Acoustic detection of fish bombing

Final Report January 2016

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Summary

Fishing with explosives is one of the most serious threats to the health, biodiversity, productivity and aesthetic value of coral reefs. In addition, it has a negative impact on the livelihoods of fishing communities who use non-destructive fishing techniques. Fish bombing on and around coral reefs, despite being illegal, has persisted in Sabah for many decades because it is easy and yields a relatively large 'catch' in a short time. Fish bombers are seldom caught because they move around over wide areas and keep well clear of patrol boats. The authorities are hampered by lack of information about where and when bomb fishers are operating and as a result fish bombing continues unabated. The Marine Conservation Society and University of St Andrews in collaboration with Sabah Parks have worked together to address this issue by developing and installing underwater detection systems that monitor incidents of fish bombing and provide real-time location data.

During the first phase of the project the hydrophone frame was constructed and deployed and underwater acoustic data collected, including the sound of exploding bombs. The technical team at St Andrews Instrumentation Ltd (SAIL) then 'classified' the fish bomb sound, isolating it from other underwater noises such as boat engines and snapping shrimps.

Software and hardware systems were then developed and taken to the site. Each integrated system consists of a hydrophone array connected by cable to a Decimus® unit on the surface. The hydrophones convert sounds into electrical signals and these are then converted to digital signals through the Decimus® and transmitted wirelessly to the Base Station laptop computer.

PAMGuard software in the laptop processes, stores and displays the data, providing real-time information on-screen. There is also an audible alert whenever a fish bomb is detected and the surveillance team can click on the screen and switch immediately to a map showing bearings to the bomb location.

Pressure detectors have also been installed in the Park to gather baseline information about fish blasting activities in the area and to monitor trends. These and the acoustic devices are providing data that has never previously been available.

The level of fish bombing is high, with an average of between 20-40 bombs per day being detonated within the Park boundaries and many more outside. A number of hot spots have been identified, both on the reef and in open water. The monitoring devices can detect small fish bombs up to at least 15km away and larger ones up to 30km away.

This project is making a real difference by addressing a long-standing problem that has proved extremely difficult to solve by other means. Until now, enforcement agencies have been severely hampered in their efforts to apprehend fish bombers by the large areas that need to be patrolled, high fuel costs, shortage of manpower and the stealthy tactics employed by bomb fishermen to avoid being caught.

This programme has succeeded in its aims of developing, deploying and training Sabah Parks staff in the use of the fish bomb detection system but is not the only strategy that will be used

to bring fish bombing to an end. Community engagement is also vitally important and further outreach and awareness activities is proposed in parallel with the monitoring and enforcement programme.In addition, training opportunities for local youth to get engaged in the growing local tourism industry are being planned, in order to provide more job opportunties for people living in the Park and ensure that benefits from the MPA are shared more equitably.

Background and rationale

This project focusses on coral reefs in the largest marine park in Sabah, Borneo, lying off Semporna in the south-east corner of the State. Tun Sakaran Marine Park (TSMP) was gazetted in 2004 and incorporates some of the most important and biologically diverse reefs in the area. The reefs are also a vitally important resource for local people, including over 300 households who live on the islands inside the Park.

Research has shown that fish bombing is one of the most serious threats to the health, biodiversity, productivity and aesthetic value of these reefs, as it is in other parts of south-east Asia. In addition, it causes significant losses in economic value for non-destructive fisheries, tourism and coastal protection. Not only does fish bombing cause extensive damage when carried out in reef areas, but recovery is very slow, if it occurs at all. In addition, because of its effectiveness, this practice contributes significantly to over-fishing.

Fish bombing on and around coral reefs in Sabah is known from the time of World War II when fishermen used munitions including hand grenades (Ali, 2008) and there are reports of dynamite being used in the SE Asia region well over a hundred years ago (Norton-Kyshe, 1898). Fishermen now use home-made bottle bombs packed with fertiliser and kerosene and detonated by a fuse inserted through the top. The bombs are deployed from small boats, and may be used at any time of day and even at night.

Fish bombing is illegal but stopping it has proved to be extremely difficult for a number of reasons. Firstly, the reef and open water areas where fish bombers operate are extensive (TSMP covers 350km^2) and logistical reasons (availability of boats and staff) it is very difficult to carry out patrols on a regular basis. Furthermore, without any prior knowledge of where the fish bombers are operating, the chances of coming across them is low.

Bomb fishermen also employ stealthy tactics to avoid being caught. They operate when no-one is around and are expert at evading the authorities. They are always on the alert for police or other security personnel and ready to make a rapid get-away, often escaping over shallow reefs where larger patrol vessels cannot follow.

Many local fishermen condemn fish bombing but there are a significant number who continue with it because it is quick, relatively cheap and yields a large ‘catch’ in a short time. A single bottle bomb can yield up to 45kg of fish (Kissol, 2012) whereas the average catch/hour using hook and line (2 units per operation) yields up to 1.88 kg (average 0.5kg) (Wood *et al*., 2004). There is no indication that the practice is dying out because young men and boys continue to be taught the technique.

Fish bombs used in Sabah are made from components that are relatively easy to obtain locally. The explosive material is a mixture of ammonium nitrate and kerosene and this is packed into glass or plastic bottles or large cans, with a waterproof fuse inserted into the top. Once the fishermen have located an aggregation or shoal of fish they light the fuse and throw the bomb into the water. The bomb explodes within a few seconds and the fishermen try to ensure that it does so at a point where it will have the most impact on the target fish. The aim is not to blow the fish to pieces but for the bomb to create a pressure wave that will stun the fish through its impact on the internal organs.

The explosion can only be heard from a few hundred metres away and creates a visible plume which subsides within seconds. However, sound travels far and fast underwater (1,500 metres per second in comparison with 343 metrees per second in air) and can be detected many kilometres from its source. Our programme to detect the location of a bomb immediately it goes off makes use of this attribute.

Aims and objectives

The aim of this project is to bring an end to fish bombing in the Tun Sakaran Marine Park and surrounding waters and so prevent further habitat destruction, loss of biodiversity and negative impacts on fisheries, tourism and economic development.

Within this general aim are three specific objectives:

1. Develop an acoustic detection system capable of recognising fish blasts and isolating the sound from other ambient noises.
2. Install the acoustic system at the site and have it running and transmitting data in real time.
3. Train Sabah Parks staff in all operational procedures so that they can record and plot all blasts and respond immediately.

Methods

The methods are set out in chronological order as follows:

1. Training project staff at University of St Andrews
2. Collection of bomb sounds and other acoustic data
3. Data analysis, software configuration and hardware setup
4. Establishment of Base Station
5. Determining the location(s) for the detection systems
6. Installing the acoustic detection system
7. Monitoring using pressure detection system

1. Training project staff at University of St Andrews

   The initial plan had been to bring research staff over from St Andrews University Sea Mammal Research Unit (SMRU) to collect acoustic data and train project and Sabah Parks staff. However, this proved impossible due to the ongoing security situation in Sabah and so Jamie Ng (SIP, project co-ordinator) and Boni Antiu (Tun Sakaran Marine Park Manager) travelled over to the University of St Andrews for training and to collect equipment necessary for data collection. This was accomplished in September 2013.

