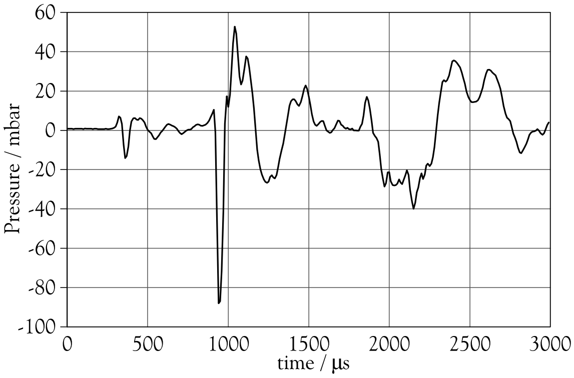

Fig. 3. Blast signal at 3000 m.

At close ranges, reflections can be easily distinguished from directly propagated signals because both retain their sharp leading edges. In Fig. 2, the inverted edge of the surface reflected signal was detected 200 µs after that of the directly propagated signal. The negative pressure produced in this case is around 700 mbar. At greater distances, the front edges of both signals are less distinct and begin to merge together. In addition the time delay between the direct and the reflected signal is reduced. This is shown in the detail of the front end of a signal at a distance of 2.6 km in Fig. 4. In this case the time delay is only about 80 µs. At intermediate ranges the reflected signal spends more time in the warmer surface water layer, and since warmer water transmits acoustic energy at greater rates than cooler water, the reflection catches up with the directly propagated signal. The proximity of the surface reflection to the direct signal is a factor in the rapid decay of the shock front beyond a distance of 2 km since the two signals destructively interfere with each

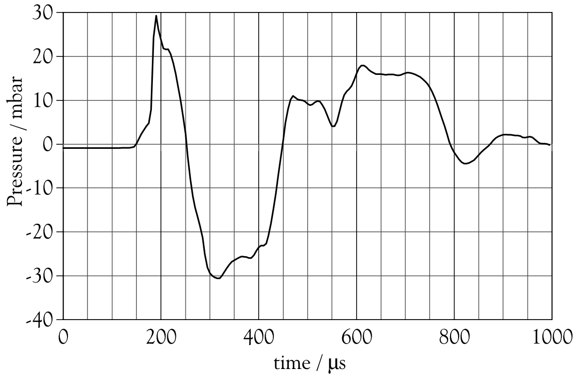

Fig. 4. Blast signal at 2600 m.

other. Signal shapes for blasts at long ranges are complex due to the interference of multiple reflections from the air–water boundary and the water–sediment boundary.

3.4. Shock wave decay

Another factor that changes the shape of distant signals arises when the pressure at the front of the wave is sufficiently low that the process that maintains the shock front is no longer effective. This is a consequence of the natural progression of a shock wave from the strong shock regime, through to weak shock and decay into sound. The highest peak pressure recorded in thus study was 1.6 bar; the peak pressure of a strong shock is typically many thousands of bar, therefore all the signals recorded in this study are classified in the weak shock regime (Medwin and Clay, 1998).

3.5. Signals from hydrophones at the same depth

Two hydrophones at the same depth record very similar signals. If one of the detectors is closer to the blast, then its signal leads the one from the other hydrophone. An example is shown in Fig. 5 which shows the signals of a blast at 12 km range recorded by 2 hydrophones, one of which was located 1 m closer to the blast. Shapes of signals from the same events recorded from hydrophones placed at different depths are markedly different, highlighting the strong dependence of surface reflections on the depth of detector.

3.6. Signals at long range

Fig. 6 shows the first 20 ms of a different blast signal at a range of 12 km. The maximum pressure of the signal is located a long time after the arrival of the leading edge compared to blasts recorded at short range. The duration of signals from distant blasts is much greater than those generated by blasts at close range. These features are also visible in Fig. 5.

