DETECTION OF SHARKS WITH THE GEMINI IMAGING SONAR

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Limiting environmental impacts of marine industrial operations and mitigating hazardous encounters between humans and marine fauna have become increasingly important as anthropogenic activity expands. To this end, significant effort has been made to develop sonar imaging of fauna and to increase detection and identification ranges. A Tritech Gemini imaging sonar was used to observe sharks of 1.4 to 2.7 m length, at ranges from 1 to 50 m, in various water depths ≤15 m. Within 5 m, shark shape, length and swimming action were readily discernible. However, as range increased, knowledge of movement patterns was required to discriminate a 'shark-like' object, before the shark became purely an acoustic target at greater ranges, where visual confirmation of the target was necessary for identification. Once the seafloor is ensonified by the acoustic beam, seafloor backscatter can dominate the image and mask shark detection. The results presented concur with other active acoustic detection studies that, for a given frequency and noise level, maximum detection and identification ranges are reliant on system source level, beam pattern, bathymetry, and target size and acoustic reflectivity.

INTRODUCTION

During typical fisheries or marine mammal surveys, traditional multi-beam sonar systems have been increasingly used for detecting, visualising and quantifying marine fauna in the waters below or to the side of a vessel [1-4]. In addition, anthropogenic marine activity over the past few decades has promoted the need for detection and identification of fauna within potentially hazardous areas, sometimes 24 hours a day. Partly as a result, multi-beam sonar systems are being modified and developed, producing forward-looking imaging sonars.

Studies on acoustic backscatter from teleosts (bony fishes) are abundant [e.g. 5-10], but when it comes to marine megafauna, while a significant amount of work has been conducted on marine mammals [11-14], there are few reports regarding the reflectance or acoustic imaging of elasmobranchs (sharks and rays). In 1970, Harden Jones [15] detected basking sharks (*Cetorhinus maximus*) at ranges of up to 180 m on a sector scanning sonar and Lieber et al. [16] furthered this work off Scotland, to begin looking at *C. maximus* ecology, using a Reson 7128 multi-beam sonar. However, these studies were conducted in deep waters, observing sharks of several metres in length. By contrast, in shallow waters, high-frequency acoustic cameras have been used in aquaria to image sharks and rays at ranges of less than 5 m [17, 18].

This study aimed to use a Tritech Gemini sonar, a low-power imaging sonar system, to investigate the detection and identification of sharks in shallow (<15 m) waters, similar to those of the beaches around the WA coastline, to gain a better understanding of the ranges at which a shark may be imaged with this system.

METHODS

The Gemini 720i 300M (Tritech, UK) system operates at 720 kHz, with 120° horizontal and 20° vertical beamwidths, and an elevation of -10°. Across the horizontal 120° the system comprises 256 dynamically focussed beams with effective azimuth-angular beam resolution of 0.5°. Along beam resolution is range setting dependent, but can be as high as 8 mm. In various depths ≤15 m, a pole-mounted Gemini was positioned 0.5-1.0 m below the water surface (Figure 1).

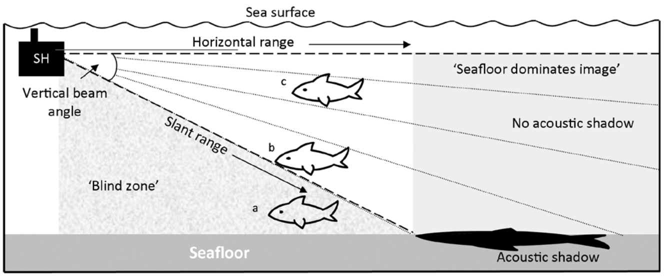


Figure 1. Schematic of Gemini imaging sonar beam and examples of sharks at similar range from the sonar head, but at varying depths that create different acoustic images, including a) outside the acoustic beam and in the 'blind zone', b) towards the lower region of the acoustic beam producing a weaker image of the shark, but a strong acoustic shadow and c) high enough in the water column to produce a strong image of the shark from backscatter in which case any shadow would be outside the designated range of the sonar. Horizontal and slant range are indicated and the "Blind zone" and region where "Seafloor dominates the image" are shown by the mottled and grey regions, respectively.

