

# Foraging on squid: the sperm whale mid-range sonar

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The sonar capabilities of the sperm whale, *Physeter macrocephalus*, have been the subject of speculation for a long time. While the usual clicks of this species are considered to support mid-range echolocation, no physical characteristics of the signal have clearly confirmed this assumption nor have they explained how sperm whales forage on squid. The recent data on sperm whale on-axis recordings have allowed us to simulate the propagation of a 15 kHz pulse as well as its received echoes from different targets, taking into account the reflections from the bottom and the sea surface. The analysis was performed in a controlled environment where the oceanographic parameters and the acoustic background could be modified. We also conducted experimental measurements of cephalopod target strength (TS) (*Loligo vulgaris* and *Sepia officinalis*) to further investigate and confirm the TS predictions from the geometric scattering equations. Based on the results of the computer simulations and the TS experimental measurements (TS squid =  $-36.3 \pm 2.5$  dB), we were able to determine the minimum requirements for sperm whale sonar, i.e. range and directional hearing, to locate a single 24.5 cm long squid, considered to be (from stomach contents) the major size component of the sperm whale diet. Here, we present the development of the analysis which confirms that sperm whale usual clicks are appropriate to serve a mid-range sonar function, allowing this species to forage on individual organisms with low sound-reflectivity at ranges of several hundreds of metres.

## INTRODUCTION

Sperm whales (*Physeter macrocephalus*) are known to spend most of their time foraging and feeding on squid at depths of several hundreds of metres where the light is scarce. It has been observed from the analysis of stomach contents that an individual adult sperm whale ingests around 1 tn of cephalopods per day. While foraging, sperm whales mostly produce a series of acoustic signals called usual clicks. The coincidence of the continuous production of usual clicks together with the associated feeding behaviour has led authors to suppose that those specific signals could be involved in the process of detecting prey. The sperm whale sonar capabilities have long been a target of speculation due to the difference between their known acoustic signal features (e.g. source level, bandwidth and directivity index) and most of the described echolocation signals of other species. Contrary to click combinations such as slow and rapid clicks or codas which are generally reported to support communication purposes (Watkins & Schevill, 1977; Weilgart & Whitehead, 1993), creaks, consisting of series of repeated clicks with very small inter-click intervals (ICI), are believed to be produced when the whale is approaching the prey at close range, prior to the ingestion. While the usual clicks of this species were considered to support mid-range echolocation, no physical characteristics of the signal had, until very recently, either clearly confirmed this assumption or explained how sperm whales forage on low sound reflective bodies like squid. The recent data on sperm whale on-axis recordings have shed some light on these questions and allowed us to perform

simulations in controlled environments to verify the possible mid-range sonar function of usual clicks during foraging processes.

The sperm whale diet, in most areas of the world, consists of cephalopods (Table 1). Amongst them, sperm whales eat primarily squid and occasionally octopus. However, there are some areas where fish can form an important part of their diet. Generally speaking, the family Histioteuthidae represents the mainstay of the sperm whale diet if measured by the number of individuals captured, although if measured by weight other species of squid appear to be also relevant (Clarke, 1980). The size of these prey varies from a few centimetres to several metres long, depending on the animal age-related diving capacity, although most of their diet consists of animals whose lengths are less than one metre.

**Table 1.** Cephalopods in the sperm whale diet.

Family	Mean percentage (by mass)	Median body mass (kg)	Mean percentage (composition for body mass)
Architeuthidae	5.1	24	0.2
Ommastrephidae	19.7	8	2.0
Octopoteuthidae	16.8	1	13.4
Histioteuthidae	23.6	0.8	23.6
Ancistrocheiridae	7.5	0.7	8.6
Onychoteuthidae	16.8	0.5	26.9
Cranchiidae	3.9	0.2	15.6

We have little information on whether squid live in groups or not, although some inference can be made from the stomach content of sperm whales: squid could appear to be solitary or living in groups of fewer than five individuals. On larger scales, however, squid do aggregate, for example for spawning. It has been stated (Whitehead, 2003) that this amounts to an increase of the squid density over areas on the order of square kilometres and it is likely that sperm whales have developed capabilities to find these aggregations of maximum-sized, incapacitated and dying squid. Squid known to present luminous organs comprised between 41 and 97% of the sperm whale diet in several locations, while in others only a few species known to be ingested by sperm whales present these characteristics. It is therefore possible that the sperm whale could use luminescence or sonoluminescence to find their prey but as a complement to other forms of prey localization. Further evidence for this is that there are records of healthy, but totally blind, sperm whales.

On-axis sperm whale clicks are broadband (ranging from 0.2 to 30 kHz), highly directional (DI=26 dB), last for a few ms and present a source level of 230 dB<sub>peak</sub> re 1µPa (Zimmer et al., 2005). Clicks recorded off the axis of the beam pattern present a much lower directivity index and are several orders of magnitude weaker than the main on-axis pulse. The on-axis clicks have an average centroid frequency of 15 kHz. Möhl et al. (2003) and more recently Zimmer et al. (2005) have constructed the beam pattern of the components of a sperm whale click, P0, P1, P2 and so on, as well as a low frequency (LF) component, each of them having its own characteristics although generated by the same acoustic event. While P1 would serve an echolocation function, the LF and P0 components would be used for dive synchronization between members as well as long-range orientation (Zimmer et al., 2005).

Due to its high directionality, the forward-directed P1 pulse seems well-suited for echolocation. The high source level of the P1 pulse and the long ICI of usual clicks suggest a potential for long detection ranges. Now, the question is: what is the scattering mechanism occurring off a squid when insonified by an on-axis sperm whale click and what would the ranges be at which prey targets are detected?