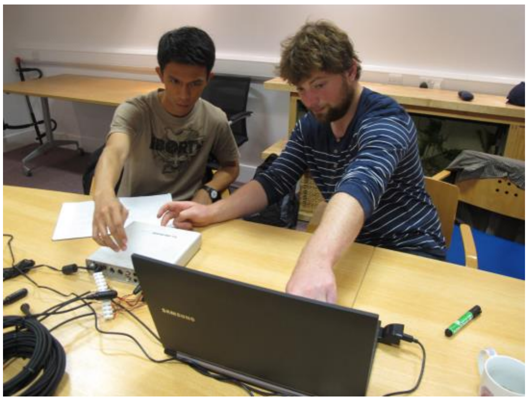


Figure 1. Jamie Valiant Ng being trained to set up the acoustic system by Jamie MacAulay at St Andrews University.

2. Collection of bomb sounds and other acoustic data

   2.1. Design and construction of hydrophone frame

A cluster of three individual hydrophones is needed to ensure that the direction that the sound of the blast is coming from can be detected. The hydrophones (purchased through SA Instrumentation (SAIL) in St Andrews, UK) were arranged in a particular way, as specified by the techinical team.

Specifically, the hydrophones needed to be at an equal distance from each other and at least 1m apart. They also needed to be maintained at the same level in the water, at an angle of 90^{O} to the sea surface. In order to meet these criteria we designed a sturdy metal frame which was made to our specifications by a workshop located in Semporna (Figures 2 and 3).

Figure 2. Drilling holes for the clamp

Figure 3. Welding the frame

The frame was in the shape of a triangle and a clamp was added to one side (Figure 2). This was fixed with bolts so that it could be tightened up against a jetty leg or other fixed object as required (Figure 5).

The hydrophones and cables were securely fastened at each corner with cable ties.

2.2. Deployment of the hydrophone frame

In the first instance, the frame was deployed by fixing ropes at each corner that were then attached centrally to a rope that led to the surface. This method enabled the team to manage the depth of the hydrophones by adjusting the length of the rope. A depth of around 4-5m was recommended by SAIL to ensure an even temperature and to minimise 'surface effects'. During these tests it was noted that the sound clarity improved the deeper the hydrophones were deployed and most of the data was subsequently collected from about 4m depth.

Using this methodology it proved possible to control the frame provided the water was perfectly still, but if there was any current then it was quickly pulled out of line, as shown in the Figure 4.

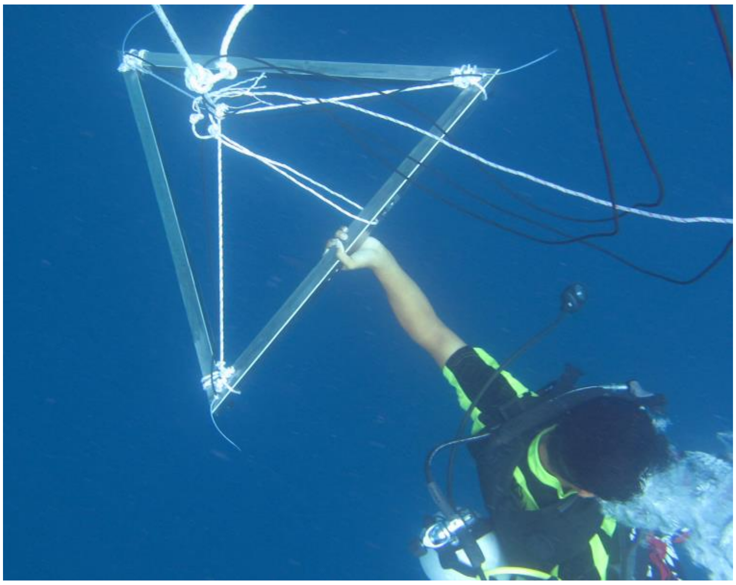


Figure 4. Diver trying to steady and level the frame as it hangs free from the boat.

It was clear that the frame needed to be attached to a structure that held it firmly at an angle of 90^{O} to the sea surface and jetty legs were initially considered to be ideal because they were very secure (Figure 5).

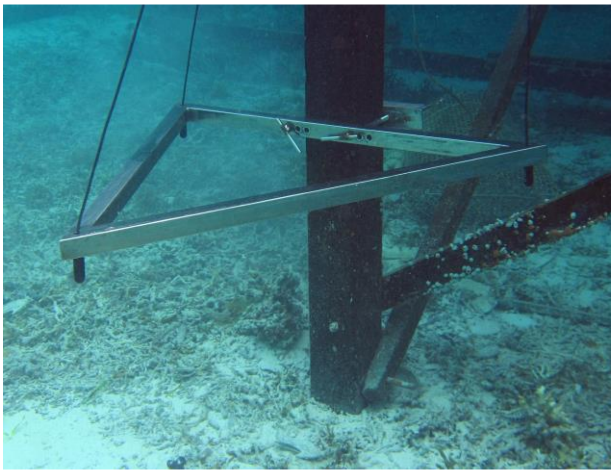


Figure 5. Hydrophone frame attached to jetty leg.

The Park jetties at Boheydulang and Selakan were unsuitable because sounds from the outer reefs (where fish bombs are used) would be blocked by islands and reefs. There is a jetty at nearby Pulau Pom Pom but we found that the water depth was too shallow at low tide. Thus the only option was to deploy the frame beyond the reef edge by some other means.

The first method used was to bolt the frame to T-bars that were attached to and weighted down by concrete blocks that held the hydrophones about 50cm from the seabed (Figure 6). This method of frame placement worked, but was laborious to set up because several divers were needed to get the apparatus in place and the heavy concrete blocks were difficult to manage underwater.

Figure 6. Attaching the acoustic frame to the concrete blocks

The second method entailed designing and making a metal, single-pole, 'ladder' that hooked over the side of the boat and held the triangular hydrophone frame securely in the water column.

The hydrophone frame was clamped to the end of the metal pole (Figures 7 and 8) and then the pole and frame were lowered into the water (Figure 9) and the top of the pole hooked on to the edge of the boat. The 'ladder' could be deployed and retrieved quite easily by one or two people. The only problem encountered was when the sea was rough and it rubbed against the side of the boat, producing scraping noises that were picked up by the hydrophones.

Figure 7. Hydrophone frame being clamped onto a horizontal plate welded onto the bottom end of the pole (left) and ready to be lowered into the water (below).

Figure 8 (above) Pole and frame ready to be deployed.

Figure 8. Hydrophone pole and frame being lowered into the water. The hook and support at the top fix the pole to the side of the boat.

For further stability, a rope was attached to the frame, run up to the boat and then pulled in the appropriate direction to ensure that the frame was lying horizontal in the water (Figure 9).