3.7. Alpheid shrimps

Alpheid shrimps (‘snapping shrimps’) generate small but violent water movements that cavitate the surrounding water to produce shock waves with peak pressures of up to 10 mbar (Fig. 7) at a range of several meters (Versluis et al., 2000). The shape of the leading part of the shrimp signals recorded in this study is similar to that recorded by Versluis et al. however they differed in the later part as Versluis et al. recorded

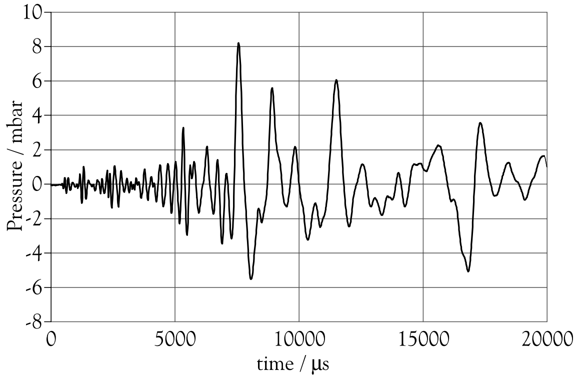

Fig. 6. Blast signal at 12,000 m.

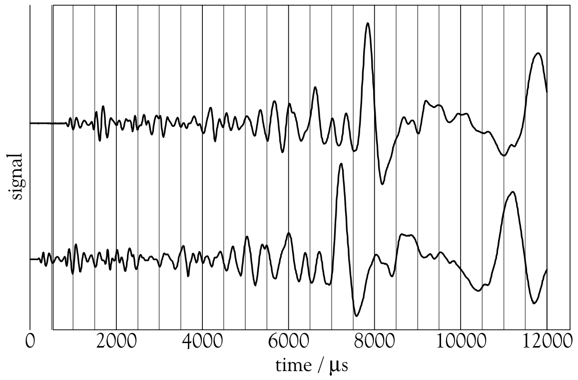

Fig. 5. Signals on 2 hydrophones at same depth, 12 km from blast.

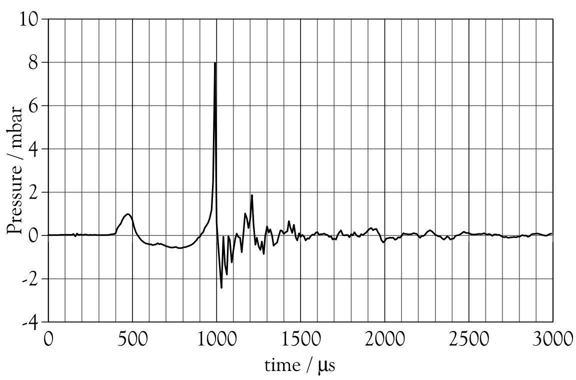

Fig. 7. Nearby shrimp signal.

reflections from aquarium walls. There were many recorded Alpheid shrimp signals that had peak pressures larger than blasts from ANFO charges at 12 km. However, the pulse is of a much shorter duration than that from a blast and this can be used to distinguish signals (compare Figs. 6 and 7).

3.8. Engine noise

Twin 130 horsepower outboard engines at full power (about 5500 revolutions per minute) at a range of 15 m produce a regular signal with a peak pressure of around 0.5 mbar, an order of magnitude smaller than a blast at 12 km. Fig. 8 shows the maximum pressure of blast signals vs distance and also shows the peak pressure from engine noise for comparison.

3.9. Land barriers

Islands are effective barriers to underwater sounds. Two blasts at a range of 2 km, with the hydrophone obscured by an island in one case and a headland in the other, produced no detectable signal, indicating negligible refraction or reflection off shorelines (Fig. 9). Since the strength of reflections depend on the shape and orientation of the reflecting surface, this result can only be regarded as an indication that shorelines normally strongly dissipate signals.