To answer this question we conducted a theoretical and experimental approach aiming at determining the squid target strength and the propagation of both the incident and reflected sperm whale acoustic signal under different environmental conditions.

## MATERIALS AND METHODS

### *Scattering and target strength*

The type of scattering that occurs off a reflective object is governed by the ratio of a representative length of the object and the wavelength. This is quantified by the product  $ka$ , where  $k$  is called the wave number ( $2\pi$  divided by the wavelength) and  $a$  represents the length of the object. Assuming the sound speed in the water is around 1500 m s<sup>-1</sup>  $ka$  can be expressed by:  $4 \times f[\text{kHz}] \times a[\text{m}]$ .

If  $ka \gg 1$ , a geometric scattering applies where the frequency dependence of the target is weak: in that case the target strength of fish, squid and crab can be approximated

**Table 2.** Values of  $ka$  at some frequencies and target dimensions relevant to sperm whale echolocation.

	L=0.05 m	L=0.2 m	L=0.5 m	L=2 m
f=0.2 kHz	$ka=0.04$	$ka=0.16$	$ka=0.4$	$ka=1.6$
f=5 kHz	$ka=1$	$ka=4$	$ka=10$	$ka=40$
f=30 kHz	$ka=6$	$ka=24$	$ka=60$	$ka=240$

only from the knowledge of the body length of the animal to within an error of 6 dB.

If  $ka \ll 1$ , the Rayleigh scattering occurs. Here the target strength increases linearly with frequency and depends little on the particular scatterer.

At  $ka$  close to 1 there is a transition region where the TS can change dramatically with frequency. Here, the specific changes depend a lot on the particular scattering object. This transition region occurs at hundreds of Hz to a few kHz frequencies for squid of the sizes typically found in the sperm whale diet. Those frequency components constitute the lower end of the sperm whale click frequency spectrum and it could be speculated that using this lower frequency end the whale is able to detect the transition region and estimate the size of the insonified object. If this was the case, the sperm whale would adopt an opportunistic feeding strategy, detecting the size of the target before any other characteristic (McLeod et al., 2005). Such foraging behaviour has been reported to be common, especially in males (Whitehead, 2003).

We can calculate  $ka$  for a few frequencies relevant to sperm whale clicks and for some assumed target dimensions (Table 2). It is clear that only for very large targets, geometric scattering applies at all click frequencies. It is difficult to assess typical sizes of sperm whale prey, but it appears that most caught squid have mantle lengths between 20 and 70 cm. The on-axis click mainly occupies frequencies above 5 kHz. From Table 2, the minimum  $ka$  at the main click frequencies for the typical targets is 4. Hence, we could say that geometric scattering applies at the main click frequencies. This property, i.e. the frequency independence of the target, will be used further to experimentally measure the squid target strength.

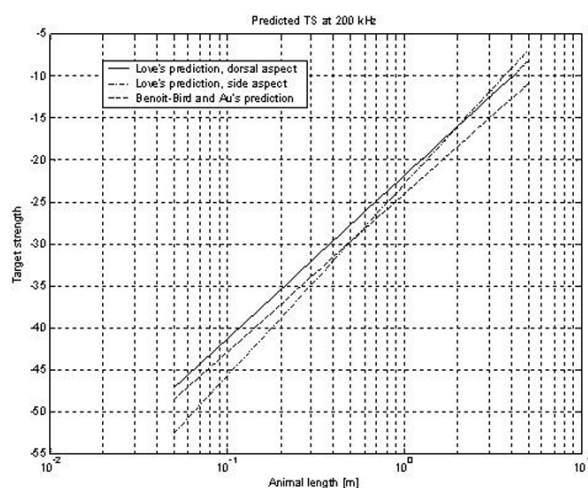
### *Squid target strength in the literature*

There are few and fragmentary measurements of the target strength pattern for live squid. In 1971, Love compiled measurements of fish (both with and without swim bladder) target strengths and devised two simple relations for predicting the TS from the wavelength and the animal length (Love, 1971):

$$\text{TS [dB]} = 19.4 \log_{10} L [\text{m}] + 0.6 \lambda [\text{m}] - 21.9 \text{ (dorsal aspect)}$$

$$\text{TS [dB]} = 22.8 \log_{10} L [\text{m}] - 2.8 \lambda [\text{m}] - 22.9 \text{ (side aspect)}$$

Several authors have also measured the TS of small squid, fish and shrimps at different frequencies and these measurements have been shown to fit Love's relations relatively well. Matsui et al. (see Love, 1971) measured backscatter from 11 squid with mantle lengths from 11 to 13 cm at frequencies of 50 and 200 kHz. The maximum



**Figure 1.** The predicted target strength at 200 kHz of animals of different length, assuming geometric scattering applies.

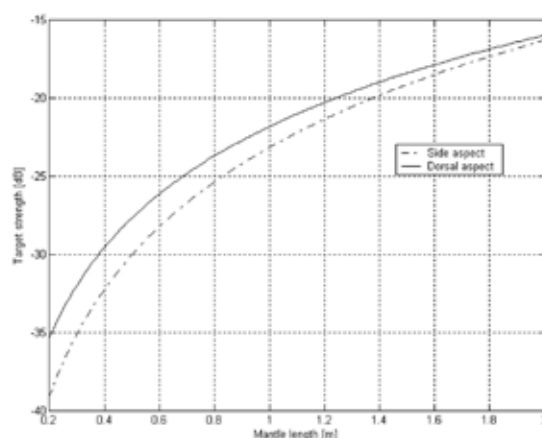
reported target strengths were  $-45$  and  $-42$  dB, respectively. The scattering was well into the geometric region ( $ka > 20$ ). Love's relations would predict target target strengths of  $-45$  to  $-39$  dB (depending on aspect) at both 50 and 200 kHz. The predicted difference between the two frequencies is less than 0.1 dB. As noted by Penrose & Kaye (1979), Love's relations fit Matsui's measurements well. From this and the fact that measured TS of prawns, crabs and copepods also fit Love's relations reasonably well, Penrose & Kaye (1979) concluded that the relations could be used to predict TS of many marine organisms. However, the conclusion is based on scant data for each family.