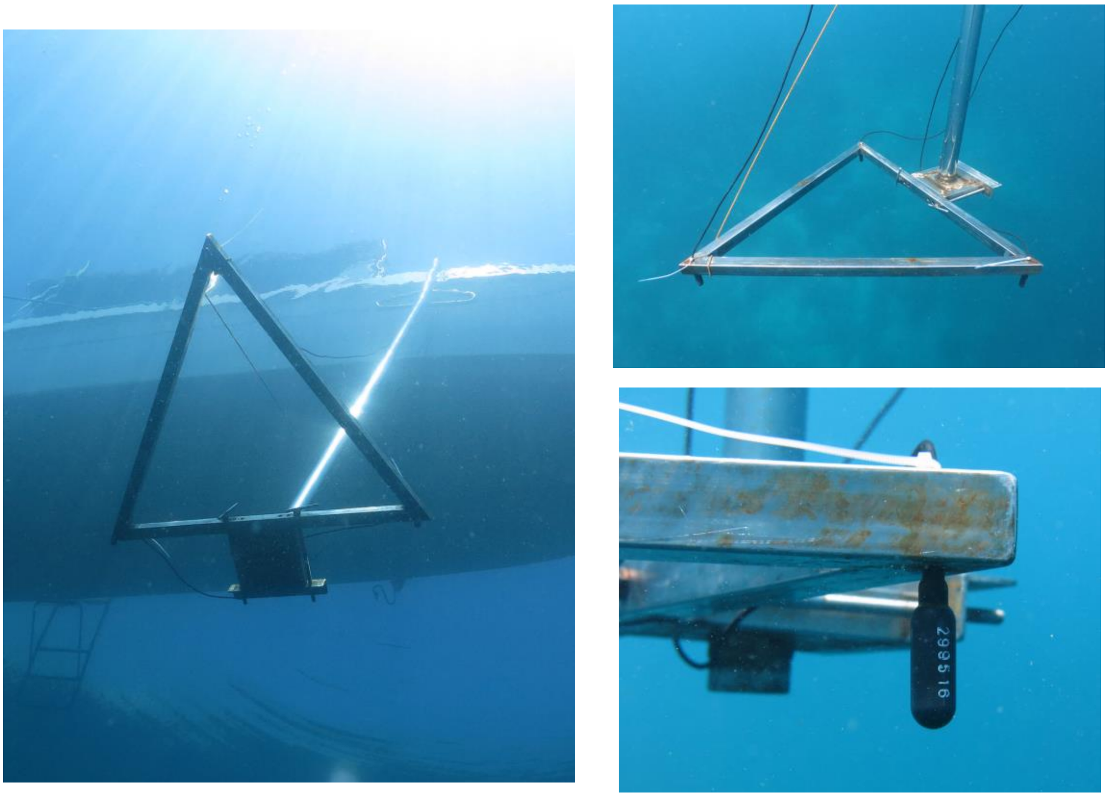


Figure 9. Above: Frame in position for recording. Top right: Frame showing the orange adjustment rope attached to one corner. Below right: Close-up of one of the three hydrophones.

2.3. Data recording

For the initial tests and collection of sounds (including fish bombs) we used hydrophones with 8m cables. The cables ran up to the boat where the recording equipment was located. This comprised an audio interface (Konnekt 24d) that contained the sound card and transmited data by firewire cable to the laptop.

Stabilised DC current for the laptop and sound card was delivered by an inverter connected to a car battery. If fully charged, the battery lasted 4-5 hours. It was then re-charged overnight, ready for the next day's fieldwork.

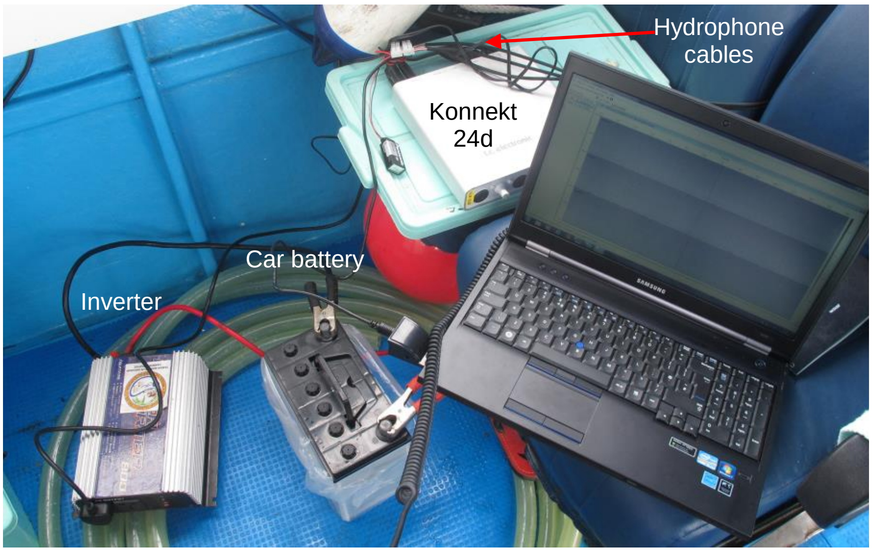


Figure 10. Recording equipment set up on the boat, powered by a car battery.

Headphones were plugged into the laptop so that the team could hear the audio signals and see how they corresponded with the digital readout on the laptop screen.

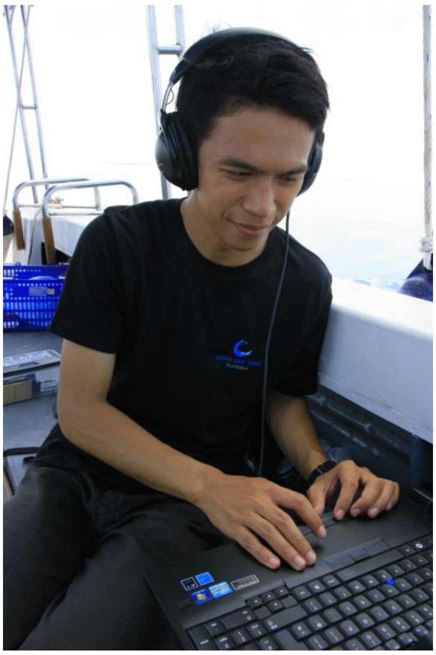


Figure 11. Data collection in operation.

2.4. Data collection sites

The hydrophone frame was deployed at various localities both inside and outside the Park in order to pick up a range of underwater sounds including fish bombs. Without prior knowledge of where bombs might be used, the unit was set up at localities where the hydrophones would cover as wide an arc of water as possible without being blocked by reefs or islands.

Recording was carried out for a total of 102 hours 01 minutes hours (total time hydrophones connected up and recording) at six localities (Table 1). The majority of data collection sites were at Sebangkat and Sibuan but some recordings were also carried out at Pulau Pom Pom and Larapan (Figure 12). Most of the recordings were made using the frame suspended from the boat on the 'ladder' (Figure 9).

Figure 12. Locations where the hydrophone frame was deployed.

3. Data analysis, software configuration and hardware setup

Acoustic data files incorporating the 102 hours of recordings were delivered to the research team at the University of St Andrews for analysis and to enable configuration of the PAMGuard software and Decimus®. This research and development phase took place at the University of St Andrews from September to November 2014.

Some of the hardware was acquired in late 2013 for the preliminary data collection phase and the rest was assembled by November 2014 and then shipped to the project site. One complete detection unit was sent via the Hong Kong office of St Andrews Instrumentation (SAIL) where further training of project staff (Jamie Ng) was carried out by SAIL systems engineer Graham Weatherup (December 8th – 12th 2014).

Units	Description
3	Decimus® passive acoustic detection system complete with 2.4GHZ communications option
3	Micromark 2.4GHZ Collinear antenna complete with pre terminated 6 meter coaxial cables
3	Portable 12v 100watt Solar battery charging system complete with regulator, cables and battery connectors.
3	HTI -90-U-PA-001 hydrophone with 8 meter cable.
1	Microhard 2.4GHZ wireless modem receiver complete with power supply
1	Samsung Series 6 Business Laptop (NP600B5B-S03UK) with PAMGuard software.

Table 1. Components of Decimus® detection system for Tun Sakaran Marine Park.

4. Establishment of Base Station

The Base Station is the central hub where the laptop computer is located. Audio signals from the hydrophones are converted to digital data and this information is then transmitted wirelessly from the Decimus unit to the laptop installed at the Base Station.