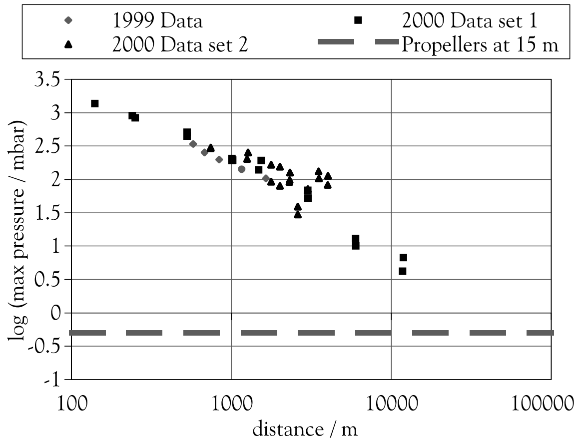

Fig. 8. Graph of maximum signal pressure vs distance.

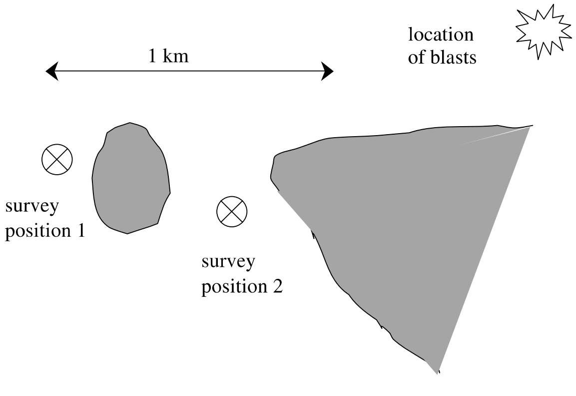

Fig. 9. Geometry of trial to detect reflections and refractions.

4. Discussion

4.1. Discriminating blast events from background noise

An automated blast detector must be able to distinguish blast events from other background sounds reliably. The processing power available to such a system varies from one design to another, however any design must incorporate an algorithm to filter blast signals from background noises. Therefore it is important to look at the blast signals and select characteristic features that can be used to discriminate them from other sounds.

Underwater explosions release large quantities of energy in such a short time that they generate shock waves. Shock wave signals are characterized by the sound pressure rising almost instantaneously to a large peak value and then falling away more slowly (Cole, 1948). The sudden rise in pressure is called the shock front. In contrast, the pressure in other underwater sounds rises much more slowly. At close range (<2 km in this study), the combination of the shock front and high peak pressure allows a blast to be discriminated easily from any other sounds. For example, the peak of the signal from a blast at 250 m is a change in pressure of half an atmosphere that occurs in less than 5 μs. The peak pressure of what would be perceived to be a loud sound to the human ear would be roughly a thousand times smaller.

Beyond around 2 km however, it appears that the shock front decays much more rapidly than predicted by the scaling theory of shock waves (Medwin and Clay, 1998), as evidenced by the lack of vertical edges in the signals at distances of 2600 and 3000 m (Figs. 3 and 4). Another feature of blasts at distances greater than about 2 km is that the maximum pressure peak no longer occurs at the beginning of the signal. These effects are likely to be linked to surface reflections and shock wave decay. The ramifications of this are that a blast detector designed to work at large ranges cannot be reliant on the distinctive properties of shock waves as opposed to sound waves.

Over a range of up to 12 km, the maximum pressure of the blast signal falls inversely with distance, as shown in Fig. 8. Maximum pressures from blasts at ranges greater than 10 km are significant compared with most sources of background noise and so can provide a reliable indication of an event. For example, extrapolation from the graph in Fig. 7 indicates that a blast at 100 km would produce a higher peak pressure than engine noise at 15 m. However, when using peak pressures as the sole discriminator, nearby Alpheid shrimp cause problems as they can produce high peak pressures. At a reef site, signals from Alpheid shrimp greater than 0.5 mbar were detected at a rate of more than 800 h^{-1}.

Fortunately, there are other features of a blast signal that assist in discriminating it from background sounds. The signal from an Alpheid shrimp, although of high peak pressure, has short duration. It therefore contains little energy compared with that of a distant blast signal, which has a duration of a good fraction of a second. (The pulse energy can be determined by integration of the pressure squared.) On the other hand, the signals from outboard engines have a very long duration compared with a blast event and therefore carry significant energy over the full time they are detected. However the frequency of the sound is relatively low compared with a blast event, and once again it would be possible to distinguish signals from these different sources with some confidence.