Measurements of target strength of small squid (size 1.2–4.2 cm), myctophid fish (size 2.2–8.2 cm) and shrimps (size 2.6–8.3 cm) have been conducted at 200 kHz by Benoit-Bird & Au (2001). They noted the importance of removing air bubbles from the animal before measurement. In this study, the target strengths of the animals were calculated by comparing the measured echo levels with levels obtained from synthetic targets of known target strengths. Echoes of 14 species of gelatinous animals were not detectable in their study. The threshold level of their system was given as  $-63$  dB. From their measurements, Benoit-Bird & Au found that the TS of the squid could be approximated by a linear regression on the logarithm of the mantle length. Specifically:

$$TS \text{ [dB]} = 18.8 \log_{10} L \text{ [cm]} - 61.7$$

where  $L$  is the mantle length. This relation is again similar to Love's. Measured values of TS were in the range of  $-60$  to  $-50$  dB. Tilt and roll by up to 10 degrees changed the TS by up to 3 dB in all studied classes. In Benoit-Bird & Au's study,  $ka$  ranged from 9.6 to 33.6 (using  $a=L$ ), therefore geometric scattering can be said to apply.

Figure 1 shows the predicted target strengths of marine animals at 200 kHz from Love's relations and also from Benoit-Bird & Au's equation. The target strength depends strongly on the animal length and geometric scattering applies for all animal lengths used in this figure: at any animal length the greatest difference between two predictions is less than 6 dB.



**Figure 2.** Target strength of squid at 15 kHz, predicted by Love's relations.

We can also use Love's relations to predict the target strengths of sperm whale prey at click frequencies. Figure 2 shows the predicted TS ranges (from side to dorsal aspects) at 15 kHz for squid of mantle lengths from 20 to 200 cm. The relations predict TS values ranging from  $-39$  to  $-17$  dB.

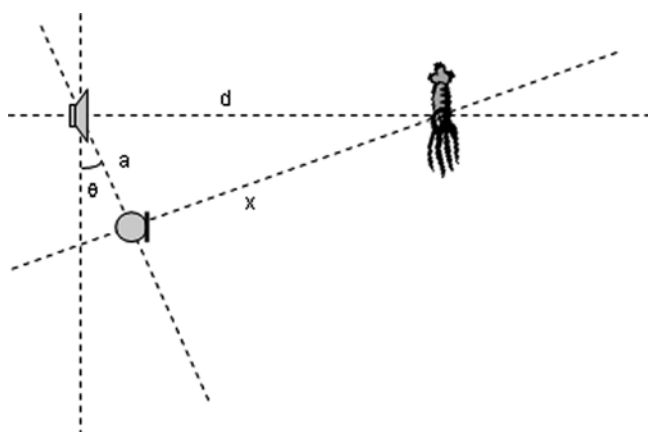
#### *Squid TS measurement: experimental approach*

To further investigate whether the target strength predictions of Love (1971) are valid for squid, and in order to see whether very weak target echoes could be accurately measured with a simple set-up and using simple means, we conducted measurements of the target strengths of a squid (*Loligo vulgaris*) and a cuttlefish (*Sepia officinalis*). Measurements were conducted in a 4×8 m freshwater pool. The depth of the pool varied from 1.2 to 2 m, but the measurements were conducted in the deep end of the pool only. The measurements were done at 15 kHz, described at the P1 pulse centroid frequency of the on-axis click. Here, geometric scattering applies (frequency independence of the target) and measurements of squid target strength could be carried out at only one frequency.

The same laptop computer handled both the signal generation and capturing, this way synchronization problems were avoided. A B&K power amplifier type 2713 provided 40 dB gain on the output signal before it was sent to the B&K type 8104 transducer. The squid echo was captured by a B&K type 8101 hydrophone and amplified by a custom-made low noise preamplifier with a variable gain setting before being recorded.

The target (squid or cuttlefish) was carefully emptied of air and cleaned of air bubbles. We estimated that during the measurements the dorsal side of the animal faced the transducer with an error of less than  $15^\circ$ .

To accurately calculate the strength of the echo from the target, we had to make sure that no other echoes arrived at the same time as the target echo. Figure 3 shows the set-up as seen from above which was designed to ensure that no other echo or reflection would arrive at the receiver at the same time as the target echo and that the source waveform was short enough so that the direct path signal would not overlap with the target echo.



**Figure 3.** Bird's-eye view of the experimental set-up with distance definitions.

The pulse length  $T$  was set to 0.5 ms. Distances were estimated as follows:  $d=50$  cm,  $a=12$  cm, and  $\theta=15^\circ$ . The distance  $x$  could not be measured but it can be estimated from the cosine theorem for the relationship between the sides of a triangle:

$$x = 48.3 \text{ cm } (x^2 = d^2 + a^2 - 2ad \cos(90 - \theta) = d^2 + a^2 - 2ad \sin \theta)$$

We took the greatest possible care in the positioning of the measurement equipment and target, and believe that the distances given here are accurate. With these distances and a pulse duration of 0.5 ms, a sound speed of  $1500 \text{ ms}^{-1}$ , and a minimum distance to another reflecting interface (the bottom) of 80 cm, the echo arrival times could be estimated as follows:

Direct path: starts at 0.080 ms and ends at 0.580 ms.

