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A direction-sensitive underwater blast detector and its application for managing blast fishing

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Abstract

Little is known about the spatial and temporal distribution of blast fishing which hampers enforcement against this activity. We have demonstrated that a triangular array of hydrophones 1 m apart is capable of detecting blast events whilst effectively rejecting other sources of underwater noise such as snapping shrimp and nearby boat propellers. A total of 13 blasts were recorded in Sepangor bay, North of Kota Kinabalu, Sabah, Malaysia from 7th to 15th July 2002 at distances estimated to be up to 20 km, with a directional uncertainty of 0.2°. With such precision, a network of similar hydrophone arrays has potential to locate individual blast events by triangulation to within 30 m at a range of 10 km.

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

1. Introduction

Destructive fishing in general and blast fishing in particular has been widely recognized for many years as one of the principle causes of reef degradation in Southeast Asia (Alcala and Gomez, 1987; McAllister, 1988; Yap and Gomez, 1985), and in some areas has been responsible for the destruction of entire reef systems (Morton, 2002; Oakley et al., 1999) and the collapse of the fish stocks they once supported (e.g. McManus et al., 1997; Alcala, 2002). Not only is blast fishing indiscriminate and wasteful, yielding products of low unit value (Fox and Erdmann, 2000), it also degrades the reef habitat. Recovery rates following blast fishing are compromised (McManus et al., 1997) and heavy bombarding can result in a permanent phase shift from that of a productive, diverse and consolidated reef structure to an unproductive and impoverished field of rubble (Fox et al., 2003). Despite the damage caused to the fishery and the reef that supports it, blast fishing is economically attractive because of the high yields per unit effort, its low cost, and the general lack of enforcement (see Pet-Soede et al., 1999). The damage caused to tourism and other services that reefs provide (e.g. shore-line protection) is externalized by those participating in the fishery, and are borne by society in general in terms of lost opportunities and services.

Despite the seriousness and widespread nature of the problem there are very few published accounts of how destructive fishing has been managed successfully that might serve as a model for more widespread application. Similarly, there are very few quantitative reports of the distribution or intensity of blasting anywhere in the

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world. We consider the lack of such information to be one of the principle reasons for the lack of a systematic approach to the management of this issue, in conjunction with the lack of political will and adequate funding. One element of the approach required to control blast fishing is to improve fisheries enforcement capability at both the community and government level.

One of the few accounts of a successful strategy to control blast fishing is that of Horrill and Makoloweka (1998) in Tanzania. They describe a collaborative approach in which village-based committees and fisheries officers supported the enforcement agencies in identifying offenders through a combination of patrols at sea and information gathered in the villages. This helped to focus the enforcement agencies' patrols, reducing the incidence of blasting from between 8 and 16 blasts per day to zero. As well as securing sustainable funding to maintain effective patrols, ensuring that the institutional arrangements are in place, and providing training and information to prosecutors and magistrates; Horrill & Makoloweka advocate the implementation of a system to monitor the effectiveness of such intervention so that it can be measured against expectations. Regular patrols have had a similar effect on the incidence of blast fishing in Komodo National Park, Indonesia (Pet-Soede, personal communication), and Alcala (2002) lists improved enforcement as one reason why the incidence of blast fishing has decreased in some areas of the Philippines in recent years. Discussions with many stakeholder groups in Southeast Asia and experience on the ground in Tanzania and Philippines have shown that stricter enforcement is an effective strategy in controlling blast fishing.

Our work aims to improve the effectiveness of fisheries patrols and to enable better intervention strategies. We previously described a hydrophone system capable of detecting underwater explosions at an estimated range of 30 km or more (Woodman et al., 2003). Here we describe further results that demonstrate that the direction of travel of underwater blast waves can be determined with great precision. In addition software has been developed that reliably filters out background noise whilst successfully flagging underwater explosions. Together, these are critical tasks in the development of a robust, accurate and reliable blast detection system. We envisage that an automated network of detectors will be capable of providing a valuable tool that can be used to improve the efficiency of fishery enforcement efforts.

2. Materials and methods

2.1. Study site

Underwater sounds were monitored from a site adjacent to the Tunku Abdul Rahman National Park (approximately 6°01′ N 116°03′ E), located 5 km from Kota Kinabalu, the state capital of Sabah, Malaysia. The site was located in the shallow Malohom bay that overlooks Sepangor bay, giving a field of view of approximately 40°. The hydrophone array used was located 4 m below chart datum on a reef slope at the end of a jetty servicing the Gayana tourist resort, close to an area where blast fishing is common practice. It also provided a sheltered environment with continuous electricity supplies for the electronics whilst being in close enough proximity to sufficient water depth for the hydrophone cables.

The method we used relied on recording and analyzing underwater acoustic signals without any prior knowledge of the timing or location of any blast events. The operating environment was similar in this respect to those facing fisheries enforcement officers in the field.

