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Locating fish bomb blasts in real-time using a networked acoustic system

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ABSTRACT

Results are presented of a demonstration of real-time fish blast location in Sabah, Malaysia using a networked hydroacoustic array based on the ShotSpotter gunshot location system. A total of six acoustic sensors - some fixed and others mobile - were deployed at ranges from 1 to 9 km to detect signals from controlled test blasts. This allowed the blast locations to be determined to within 60 m accuracy, and for the calculated locations to be displayed on a map on designated internet-connected computers within 10 s. A smaller three-sensor system was then installed near Semporna in Eastern Sabah that determined the locations of uncontrolled blasts set off by local fishermen. The success of these demonstrations shows that existing technology can be used to protect reefs and permit more effective management of blast fishing activity through improved detection and enforcement measures and enhanced community engagement.

1. Introduction

Blast fishing (also known as dynamite fishing and fish bombing) is an illegal destructive fishing technique that uses underwater explosions to kill and stun fish so they can be more easily harvested. The use of explosives for fishing has been reported as far back as 1898 in Hong Kong (Cornish and McKellar, 1998). Today blast fishing and other destructive fishing techniques and overfishing are reported to be a medium to severe threat to nearly 60% of reefs globally (Burke et al., 2011), with the greatest prevalence occurring in countries in the coral triangle in Southeast Asia (Burke et al., 2012) and in Tanzania (Wells, 2009).

Fishers using explosives typically target schooling fishes such as Rabbitfish (siganids) and Fusiliers (caesionids), but reef fish are also targeted (Fox and Erdmann, 2000) resulting in structural damage that leads to a loss of fish diversity and abundance, and reduces the capacity of the reef to recover naturally. The effect is stark. Reefs in Indonesia that have been subjected to frequent and chronic dynamite fishing are reduced to fields of unstable rubble that showed zero natural recovery after five to seven years (Fox et al., 2003; Fox and Caldwell, 2006). This eliminates the benefits provided by reefs in the forms of protein and tourism, and threatens biodiversity. Additionally, the blasted reefs have a much-reduced capacity to regenerate and therefore their efficiency as physical buffer against wave action is impaired.

Recovery rates of blasted reefs vary according to the level of damage, the stability of the crater or rubble field, and the potential of surrounding reef to produce larvae. Working in the Philippines, Alcala and Gomez (1979) estimated that reestablishing 50% of initial coral cover would take 40 years. Riegl and Luke (1998) estimated recovery of damaged reefs in Egypt would take 'several hundred years', while Raymundo et al. (2007) reported no recovery on a blasted reef in the Philippines after 20–30 years, which is consistent with Fox and Caldwell's (2006) findings.

The impact and risk to coral reefs caused by destructive fishing is so immediate and so severe that the elimination of destructive fishing practices is a key element of Goal 14 of the Sustainable Development Goals that set out a framework for global sustainable development from 2015 to 2030 (UN, 2016).

A study of the yield and economics of dynamite fishing by Fox and Erdmann (2000) indicates why dynamite fishing is common: fishermen collected several kilograms of fish from each blast, which was collectively worth five times the average daily labouring wage in the area (Fox and Erdmann, 2000). The high economic return arising from this catch per unit effort (CPUE) provides sufficient motivation to make the practice widespread, even at the expense of losing future fish production potential. Other key factors are the general lack of effective monitoring, surveillance and control (MSC) by government agencies, links with organized crime, and ineffective laws regulating illegal fishing that together result in low detection, detention, and prosecution rates (Sebastian, 2016).

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In principle, strategies for managing blast fishing activities will require a combination of community development including increased awareness and education i.e. soft measures, and enforcement i.e. hard measures. To optimize a management plan's effectiveness, the balance of soft and hard measures must be matched to the root causes and social structure of the blast fishing activity. Dealing with criminal syndicates will require greater emphasis on enforcement while addressing blast fishing carried out in response to severe overfishing and poverty will require a more community-development orientated approach. Certainly, economic analysis of strategies of enforcement (as compared to rehabilitation of dynamited reefs) by Haisfield et al. (2010) in Indonesia indicated that enforcement was between 5 and 70 times more cost effective. This supports the principle that prevention is more effective than cure, even when cost-effective and low technology approaches are used, such as that of Raymundo et al. (2007). Evidence from COREMAP, a coral reef management program conducted in Indonesia for over 15 years, indicates that the reduction of blast fishing is most effective when the local community and enforcement agencies are sufficiently empowered in the enforcement process (IUCN, 2002). A paper by (Braulik et al., 2017) presents results of acoustic monitoring of blast fishing hotspots in Tanzania and confirms heavy activity near Dar Es Salaam.

The aims of this paper are to show that an underwater acoustic location system based on a mature technology used to locate gunshots can readily locate fish blasting and that there is significant scope to develop t affordable systems that can detect blast fishing over large areas. We describe testing in Sabah, Malaysia, where a technology first developed for locating gunshots in US cities for law enforcement, was adapted for determining the locations of underwater explosions. The testing was successful in detecting both controlled blasts and ongoing community blast fishing activity. The testing also identified performance enhancements to pursue for future deployments, such as improved discrimination algorithms to reduce the effects of background noise, for example snapping shrimp clicks, and lapping sounds at piers or boats.

In parallel with an integrated approach to the management of marine resources by governments, this technology provides the means to better utilize enforcement resources and improve the chances of obtaining successful convictions against blast fishermen. Such an approach should have a deterrent effect on blast fishing and allow societal measures to curb this practice.

2. Background

2.1. History of acoustic blast monitoring in Sabah

The practicality of acoustic detection and location of blasts from fish bombs was investigated by two of the authors in the early 2000s (Woodman et al., 2003, 2004). This work indicated that the acoustic signal from a blast should be readily detectable at ranges up to 30 km in open water, and that the angle to the blasts could be determined to within a degree. It was found that islands blocked acoustic signals, and confounding noise sources such as nearby snapping shrimp (alpheids) would need to be filtered out.

Using similar angular detection techniques, Marine Conservation Society and St Andrews Instrumentation Limited have been working with Sabah Parks Authority over the last few years to monitor blasting in Tun Sakaran Marine Park on the east coast of Sabah (Wood and Ng, 2014). Their work has measured the rate of blasting near several islands, thus bringing much-needed attention to the prevalence of blast fishing and the potential for technology to locate individual blasts.

This paper is the third in a series in the Marine Pollution Bulletin begun by Woodman et al., (2003 and 2004), and validates their supposition that measurements with a networked acoustic array would allow accurate and precise locations of blasts.

2.2. The ShotSpotter system for gunshot location

The company that created ShotSpotter was founded in 1996 in California to develop acoustic detection and location technology for gunshots (Showen, 1997) and (Showen et al., 2008). Based on the similarities of their respective work, two of the authors (Showen and Woodman) began to discuss the possibility of using ShotSpotter's technology as a means to detect fish bombs in 2012. The premise was that adaptation of a successful system for gunshot location would be significantly cheaper than development of a new system designed for real-time location of blast fishing.

The impetus to install an acoustic gunshot location system is the unfortunate occurrence of significant urban gunfire in many cities. The systems have been shown to aid police in suppressing gunfire by indicating the precise locations and the number of gunshots in a particular shooting event in real time.

The ShotSpotter System uses a combination of the measured ‘time of arrival’ (ToA) and ‘angle of arrival’ (AoA) at the distributed sensors to determine blast locations. (Showen et al., 2009). Many navigation systems, including LORAN and GPS, use the ToA method that is colloquially known as triangulation but is more properly called multilateration. (https://en.wikipedia.org/wiki/Multilateration). See also (Hamann, 2007) for a straight-forward mathematical explanation at http://w3.uwyo.edu/~hamann/TrilatShow.pdf.

When a set of sensors at known positions receive impulses at different arrival times, it is readily possible to compute the location of the gunshot or blast. The difference in arrival time between a pair of sensors defines a locus of possible blast locations along a hyperbola, and the intersection of multiple hyperbolae provides a location.