Target echo: starts at 0.656 ms and ends at 1.116 ms.

Other echoes: start later than 1.067 ms.

Theoretically, the direct path pulse and the target echo would not overlap, but the last approximately 0.1 ms of the target echo might overlap with other reflections. To make sure that only the target echo is being analysed we restricted the analysis to 0.7–1.0 ms after the pulse transmission. The target details are shown in Table 3.

A calibration measurement was conducted without any target present in the pool and with the hydrophone 1 m away from the transducer. The source level of the transducer was 90.2 dB re  $1 \mu\text{Pa/V}$ . There is a tolerance on this value, and its effect on the measurements will be discussed in the next section. The amplitude of the generated signal at the laptop computer was 1 V and the power amplifier added 40 dB, so the source level was 130.2 dB re  $1 \mu\text{Pa}$ . In linear units, this is 3.24 Pa. The pre-amplifier was set to 40 dB. Hence, the signal amplitude at the hydrophone was 0.38 mV. This means that the transduction ratio of our system was  $3.24 \text{ Pa}/0.38 \text{ mV}=8.53 \text{ kPa V}^{-1}$ .

The hydrophone was positioned next to the transducer. The squid was suspended into the water. The transducer was set to send out a 0.5 ms burst of a 15 kHz sine wave every 100 ms. The sine wave was ramped up and down during the first 0.1 ms with a half-sine window. The transmitted burst is shown in Figure 4, as well as its spectrum. The bandwidth of the spectrum around 15 kHz is estimated at 4 kHz between the half power points. This spreading occurs because the

**Table 3.** Details of the target specimens.

Specimen	Length (cm)
<i>Loligo vulgaris</i>	
Dorsal mantle length	24.5
Ventral mantle length	21.8
Total length including tentacles	35.5
Maximum body width (including wings)	15.0
Maximum body width (excluding wings)	6.9*
Head width	3.9
Head length (including tentacles)	13.1
<i>Sepia officinalis</i>	
Dorsal mantle length	15.6
Ventral mantle length	13.4
Total length including tentacles	27.3
Maximum tentacle length	9.2
Maximum body width (including wings)	11.2
Maximum body width (excluding wings)	9.5
Head width	7.2
Head length	12.1

\*, unreliable because body flattened.

pulse is so short—the shorter the pulse the wider must necessarily be its spectrum. The transmitted burst and its spectrum are shown in Figure 4.

## RESULTS AND DISCUSSION

Measurements were taken without a target, with the squid target and with the cuttlefish target. The pre-amplifier settings were 30, 40 and 50 dB, respectively, and this was taken into account when estimating the received pressures. As Figure 5 shows, there is a clear gap between 0.7 and 1.0 ms in the response between the direct pulse and the first reflection from the surface or bottom.

The squid signal appears in this gap (Figure 6) and shows that the response clearly changes when introducing the squid target (the waveforms were obtained by averaging 5000 returns) The differences are greatest at 0.75–0.8 ms and 0.85–0.95 ms. The greatest peak-to-peak amplitude of the squid echo is 0.41 Pa.

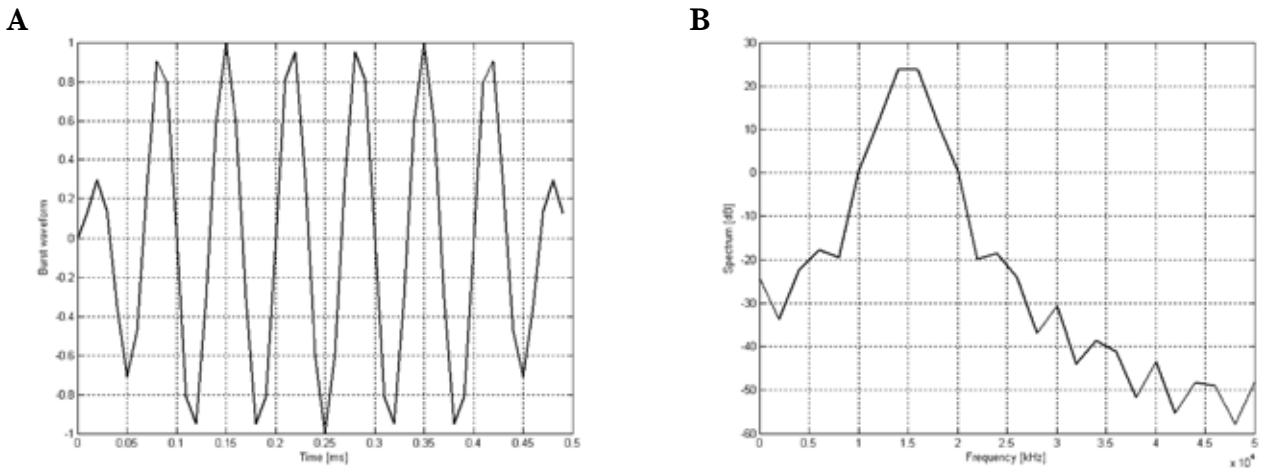
The same measurement was conducted with the cuttlefish echo between 0.7 and 1.0 ms. The maximum peak-to-peak amplitude is 1.16 Pa.

### Target strength estimation

The target strength of a scattering object is defined as:

$$TS = 10 \log_{10}(I_r/I_i) = 20 \log_{10}(p_r/p_i)$$

where  $I_r$  represents the acoustic intensity of the scattered sound at a distance of 1 m and  $I_i$ , the incident acoustic energy.