2.2. Range estimates

As the only available information on a detected blast was derived from its acoustic signal, estimates of range were calculated by comparing the peak pressure with data from charges detonated at known distances (Woodman et al., 2003). The method assumes that there is a clear line of sight to the blast and that the mass and composition of the charges used in this study are similar to the ones previously recorded, i.e. comprised of 625 ml of ammonium nitrate fuel oil (ANFO) mixture. As the peak pressure of an underwater shock wave scales roughly with the third power of the charge weight (Woodman et al., 2003), bombs of double or half the assumed mass would be expected to produce a signal around 25% larger and 20% smaller respectively. This would correspond to the estimated blast location to be shifted 25% closer or 20% further away respectively. The magnitude of this error is similar to intrinsic uncertainty in the determination of range due to the scatter in the data in the previous study (Woodman et al., 2003).

Whilst the range determination presents considerable uncertainties in locating a blast with one detection system, using two or more systems will improve the estimate significantly based on triangulation from precise direction information.

2.3. Hardware and software

Three hydrophones (Type 8103 Brüel and Kjær) were fixed onto the apices of an equilateral triangle constructed from stainless steel. The hydrophones were positioned approximately 1 m apart and their precise separations were measured to the nearest 1 mm. The array was fixed to a heavy concrete base using a wooden pole and the hydrophones were leveled. The hydrophones were numbered anti-clockwise and the orientation of the triangle was determined by measuring the bearing of the triangle's centerline using a compass. This allowed the true bearing of a blast signal to be determined from its bearing relative to the triangle.

An amplifier (Nexus type 2690 charge-conditioning amplifier) produced calibrated voltage outputs proportional to sound pressure levels at each hydrophone, that were digitized by a National Instruments DAQPad 6070E before being recorded. Data were analyzed using purpose-built software written in National Instruments' Labview programming environment.

Two monitoring options could be selected. The first ('recording mode') was designed to continuously record sound over a pre-determined interval as a digital file. The high sampling rate of the sound pressure level (200,000 samples per second on three channels) produced a dataset of around 24 GB in 6 h. Analysis of this data allowed the background noise of a shallow reef with tourist boat traffic to be determined.

The second monitoring option ('detection mode') was designed to monitor significant underwater sounds by only recording short sections of the data stream containing events with sound pressure levels over a pre-set threshold value. This was achieved by dividing the incoming data stream into 100 ms time bins and comparing the maximum sound pressure level in the bin with the threshold value. The threshold was typically set at between 7 and 10 mbar (177–180 dB re 1 μPa), a level that is below the peak pressure of blast signals at a range less than 12 km but high enough to reject most background noise including snapping shrimps (alpheids) and boat engine noise (Woodman et al., 2003). If an event above the threshold was detected, data from the pre-trigger time bin and all the time bins where the threshold was exceeded were concatenated into one short file and subsequently recorded.

2.4. Method for determination of blast direction

The relative arrival times of a blast wave at the three hydrophones depend on its direction of propagation. The cross correlation of signals from each of the hydrophone pairs (1–2, 2–3 and 3–1) yields three time differences from which there is sufficient information to determine direction. In general there are two possible blast directions that can generate the measured time difference for each pair of hydrophones (they are mirror images in the line joining the hydrophones); so the three time differences generate a total of six possibilities for the blast direction. In general, three of these possible directions are consistent and correspond to the true direction of the blast. These three are termed the *three consistent directions*, whilst the other three are inconsistent with each other and can be rejected.

The uncertainty of the time delays was estimated to be about 2 μs, based on the data sampling time of 5 μs and the uncertainty of the interpolation method used to locate the peak of the cross correlation. The uncertainty in the calculated direction of travel of the blast is a function of both the direction itself and the uncertainty in the time delays. When the line joining a pair of hydrophones is almost perpendicular to the blast wave direction, the precise time delay varies rapidly with angle; therefore, working backwards from a known time delay, the uncertainty in direction is small (the method is sensitive in this case). By contrast, when the line joining a pair of hydrophones is nearly parallel to the blast direction, the time delay is close to a maximum and only varies slowly with angle; hence calculated uncertainties in direction are large. As a result of this there is variation in the uncertainties of the three consistent directions, and it is therefore appropriate to take a weighted mean to calculate the final value of the blast direction.

2.5. Noise rejection

A number of analytical methods were developed to characterize recorded events. In addition to the peak acoustic pressure of an event, two parameters proved useful: 'equivalent energy' and pulse length. Equivalent energy is a measure of the amount of acoustic energy contained in the signal (see McCauley et al., 2000 for more details of its calculation), and is expressed in decibels (dB re 1 μPa^2). The pulse length of a signal is defined as the time taken for 90% of the equivalent energy to be delivered.

3. Results

3.1. Recorded blast events

A total of 13 blasts were recorded between 7th and 15th July 2002 (Table 1). A map showing the study site and the estimated location of some of the blasts is shown in Fig. 1. (The other blasts tended to overlay the ones shown and hence were removed for clarity.) The blast direction was well known, however the range estimated by signal strength is highly uncertain. The continuous sections of the marked lines indicate the limits of the probable locations of the blast. Blasts A–E had relatively strong signals and occurred within a few km of the detector, however blasts L and M were both weak. They were probably distant, with ranges estimated to be around 20 km, although different charge sizes and partial obscuring of the signal could also account for their weakness.