Fig. 1, adapted from (Showen et al., 2009) illustrates how blast locations can be calculated using a combination of ToA and AoA methods. Using them both together reduces the number of sensors required for many geometries. Using both can also guard against being fooled by an echo instead of a directly propagated path, or lift an ambiguity when only two independent hyperbolae are available and they intersect at two locations.

The simplest case of using ToA and AoA together is illustrated here using only two sensors. The cross-hatched area is a potential blast location, the size of which is determined by the accuracy of the two angle measurements – possibly enlarged by orientation errors at each sensor. The hyperbola is given by the ToA measurement between the two sensors, and further constrains the blast location to a small segment around the hyperbola. If there were a third sensor detecting the blast, then the resulting intersecting hyperbolae would even more constrain the blast location to a very small region. In that case, the accuracy of the location would be determined by the relatively small changes in the speed of propagation between the paths or in the small uncertainties in the sensor positions.

ShotSpotter has created a National Gunfire Index for several years, documenting and analyzing the incidence of gunfire and describing many aspects of data usage and collection (http://www.ShotSpotter.com/2016NGI). The system is demonstrably a mature technology, which presents a real opportunity to combat the blast fishing problem. Such data can be used to determine ‘hot spots’ where the prevalence and timing of gunfire can be quantified to enable planning for future interdiction (Watkins et al., 2002). One of the notable findings is that typically less than 20% of the gunfire detected by ShotSpotter is reported to the police through an emergency ‘911’ call. (Carr and Doleac, 2016). Such methods applied to the blast fishing problem, have great potential to better understand the extent of the blast fishing culture.

According to the US Department of Justice, ‘The certainty of being caught is a vastly more powerful deterrent than the punishment’ (DOJ, 2016). In the case of blast fishing this dictum may also prove true.

Our relatively short-range impulsive location method can be contrasted with the detection or tracking of quasi-continuous marine mammal sounds (Møhl et al., 2001). Additionally, we are not using the

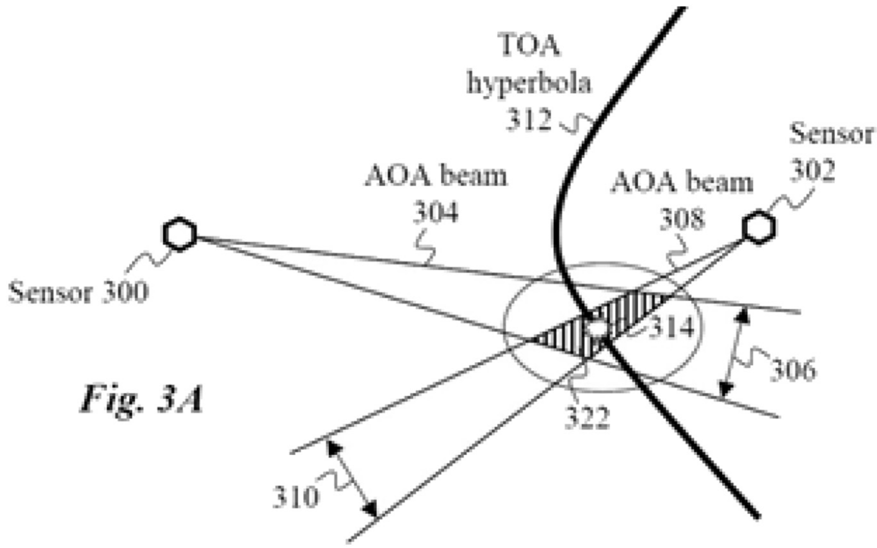

Fig. 1. This diagram in patent format is adapted from ShotSpotter patent US 7,474,589, showing a blast located by two separate sensors each having an angle measurement and giving an accurate time of arrival. The distances corresponding to 306 and 310 come from the uncertainty in the angular measurements.

long-range SOFAR Channel – see link at https://en.wikipedia.org/wiki/SOFAR_channel. An underwater example of location at great ranges comes from the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) system used to monitor nuclear testing (Prior et al., 2005).

2.3. *Adapting gunshot location systems for use in locating fish bombs underwater*

The mathematical techniques used by ShotSpotter's system as shown in Fig. 1 can be used without modification for detecting and locating fish bombs. Sound travels at a speed approximately 4.5 times greater in water than in air, and propagates over much greater distances. Also, the charge weight of a fish bomb may be two to three orders of magnitude greater than a bullet, and a much greater fraction of explosive energy is converted into acoustic waves (Arons and Yennie, 1948).

The noise sources underwater are different to those routinely filtered out by ShotSpotter's urban system. These include snapping shrimp and localized impulsive events from fish or other marine animals touching the hydrophones, or water lapping sounds. Hence effort will be required to optimize operations underwater.

2.4. *Acceptance of acoustic location method in courts*

Supplemental forensic evidence generated by the ShotSpotter system has increased successful prosecution rates for the illegal use of guns. Inevitably the veracity of this acoustic system has been challenged and scrutinized by the US legal system. Both federal and state courts have upheld the admissibility of ShotSpotter data and the methodology applied (eg. State of Nebraska v. Hill, 2014, and State of Minnesota v. Brooks, 2016). We expect this legal precedence to reduce the effort required to enable acoustic location evidence to be accepted when prosecuting fish bombers.

2.5. *Sabah government request for proof of concept*

The merits and potential of using an acoustic system to detect and locate fish bombs in real time were discussed with the directors of the Department of Fisheries Sabah and Sabah Parks on several occasions in 2015. Based on these discussions, a controlled trial was commissioned by the Department of Fisheries to provide a proof of concept. It was widely understood and agreed that a controlled test was necessary to provide convincing proof for government agencies and other stakeholders that the system worked properly, and that the location data was substantive enough that it could serve as forensic evidence in court cases against fish bombers. A film documenting the trial can be viewed at -https://www.youtube.com/watch?v=pm2lvTnPJMU&t=24s

3. Equipment and methods

3.1. *Equipment modifications and installation*

The ShotSpotter system used in Sabah was slightly modified from the standard urban configuration. Two hardware modifications were made to it:

1. The two microphones were removed from the circuit board and replaced with signal cables leading to two hydrophones (Aquarian model H2a). The standard 20 cm spacing of the microphones was scaled up to 90 cm to compensate for the higher speed of sound in water. The hydrophones were mounted on a horizontal boom to permit measurement of the angle to the blast.
   The expectation for the trial was that blasts would be located by the Time of Arrival technique. Angle of Arrival information is routinely collected in ShotSpotter systems to augment the determination of locations. A supplementary goal of this trial was to investigate the utility of the Angle of Arrival information for location of fish bombs.
2. The circuit boards were removed from their outdoor weather housings and placed into plastic cases along with rechargeable batteries for power.

Fig. 2 shows the equipment used in this trial. Visible at the upper edge of the case are the two black cellular modem antennas.

There were no software modifications to ShotSpotter's Acoustic Location Kernel - the only changes were to the following parameters:

1. A constant velocity of sound for underwater propagation was specified, overriding the standard method of consulting weather services online to compute the local speed of sound in air.
2. Long-term GPS latitude and longitude averaging was turned off in the system due to the need to accommodate the motion of the boat-mounted sensors. As a result, the pier mounted sensors had larger GPS errors than normal for an operational system.

Each sensor contained a standard ShotSpotter processor board, a cellular modem, and a GPS receiver to provide accurate location and timing (the relative time of arrival of each blast impulse is accurate to within one millisecond). Sensors were then connected to the internet. After each blast location was computed, it was placed on a standard

Fig. 2. This photo shows the ShotSpotter sensor rehoused in a plastic case. Hydrophones and cables are shown before being installed in booms. The inset on the lower right shows the hydrophones in their boom and mounted underwater.

web-based map and displayed to the test team and government officials. The presentation also included an image of the acoustic waveform, and the ability to listen to the blasts from each sensor.