Options for the location of the Base Station were reviewed and Sibuan (Figure 12) was selected because it fulfilled the required criteria of having permanent staff, a (normally) reliable 24-hour electical supply and proximity to the outer reefs where the hydrophones need to be placed in order to 'listen' over as wide an area as possible without interference from reefs and/or islands.

Boheydulang is also permanently staffed but its location inside the lagoon (Figure 12) means that it would be too far from the hydrophones (which need to be on the outer reefs) and therefore out of radio range. Mantabuan would be a suitable location for the Base Station with regard to its proximity to fish bombing activities, but it is not always staffed and often does not have any electrical power supply.

5. Determining the location(s) for the detection systems (hydrophones and Decimus units)

The Decimus units have to be located within radio signal range of the Base Station and the attached hydrophones need to be in a position where they have as wide a coverage as possible. If there were no issues with security and deployment in open water, two hydrophone systems deployed as shown in Fgure 13 would cover a large area of sea and reef in and beyond the Park and overlap in such a way as to provide effective localisation. A third unit could be added to provide even more accurate localisation.

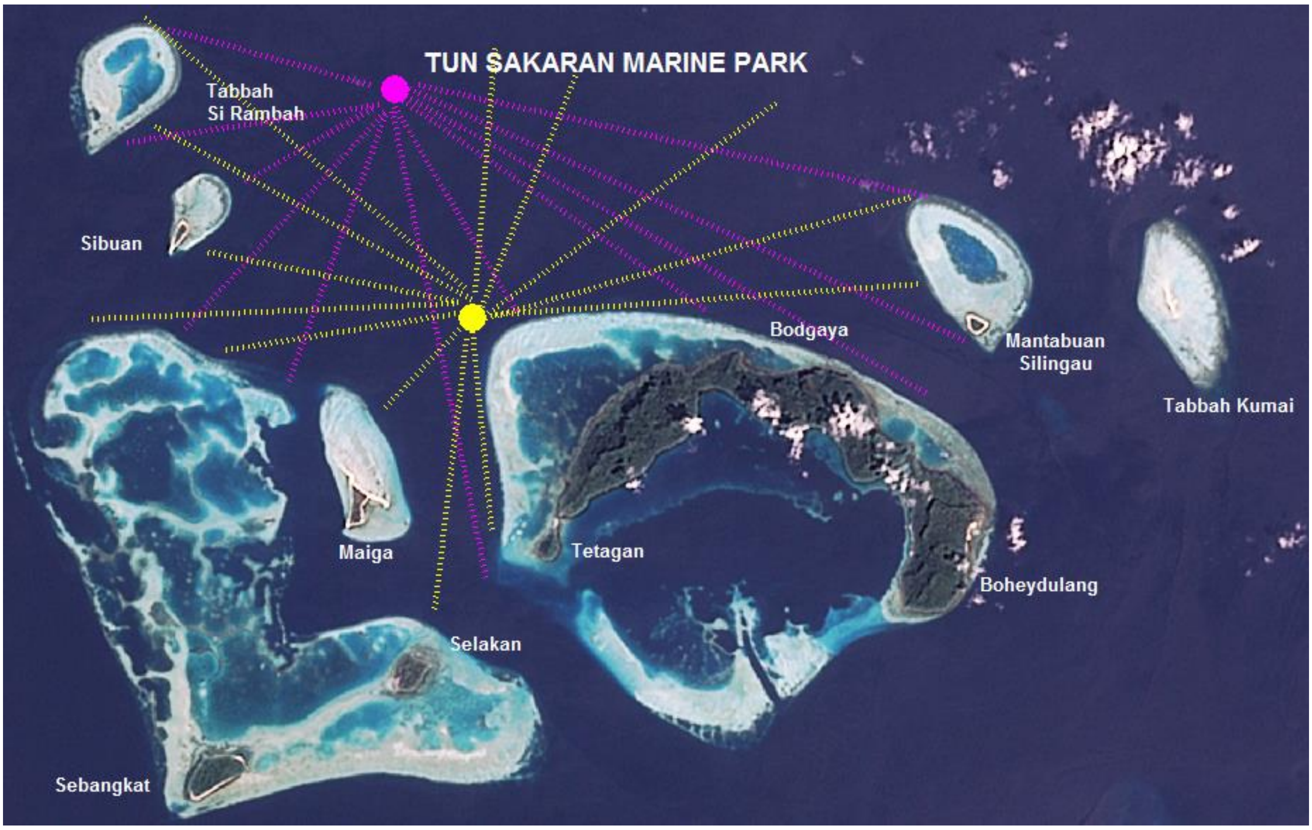


Figure 13. Examples of ideal locations for the Decimus / hydrophone systems.

Unfortunately, theft is a well acknowledged problem in the area. Virtually any item of potential use or value deployed in the sea and left unguarded is likely to be stolen. This includes buoys, ropes, timber, boats and engines. In addition, bomb fishermen would undoubtedly be aware that these were detection systems and might (as illustrated by the forcible removal of two underwater pressure detectors) decide to put them out of action / take them away.

Locations in the open sea are advantageous because the hydrophones can pick up uninterrupted sound waves through 360°. However, sound waves generated by fish bombs will be defracted round obstacles such as islands and reefs and thus a detection unit placed in front of an island/reef will still be able to detect bombs on the other side of the island. The disadvantages are that the amount of diffraction will depend on the wavelength of the noise and the process of diffraction will have an impact on the accuracy of the detection.

The hydrophones needed to be at a depth of around 4m depth in order to be at a stable temperature and avoid distortion of sound waves that can occur close to the water surface. The frame also has to be level (horizontal).

Possible locations for the detection units were identified with reference to bathymetric data and taking into account the factors above. Field trials were then carried out at these locations to determine radio signal strength. This was done by deploying the hydrophones using the boat and pole as described in Section 2.3.

6. Installing the acoustic detection system

Ideally, the hydrophone frame would be clamped to an immovable object on the outer reef such as a jetty. However, as described in Section 2.3 the jetties in and around TSMP are not in suitable locations.

A small platform that would incorporate all the hardware, including the solar panel, was designed early in 2015 and passed to Sabah Parks (SP) for approval (which was given in May 2015). The budget has also been agreed by SP and construction is pending.

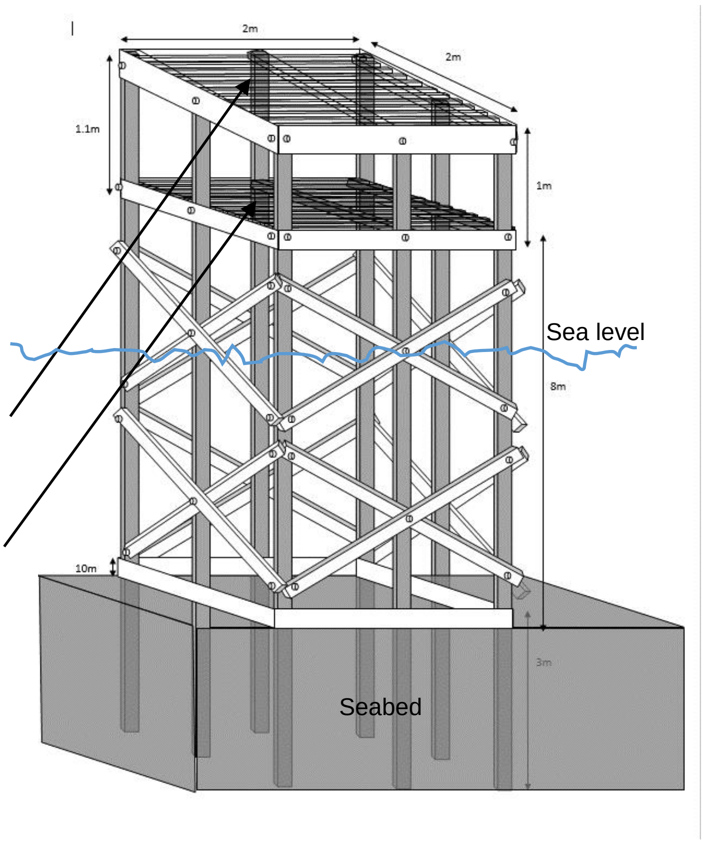


Figure 14. Design for Decimus® platform with 8m superstructure to allow for tidal rise and fall