A typical blast signal captured by the array is shown in Fig. 2, and clearly illustrates the relative delays of signals recorded by each hydrophone. Signals had features similar to those found in previous work (Woodman et al., 2003) and satisfied the analytical requirement that

Table 1
Characteristics of blast events recorded during this study

Code	Date	Time	Bearing	Peak pressure		Equivalent energy	Estimated range (km)[a]		
			Degrees	mbar	dB[b]	dB[c]	Best	Maximum	Minimum
A	7/7/02	09:08:36	41.03	26.6	188.5	149.4	4.5	5.8	3.4
B	7/7/02	13:08:49	23.34	33.5	190.0	153.6	3.9	5.1	3.0
C	8/7/02	07:33:54	28.17	37.5	191.5	160.6	3.5	4.5	2.7
D	8/7/02	08:58:26	26.27	65.7	195.7	157.8	2.4	3.1	1.8
E	11/7/02	15:52:25	31.01	21.8	186.8	159.5	5.2	6.8	4.0
F	14/7/02	09:00:35	28.54	45.6	191.3	162.1	3.5	4.6	2.7
G	14/7/02	09:23:56	27.89	41.8	186.7	159.6	5.2	6.8	4.0
H	14/7/02	12:29:01	25.28	12.4	181.2	143.9	8.6	11.1	6.6
I	14/7/02	12:34:03	24.84	23.2	186.6	148.3	5.3	6.9	4.1
J	15/7/02	09:56:30	25.49	25.2	187.7	148.3	4.8	6.3	3.7
K	15/7/02	14:53:29	25.56	21.0	186.5	147.8	5.4	7.0	4.1
L	15/7/02	10:26:39	45.04	6.6	176.4	139.2	13.0	17.0	10.0
M	15/7/02	10:59:11	46.03	4.7	173.3	137.6	17.1	22.2	13.1

[a] Range estimated from peak signal pressure.
[b] dB re 1 μPa.
[c] dB re 1 μPa^2.

any particular blast event produces similar-shaped signals at each of the three hydrophones.

3.2. Direction of shock waves

The precise speed of sound is required to determine the blast direction using the time delays, and this depends principally on the temperature and salinity. Point measurements of 30 °C and 30 ppt were recorded and it is known that the usual ranges are 29–31 °C and 29–31 ppt during July (Alex, 2002). Following Mackenzie (1981), the precise value of the speed could have varied between 1535 and 1545 $m s^{-1}$ for the recorded blast events. To study the implications of this variability the blast direction analysis was undertaken for each of the integer sound speed values between the two limits and the results are presented in Table 2 (present in odf online versions of this paper). For each sound speed, the top six figures are the three consistent directions and their uncertainties. The two figures in the bottom row are the weighted mean and its standard error. Examination of rows of data in Table 2 reveals that each of the three consistent directions vary systematically as the sound speed changes. Usually one of these consistent directions has a higher value of uncertainty: e.g. the third direction in blast E has an uncertainty between 1.04° and 1.41° over the range of sound speeds, and the value varies considerably between 29.40° and 32.38°. This is an example of the large direction uncertainty when a blast wave travels nearly parallel to the line joining a hydrophone pair. Fortunately, the other two pairs of hydrophones in the triangular array are aligned differently to the blast wave and the directions they record have a much lower uncertainty and associated variability: the uncertainties for these two directions are 0.22° and 0.19° in the top two rows of blast E. One of the low-uncertainty values increases and the other decreases as the sound parameter is varied so that the weighted mean direction is remarkably constant, changing only from 31.00° to 31.01° (the square of the reciprocal of the uncertainty were used as weights). These results suggest that using an inaccurate sound speed produces little systematic error in the weighted mean direction.

A computer simulation was undertaken to investigate the effects of changing sound speed in more detail. For 10,000 randomly selected simulated blasts with time delays determined using a sound speed of 1535 $m s^{-1}$, the calculated weighted mean direction using a sound speed of 1545 $m s^{-1}$ differed by 0.015° or less in 90% of cases. This is a very small error when compared with the error caused by the uncertainties in signal time delays. In another study, the estimated 2 μs time delay uncertainty (see Section 2.4) was reproduced by adding Gaussian noise with a standard deviation of 2 μs to the simulated signal time delays. The effect of such noise was to increase the spread of the calculated weighted mean direction: the discrepancy with the simulated direction was within 0.25° in greater than 90% of cases. The conclusion of this is that the random errors in the weighted mean direction arise principally because of random errors in the signal time delays at hydrophones rather than systematic effect of choosing the wrong speed of sound within a range of 1535–1545 $m s^{-1}$. Reasonable estimates of the signal time delay errors indicate that blast direction can be determined to within 0.2°.

3.3. Rejecting background noise

During analysis of recorded data a 3 mbar (169.5 dB re 1 μPa) trigger level was chosen, corresponding to the