Background noises not investigated here may also cause problems. Signals with significant energy are generated when the hydrophone is physically impacted, which could be caused by grazing fish for example. Therefore hydrophones in any automated detector would have to be protected from direct contact, and the degree of protection would have to be assessed and monitored periodically. It is recommended that future development of an automated detector should quantify the frequency of false positives blast events using a variety of discriminators. However data collected in this study suggest that there is good potential for the development of an appropriate algorithm to discriminate blast events from background noise straightforwardly at a range of 12 km and perhaps beyond 30 km. With a network of hydrophones for direction determination as discussed below, the power to reject false positive signals from localized disturbances rises enormously.

4.2. Determination of blast direction

A detection system able to locate the position of blasts would have additional utility. An array of detectors capable of pinpointing blast events at long range would be able to monitor large marine areas. Such a system would be able to determine the temporal and spatial distribution of fish blasting in a known area. It would also allow the effectiveness of community management and local fisheries enforcement by measuring the change in blast frequency in that area as resources were deployed.

There are a number of possible configurations of an array of detectors that allow the determination of the location of a blast event. Two approaches are discussed below.

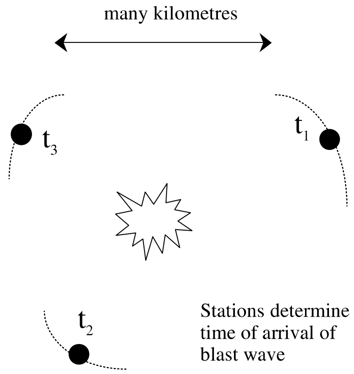

Fig. 10. Approach 1.

4.2.1. Approach 1: differences in signal arrival times at widely spaced individual detectors

The times of arrival of a blast signal at three widely spaced stations are recorded (t_1, t_2 and t_3 in Fig. 10). It is then feasible to determine the origin of the signal using coordinate geometry.

4.2.2. Approach 2: direction of incident signals at widely spaced arrays of detectors

Each detection station consists of an array of closely spaced detectors (as shown in the detail of Fig. 11). The blast wave arrives at the three detectors of one station at slightly different times (t_1, t_2 and t_3 in Fig. 11), and from the measured time differences it is possible to uniquely determine the direction of travel of the blast wave. To determine the source of a blast signal requires a minimum of two detection stations for triangulation.

Although the Approach 1 requires fewer detectors at each station and is thus simpler, the requirement for synchronization between the timing circuits at different stations poses a severe technical constraint. Isolated electronic clocks running on independent power supplies inevitably drift with respect to each other. A relative drift of 1 s between two electronic clocks could produce an error in the predicted location of the blast event of

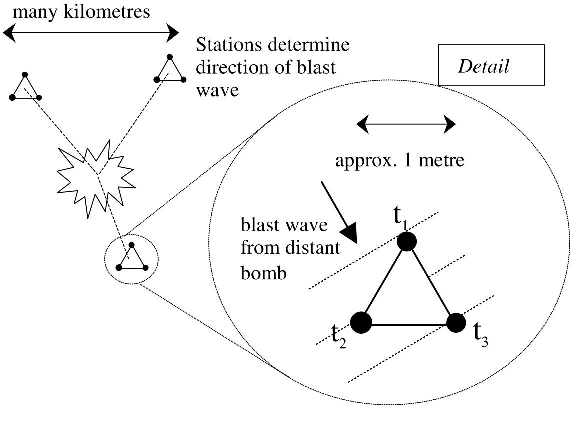

Fig. 11. Approach 2.

around 1.5 km. Synchronization of the clocks at the detection stations using telemetry would significantly improve accuracy but introduces additional complications and expense.