Theoretically, a target's range and position in the water column have considerable impact as to whether it is located within the sonar beam (Figure 1, conditions a, b and c). With decreasing horizontal range, it is increasingly likely that the target will be below the acoustic beam and therefore not ensonified or detected (Figure 1, condition a). Once within the beam the target will reflect acoustic backscatter to the receiver and targets at shorter slant range than the seafloor provide the highest signal-to-noise ratio (SNR). If the target is within the acoustic beam and at shorter slant range than the first contact of the acoustic beam with the seafloor, one expects not only some reflected backscatter, but also an acoustic shadow of the target (Figure 1, condition b). Those high in the acoustic beam create an acoustic shadow that is outside the range-setting of the sonar (Figure 1, condition c). As the return from the seafloor is high, in comparison with that of a mid-water target, once part of the acoustic beam insonifies the seafloor, the sonar image is dominated by backscatter from the seafloor, and any target at the same slant range will be difficult to discern from the reverberation. Therefore, the optimum system performance is when the target's range is less than that of the seafloor. Some systems are able to mitigate these issues in real-time or post-processing, by removing accumulated backscatter over a designated time to account for stationary objects. These "movement filters" are designed to remove background noise and highlight moving targets. However, the resulting images often lose resolution in the moving target and the process is non-trivial if either the system is moving (even minor movements relating to wave patterns or surge) or there is significant noise e.g. cavitation from waves, vessels or animal movement. In this study this removal of background noise was not used as the sonar head was not completely stationary.

The Gemini was deployed at the following locations around Australia:

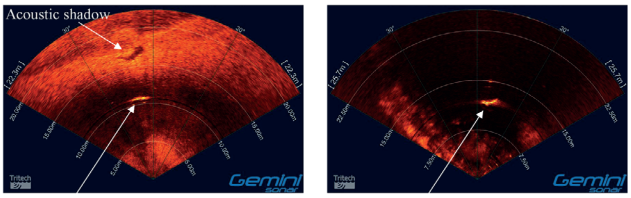
- In waters off the Gold Coast, Queensland, carcasses of a recently captured 1.8 m bull shark (*Carcharhinus leucas*) and a 2.7 m great white shark (*Carcharodon carcharias*) were suspended at a depth of 3 m from plastic floats (one at the head and one at the tail), using detergent-covered monofilament fishing line. To remove air from body cavities and denticles that would have previously been filled by water or mucus before the shark was removed from the water, each shark was flushed with a deck hose, lowered, tail first into the water and bubbles allowed to escape. It was then brushed down and briefly dragged through the water. The sharks then drifted in the water column at two locations (7.5 and 15 m water depth) while being imaged using the Gemini system at ranges between 5 and 50 m. Imaging of the floats alone was also conducted at ranges of up to 25 m to ensure that these did not contribute to the sonar images of the shark carcasses. The seafloor in this area comprised a coastal sand substrate (based on visual classification).
- In Ocean Park Aquarium, Shark Bay, Western Australia, in a 3.5 m deep, 30 m diameter pond, images of 2.4, 2.0 and 1.7 m lemon sharks (*Negaprion brevirostris*), a 1.2 m nervous shark (*Carcharhinus cautus*) and a 1.5 m sandbar shark (*Carcharhinus plumbeus*) were collected as they swam past a near-stationary sonar system. The bottom of the pond comprised a concrete base, covered by a thin layer of fine sand.
- In the Eastern Gulf of Shark Bay, around channels that are approximately 7 m deep, the Shark Bay Ecosystem Research Project (SBERP) has run a shark tagging program for over 15 years. The Gemini system was pole-mounted on the starboard side of the Department of Parks and Wildlife *RV Sirenia II* and directed athwartships towards the SBERP vessel as a tagged shark was released from its port side. This occurred at a range of approximately 25 m.