Pier-mounted installations were accomplished using scuba gear and an underwater compass to determine orientation of the boom. For boat mounts, the booms were simply lowered to one-meter depth beside the gunwale using the hydrophone cables.

The boat from which the bombs were thrown was also equipped with a sensor so that its position was continually tracked, and the acoustic signal generated by the blast at close range could be determined. This sensor, in a standard ShotSpotter test practice, was designated as 'foreign' in the database which prevented it from participating in computing the location. The hydrophone was mounted inside the boat hull using the vendor-supplied cup as shown in the lower left of Fig. 2.

3.2. Trials in Gaya Bay

The trial of the ShotSpotter system with controlled explosions was undertaken from 25-30th November 2015. The chosen location was Gaya bay to the north of the state capital Kota Kinabalu, where previous related work by Woodman et al. (2004) had been conducted, as shown in Fig. 3. The test was designed to: 1) minimize environmental impact arising from explosions; 2) utilize the commercial cellular network coverage; 3) to capitalize on existing secure platforms for mounting sensors; and 4) to illustrate use of both pier-mounted and boat-mounted sensors, showing the flexibility that can be achieved during future operational installations. After noting that the southernmost sensor only received small impulses that did not often contribute to the blast location determinations, we deduced that the problem was caused by attenuation from shallow-water shoals. That sensor was placed on a boat for the final days of the experiment. With this geometry the distances from the sensors to the blasts were between 1 and 9 km.

Prior to the test blasts, a diver checked the surrounding area to ensure that it was well away from any reef structures and in deep water (greater than 25 m) with no fish or other marine life nearby. The detonation of the fish bombs was managed under the supervision and control of the Sabah Department of Fisheries, and observed by senior personnel from Sabah Parks.

The Sabah government commissioned Scubazoo Images (a locally-based film production company) to document the trial with a film https://www.youtube.com/watch?v=pm2lvTnPJMU&t=24s

Explosives were deployed from a small fishing boat that also had a sensor equipped with GPS to show the location of the blast, and an internal hull-mounted hydrophone to monitor the blast strength. The bombs were constructed of materials that had been previously confiscated by the authorities. The devices were typical of those commonly used in Sabah, 375 ml of a mixture of ammonium nitrate and fuel oil inserted into a glass beer bottle. A detonator was sealed into the neck of the bottle and a waterproof fuse was used to initiate detonation, with a delay of approximately 10 s.

For each of the four sensors mounted to piers, the hydrophone boom was mounted horizontally on a measured bearing in order to determine the angle of arrival of the blast. The booms were deployed mid-way between the sea surface and seabed at depths ranging from one to four meters depending on the available depth of water. The two mobile sensors on small boats were positioned at various locations and ranges for each blast. The boat mounted hydrophones were submerged about 1 m. The cellular network available in Gaya Bay limited the range of a boat-mounted sensor to within about 9 km of the blast position.

3.3. Trials in Semporna, East Sabah

Additional testing of the system was then performed in the Celebes Sea south of Semporna, but in this setting the blasts were generated by local fishermen, therefore not under controlled conditions. These tests were completed between 3–6th December 2015.

With the support of tourist resorts, sensors were mounted onto jetties on the islands of Mabul and Kapalai, and on the Seaventures dive rig, a mobile oil platform that has been converted into a diving resort offshore of the island of Mabul.

An important difference from the Gaya Bay tests was that the array of hydrophones was quite a distance to one side of the blasts (of order 8 km) instead of surrounding them. Theory, backed by years of experience with the outdoor array indicate that this produces larger location errors in the direction radial to the array.

Fig. 4 shows a map of the area where the Semporna trials were undertaken. The world-famous diving site at Sipadan is at the bottom. These three sensors were all mounted at resort sites where underwater blasts have been noted by resort owners and divers.

4. Results and analysis

4.1. Gaya Bay results

The testing began with collecting background acoustic data for a day to ensure that our selected installation locations did not exhibit excessive noise. After the locations were vetted, we installed four sensors on jetties over two days. The plastic case housing the electronics for each sensor was then either locked or guarded to prevent tampering. A number of sensors had access to power and these were left on permanently to monitor the background in case blast fishing was occurring overnight. No detections of uncontrolled blasts occurred in Gaya Bay during our observation period.

A total of nineteen controlled underwater explosions were generated after the system became operational, and the ShotSpotter system detected and located all of them. The locations of 16 of 19 explosions were determined automatically within 10 s of the blast, with an accuracy of 60 m or better. The other 3 blast locations were automatically detected but their location errors were increased by up to 400 m because the computer selected a non-blast noise impulse at one of the sensors. When using the ShotSpotter Analysis Tool – as seen in Fig. 7 below – it is usually possible to look and listen to the audio waveform and correct such a mistake, typically within about 5 min. Use of this tool on the 3 blasts in question corrected their errors to within 60 m.

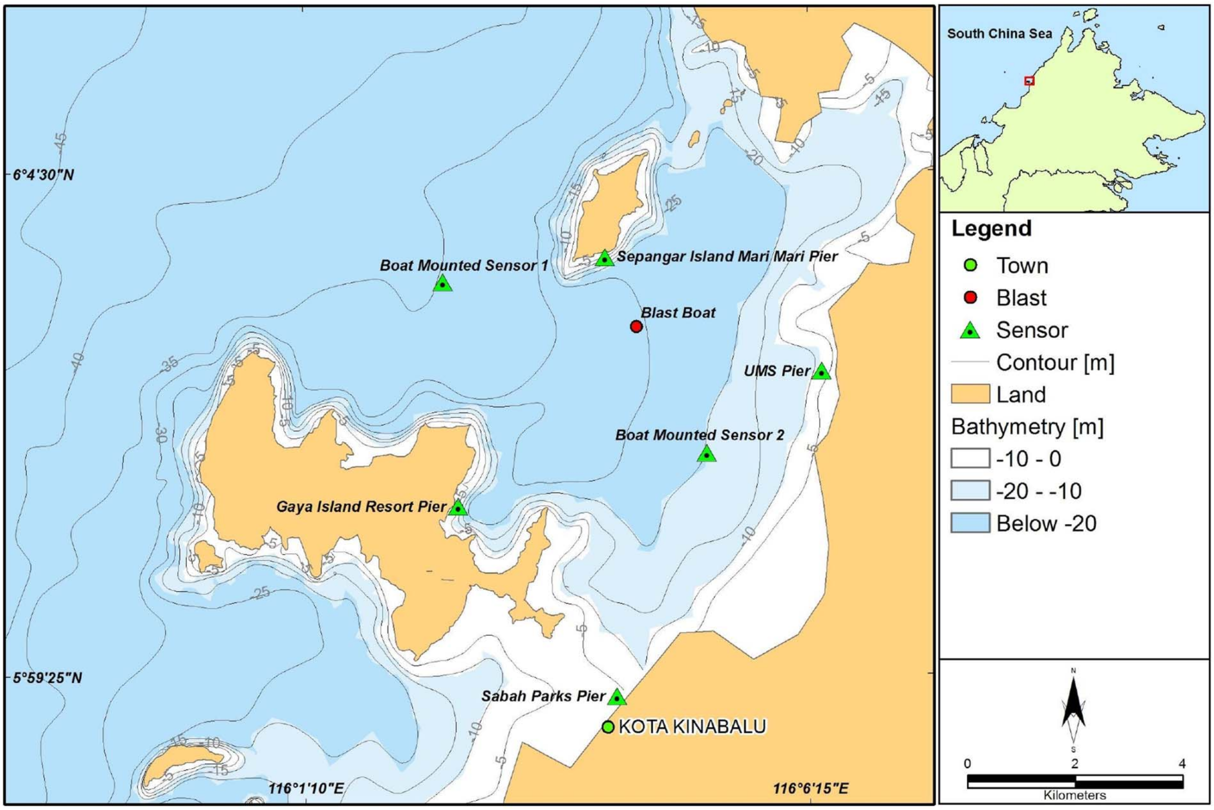

Fig. 3. The 6 green pyramids indicate 4 pier-mounted sensors and two boat-mounted sensors. The southernmost sensor had significant blockage by shoals and it seldom participated in the solutions. The red circle shows the location of the blast boat, which moved east to west about 2 km during the testing. The two sensor boats were directed to move between blasts; boat sensor 1 moved incrementally to the West up to 9 km from the blast boat until it's cellular communications failed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In future deployments we expect impulsive noise filtering algorithms to reduce this problem. Fig. 5 shows the positions of the blasts south of Sepangar Island. The sensors used to compute these locations were positioned at distances between about 1 to 9 km from the blast.