**Figure 4.** The sent burst waveform and its spectrum (logarithmic scale, arbitrary reference).

The same correspondence applies for the pressures  $p_r$  and  $p_i$ . The illuminating source should be distant, so that the illuminating sound wave is plane. Here, the source was 50 cm away, which at 15 kHz corresponds to 3.3 wavelengths. Since  $kd=20 \gg 1$ , the experimental set-up corresponds to a far-field configuration. The source is also sufficiently small so that the wavefront is approximately plane over the extent of the target.

We measured the pressure of the scattered sound field at a distance  $x$  from the scatterer. Therefore,

$$P_r = P_{\text{measured}} * x$$

We have previously calculated the sound pressure of the incident field at 1 m distance as 3.24 Pa. Here we need the pressure at a distance  $d$  from the source. This can be obtained simply by:

$$TS = 20 \log_{10}(p_r/p_i) = 20 \log_{10}(p_{\text{measured}}/p_{1m}) + 20 \log_{10}(xd)$$

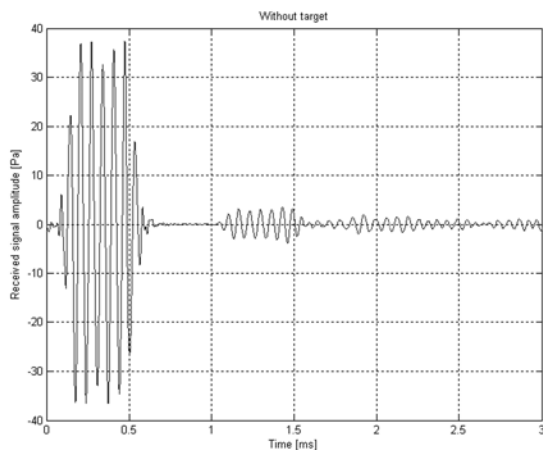
Using  $p_{\text{measured, squid}} = 0.41 \text{ Pa}/2$ ,  $p_{\text{measured, cuttlefish}} = 1.16 \text{ Pa}/2$ ,  $p_{1m} = 3.24 \text{ Pa}$ ,  $d = 50 \text{ cm}$  and  $x = 48.3 \text{ cm}$ , we obtain the target strength of the squid as  $TS_{\text{squid}} = -36.3 \text{ dB}$  and that of the cuttlefish as  $TS_{\text{cuttlefish}} = -27.3 \text{ dB}$ .

It is interesting to compare these values to what would be predicted from Love’s general relations for scattering in the geometric scattering region (which applies here). The one for dorsal aspect reflection is:

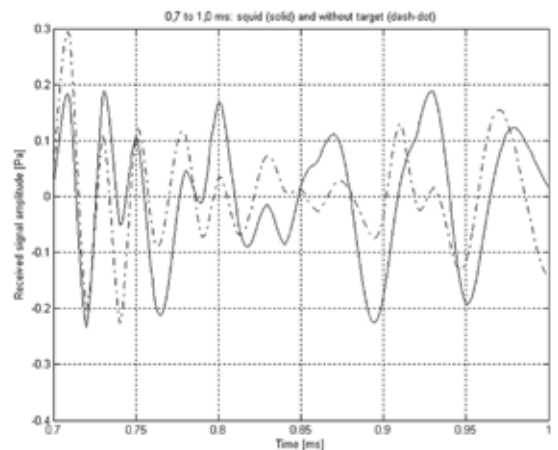
$$TS \text{ [dB]} = 19.4 \log_{10} L \text{ [m]} + 0.6 \lambda \text{ [m]} - 21.9$$

The squid, with a mantle length of 21.8–24.5 cm (ventral–dorsal), is predicted to have a target strength at 15 kHz of between  $-33.7$  and  $-34.7 \text{ dB}$ . This agrees well with our measured value, especially considering the tolerances detailed below. However, it has to be noted that the measurements were conducted with dead cephalopods in a fresh water environment that could explain the observed few dB of difference.

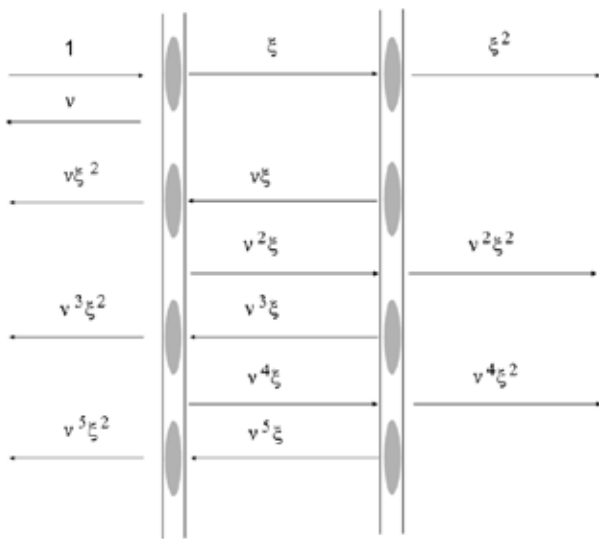
For the cuttlefish, with a mantle length of 13.4–15.6 cm (ventral–dorsal), the predicted TS is between  $-38.8$  and  $-37.5 \text{ dB}$ . The measured value is more than 10 dB higher. This discrepancy cannot be blamed on the measurement tolerances. Instead it appears likely that the cuttlefish reflects far more acoustic energy than many other sea animals of the same size because of its cuttlebone, which is very light and thus likely to have a very different acoustic impedance to



**Figure 5.** Received waveform converted to pressure, no target present.



**Figure 6.** Received sound pressures from 0.7 to 1.0 ms lags without a target (dash-dot) and with a squid target (solid).



**Figure 7.** Setup for estimating the target strength of a school of fish/squid.

water. This probably causes the greater reflection than that which occurs off, for example, a squid.