In each case, system settings of range and gain were varied where possible, in an attempt to visually attain the optimum SNR for the intended targets. The Gemini system does not record the raw signal, but as a series of individual images, which can be reviewed as moving images, therefore analysis of the SNR for each situation was only through visual assessment of the colourbar.

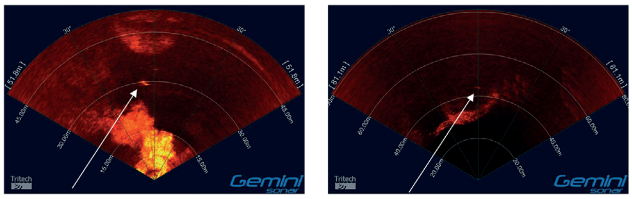
All experiments were performed according to the Australian Code of Practice for the care and use of animals for scientific purposes.

RESULTS

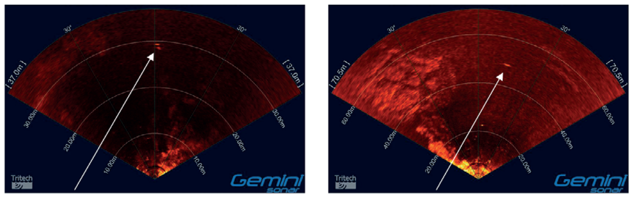
All three locations provided images on the Gemini sonar and interesting information on the detection of sharks. In each case, an acoustic target could be detected at horizontal ranges up to the point where the acoustic beam encountered the seafloor (Figure 1). Therefore, the maximum detection range, in these tests, was a function of the beam pattern and water depth, rather than the system source level or acoustic reflectance of the shark. Unfortunately, given the logistical and time constraints, the maximum depth in which the study could be conducted was 7 and 15 m for live and deceased sharks, respectively, thus the maximum depth-independent detection range could not be tested. However, the study areas did reflect conditions of a significant number of shark encounters along the coast of Western Australia.



2.7 m Great White at 11m in 7.5 m of water 2.7 m Great White at 11 m in 15 m of water



2.7 m Great White at 30 m in 15 m of water 2.7 m Great White at 45 m in 15 m of water



1.8 m Bull shark at 29 m in 15 m of water 1.8 m Bull shark at 50m in 15 m of water

Figure 2. Screen shots from the Tritech Gemini imaging sonar system of a 1.8 m bull shark (*Carcharhinus leucas*) carcass and a 2.7 m great white shark (*Carcharodon carcharias*) carcass at various ranges, suspended at 3 m depth, in 7.5 and 15 m of water. Various gain settings were used to produce these images and the brighter responses represent a strong acoustic return.

The shark carcasses provided immobile targets of known location and therefore a more stable platform with which surveys could be conducted for a matter of minutes, rather than seconds. Both bull and great white carcasses were tested to a range of 50 m (Figure 2 bottom right images) and in both cases targets were discernible, though realistically only as a 'large blob'. In both water depths, even at ranges of 10-15 m (the closest range at which the Gemini was tested) the sharks were not always discernible as a shark-like object, but an acoustic target of length similar to that of the shark (Figure 2, top row). This was unlikely due to the orientation of the shark as each shark was imaged from all sides. The top left image in Figure 2 illustrates how the seafloor backscatter dominates the image, as well as the acoustic shadow of the shark against the seafloor.