In Fig. 6a, the location errors are shown with respect to the blast boat at the plot origin. In Fig. 6b, a histogram of the errors is presented. The peak of the distribution is at 40 m, but since the bombs were thrown to the side of the boat a distance estimated to be 15 ± 5 m, the actual peak in the distribution of location errors may be closer to 25.

The impulses and relative times of arrival from one of the delayed blast events in Gaya Bay are shown for five sensors as audio waveforms in the lower right corner of Fig. 7. The accompanying Supplementary folder contains these audio files. Note that each of the blast waveforms have three matching components, which are a triple bubble collapse pattern - this is discussed in Section 4.3. The relative arrival times of different pairs of sensors produce separate hyperbolae as shown in the lower left. The dots with labels above them represent the positions of the sensors, and the colors match with the audio waveforms for easy identification. The hyperbolae are composite dashed lines of two colors indicating the two sensors that match.

The green bars on the right of the audio waveforms indicate which sensors participated in computing the location. The grey bar to the right of the cyan waveform indicates the signal from the non-participating control sensor, mounted on the blast boat. The blast boat's cyan position marker can be seen in the hyperbola figure at the intersections of the hyperbolae. More participating sensors rapidly increases the number of intersecting hyperbolae and in general this increases the accuracy of the computed location. In addition, this extra redundancy reduces the likelihood that an incorrect pulse will be used in the final solution. The system automatically selects between all available intersecting pairs of hyperbolae and determines the most consistent location solution.

The audio waveforms from the different sensors are displayed in the upper right corner and can be played through any sound system connected to the computer, thus allowing the user to confirm that the events are underwater explosions. If the computer's automatic selection of impulses is incorrect, manual intervention using this tool usually allows corrections to be quickly made, typically within 5 min. The reader can listen for themselves to these 4 audio waveforms which are in the Supplementary File.

4.2. Semporna results

The installation in Semporna was more constrained than in Gaya Bay due to the sparseness of available mounting locations for sensors. It was a more challenging experiment, as the location and timing of the blasts was unknown. Fig. 8 shows the positions of the three sensors deployed in the Semporna area, and the computed locations of two uncontrolled blasts from local fishermen.

After installation, there were only two days of monitoring available, during which time four blasts were detected. Only two of these were received on all three sensors. The other two, near Mabul, were louder, but because of blockage by the nearby reefs, could not be located. Both blasts that were detected by three sensors were located at the edge of the reef over 8 km northeast of Mabul. The separation between the two blasts was half a kilometer, with the second occurring 64 min after the first. Two small boats were photographed using a telephoto lens 15 m above the water from the Seaventures platform in the direction of the blasts. This indicates that fishers were active in the area and could be responsible for the activity. Since the sensor array is positioned quite far to the side of the blasts, the narrow error ellipses indicate greater uncertainty in range than angle.

The three acoustic waveforms from blast 1 are shown in Fig. 9. They

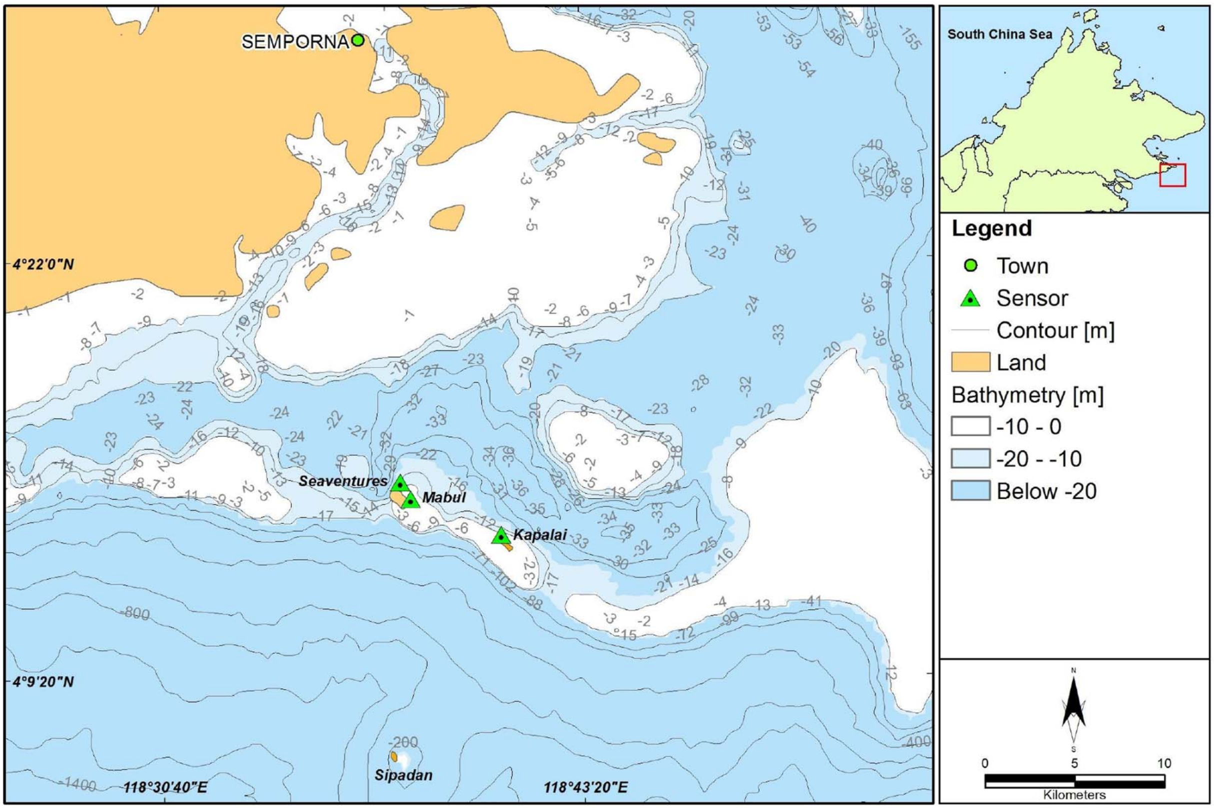

Fig. 4. Map with contours showing the position of the three sensors deployed in the Semporna area (green triangles), an area known for blast fishing activity. The islands to the south of the sensors obstruct most of the acoustic pathways toward the south. Many tourists visit the area to dive the world-renowned island of Sipadan near the bottom of the map. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