As an interim measure, we designed and constructed a floating platform to accommodate the Decimus unit, battery and antenna and a sea-bed holding structure for the hydrophone frame.

The floating platform is towed out to the site and attached by rope to large concrete anchors to prevent it being dragged by the wind or by tidal currents. The hydrophones are connected to the Decimus unit on the platform by 8m or 12m-long cables.

Figure 15 (above). Decimus® in protective pelicase.

Figure 16 (above right). Decimus® being installed in the lidded box (right), which also contains the battery and a support for the antenna.

Figure 17 (right). Decimus® on site and the radio being being switched on prior to start of data collection and transmission.

The seabed structure was made from reinforcing bars that were cut, welded and then coated with resin to stop them rusting. The hydrophone frame is attached to the outer structure by bungees which hold it firmly in place and cushion movements so that scraping noises are not generated.

Seabed holding frame

Hydrophone frame

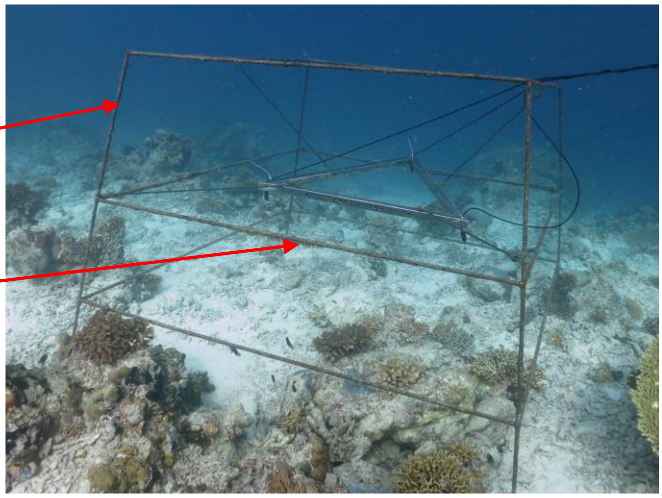


Figure 18. Hydrophone frame installed on seabed.

The geograpical location (lat, long) of each hydrophone frame is recorded using GPS and the bearing of the 'header' hydrophone is also measured during the set-up process. These details are entered into the PAMGuard software and only have to be changed if the position of the device is altered.

7. Monitoring using pressure detection system

As part of the effort to monitor fish bomb activity, we collaborated with a Hong Kong based NGO (Reef Defenders) to obtain baseline data on fish bombing. The fish bomb detectors have been developed by Oceanway Ltd Hong Kong and detect changes in water pressure created by the bomb(s). The batteries that power the units last for over 6 months so they can be left in place for that length of time or retrieved earlier if required.

Figure 19. Bomb detector in place

Six pressure detectors were installed in the Tun Sakaran Marine Park on June 23rd 2015 to gather information about fish blasting activities in this area. All installation sites were revisited on Sept 18th 2015 and the detector mounting bases located, but two of the units were missing. Evidence showed that they had been deliberately targeted. Six new units were installed and the 4 intact units taken for analysis.

The six sites were revisited again on Nov 1st 2015 and on this occasion all the units were found to be intact. These were taken out so that the data could be retrieved. Six new detection units were put in their place.

Results

1. Research and Development: ‘classification’ of fish bomb acoustic signal

A total of 102 hours 01 minutes of recorded audio data was collected from in and around TSMP (Figure 1) during which time a total of 23 bomb sounds were heard. This is equivalent to one every 4.4 hours. The location of the bombs could not be detected from this data set and they could have been either inside or outside the Park boundary. The distance that the sound of a fish bomb travels across open water depends on its size, but experience while diving shows that even small bottle bombs can be heard by the human ear from well over 5km away and possibly as much as 8-10km. The hydrophones are more sensitive and can probably detect bombs from over twice this distance.

Software in the laptop converted and displayed the sound as a spectrogram image that was displayed on the screen (Figure 20) and the bombs could also be heard through the headphones.

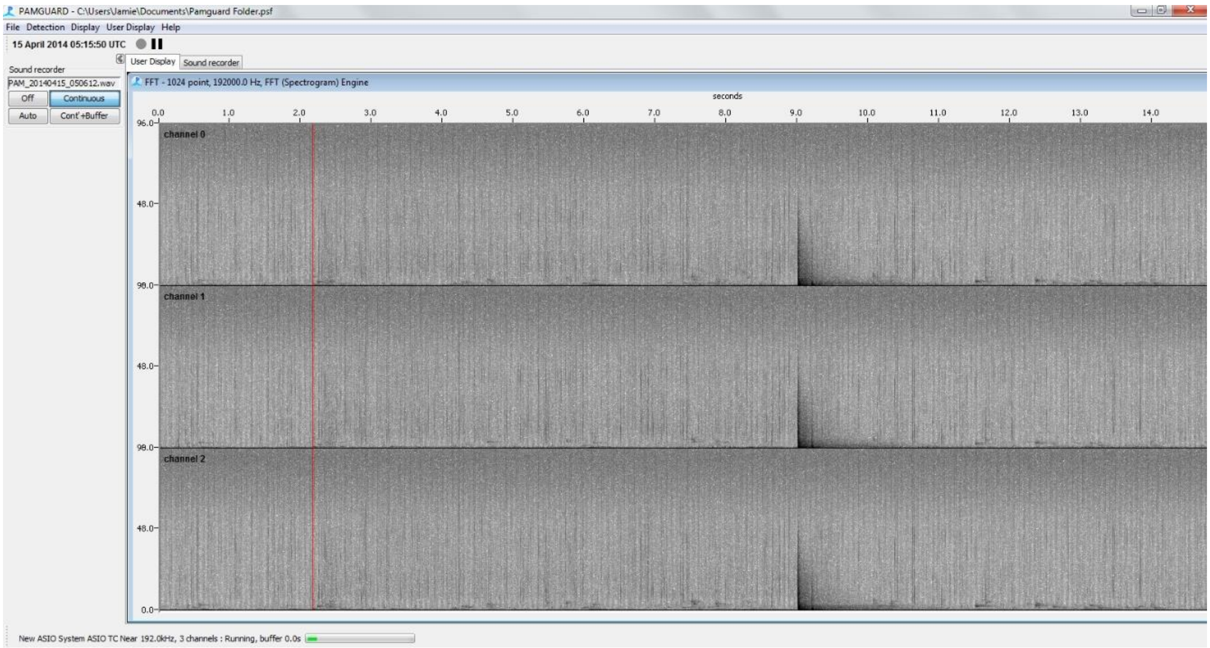


Figure 20. Example of the digitised acoustic data showing the 3 separate hydrophone channels and the visibly high frequency signal of an exploding fish bomb.