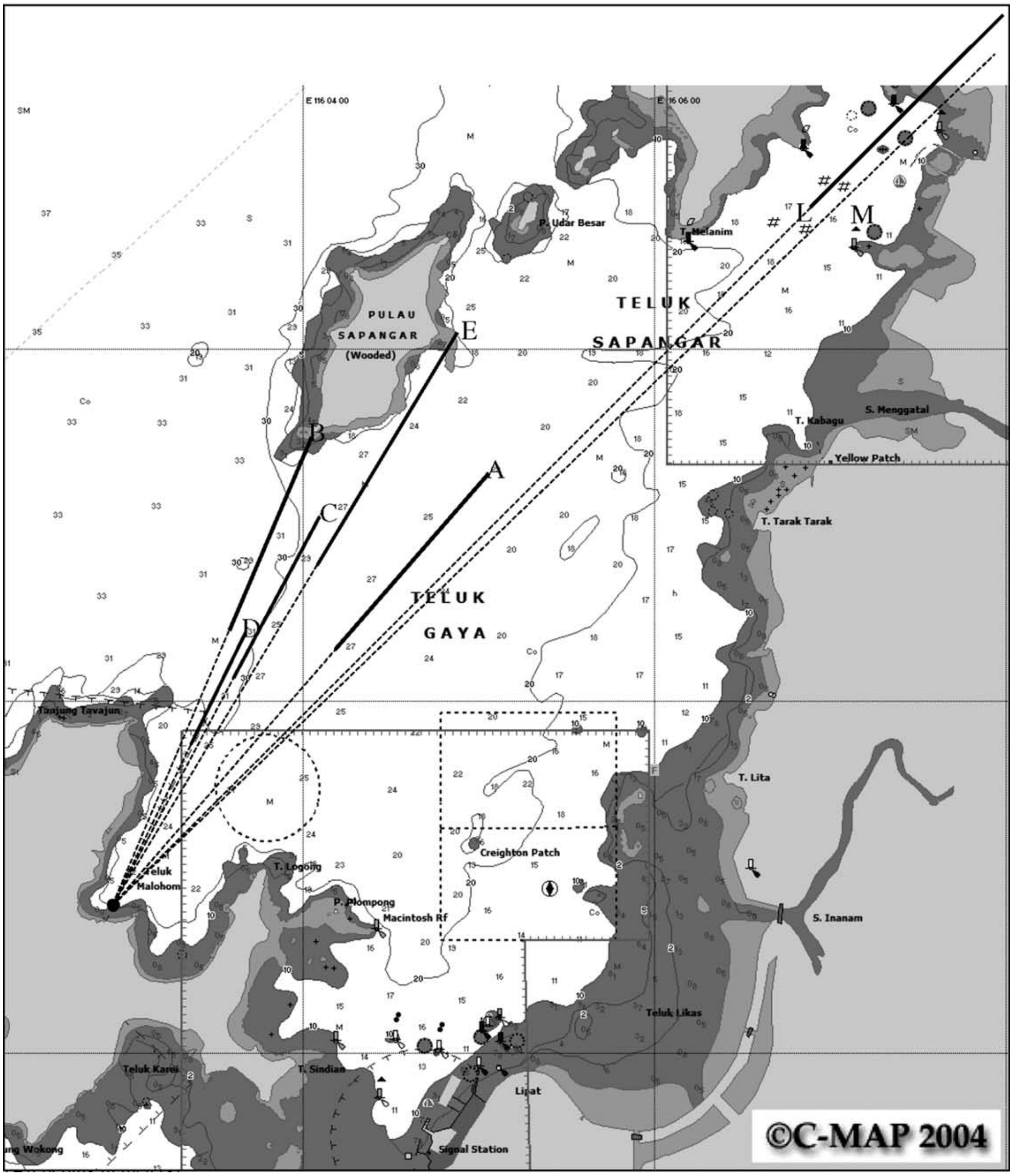

Fig. 1. The calculated bearing and range of seven of the blast events (A–E, L and M) recorded during this study. In each case, the thick lines represent the maximum and minimum distance to the blast's origin as estimated from the signal's peak pressure. Key: white—deep water, light grey—land, darker greys—shallow water. All depths in metres.

signal of a typical blast from a 625 ml ANFO bomb at a range of 20–30 km (Woodman et al., 2003). At this level there were typically between 2 and 9 events min^{-1}, the vast majority caused by snapping shrimp (family Alpheidae, see Woodman et al., 2003; Versluis et al., 2000). The largest shrimp-generated noises were recorded at peak sound pressure levels up to 21 mbar (186 dB re 1 μPa), however they contained equivalent energy of less than 130 dB re 1 μPa^2, significantly less than the equivalent energy of a typical blast (135 dB re 1 μPa^2 or more).

During the trial the propeller of a diesel powered passenger ferry passed within 5 m or so of the hydrophone array. Despite its proximity, peak sound pressure levels generated by the vessel's engines and propeller were less than about 1.5 mbar (163.5 dB re 1 μPa), insufficient to trigger the blast detection system. However, a shrimp event in combination with boat noise could contain an equivalent energy of up to 140 dB re 1 μPa^2, overlapping with the range of values expected from blast events. Analysis of the pulse length of the combination event showed the duration was always close to 300 ms while