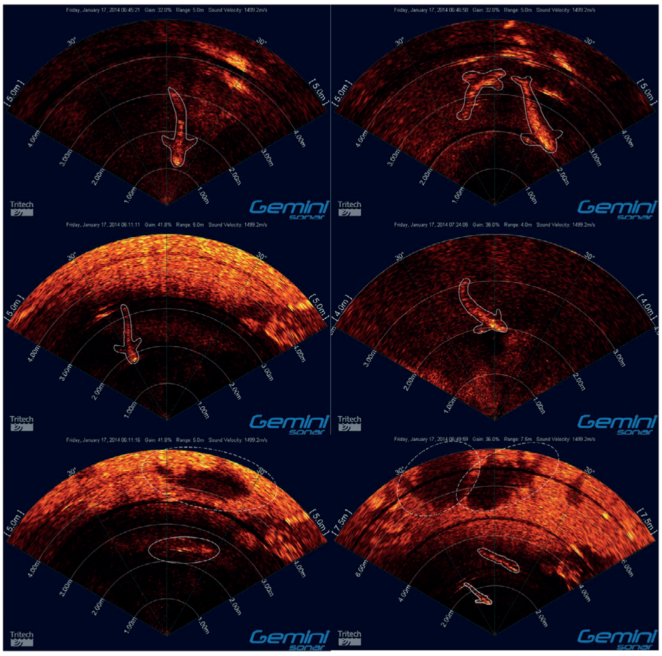


Figure 3. Screen shots from the Tritech Gemini imaging sonar system of a 1.7 and a 2.2 m lemon shark (*Negaprion brevirostris*) in 3.5 m depth at Ocean Park Aquarium, Shark Bay. Outlines of the backscatter from the sharks are shown by the continuous lines, and outlines of the acoustic shadows by the dashed lines.

The Ocean Park images (Figure 3) illustrated that at ranges <5 m it is possible to discern the shape of the shark. Once again, this was limited by the depth of the lagoon, thus in deeper water it may be possible to produce shark-like images at ranges in excess of 10 m. The swimming actions of the sharks, compared with those of fish, were clearly apparent through time and illustrated that at close range, the entire body of the shark could be imaged under certain conditions. Sharp turns and sudden movements of the sharks resulted in loss of image, but also often generated acoustically visible cavitation and vortices.

The release of a shark in the Eastern Gulf of Shark Bay highlighted that in approximately 7 m of water the live sharks could be discerned to at least 25 m (Figure 4). Though only observed briefly, no swimming pattern could be seen and, similar to the carcass, the shark was merely an elongated acoustic target of >2 m length. In the case of the shark in Figure 4, an accompanying cobia (*Rachycentron canadum*) happened to be alongside the shark at the time of release. The difference between the elasmobranch and the swim-bladdered fish (cobia) was visible, though not at all times, in that the length of the shark target was mostly greater than that of the cobia. This release also highlighted the issue of the position in the water column as the shark (and its accompanying cobia) only remained in the beam for a few seconds before diving. Both animals presumably dived to the seafloor and into the "blind zone", beneath the acoustic beam, which would occur at ranges less than approximately 19 m.