The technical team at SAIL worked with this acoustic information and successfully isolated and ‘classified’ the signal generated by fish blasts, separating it from other sounds such as boat engines, divers and noises from the reef itself, such as snapping shrimps. They then built the software and hardware system that would be set in place to detect fish bombs in real time

2. Signal strength tests

The communication link between the Decimus unit and the Base Station is digital rather than analogue and is used to transmit data packets representing noise levels and detections rather than an ‘audio feed’.

One of the first tasks prior to full deployment of the system was to test the strength of the radio signals. Procedures are described in the Methods section. Information on signal strength was accessed from the PAMGuard System Information (radio information) on the laptop (Figure 21).

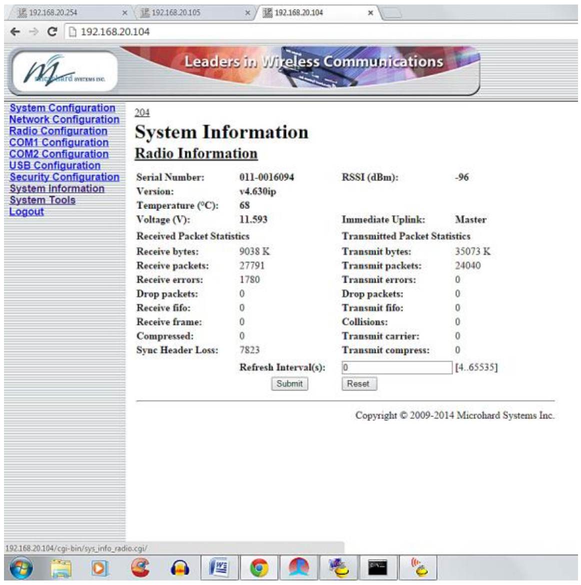
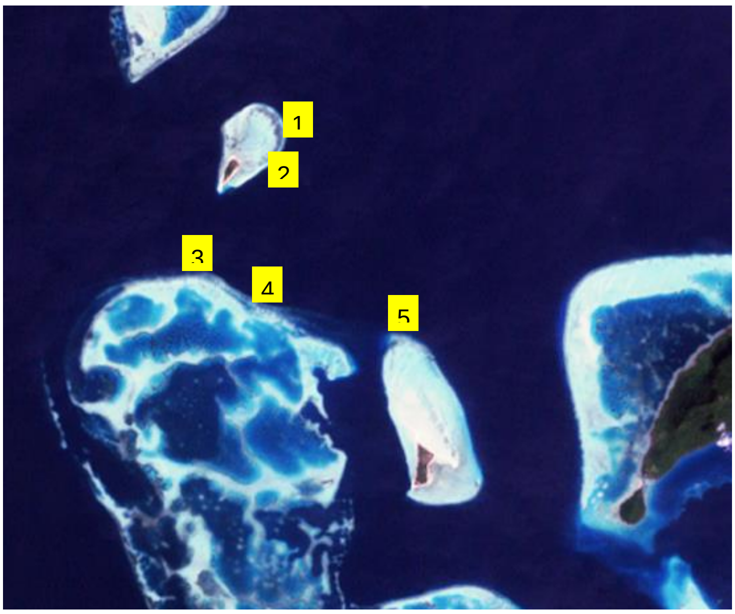


Figure 21. Radio information displayed on screen at the Base Station. Signal information is given in RSSI units (Received signal strength indicator).

The RSSI units indicate the power level recieved by the antenna and in a series of tests at various locations ranged from about -50 to -108. An RSSI of -50 represents a good signal giving a strong reliable communication link between the units. -90 is close to the poorest signal strength that will allow data transfer between the devices and at this level communication will be slow and less reliable. The results of tests carried out at possible locations for the Decimus detection unit is shown in Figure 22. There was reasonable but not complete correlation between signal strength and distance from the Base Station, with Location 2 (600m from the Base Station) showing the strongest signal.



Map ref	RSSI	Km from Base Station
1	-85	1.3
2	-59	0.6
3	-78	1.7
4	-81	2.4
5	-87	4.0

Table 2. Signal strngth (RSSI) at five locations around the Base Station

Figure 22 Test locations for radio signal strength

The signal at some of the possible deployment sites which were only a few kilometres from the Base Station was poorer than expected and the technical team at SAIL therefore carried out a sequence of tests in the UK to investigate why this might be occurring. A number of variables were identified which were shown to negatively influence signal strength. It was tentatively concluded that the poor radio reception observed in Sabah cannot be attributed to a single factor but rather to a range of contributory factors.

The largest contributor to reduced signal strength appeared to be the heating effect of the radios. Temperatures of up to 60^{o}C were recorded in the Decimus Unit, probably caused by heat from the radio building up due to poor conduction from the radio enclosure and lack of air circulation. The tests showed that between the temperatures of 16 – 77^{o}C, RSSI degradation of 15dB (decibels) is observed (SAIL, 2015). Ensuring that the unit is shaded should help to some extent, but so far it has not proved possible to reduce the effect of the heat generated by the radio because of the high ambient temperature (usually 30^{o}C+).

Another contributory factor may be connected with the elevation of the antennae on the Decimus unit and at the Base Station. We were advised to place the antennae as high as possible with a clear line of sight between them. The Base Station antenna was placed on the roof of the Sabah Park's house but the possibility of elevating the Decimus antenna was limited because it was on the boat and became too unstable if raised too high. Tests were carried out with the antenna between about 1m to 3m above the float that housed the Decimus unit and this difference did not affect signal strength.

The type of antenna may also have played a part. Manufacturer datasheets showed approximate equivalence between the 'Marine Mart ' antenna used in Sabah and the 'Shakespeare' antenna used previously by SAIL, but the tests in Scotland revealed a drop-off of several dB in signal strength with the former (SAIL, 2015).