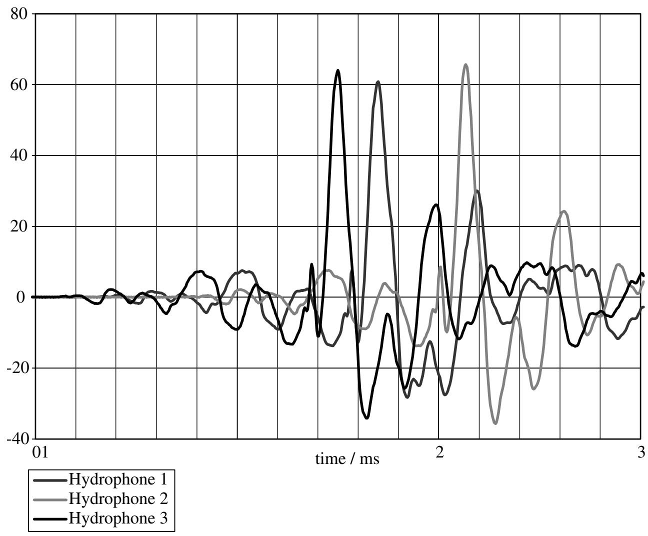

Fig. 2. A blast signal recorded by the hydrophone array showing the time delay caused by the shock wave reaching each hydrophone at different times. The shape of the signal recorded on each hydrophone is very similar for each event ensuring a sharp peak in the cross-correlation functions of pairs of signals.

blast events typically deliver 90% of their equivalent energy in less than 10 ms.

Mechanical contact with individual hydrophones, e.g. caused by fish grazing on algae growing on the hydrophones, is another possible source of anomalous noise. Such signals are large but since they only affect one of the three hydrophones they are straightforward to characterize.

Based on these findings, an algorithm was developed that could discriminate blast events from background noise and tested using the 20 h of recorded data with a trigger sound pressure level of 3 mbar (169.5 dB re 1 Pa). It correctly identified a total of 8 blast events (including two additional blasts L and M that had not been flagged when they occurred as they were under the monitoring trigger level of 7 mbar) and rejected 4279 noise events. More importantly it did not generate any false positive results.

4. Discussion

4.1. Blasting activity

The results show that significant fish blasting took place around Sepangor Island (Fig. 1 only shows some blasts for clarity). Although there is considerable uncertainty in the range estimates based on signal strength, it seems that some fishermen (e.g. blasts A, C and D in Fig. 1) might be targeting pelagic species such as Caesionids in deeper water (as has been observed in Indonesia by Fox and Erdmann, 2000). Eight of the 13 blasts occurred between the hours of 07:00 and 11:00, while the remainder occurred between 12:00 and 16:00.

4.2. Accuracy and precision of the system

This work has demonstrated the potential for the determination of the direction of a blast with a precision of ±0.2°. In this trial the final determination of the bearing was limited to a precision of ±2° because the orientation of the hydrophone array was measured using a hand held compass. An electronic compass would reduce the bearing uncertainty to around 0.2° whilst correcting for the local magnetic effects of ferrous metals, thus ensuring that the accuracy of the system is high. (A further benefit of using an electronic compass is that a boat mounted detection system could automatically correct for its shifting orientation and tilt.) With accuracy and precision at this level, a network of two or more arrays could locate a blast event occurring at a range of 10 km to within a radius of about 30 m.

4.3. Rejection of noise and detector sensitivity

The characteristics of signals produced by underwater explosions are such that they can be distinguished from most background noises in a reef environment with a high degree of certainty. The filtering algorithms applied in this study demonstrated complete rejection of noise events and a level of sensitivity such that distant blasts at an estimated 30 km would still be detected. These are promising results for an automated detection system as rejection of false positive signals is very important, whilst a high level of sensitivity indicates that large sea areas can be monitored using relatively few detection arrays.

4.4. Applications

4.4.1. Raising awareness

It is notable that all blasting took place during daylight hours within a few kilometers of Kota Kinabalu, a busy port that hosts the state coastguard and marine police, and a marine protected area in which diving is a popular activity. This suggests that the enforcement authorities and other stakeholders now tolerate blasting, or that current enforcement measures do not detect it, or both.

This system has the potential to raise the awareness of the authorities of the seriousness of the problem in cases such as these. With elevated public and political will, it is more likely that sufficient resources are allocated to solve the underlying socio-economic roots that contribute to fish blasting. A solution to the blast fishing problem will require elements of community-based enforcement, alternative income generation and education. However, until such solutions have been developed, centralized