The requirement for synchronization of timing circuits is considerably reduced by the design in Approach 2. The time of arrival of the signals at the three detectors in each substation is recorded by the same timing circuit, and so the time differences between detectors are insensitive to the drift of the electronic clock. With a blasting frequency of one per minute or less, the clocks on different stations would still allow unique identification of blast events if they were many seconds out with each other.

However the design in Approach 2 does impose strict requirements on the determination of the arrival times at the three closely spaced detectors in each station. With a detector separation of 1 m, the maximum time difference of arrival of the blast signal between two detectors is close to 650 μs. If the error in determining blast direction is to be less than 1%, this requires determination of the time difference within about 10 μs. At first glance this would seem to be difficult given the complexities of the recorded signals (particularly those at distances greater than 2 km where the shock front is absent). However, Fig. 5 shows that the signals from two separated detectors at the same depth are similar although they differ markedly when recorded at depths separated by a few meters. In principle the time difference can be accurately determined by cross correlating the two signals. A clear peak in the cross correlation graph at the expected time difference was observed with the data recorded during this study.

4.3. Objectives and testing of an automated detection system

A number of automated detection systems are conceivable. The simplest would be an inexpensive, portable and robust device suitable for monitoring blasting in remote locations. Such a device could only monitor the frequency of blast events without determining their location. It could be battery powered, deployed underwater and left passively collecting data for subsequent retrieval and analysis. A more sophisticated system would be composed of a network of semi-permanent detection stations capable of determining the frequency and location of blasts and providing the capability of alerting the fisheries enforcement officers to the detection of a blast signal.

However there are a number of steps in the development process before any such devices can be manufactured. In order to have confidence in an automated detection system, it must reliably detect blast events and reduce the number of false positives to acceptable levels. The only effective means of testing such a system is to trial a prototype for a statistically significant set of blast events over a wide range of background conditions. As it is not possible to conceive of testing such a device in the controlled circumstances used in this study, it must be field tested for an extended period of time in a region where blasting occurs regularly. The difficulty here is that without an existing detection system, it is not possible to measure the success of the prototype bomb detection system in the first place as the bombing location and frequency is unknown. The solution to this problem is to first engineer a sensitive and robust detection system consisting of a network of hydrophones. Such a system would be carefully designed to reduce false positive signals to negligible levels, and this system would then provide the benchmark against which other less robust systems could be measured. It is also straightforward to reduce the probability of missing a blast event to very low levels, as this study has proved that blasts can be readily detected to a distance of at least 12 km in open water. Of course some areas in the zone to be monitored will be in the shadow of obstructions. However the total area of these blind spots can be reduced to acceptable levels with more detection stations.

The detection stations would require computing power and storage systems and therefore easy access to electrical power, protection from the elements and security against theft. Marine structures such as oil rigs and lighthouses are possible candidates for locating detection stations. Each station would use technology similar to that used in this trial to continuously monitor for blast events. Analysis of recorded data files and cross checking the consistency of the data between a number of detectors would be sufficient to allow the rejection of any false positive signals. Localized non-blast events such as sea-surface wave noise or physical contact of a hydrophone would be easy to identify.

Once a long-term monitoring system is operational and reliably locating blast events occurring in an area, it would be possible to test a number of smaller simpler devices. The data provided by the automated detector under test could be closely correlated with the reliable data set from the long-term detection system.

4.4. Applications

There is no doubt that fish bombing is a significant threat to the integrity of coral reefs, particularly in Southeast Asia. While socio-economic conditions that maintain the continued use of fish bombing remain, the practice will continue and the associated economic loss will accelerate. Any long-term management intervention to reduce the incidence of fish blasting must focus on its underlying causes and must include the development of alternative income generating opportunities. Perhaps the greatest value of a blast detection system is its ability to directly measure the success of community management action designed to address the underlying causes of fish blasting, rather than as a surveillance and control tool. Only in some specific cases such as high value or remote protected areas or offshore infrastructure (e.g. undersea pipelines or cables) might this sort of system be able useful as an enforcement tool or a deterrent.

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