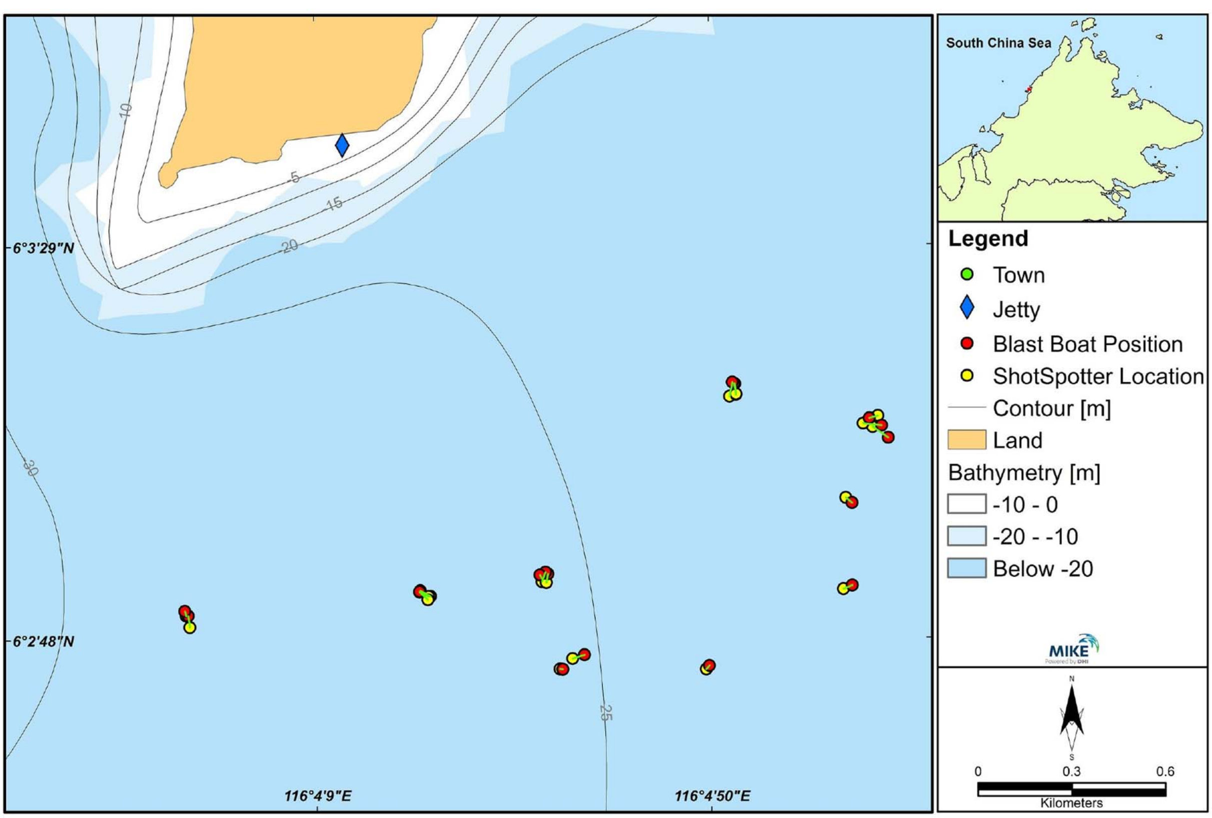

Fig. 5. Computed ShotSpotter locations. Plot of blast boat positions (red) and ShotSpotter locations (yellow). A green line connects the location pair. The nearby sensor on the Sepangar Island jetty is shown as a blue diamond. The other sensors (fixed and mobile) were between 3 and 9 km distant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

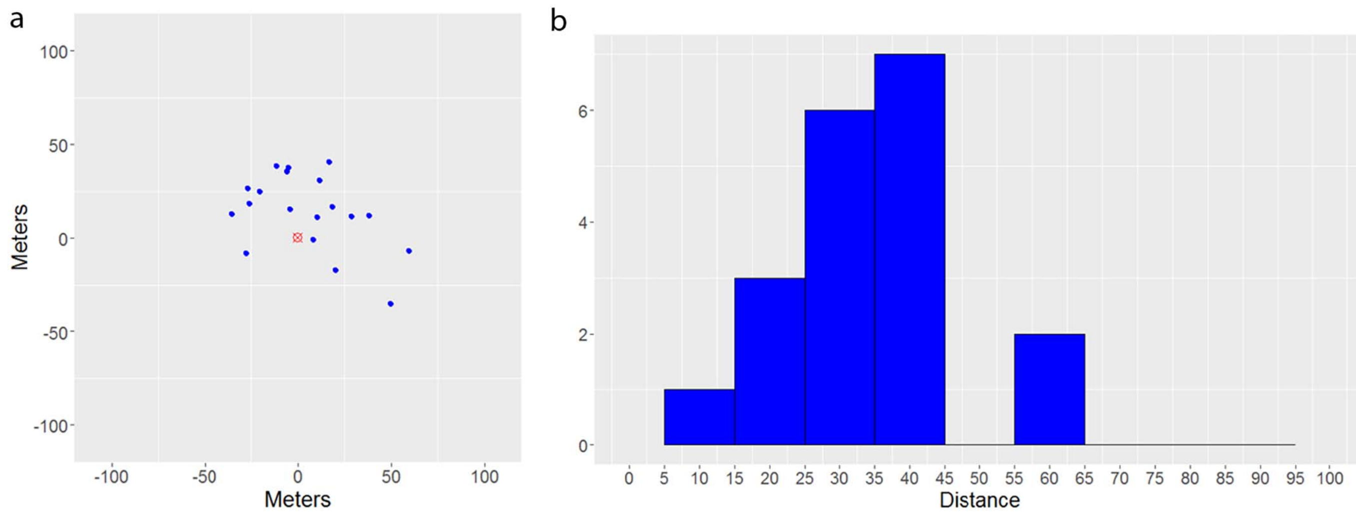

Fig. 6. Details of Locations in Gaya Bay. Plot (a, left) gives the errors in location with respect to the blast boat indicated at the center in red. Plot (b, right) is a histogram of the magnitude of the location errors. Note that the blasts were not on the blast boat, but were tossed at arbitrary directions 10 to 20 m to the side. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

all have signal-to-noise ratios in excess of 10:1 and the sounds were positively identified as blasts by experienced divers listening to the sensor outputs at a computer. These three acoustic waveforms are included in the Supplementary File.

4.3. Acoustic signature of an explosion and agreement with theory

The rapid oscillation of the gas bubble resulting from an underwater explosion produces a distinct signature. Each of the five sensors shown in Fig. 7 shows three distinct impulses from the bubble oscillation. This signature can serve as a key feature of the acoustic signal that provides additional confidence in the identification of blasts. It is therefore valuable to ensure that the observed bubble pulse is consistent with what we knew of the fish bombs and the theory of underwater explosions (Cole, 1948).

The period of the bubble pulse is predicted by the well-established Rayleigh-Willis formula:

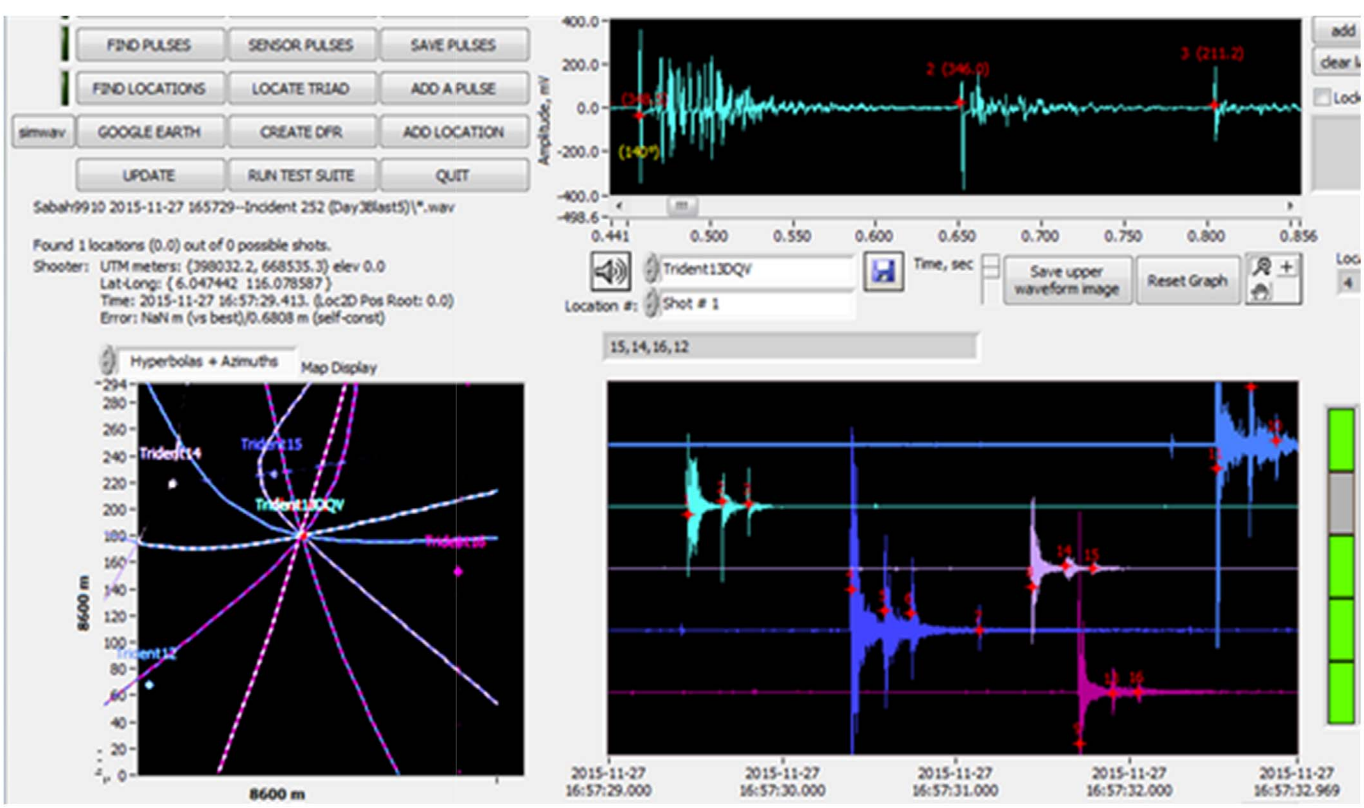

Fig. 7. ShotSpotter analysis tool showing the calculated blast locations as a set of intersecting hyperbolae. The five waveforms show the relative arrival times of the blast from five sensors, which all exhibit a triple bubble collapse pattern. The first arrival is from a monitor on the blast boat; this is not used in the location calculation. The signal from the furthest sensor arrives just over 3 s after the blast boat, so its range was about 4500 m.

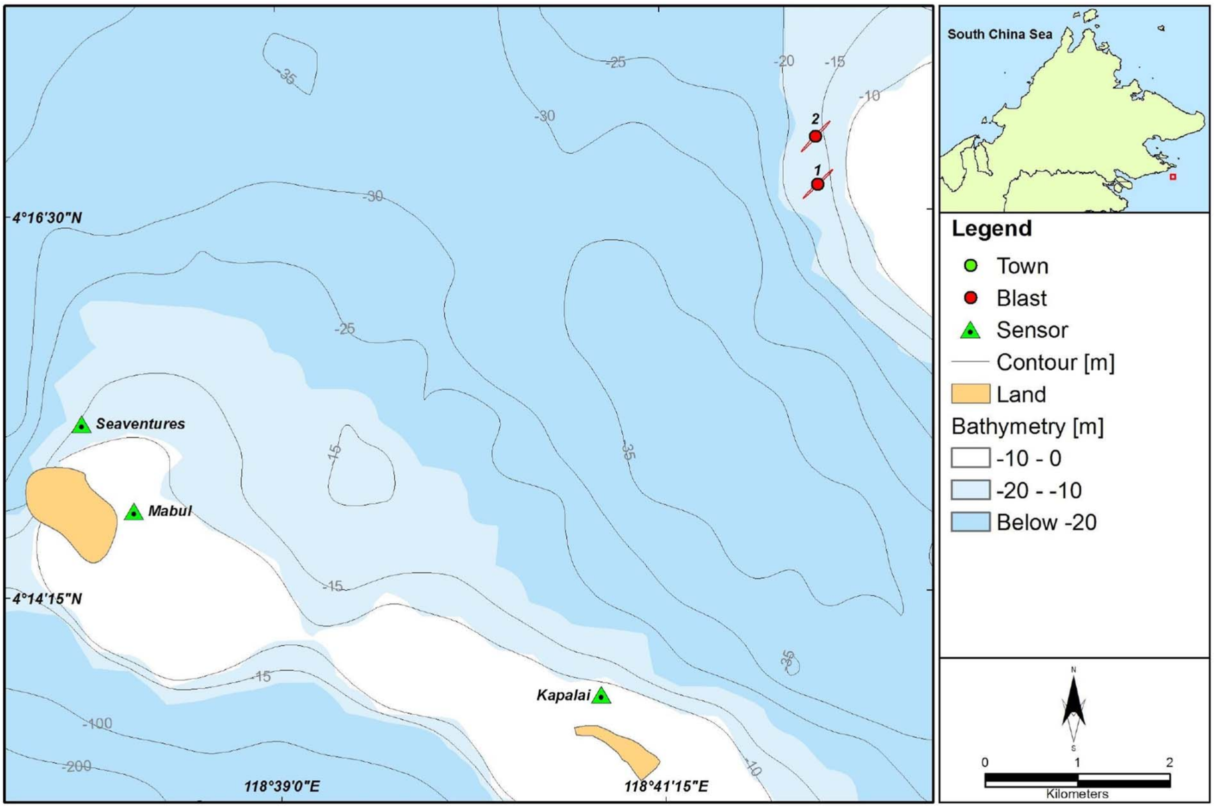

Fig. 8. Map with bathymetry contours showing the locations of two strong blasts (labelled 1 and 2) over 8 km away from the three-element sensor array (green diamonds). All three of the sensors are mounted on stilts or columns at approximately half the water depth. The narrow red ovals indicate expected location errors corresponding to GPS sensor position variation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$T = \frac{\left(0.0452Q^{1/3}\right)}{\left(\frac{D}{0.3048} + 33\right)^{5/6}}$$

where T is the time period of the oscillation in seconds, Q is the source energy in Joules, and D is the depth of the bubble center in meters. We used figures from Buczkowski and Zygmunt (2011), who establishes that the detonation energy per unit mass of ammonium nitrate/fuel oil explosive is 3890 kJ/kg. Table 1 shows the dependency of the bubble pulse period with depth and charge weight.

The first bubble interval from the Gaya Bay trials was 0.189 s. An upper limit of the charge weight is around 645 g given the size of the bottles used for holding the explosive (the bottles were 375 ml beer bottles and ammonium nitrate has a density of 1.72 g cm-3, although

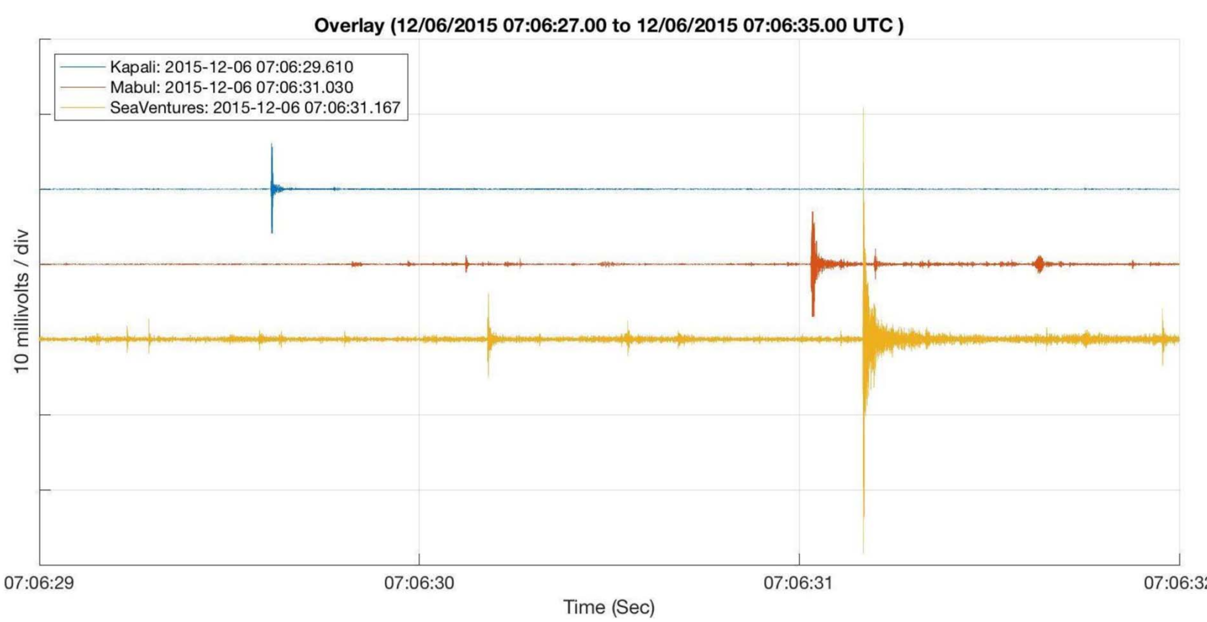

Fig. 9. This plot shows the acoustic waveforms received on the three sensors (Kapalai, Mabul, and Seaventures) used in locating uncontrolled blast 1. A weak second bubble collapse is present. The many small impulses are mostly lapping sounds. Acoustic wavefiles are available in the Supplementary File.