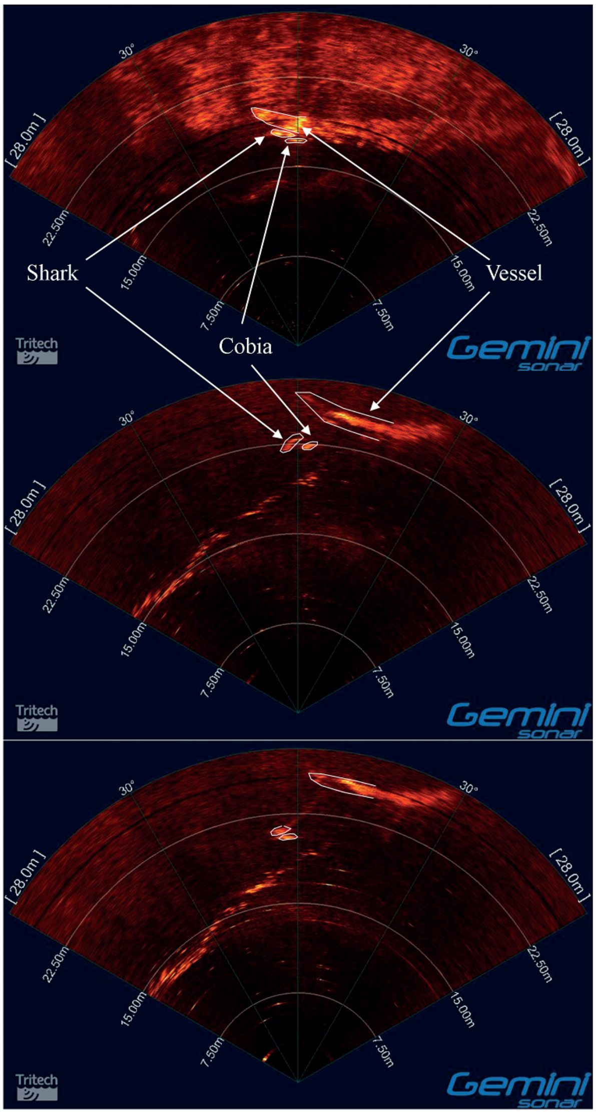


Figure 4. Screen shots from the Tritech Gemini imaging sonar system of a 2.2 m tiger shark (*Galeocerdo cuvier*) and its accompanying cobia (*Rachycentron canadum*) as the shark was released from a vessel at a range of 25 m.

DISCUSSION

This study has provided some estimates of likely ranges at which a shark could be detected with a 'low-power', wide-beam imaging sonar, such as the Gemini trialled in this study, under conditions similar to those of the WA coastline. Lieber et al. [16] used a Reson 7128 imaging sonar to detect 5-10 m length basking sharks (*Cetorhinus maximus*) at ranges of over 100 m and produced images where pectoral fins and the thunniform swimming action were visible in excess of 30 m from the transducer. These ranges are significantly longer than those observed here. However, there are significant differences between the two studies that are important to the development of a system for detecting sharks along WA beaches. Contributors to the differences in images with this study were, not only the size of the sharks (5-10 m, compared with the 1.8 m bull shark and 2.7 m great white in this study), but also the power of the system (220 dB for the Reson, compared with 160 dB for the Gemini used here), and importantly the water depth (>20 m compared with around 10 m in this study) and the resolution of the two sonar systems. In addition, the lagoon at Ocean Park comprises a rigid bottom that reflects significant backscatter and therefore noise on the sonar image. By contrast with performance, the advantage of the Gemini system in the possible detection of sharks off the coast is that it is a “low-power” system that can achieve the same results operating from 12 V battery power and thus could easily be deployed remotely.

This study has also conceptually highlighted several of the issues associated with sonar detection and identification of sharks in shallow water, not least of which is the need for an appropriate beam pattern. If positioned near the sea surface or seafloor the 20° vertical beamwidth of the Gemini system (with its offest of -10°) ensonifies the seafloor (or sea surface, respectively) at ranges of around three times the depth of water below the sonar head. At these ranges, discrimination of mid-water targets becomes problematic, particularly if the sonar head is mobile, as seafloor backscatter changes and persistent contributions to the image cannot be easily removed. To increase the detection range significantly would require a reduction in vertical beamwidth to increase the range at which the seafloor is ensonified. In contrast, too small a vertical beamwidth would only ensonify a small portion of the water column at close ranges (for example, a 1° beam ensonifies approximately 1 m of water column at a horizontal range of 50 m). Thus a compromise is required to detect targets at ranges more suitable for mitigating encounters between sharks and humans or excluding them from a hazardous area. Alternatively a vertical array of narrow beam systems would increase vertical coverage, though at ranges where these beams (or sidelobes) converge, issues of interference would increase. However, a vertical array in shallow waters (<15 m) may not provide suitable benefits at ranges of greater than 75 m due to the limited separation available.