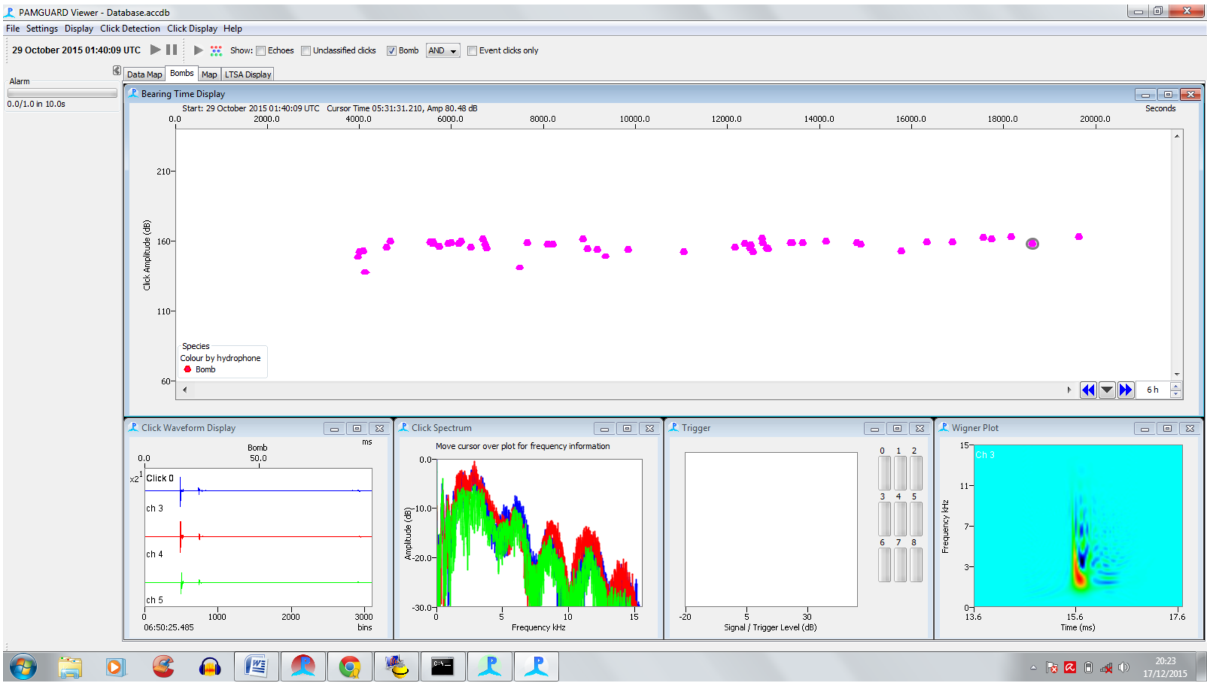
One of the acoustic detection units has been established at Sibuan, close to the Base Station, where the radio signal is always strong. Another unit has been regularly deployed at Sebangkat. Before deploying the other units elsewehere, checks are made to ensure that the radio signal is suffient to transmit data. We have found that the signal from a given location may vary from day-to-day for no obvious reason.

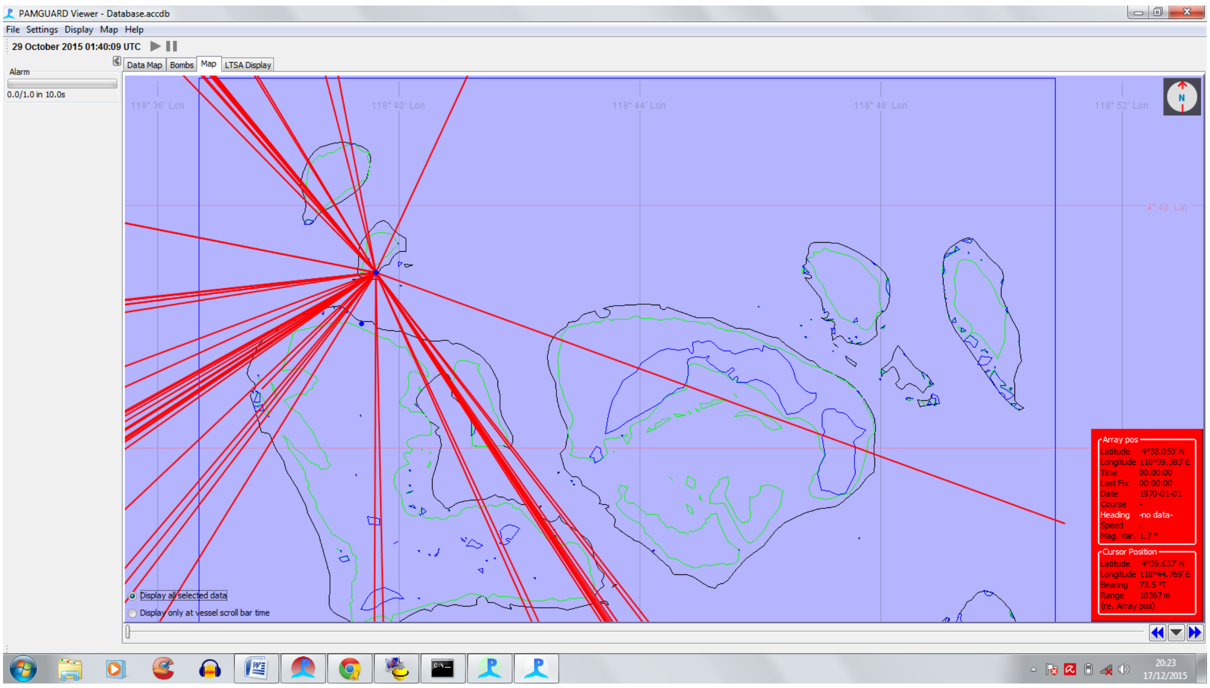
3. Real-time records of fish bombing

Hundreds of fish blasts have been detected during the field trials and the data sets are providing temporal and spatial information about the frequency and location of fish blasting in the area. The data are currently being analysed in order to further refine the software and ensure that the system is accurately distinguishing 'classified' (fish bomb) sounds from 'unclassified' sounds.

Figures on the following pages show examples of the classified data streams shown onscreen through the PAMGuard software.

Figure 23. Example of screen displays from the laptop computer at the Base Station. The pink spots in the top screen represent bomb alerts over time. The red lines shown on the map on the lower screen show the bearing of each of these bomb sounds from the hydrophones.





4. Monitoring using pressure detectors

A total of 1,821 individual blasts within TSMP were recorded on 4 detectors during the 87 day recording period from June 23rd to Sept 18th. These records excluded 'bounces' and duplicates and provided a mean figure of 20.9 blasts per day over the area monitored within the Tun Sakaran Marine Park (Reef Defenders, 2015).

A total of 1911 blasts were recorded within TSMP on 6 detectors during the 46 day recording period from Sept 18th – Nov 1st 2015. This gives a total number of 41.5 blasts per day in areas in TSMP covered by the detectors (note that this was a larger area than in the previous period).

Analysis of the two data sets revealed 10 'hot spots' within TSMP and another 3 outside the park. Bombing is occurring in areas with shallow <15m coral areas as well as in water deeper than 15m (Figure 24). From the data it is clear that at least five groups of blasters may be operating at any one time (Reef Defenders, 2015).

Figure 24. Tun Sakaran Marine Park and surrounding area showing the location of the pressure detectors (TS-1 to TS-6) and the fish bomb hotspots (A-N, with the size providing an indication of the relative amount of fish bombing recorded). Source: Reef Defenders Report, December 2015.

Conservation achievements

This project has launched a programme that is anticipated will lead to the elimination of fish bombing in the 350 km^2 Tun Sakaran Marine Park in Sabah and will therefore prevent further degradation of coral reef habitats and loss of biodiversity.

Research by reef scientists from the Marine Conservation Society (MCS) in collaboration with Sabah Parks has shown clearly that fish bombing is the most serious threat to the health, biodiversity, productivity and aesthetic value of reefs in the Tun Sakaran Marine Park (Wood, 2006, Wood and Dipper, 2008). This is the largest marine park in Malaysia and was gazetted in 2004 on account of its high conservation importance. Reefs in the area are located within the Coral Triangle and recognised locally, regionally and internationally for their high biodiversity and value for tourism, fisheries and the local economy.

Fish bombing not only causes habitat degradation but also impacts on the stony corals that form the basis of the reef ecoststem and are themselves widely threatened. Over 30% of reef corals worldwide are listed in categories with elevated risk of extinction in the IUCN Red List of Threatened Species. The proportion of corals threatened with extinction has increased dramatically in recent decades and exceeds most terrestrial groups (Carpenter *et al*., 2008).