Table 1
Bubble pulse period in seconds from Rayleigh-Willis formula. The cells shaded green show time periods that match the bubble pulses observed in the field tests in Gaya Bay, which had a pulse interval of 0.190 s between the first and second pulses.

Charge mass/g	Explosion depth/m											
	1	2	3	4	5	6	7	8	9	10	11	12
100	0.165	0.154	0.144	0.135	0.128	0.121	0.115	0.110	0.105	0.101	0.097	0.093
200	0.208	0.194	0.182	0.171	0.161	0.153	0.145	0.139	0.132	0.127	0.122	0.117
300	0.239	0.222	0.208	0.195	0.185	0.175	0.166	0.159	0.152	0.145	0.140	0.134
400	0.263	0.244	0.229	0.215	0.203	0.192	0.183	0.175	0.167	0.160	0.154	0.148
500	0.283	0.263	0.246	0.232	0.219	0.207	0.197	0.188	0.180	0.172	0.165	0.159
600	0.301	0.280	0.262	0.246	0.232	0.220	0.210	0.200	0.191	0.183	0.176	0.169
700	0.317	0.295	0.276	0.259	0.245	0.232	0.221	0.210	0.201	0.193	0.185	0.178
800	0.331	0.308	0.288	0.271	0.256	0.243	0.231	0.220	0.210	0.201	0.193	0.186
900	0.344	0.320	0.300	0.282	0.266	0.252	0.240	0.229	0.219	0.210	0.201	0.194
1000	0.356	0.332	0.310	0.292	0.276	0.261	0.248	0.237	0.226	0.217	0.208	0.201

the ammonium nitrate used consisted of pellets so that the gaps between them would reduce the average density), and this would be consistent with a maximum detonation depth of around 10 m.

The signals in Semporna by comparison only exhibited two bubble components (see Fig. 9) as opposed to the triple-bubble structure typical of the controlled explosions in Gaya Bay for reasons that are unknown as we could not survey the site of the explosions. The bubble interval is less, about 0.160 s, implying a greater depth of explosion if the explosive charge was the same size. This is speculative however as we have no information about the size of the explosives used by the fishermen in Semporna or any possible common adaptations such as ballast attached to the charge.

4.4. Estimating the detection range of blast signals

Estimates of the upper limits of the useful range of sensors is important for indicating the required sensor spacing needed to reliably locate blasts. As discussed in the Background section, the required sensor spacing is an important factor in estimating the costs for a blast detection system. To this end, a boat-mounted sensor was moved progressively further to the west up to a distance of 9 km, beyond which the cellular telephone communications signal was unfortunately inadequate.

At this 9-km range, the blast signal strength was about 100 times the acoustic noise level measured just before the explosion event. Prior ShotSpotter experience in cities indicates that signal-to-noise levels of 2 to 10 on reporting sensors give reliable locations. Woodman et al. (2003) reported signals from bombs of similar charge weight at up to 12 km distance from which they estimated a maximum detectable range of 30 km. It was not possible here to test that prediction with the available cellular coverage, but the high signal to noise ratio at 9 km distance is in line with the earlier estimate.

The authors intend to investigate the upper limits to detection range with an array of sensors and a statistically significant number of blasts. It is hoped that numerical acoustic propagation models based on bathymetric and other data will allow a comparison between the recorded signals (amplitude and delays) and the model predictions.

4.5. The effect of physical oceanographic parameters on detection accuracy

As the time of arrival of a blast signal at different sensors depends on the speed of sound in water, physical factors that change the speed of sound will also affect the calculated location of the blast. It is therefore important to estimate the size of this effect on the reported results and whether it would have a serious impact on location accuracy.

There is a well-established relationship between the speed of sound in water and the temperature, the salinity, and depth, Mackenzie (1981). The depth factor in shallow coastal waters has such a small effect that it can be safely ignored. The annual temperature variation in Sabah is only a few degrees centigrade; a meter below the surface the temperature varies between extreme values of 24.9 and 30.4 (Chiffings, 2017). Away from estuaries, the salinity varies little and is typically between 32.6 and 35.3 parts per thousand (ppt) (Chiffings, 2017). We may therefore expect the speed of sound to vary between 1536.7 and 1545.4 ms^{-1}, a variation of less than 1%. This small change in the calculated sound speed during the trial has only a tiny effect on the locations as determined by multilateration. This is particularly true in the case that blasts occur inside an array of sensors where errors in the calculated location tend to cancel. It is more of an issue when blasts occur outside of an array of sensors, in which case calculational errors compound each other.

4.6. Analysis of experimental errors and limitations

Aside from effect of physical oceanographic parameters on detection accuracy, there are equipment and experimental inaccuracies. With a measured location accuracy of better than 60 m, some additional insight into these known errors is worthy of discussion. Three known location errors arise from independent sources and they contribute to explaining the observed errors:

1. Throwing the bomb some ten to twenty meters from the boat in various directions places the explosion at a different location than the blast boat sensor.
2. The standard ShotSpotter sensor co-locates the microphones with the GPS receiver, but in this work the hydrophones were positioned up to 15 m to the side from the GPS receivers.
3. Random errors in the GPS-determined positions of the sensors. These instantaneous position errors are typically only a few meters. For this experiment, the long-term averaging of sensor position that is normally computed for the permanently positioned outdoor

system was turned off to accommodate the mobile boat-mounted sensors. Hence only the position reported by the GPS receiver at the time of the blast was used. For future tests the software could be altered to use appropriate GPS averaging for mobile and stationary sensors.

In planned deployments of an acoustic monitoring system, we should expect that the systematic error identified in (1) does not apply (2) will be corrected, and (3) will be accomplished such that the overall accuracy will be improved.

When the blasts are well outside of the acoustic array as they were in Semporna, the location errors become larger, from a similar geometric dilution. The red ellipses in Fig. 8 assume errors corresponding to a geometrical (Positional) Dilution Of Precision and neglects the other two sources.

A Dilution Of Precision measurement (PDOP) is obtained from the GPS chip in the sensor - this is saved in our database and used in our location error analysis, see (DiBias, date unknown). This parameter characterizes the instantaneous GPS satellite constellation, and is larger when the constellation is less favourable. We have investigated the statistical variation of the GPS-reported values of latitude and longitude and have confirmed an empirical relation to the PDOP parameter. Inserting this relationship into our location routine provides the narrow red ellipses shown in Fig. 8.

5. Discussion

5.1. Proof of concept

The results of the field trials reported here indicate that ShotSpotter's acoustic system for locating gunshots can be implemented underwater with very little modification to automatically locate fish bombs.

Under controlled conditions, the system provided the location of purposefully generated blasts within a mean error of less than 60 m. The system was also deployed in operational field conditions in Semporna with encouraging results: two uncontrolled fish bombs were detected and located.