Table 2
Direction calculations for the thirteen recorded blasts

Blast code	Date	Time	Speed of sound in m s^{-1}																					
			1535		1536		1537		1538		1539		1540		1541		1542		1543		1544		1545	
			Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc
A	7/7/02	9:08:36 AM	41.03	0.20	41.01	0.20	40.99	0.20	40.97	0.20	40.95	0.20	40.93	0.20	40.91	0.20	40.89	0.20	40.87	0.20	40.85	0.20	40.84	0.20
			41.02	0.21	41.05	0.21	40.97	1.87	41.09	0.21	41.12	0.21	41.14	0.21	41.17	0.21	41.19	0.21	41.22	0.21	41.24	0.21	41.26	0.21
			42.17	1.64	41.62	1.75	41.07	0.21	40.14	2.03	38.55	2.23	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF	INF
St dev of dirctns			*0.099*		*0.052*		*0.041*		*0.088*		*0.180*		*0.11*		*0.13*		*0.15*		*0.17*		*0.19*		*0.21*	
wtd mean/st error			41.03	0.17	41.03	0.17	41.03	0.17	41.02	0.17	41.02	0.17	41.03	0.18	41.03	0.18	41.03	0.18	41.03	0.18	41.04	0.18	41.04	0.18
B	7/7/02	1:08:49 PM	23.48	0.25	23.45	0.25	23.41	0.25	23.31	0.66	23.34	0.25	23.30	0.25	23.26	0.25	23.23	0.25	23.19	0.25	23.15	0.25	23.11	0.25
			23.29	0.18	23.30	0.18	23.31	0.18	23.32	0.18	23.33	0.18	23.34	0.18	23.36	0.18	23.37	0.18	23.38	0.18	23.39	0.18	23.40	0.18
			22.89	0.65	23.03	0.65	23.17	0.66	23.37	0.25	23.45	0.67	23.59	0.68	23.74	0.68	23.89	0.69	24.03	0.70	24.18	0.70	24.34	0.71
St dev of dirctns			*0.136*		*0.097*		*0.059*		*0.024*		*0.024*		*0.059*		*0.096*		*0.134*		*0.171*		*0.208*		*0.246*	
wtd mean/st error			23.34	0.16	23.34	0.16	23.34	0.16	23.34	0.16	23.34	0.16	23.34	0.16	23.34	0.16	23.34	0.16	23.34	0.16	23.34	0.16	23.34	0.16
C	8/7/02	7:33:54 AM	28.23	0.23	28.20	0.23	28.17	0.23	28.14	0.23	28.11	0.23	28.08	0.23	28.04	0.23	28.01	0.23	27.98	0.23	27.95	0.23	27.92	0.23
			28.14	0.19	28.15	0.19	28.16	0.19	28.18	0.19	28.19	0.19	28.21	0.19	28.22	0.19	28.23	0.19	28.25	0.19	28.26	0.19	28.27	0.19
			27.72	0.90	27.92	0.92	28.14	0.93	28.35	0.95	28.57	0.97	28.80	0.99	29.03	1.01	29.27	1.03	29.52	1.06	29.77	1.08	30.03	1.11
St dev of dirctns			*0.086*		*0.045*		*0.005*		*0.034*		*0.073*		*0.112*		*0.151*		*0.189*		*0.226*		*0.263*		*0.300*	
wtd mean/st error			28.16	0.16	28.17	0.16	28.17	0.16	28.17	0.16	28.17	0.16	28.17	0.16	28.17	0.16	28.17	0.16	28.17	0.16	28.17	0.16	28.16	0.16
D	8/7/02	8:58:26 AM	26.45	0.23	26.42	0.24	26.38	0.24	26.35	0.24	26.32	0.24	26.28	0.24	26.25	0.24	26.22	0.24	26.18	0.24	26.15	0.24	26.12	0.24
			26.21	0.19	26.22	0.19	26.23	0.19	26.25	0.19	26.26	0.19	26.27	0.19	26.28	0.19	26.30	0.19	26.31	0.19	26.32	0.19	26.33	0.19
			25.29	0.75	25.46	0.76	25.63	0.77	25.80	0.78	25.97	0.79	26.15	0.80	26.33	0.81	26.51	0.82	26.69	0.84	26.88	0.85	27.07	0.86
St dev of dirctns			*0.220*		*0.180*		*0.140*		*0.101*		*0.061*		*0.023*		*0.019*		*0.057*		*0.095*		*0.133*		*0.171*	
wtd mean/st error			26.27	0.16	26.27	0.16	26.27	0.16	26.27	0.16	26.27	0.16	26.27	0.16	26.27	0.16	26.27	0.16	26.27	0.16	26.27	0.16	26.27	0.16
E	11/7/02	3:52:25 PM	31.18	0.22	31.15	0.22	31.12	0.22	31.09	0.22	31.07	0.22	31.04	0.22	31.01	0.22	30.98	0.22	30.95	0.22	30.93	0.22	30.90	0.22
			30.91	0.19	30.93	0.19	30.94	0.19	30.96	0.19	30.97	0.19	30.99	0.19	31.01	0.19	31.02	0.19	31.04	0.19	31.05	0.19	31.07	0.19
			29.40	1.04	29.65	1.07	29.91	1.09	30.17	1.12	30.45	1.15	30.74	1.18	31.03	1.22	31.35	1.26	31.67	1.31	32.02	1.35	32.38	1.41
St dev of dirctns			*0.257*		*0.213*		*0.169*		*0.126*		*0.083*		*0.040*		*0.004*		*0.043*		*0.084*		*0.125*		*0.165*	
wtd mean/st error			31.00	0.16	31.00	0.16	31.00	0.16	31.00	0.16	31.00	0.16	31.01	0.16	31.01	0.16	31.01	0.16	31.01	0.17	31.01	0.17	31.01	0.17