The transducer tolerance of 2.5 dB translates to the same tolerance on the TS. It leads to ranges of:

$$TS_{\text{squid}} = -36.3 \pm 2.5 \text{ dB} = -38.8 \text{ to } -33.8 \text{ dB}$$

and

$$TS_{\text{cuttlefish}} = -27.3 \pm 2.5 \text{ dB} = -29.8 \text{ to } -24.8 \text{ dB}$$

#### *Several squid targets*

Some species of squid form large aggregations when spawning. It would be highly advantageous for the sperm whale to go after such aggregations because the spawning squid are at maximum size and physically incapacitated. We can expect that the return from an aggregation of several squid will be greater than that from one squid. However, the click echoes from the aggregation might not arrive at the same time if the aggregation is large. One can also not simply sum the contributions from each individual, because different squid will block each other from receiving click energy. A more careful analysis is necessary. Such an analysis was carried out by Love (1981). He assumed that the school is ellipsoidal in shape, and that fish/squid are situated in relation to each other as on the eight corners of an imagined rectangular box and with one fish/squid in the centre of the box. Further assumptions are that the school is elongated in the direction of travel; specifically, that  $N_x = 2N_y = 3.25N_z$ . These assumptions were at least to some extent supported by observations.

The target strength and acoustic cross-sections ( $\sigma$ ) are related by:

$$TS = 10 \log_{10}(\sigma/4\pi)$$

Considering again our *Loligo vulgaris* specimen, a target strength of  $-36.3$  dB (measured dorsally but should be nearly the same ventrally, which is the aspect the sperm whale sees when looking from above) corresponds to an acoustic cross-section of  $\sigma = 0.0029 \text{ m}^2$ .

It has been shown that losses upon acoustic reflection/transmission by a fish are small and can be neglected for many frequencies and fish lengths. Then, assuming that the school is built by fish/squid units in several parallel planes, each reflecting a fraction  $v$  of incoming acoustic energy and transmitting a fraction  $\xi$ , we can analyse the total reflection from a school (see Figure 7).

The result is that the number of fish/squid directly insonified is:

$$F_{\text{dir}} = N_{\beta} (1 + \xi^2 + \xi^4 + \xi^6 + \dots)$$

where  $N_{\beta}$  is the number of fish/squid in each plane and the number of terms in the sum is equal to the number of planes in the school  $N_{\alpha}$ . The number of fish/squid effectively insonified by multiple reflections is approximately, assuming that  $v \ll 1$ ,

$$F_{\text{mult}} = N_{\beta} v^2 (\xi^2 + 3\xi^4 + 6\xi^6 + 10\xi^8 + \dots)$$

where again the number of terms in the sum is equal to  $N_{\alpha}$ . Adding the contributions, we obtain the total effective number of fish/squid insonified as:

$$F = N_{\beta} [1 + \sum_{p=1}^{N_{\alpha}-1} (1 + (1-\xi)^2 p(p+1)/2) \xi^{2p}]$$

The target strength of a school can be related to that of an individual by:

$$TS_{\text{school}} = TS_{\text{individual}} + 10 \log_{10} F$$

which shows that we can now obtain the target strength of the school if we can estimate  $N_{\alpha}$ ,  $N_{\beta}$  and  $\xi$  or  $v$ .

For the modelling scenario considered here, the sperm whale looks straight down towards the seabed. The fraction of energy reflected by a school unit can be calculated as the ratio of the acoustic cross-section of a school unit to the geometric cross-section. As there are two fish in each school unit (1/8 in each of the 8 corners and one in the centre), we obtain:

$$v = 2\sigma/A$$

where  $A$  is the geometrical area of the upper face of one school unit and  $\sigma$  the acoustic cross-section of one fish/squid. The area depends on the packing density of the school. We have little or no information about this for squid, but this will not stop us from guessing. Let us adopt the 'loose' packing density specified in Love's publication. This implies that  $\rho_x = L/x = 3/8$ ,  $\rho_y = L/y = 4/9$ , and  $\rho_z = L/z = 1/3$ . Assuming that the school is composed of *Loligo* spp., all of equal mantle length 24.5 cm, we obtain the dimensions of a school unit as  $x = 65$  cm,  $y = 55$  cm,  $z = 74$  cm. The area of a horizontal face is  $A = (xy) = 0.36 \text{ m}^2$ . Given the value for the acoustic cross-section calculated above, we then have:

$$v = 0.0162$$

which is indeed much less than 1. It corresponds to  $\xi = 0.9838$ .

Let us study a squid school of volume  $1000 \text{ m}^3$ . Love (1971; table 4) shows that with an ellipsoidal shape, the lengths of the school ellipsoid axes are  $X = 23.56$  m,  $Y = 9.94$  m, and  $Z = 8.63$  m. Love's table 7 (1971) gives the number of planes  $N_{\alpha}$  and the number of squid in each plane  $N_{\beta}$  as:

$$N_{\alpha} = Z/z = 8.63/0.74 = 11.66 \approx 12$$

$$N_{\beta} = (\pi/3)XY/xy = (\pi/3) * 23.56 * 9.94 / (0.65 * 0.55) \approx 686$$

The total number of squid in the school is approximately 8000. However, the sperm whale click is a very short duration signal, so the whole school might not be illuminated by it simultaneously. If not, this should be taken into account when estimating the target strength. If the click duration is  $\tau$  then, considering two-way travel, the vertical dimension of the school should be less than  $c\tau/2$  for it to be illuminated simultaneously by the click. A value of  $\tau = 1$  ms appears reasonable for sperm whale on-axis clicks, so with a sound speed of 1500 m/s we arrive at a half-pulse length of 0.75 m. This is certainly much less than the vertical dimension  $Z$  of the school. We can take this into account by using  $c\tau/2$  as the effective vertical dimension of the school. We then arrive at

$$(N_{\alpha})_{\text{effective}} = c\tau/2z = 0.75/0.74 \approx 1$$

The main lobe of the sperm whale beam pattern is wide enough to cover the full horizontal extent of the school. If it had not been, we would have had to compensate for this as well.