The following is therefore suggested for testing as one possible, easy-to-deploy and integrate method of detecting sharks in shallow water. The sonar system would be positioned near to the seafloor, with enough altitude to prevent the bottom edge of the acoustic beam from contacting the seafloor. The sonar system would be dual frequency with different acoustic beam patterns for each frequency, designed to cover the short range and long range separately. The beamwidth either side of the sonar for both beam patterns would be as wide as possible (120-150°). The short range (e.g. 5-30 m, depending on water depth) would be covered by a high frequency beam, >700 kHz, with a larger vertical beamwidth (10-15°) that provides high resolution imagery over ranges of up to approximately three times the water depth and quickly includes a large percentage of the water column (Figure 5). To detect targets in the long range would require a lower frequency (400 kHz) beam of finer vertical beamwidth (3-5°) to ensure that neither seafloor or water surface are ensonified until at ranges of >10 times the water depth. The sonar would be set such that these two beams ping alternately each at 1 Hz ping rate. Thus any targets in the short range and the long range are being ensonified once each second. However, these beam patterns would leave a volume of water that is not ensonified by the long-range beam, and saturated by reverberation in the short-range beam (Figure 5), thus an ideal set requires investigation. A vertical array of sonars could limit such inadequately sampled volumes of water, but this cost at the cost of greater power requirements to operate them. Additionally, as the bathymetry of beaches can vary significantly it may be necessary to fine-tune these beam patterns to maximise detection ranges for a particular beach. Therefore a system would be required where beam patterns of the system can be scripted by the user. This process of beam steering is becoming more common in the use of multi-beam systems, though to the authors knowledge few systems exist with multiple frequency beams of differing beamwidth and with beam patterns and steering suitable to this application.

Lucifredi and Stein [19] designed a monostatic seafloor mounted system with an electronically steered vertical line array and 60 element receiver array to track gray whales (*Eschrichtius robustus*) in 70-100 m of water, off the California coast. This was a well-designed research tool, capable of vertical steering of a 6° vertical beam, providing good long-range detection with considerable contributions to automated detection. As very strong scatterers, gray whales, or pods of gray whales could be detected in excess 400 m, in these depths, however, interactions with surface, bottom and kelp were still present.

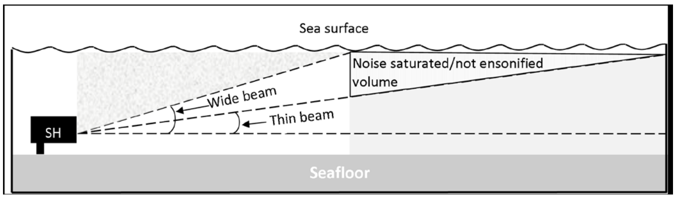


Figure 5. Schematic of the effective volumes of water ensonified by using two beam patterns of differing vertical beamwidth. The acoustic blind zone where no water is ensonified by either beam is shown to the left of the figure in mottled grey, while the volume of water only ensonified by the wider beam and at ranges where the response is likely to be dominated by the backscatter from the sea surface is shown in the hatched grey area to the right of the figure. Thus the area in white illustrates the volume of water where targets would be detected by both beams and the area in grey on the right hand side of the figure illustrates the volume of water in which targets are only likely to be detect by the thinner acoustic beam.

The study has also found that at large ranges, where the target is only covered by a few of the acoustic beams, while a shark may not be imaged, it can sometimes be discriminated from smaller targets, such as individual fish. Similar to teleosts, the reflectance by sharks is very stochastic, however, even at range when swimming motion is not discernible, and the shark appears simply as an acoustic target, the swimming may produce regular oscillations in target strength. The real-time monitoring of sharks at the Ocean Park Aquarium implied that this could be possible, but requires further testing for ranges useful to shark detection. One of the next steps in assessing the possible performance of sonar systems in detecting, identifying and tracking sharks involves identifying frequency and length dependent target strength (and its variation) and to verify computer models of the effect of varying vertical beamwidth.

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