F	14/7/02	9:00:35 AM	28.75	0.23	28.72	0.23	28.69	0.23	28.66	0.23	28.63	0.23	28.59	0.23	28.56	0.23	28.53	0.23	28.50	0.23	28.47	0.23	28.44	0.23
			28.45	0.19	28.46	0.19	28.48	0.19	28.49	0.19	28.50	0.19	28.52	0.19	28.53	0.19	28.55	0.19	28.56	0.19	28.57	0.19	28.59	0.19
			26.99	0.85	27.18	0.86	27.38	0.88	27.58	0.89	27.78	0.91	27.99	0.92	28.20	0.94	28.42	0.96	28.64	0.98	28.87	1.00	29.11	1.02
St dev of dirctns			*0.299*		*0.257*		*0.216*		*0.175*		*0.134*		*0.093*		*0.054*		*0.019*		*0.032*		*0.069*		*0.108*	
wtd mean/st error			28.53	0.16	28.53	0.16	28.53	0.16	28.53	0.16	28.53	0.16	28.54	0.16	28.54	0.16	28.54	0.16	28.54	0.16	28.54	0.16	28.54	0.16
G	14/7/02	9:23:56 AM	28.03	0.23	28.00	0.23	27.97	0.23	27.94	0.23	27.91	0.23	27.90	0.92	27.84	0.23	27.81	0.23	27.78	0.23	27.75	0.23	27.72	0.23
			27.83	0.19	27.84	0.19	27.85	0.19	27.87	0.19	27.88	0.19	27.89	0.19	27.91	0.19	27.92	0.19	27.93	0.19	27.95	0.19	27.96	0.19
			26.90	0.85	27.10	0.86	27.29	0.87	27.49	0.89	27.69	0.90	27.88	0.23	28.11	0.93	28.33	0.95	28.55	0.97	28.77	0.99	29.00	1.01
St dev of dirctns			*0.195*		*0.154*		*0.113*		*0.073*		*0.034*		*0.009*		*0.046*		*0.085*		*0.124*		*0.162*		*0.200*	
wtd mean/st error			727.88	0.16	27.88	0.16	27.88	0.16	27.88	0.16	27.89	0.16	27.89	0.16	27.89	0.16	27.89	0.16	27.89	0.16	27.89	0.16	27.89	0.16
H	14/7/02	12:29:01 PM	25.50	0.24	25.47	0.24	25.43	0.24	25.40	0.24	25.36	0.24	25.33	0.24	25.29	0.24	25.26	0.24	25.22	0.24	25.19	0.24	25.16	0.24
			25.21	0.18	25.22	0.18	25.23	0.18	25.24	0.18	25.25	0.18	25.26	0.19	25.28	0.19	25.29	0.19	25.30	0.19	25.31	0.19	25.32	0.19
			24.25	0.70	24.40	0.71	24.56	0.72	24.72	0.73	24.87	0.73	25.04	0.74	25.20	0.75	25.36	0.76	25.53	0.77	25.70	0.78	25.87	0.79
St dev of Dirctns			*0.253*		*0.214*		*0.174*		*0.135*		*0.096*		*0.057*		*0.018*		*0.021*		*0.059*		*0.098*		*0.136*	
Wtd mean/st error			25.27	0.16	25.27	0.16	25.28	0.16	25.28	0.16	25.28	0.16	25.28	0.16	25.28	0.16	25.28	0.16	25.28	0.16	25.28	0.16	25.28	0.16
I	14/7/02	12:34:03 PM	24.92	0.24	24.89	0.24	24.85	0.24	24.85	0.73	24.78	0.24	24.75	0.24	24.71	0.24	24.68	0.24	24.64	0.24	24.61	0.24	24.57	0.24
			24.81	0.18	24.82	0.18	24.83	0.18	24.84	0.18	24.86	0.18	24.87	0.18	24.88	0.18	24.89	0.18	24.90	0.19	24.91	0.19	24.92	0.19
			24.38	0.71	24.53	0.72	24.69	0.72	24.82	0.24	25.01	0.74	25.17	0.75	25.34	0.76	25.50	0.77	25.67	0.78	25.84	0.79	26.02	0.80
St dev of dirctns			*0.108*		*0.069*		*0.031*		*0.013*		*0.049*		*0.087*		*0.125*		*0.162*		*0.200*		*0.237*		*0.275*	
wtd mean/st error			24.83	0.16	24.83	0.16	24.84	0.16	24.84	0.16	24.84	0.16	24.84	0.16	24.84	0.16	24.84	0.16	24.84	0.16	24.84	0.16	24.84	0.16
J	15/7/02	9:56:30 AM	25.60	0.24	25.57	0.24	25.53	0.24	25.50	0.24	25.49	0.76	25.43	0.24	25.39	0.24	25.36	0.24	25.32	0.24	25.29	0.24	25.26	0.24
			25.46	0.18	25.48	0.18	25.49	0.18	25.50	0.19	25.51	0.19	25.52	0.19	25.54	0.19	25.55	0.19	25.56	0.19	25.57	0.19	25.58	0.19
			24.83	0.73	24.99	0.74	25.16	0.75	25.32	0.76	25.46	0.24	25.66	0.77	25.83	0.78	26.00	0.79	26.18	0.81	26.36	0.82	26.54	0.83
St dev of dirctns			*0.146*		*0.107*		*0.068*		*0.033*		*0.024*		*0.055*		*0.092*		*0.130*		*0.167*		*0.205*		*0.242*	
wtd mean/st error			25.49	0.16	25.49	0.16	25.49	0.16	25.49	0.16	25.49	0.16	25.49	0.16	25.49	0.16	25.49	0.16	25.49	0.16	25.49	0.16	25.49	0.16
K	15/7/02	2:53:29 PM	25.75	0.24	25.71	0.24	25.68	0.24	25.64	0.24	25.61	0.24	25.57	0.24	25.54	0.24	25.51	0.24	25.47	0.24	25.44	0.24	25.40	0.24
			25.49	0.18	25.50	0.18	25.51	0.18	25.53	0.19	25.54	0.19	25.55	0.19	25.56	0.19	25.57	0.19	25.58	0.19	25.60	0.19	25.61	0.19
			24.69	0.72	24.85	0.73	25.01	0.74	25.17	0.75	25.34	0.76	25.50	0.77	25.67	0.78	25.84	0.79	26.02	0.80	26.19	0.81	26.37	0.82
St dev of dirctns			*0.212*		*0.172*		*0.133*		*0.093*		*0.054*		*0.016*		*0.024*		*0.062*		*0.100*		*0.138*		*0.176*	
wtd mean/st error			25.55	0.16	25.55	0.16	25.55	0.16	25.56	0.16	25.56	0.16	25.56	0.16	25.56	0.16	25.56	0.16	25.56	0.16	25.56	0.16	25.56	0.16