For  $N_{\alpha} = 1$ , there is only one illuminated plane, and we have:

$$F = N_{\beta} = 686$$

This implies that in effect,  $686/8000 = 8.6\%$  of the fish/squid are insonified simultaneously by the click in this case.

From

$$TS_{\text{school}} = TS_{\text{individual}} + 10\log_{10} F$$

we now estimate that for a loosely-packed ellipsoidal 1000 m<sup>3</sup> school of *Loligo vulgaris*, each of mantle length 24.5 cm, the target strength is  $-36.3 + 28.4 = -7.9$  dB.

With a 'dense' packing density instead of the 'loose' one (table 1, Love 1971), we have instead  $\rho_x = L/x = 3/4$ ,  $\rho_y = L/y = 3/2$ , and  $\rho_z = L/z = 4/3$ . The dimensions of a school unit are now  $x = 33$  cm,  $y = 16$  cm,  $z = 18$  cm and  $A$  is  $0.053$  m<sup>2</sup>.

This gives  $v = 0.109$  which is about seven times greater than for the loosely-packed school. It corresponds to  $\xi = 0.891$ .

For the school of volume 1000 m<sup>3</sup> Love's table 4 now gives  $X = 35.34$  m,  $Y = 8.84$  m, and  $Z = 6.12$  m. Love's table 7 gives the number of squid in each plane  $N_{\beta}$  as:

$$N_{\beta} = (\pi/3)XY/xy = (\pi/3) * 35.34 * 8.84 / (0.33 * 0.16) \approx 6196$$

The vertical extent of the school is still greater than the length of the click, so we have:

$$(N_{\alpha})_{\text{effective}} = c\tau/2z = 4.16 \approx 4$$

Compared to the loosely-packed school, there are about nine times as many individuals in each plane. In total there are:

$$N_{\alpha} = Z/z = 6.12/0.18 = 34$$

planes in the school. The total number of squid is 210,000 – about 27 times as many as in the loosely-packed school. Finally, we arrive at  $F = 18,500$ .

Then  $18500/210000 = 8.8\%$  of the fish/squid are effectively insonified simultaneously by the click. This is roughly the same as for the loosely-packed school. The target strength of the school is  $10\log_{10} F = 42.7$  dB greater than that of the

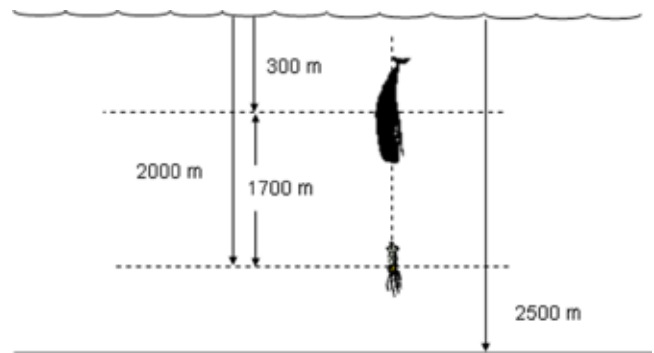


Figure 8. Propagation simulation scenario.

individual. If noise was the only limiting factor to the sonar performance, this would permit truly extraordinary detection ranges. However, since there are about 27 times more individuals in the densely-packed school the comparison is perhaps not completely fair.

#### Prey target detection range

Different numerical techniques for estimating the propagation of acoustic energy in the ocean were considered. It was found that at frequencies above a few kHz, ray tracing was the best option. Seeing that it is the least computationally intensive of the available methods, it would also be desirable to use it at lower frequencies. This might be possible if all dimensions in the environment are much smaller than the wavelength. However, no detailed verification was performed.

Normal mode modelling and wave number integration were also found to be suitable for the application, although the computational requirements of these models at 15 kHz and in typical sperm whale environments appeared heavy enough, at least at present, to prevent their use.

Parabolic equation models suffer from the same high frequency problem, and are also only suitable for propagation near the horizontal plane. There are high-angle parabolic equation models, but these were not easily available to us. We therefore decided to use ray tracing.

The Laboratory of Applied Bioacoustics (LAB) has developed a ray tracing software called *Songlines* for use in the Whale Anti-Collision Project (André et al. 2004, 2005; Delory et al., this volume). This software runs broadband propagation modelling in three dimensions with target reflections, and so was nearly ideal for the task at hand. It was modified to run at higher frequencies and to re-specify the target strength of the reflecting object, and then was applied to the present problem. A scenario with a vertically-diving sperm whale at a depth of 300 m and a squid at 2000 m depth was developed in the model. The depth at the modelling location was 2495 m (Figure 8). All propagation was vertical and along straight rays. This permitted a simple modelling which still allowed us to draw interesting conclusions (see Table 4 for levels, including transmission loss, expected and estimated delays in the simulation).

The sperm whale click source level of 230 dB<sub>peak</sub> and the diameter of the modelled circular piston radiator of 0.8 m, as given by Möhl et al. (2003), were used to estimate the detection range. The *Loligo vulgaris* specimen with a target

**Table 4.** Simulation expected levels (spherical spreading,  $-20 \log_{10} r$  one-way, with perfect reflections at surface and bottom) and delays.