When a bomb explodes close to the reef it stuns or kills fish within a radius of about 10-15m, indiscriminately kills other marine life and causes significant physical damage over an area around 5m in diameter. Even massive corals are broken and reduced to rubble and they may also bleach and die from the shock of the explosion (Figure 25).

Figure 25. Recently bombed, broken reef

Figure 25. Healthy reef

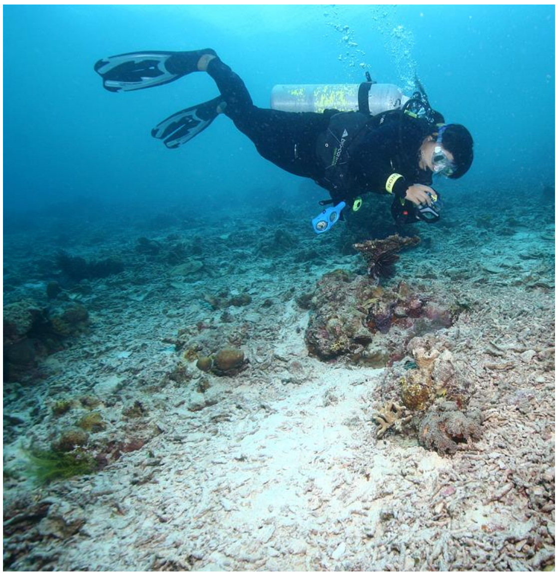


Figure 26. Fish-bombed reef

Whilst the impact of a single bomb might be considered relatively small, the cumulative effect of fish blasts is huge. The fish bomb detection systems established during this project show a minimum average of 40 blasts per day throughout the Park. This could add up to around 14,000 bombs per year if they are used amost every day. Bombs are used along the reef rim/upper slope and if each bomb causes damage or destruction over 5m then a total length of about 70,000 metres (75km) of this habitat could be damaged in just a year. The Tun Sakaran Marine Park has about 100 km of fringing reef, so, if the bombs were evenly spread it would take less than 2 years for the entire system to be affected.

Studies from Sabah and elsewhere in South-East Asia have shown that in addition to the immediate impacts, recovery from fish blasting is notoriously slow and many of the damaged reefs may never fully regain their diversity and habitat complexity (Wood & Dipper 2008, Fox *et al*, 2003). A critical issue is that it is difficult for corals to colonise broken-up and unstable surfaces created by fish bombs.

Fish bombing also takes place in open water some way above the seabed. Whilst this may not result in habitat damage in the same way as bombng on reefs does, it can readily lead to resource over-exploitation because the power of the explosion has the capacity to wipe out large shoals of fish in an instant, including young fish that have not yet had a chance to breed.

Our project has taken a major step in bringing a halt to fish bombing in and around the Marine Park by setting underwater detection systems in place. For the first time, accurate baseline data has been collected and a monitoring programme established. Hot spots where fish bombers are operating have been identified and patrols are being stepped up. The real time acoustic system has just gone live which means that Sabah Parks will be able to detect bombing activity as it occurs and take appropriate action.

A measurable indicator of conservation success will be the reduction in number of bombs being detonated in TSMP, as determined through the monitoring system now in place. This will be a major achievement. Complete success will have been achieved when incidents of fish bombing are reduced to zero. Considering that fish bombing is well entrenched and has been going on in the area for well over 60 years, it is anticipated that it will be a few years before it has been completely eradicated.

Discussion

Over 60% of the world's coral reefs are under immediate and direct threat with those in SE Asia at particularly high risk ((Burke *et al*., 2002). Biodiversity loss has occurred at an alarming rate over past decades mainly as a result of destructive fishing and over-exploitation of marine resources. Pollution, global climate change and predator plagues are additional threats.

Reefs in the Semporna area where this project was carried out are within the Coral Triangle and recognised internationally for their high biodiversity and value for tourism, fisheries and the local economy. Fish bombing is the most serious threat to the health of coral reefs in this area and has been practiced for decades with impunity. Apart from biological impacts on reef habitats and biodiversity, fish bombing has serious and significant economic consequences. For example, a study in Indonesia showed a net loss of up to US$306,800 per km^2 of coral reef after 20 years of fish blasting (Pet-Soede *et al*, 1999).

Many local fishermen condemn the use of explosives to catch fish, but others are attracted to this method because it is quick, relatively simple and yields a large ‘catch’ in a short time. A single bottle bomb that stuns or kills fish over an area 10-20m^2 yields up to 45kg of fish (Kissol, 2012) whereas the average catch/hour using hook and line (2 units per operation) yields up to 1.88 kg (average 0.5kg) (Wood *et al*., 2004). The ‘efficiency’ of fishing with explosives has contributed to the decline in marine resources and this in turn can lead to even more bombing as it is the most effective method of last resort to target dwindling stocks.

Fish bombing is illegal but over the many decades that it has been going on in Sabah only a very small number of arrests are made each year. In most instances fish bombers avoid being caught and so destruction of the reefs continues. The main reason why fish bombing goes undetected is that the fishermen operate in places where they will not be seen or heard by the authorities. A patrol boat would need to be very close by to see the water spout or hear the sound of the explosion above water and the fishermen keep careful watch to ensure they are not being observed.

Sound travels far and fast underwater and through the project we have successfully developed and deployed an acoustic device that recognises the distinctive sound of fish bombs and sends information in real-time to a central Base Station within the Park. The system consists of an array of three hydrophones which detect both the sound and the direction (bearing) from which it is coming. Deployment of second and third units allows triangulation so that the precise location of the explosion can be determined. An audible alert is made each time a ‘classified’ bomb sound is detected and the real time data and map are displayed on screen at the Base Station.

In addition to the real-time alerts, we have also worked with Reef Defenders to establish a robust method of monitoring the entire sea area within the Park and around its boundaries. The pressure detectors developed by Oceanway are finely tuned and provide temporal and spatial data on fish bombs. With both these systems in operation, the extent of fish bombing is much better understood, trends are being documented and Sabah Parks can locate and apprehend fish bombers.

One issue with deploying remote sensing units at sea in the Semporna area is that they are vulnerable to being stolen or damaged, possibly because the fishermen resent being ‘watched’. Following the theft of two of the the six pressure detectors during the Phase 1 deployment, they were then hidden more carefully and they have remained safe. The acoustic dtection units cannot be concealed in the same way because there is hardware on the surface. Since monitoring data has shown that fish bombing occurs during daylight hours in and around the Park (possibly due to a local curfew which has been in place since 2014), the units have been deployed during daylight hours and taken ashore before dark.

This programme has succeeded in its aims of developing, deploying and training Sabah Parks staff in the use of the fish bomb detection system but is not the only strategy that will be used to bring fish bombing to an end. The drivers of fish bombing are to be fully explored and complex social, cultural and economic issues addressed. Engagement with communities who are involved in this practice will be stepped up and further efforts made to emphasise the long-term negative impacts of bomb fishing on people's livelihoods and food security. Environmental courses combined with introductory training for work in the tourism sector are being planned for communities living in the Park. Local people have considerable knowledge of the area and their many skills need to be recognised and encouraged. Currently, local communities are side-lined while 'outsiders' benefit and this is likely to result in them being less motivated to help protect the area, use its resources wisely and refrain from activities such as destructive fishing.

Various socio-economic issues also need to be addressed in parallel with the enforcement initiative and there needs to be more awareness of the wide benefits of bringing an end to destructive fishing. As part of the legacy of this current project an outreach and engagement programme has been planned, together with training opportunities for local youth to get engaged in the growing local tourism industry.

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