To our knowledge, this is the first occasion that a controlled and validated trial of a real-time location system for fish bombs has been demonstrated, as well as the first occasion that the 'time of arrival' (ToA) multilateration method to determine the blast location has been used for this purpose.

The signal detection and location algorithms were designed for use with gunshot signals, not underwater blast signals, and an important hypothesis that we did confirm with these experiments is that these two signals have enough in common that the gunshot algorithms worked very well with little modification. A number of straightforward improvements to the hardware and software can be made, including:

i) The design and deployment modes of sensors;
ii) Better provision of internet access; and
iii) Adaptations of the analysis software to better suit the underwater medium and its noise sources.

Further deployments will help to establish a set of comprehensive data that will enable a much more detailed analysis of the uncertainty in the calculated blast locations and more clearly quantify systematic errors in the system.

5.2. Factors relating to effectiveness of acoustic detection systems

Underwater detection and location of blasts may in the future encounter problems only partially seen in our initial efforts.

The ShotSpotter experience typically requires urban sensors with spacings of around 500 m, which often allows four or more sensors to respond. Given the far greater transmission efficiency of sound underwater, the required sensor spacing for blast fishing will likely be many kilometers implying a significant reduction in sensor spacing and therefore cost. However, the underwater environment is more challenging for sensor emplacement than the urban environment.

A list of key issues which need to be considered include:

1. High-quality cellular communications is often not available where fish bombing occurs. If cellular service cannot readily be implemented then satellite or other radio services can be utilized. If a cellular communication network is added to accommodate the needs of a fish blast detection system, this can be an additional benefit to local communities. Other benefits include the capacity to track boats which have our sensors mounted on them, which can be offered as a service to boat owners as an alternative to Automatic Identification Systems (AIS).
2. Shallow water or reefs or islands can impair or block propagation. It will often be difficult in convoluted reef geometries to find suitable places or platforms to mount sensors. All available platforms such as piers, buoys, boats, and robots should be considered. Additionally, limiting the number of sensors required to provide a location will be a priority, such as by using angle of arrival in combination with time of arrival.
   Background noise can limit the effective sensor range and impulsive noise can produce false pulses. Localized filtering of noise events on each sensor would be highly beneficial and this will require a program for development and testing. Local sounds only detected at a single sensor (such as fish or lapping sounds) will not result in a calculated location. Nor will such local sounds have the audible reverberation characteristic of blasts.
3. The ShotSpotter experience has shown that a combination of automatic computer alerts and manual review by humans is often a good solution. Human reviewers using recordings of the audio channel plus a visual presentation of the waveforms can usually discard impulses that are not caused by gunshots. It is still an open question if future underwater systems will need humans to review alerts before sending to marine law enforcement. It may be that the law enforcement personnel will require some simple training to interpret bomb sounds and readily distinguish them from sources of noise.
4. Mitigating risks such as sensor theft and vandalism will require planning and local knowledge. A number of reasonably secure locations suitable for mounting sensors exist in Sabah, such as privately owned jetties and oil rigs. In some instances, the owners may be supportive because they suffer economic losses because of fish bombing. Mobile platforms such as boats may prove effective as well because of the high level of security. This will be offset by periods of time when the sensor is exposed to a lot of noise from the boat moving through the water, or because the boat is not in a good location for detecting blast signals. All of this will require testing in the next phase of trials.

Finally, a collaborative approach to the technology, such as open-source sensor and hardware design, open interface to location services in the cloud, and a partnership-based approach overall can help various group efforts to use more effective tools for fighting blast fishing. We are actively leading the development of the system in this direction.

5.3. Incorporating blast fishing detection into reef management to meet UN sustainable development goal 14

Inevitably a technology-based detection system requires human and financial resources for installation and operation. Such resources are already under pressure, so there is bound to be debate about how resources are best used to achieve the goal of suppressing blast fishing: should interventions target enforcement; should they emphasize community management; improve education and so on. We argue here that automated blast-detection systems are not a replacement for community engagement and education, but that they *enable* a *necessary* enforcement capacity that has hitherto been lacking. An automated detection system also allows the development of quantitative Key Performance Indicators that would significantly assist in management of the programmes designed to curb blasting.

It is difficult to justify community education and enforcement schemes over the long term without adequate data to demonstrate impact through Key Performance Indicators. Clearly an extensive blast detection network enables the identification of hotspots and peak times and other information useful for management, just as ShotSpotter has been able to highlight important patterns in gun crime to law enforcement agencies in the USA with its National Gunfire Index. Changes to management practices, such as enhanced community education or the introduction of an alternative income generating project can then be effectively assessed for their impact on destructive fishing practices.

We believe that the impact and transparency of enforcement effort can be significantly improved with real-time and accurate location of individual blast events. Each detected blast will effectively generate a case that can be tracked through a wider system to determine the overall efficacy of enforcement, from detection to apprehension and onto conviction and penalties. Certainly it will be more difficult for any endemic corruption to continue if the overall system is transparent and open to scrutiny by multiple stakeholders. Without such a system, petty corruption is unfortunately very difficult to control. (Sebastian, 2016).

The process of enforcement can be made significantly more efficient and impactful by combining technologies. The core requirement is the generation of robust evidence that may be incorporated in the applicable legal systems to obtain convictions of perpetrators. The backbone for this is incontrovertible evidence that a bomb exploded underwater and connecting that with a vessel that can be identified and tracked remotely. Much of the technology for the latter has in many areas been implemented through coastal radar systems and remote imagery. With such systems in place there will be less need for random patrols giving chase to suspect vessels as this can be much more efficiently replaced with targeted operations to surprise suspects with onboard inspections when such activities are least expected. The reduced need for inefficient and ineffective patrol operations may lead to significant savings.

The potential for enhanced enforcement will be important to demonstrate to governments, but should only form part of a more holistic approach. The goal of suppressing and ultimately eliminating blast fishing will be served well by the provision of timely, accurate and robust information to key players in the nexus of local communities, law enforcement agents and wider civil society. Experience from the COREMAP project in Indonesia (IUCN, 2002) shows that empowering the local community with respect to their role in the management of coastal resources is effective at reducing the incidence of blast fishing. The system described here is capable of simultaneously alerting community leaders, enforcement agents and civil society, which will encourage more effective action, accountability and collaboration to end this practice. An effective public awareness campaign is also required to make blast fishers aware that the detection of a fish bomb is a certainty and that the event will be reported widely. The value of a blast fishing detection system is therefore as a deterrent in addition to serving as a mechanism for collecting evidence for prosecutions.

The urgency for eliminating destructive fishing practices goes beyond the loss of the ecological services provided by a healthy coastal environment and coral reefs. Moreover it includes the social consequences of food insecurity and poor quality of life amongst large and impoverished coastal populations in Southeast Asia, Tanzania, and other territories, particularly those that make and use explosive devices on a daily basis. Long-term social and political stability in such areas is therefore linked to the sustainable development and exploitation of coastal natural resources and should be a major political motivation for the elimination of blast fishing.

6. Conclusion

By collaborating with governments and other stakeholders and integrating detection technology closely with legal systems and the development of alternative livelihoods, we feel there is tremendous potential to realize part of Goal 14 (Conserve and sustainably use the oceans, seas, and marine resources) of the UN's Sustainable Development Goals.

Climate Change and the associated trend in ocean acidification pose a major threat to coral reefs globally. To survive more extreme conditions, reefs need to be more resilient. Unfortunately, reef health in large areas is being undermined on a significant scale by blast fishing as well as other destructive techniques (Burke et al., 2011 and 2012). However, there is now potential to develop systems that can effectively suppress blast fishing and these should be developed and implemented with some urgency.

This paper demonstrates that a networked acoustic location system can determine the location of blast events accurately and reliably in real time. This information gives authorities the ability to better enforce the law, and learn how to suppress the practice of blast fishing. Now that a technical means to find the blasters is shown to be feasible, a societal means to stop the practice should follow.

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