Table 2 (*continued*)

Blast code	Date	Time	Speed of sound in m s^{-1}																					
			1535		1536		1537		1538		1539		1540		1541		1542		1543		1544		1545	
			Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc	Dirn	Unc
L	15/7/02	10:26:39 AM	45.03	0.22	45.03	0.19	45.02	0.19	45.00	0.19	44.99	0.19	44.97	0.19	44.95	0.19	44.94	0.19	44.92	0.19	44.91	0.19	44.89	0.19
			45.05	0.19	45.06	0.22	45.09	0.22	45.12	0.22	45.15	0.22	45.17	0.22	45.20	0.22	45.23	0.22	45.26	0.22	45.29	0.22	45.31	0.22
			45.24	1.18	44.94	1.22	44.63	1.26	44.30	1.31	43.95	1.36	43.59	1.41	43.19	1.47	42.76	1.54	42.29	1.63	41.77	1.73	41.15	1.84
St dev of dirctns			*0.025*		*0.018*		*0.059*		*0.100*		*0.140*		*0.180*		*0.219*		*0.258*		*0.296*		*0.334*		*0.372*	
Wtd mean/st error			45.04	0.16	45.04	0.16	45.04	0.16	45.04	0.16	45.04	0.16	45.04	0.17	45.04	0.17	45.04	0.17	45.04	0.17	45.04	0.17	45.05	0.17
M	15/7/02	10:59:11 AM	46.03	0.22	46.03	0.19	46.01	0.19	46.00	0.19	45.98	0.19	45.97	0.19	45.95	0.19	45.94	0.19	45.92	0.19	45.91	0.19	45.89	0.19
			46.04	0.19	46.05	0.22	46.08	0.22	46.11	0.22	46.14	0.22	46.17	0.22	46.20	0.22	46.23	0.22	46.26	0.22	46.29	0.23	46.32	0.23
			45.42	1.16	45.13	1.20	44.83	1.24	44.51	1.28	44.17	1.32	43.82	1.38	43.44	1.43	43.04	1.50	42.59	1.57	42.11	1.66	41.55	1.77
St dev of dirctns			*0.075*		*0.109*		*0.145*		*0.181*		*0.217*		*0.253*		*0.289*		*0.323*		*0.357*		*0.392*		*0.425*	
Wtd mean/st error			46.03	0.16	46.03	0.16	46.03	0.16	46.03	0.16	46.03	0.16	46.03	0.17	46.03	0.17	46.03	0.17	46.03	0.17	46.04	0.17	46.04	0.17

Notes: 1. All directions given in degrees.
2. Greyed areas indicate 'best' speed of sound that minimizes standard deviation of directions.
3. INF for blast A indicates that no physical direction can account for the signal time delay at the given sound speed.

fisheries monitoring, surveillance and control techniques have a part to play by increasing the costs of participating in the fishery. A blast detection system can achieve this by increasing the risk of detection, apprehension and conviction.

The enforcement response must be in keeping with the particular conditions under which it occurs. For many open resource situations, the best approach for improving enforcement efficiency would be the use of a detector mounted on a patrol vessel to provide a bearing and an estimated range of blasts. This has the advantage that larger sea areas could be patrolled effectively and the detector is less vulnerable to rough seas or theft. Two or more patrol boats would allow accurate triangulation of blast events. Enforcement agencies in many countries have found it difficult to convict blast fishers due to the lack of evidence. In most circumstances, explosives along with any blast-caught fish are quickly dumped overboard by fishers on approach of an enforcement vessel. The precise location and time information of blasts furnished by a blast detection system offers a new class of evidence to support convictions. Test cases will be required in order to establish the quality of the evidence provided, however if these are successful the submission of blast detection data could become routine in future.

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Appendix A

The equivalent energy is obtained from integrating the square of the sound pressure level (in microPascals, μPa) over time (McCauley et al., 2000). It is usually expressed in dB, a logarithmic scale where an increase in 10 dB corresponds to a factor of 10 increase in the signal energy and the zero of the dB scale corresponds to 1 $\mu Pa^2 s$. The unit has been used in acoustic studies of airguns used in the oil and gas exploration industry. In order to convert to a true physical unit, the energy density, the zero of the dB scale is shifted such that 0 dB corresponds to 1 J passing through a square meter area perpendicular to the blast direction. Thus equivalent energy expressed in dB can be converted to true energy density also in dB by subtracting 181.7 dB.

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