Path		Distance travelled [m]	Transmission loss [dB]	Expected level [dB]	Expected delay [s]	Estimated level [dB]	Estimated delay [s]
<b>Sperm whale (SW) =&gt; SW</b>							
Direct	Travel 1 m	1	0	233	0.00067	233	0.00066
Via surface	Travel 300 m, refl, travel 300 m	600	-56	177	0.40	177	0.40
Via bottom	Travel 2200 m, refl, travel 2200 m	4400	-73	160	2.93	160	2.88
<b>SW =&gt; squid target</b>							
Direct	Travel 1700 m	1700	-65	132	1.13	132	1.13
Via surface	Travel 300 m, refl, travel 2000 m	2300	-67	130	1.53	130	1.53
Via bottom	Travel 2200 m, refl, travel 500 m	2700	-69	128	1.79	124	1.78
<b>SW =&gt; squid target =&gt; SW</b>							
Direct, Direct	Travel 1700 m, target, travel 1700 m	3400	-129	68	2.23	67	2.26
Via surface, Direct	Travel 300 m, refl, travel 2000 m, target, travel 1700 m	4000	-132	65	2.67	63	2.64
Direct, via surface	Travel 1700 m, target, travel 2000 m, refl, travel 300 m	4000	-132	65	2.67	63	2.64
Via bottom, Direct	Travel 2200 m, refl, travel 500 m, target, travel 1700 m	4400	-133	64	2.93	62	2.89
Direct, via bottom	Travel 1700 m, target, travel 500 m, refl, travel 2200 m	4400	-133	64	2.93	58	2.91
Via surface, via surface	Travel 300 m, refl, travel 2000 m, target, travel 2000 m, refl, travel 300 m	4600	-134	62	3.07	60	3.04
Via bottom, via surface	Travel 2200 m, refl, travel 500 m, target, travel 2000 m, refl, travel 300 m	5000	-136	61	3.33	60	3.29
Via surface, via bottom	Travel 300 m, refl, travel 2000 m, target, travel 500 m, refl, travel 2200 m	5000	-136	61	3.33	55	3.29
Via bottom, via bottom	Travel 2200 m, refl, travel 500 m, target, travel 500 m, refl, travel 2200 m	5400	-137	60	3.52	53	3.53

refl, reflection.

strength of  $-36.3$  dB used for the measurements was also used as the imagined target in these simulations. The simulations were run for all frequencies in the geometric scattering region of the specimen, which was determined to lie above 10 kHz. The upper frequency of the simulations was the Nyquist frequency of 48 kHz.

The simulation results showed that in order for the spectrum level of the direct/direct path target echo to be the same as a typical deep-sea noise level at sea state 1 (a reasonable RMS noise level in the RMS bandwidth of the on-axis click is 70 dB re  $1 \mu\text{Pa}$ , see Urick, 1983, p.202), the sperm whale would need a hearing directivity of between 21 and 24 dB for frequencies between 13 and 18 kHz. Hearing directivities of 21 dB have been measured for dolphins, thus such values do not appear unreasonable. Möhl et al. (2006) have recently brought data on the sperm whale usual click hyper-directional index and have extrapolated on the hearing directivity that well matches the conditions of this simulation. This implies that it seems likely that the sperm whale could detect a single small squid of around 25 cm long at a range of 1.7 km against a sea state 1 noise background. Higher sea states would require a more directional hearing or a better signal processing by the sperm whale auditory system. Directional hearing would also be helpful in attenuating the returns from surface and bottom reverberations. The effects of reverberation from non-specular scattering at the sea surface and seabed were not included in these first simulations.

A validation of these simulations, taking into account the surface, volume (reverberation index =  $-100$  dB/m<sup>3</sup>) and bottom reverberation was performed with the Venus

software from Thales Underwater Acoustics. The scenario took place in the Canary Islands:  $28^{\circ}20'35\text{N } 15^{\circ}51'49\text{W}$ . The beam pattern of the source and the receiver was determined taking into account the data on on-axis sperm whale signals (Möhl, 2003) and the local oceanographic conditions (Venus worldwide database). The simulation ran with the following scenarios:  $\text{TS}_{\text{squid}} = -36$  dB, centroid  $F=15$  kHz,  $\text{SL}= 226$  dB<sub>peak</sub>, noise level = 33.3 dB/Hz (sea state 1), 43.4 dB/Hz (sea state 3) and 47.7 dB/Hz (sea state 5). The results confirmed the previous data, giving detection ranges of 2.2, 1.5 and 1.2 km for a 25 cm squid with a single sperm whale click. This implies that the range of the sperm whale sonar for a loose or dense squid aggregation could be much greater than what was estimated for a single squid. Not considering absorption but only spherical spreading, the same direct/direct path return level at the sperm whale location was achieved when the target was at a 8.7 km distance. This would be a phenomenal range at which to detect the school. However, reverberation from the surface and seabed even in the deepest ocean would have set in long before an echo from 8.7 km away could return. This further stresses the need to study this reverberation in the case of squid aggregation in order to find out whether it could be a limiting factor to the sonar function of the sperm whale clicks.

## CONCLUSION

Target strength experiments in fresh water on small squid at 15 kHz confirmed theoretical measurements and gave values of  $-36.3$  dB for squid with a mantle length of 25 cm.



This target strength would allow a sperm whale on-axis click to detect a single 0.2 m squid at a range of 1.2 to 2.2 km depending on sea state noise levels, with a reasonable directional hearing. Large aggregation of squid would extend this range: depending on the packing density, taking the sperm whale click duration into account the target strength of a 1000 m<sup>3</sup> school would be between 28 and 43 dB above that for a single squid. Such a school would be detectable at ranges of several km even with low directional hearing and basic auditory processing.

Sperm whale usual clicks appear to be suited for mid-range echolocation on very low reflective and relatively small organisms such as squid (<1 m), at ranges of at least several hundreds of metres.

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