Submitted to:
Dave Foskett
The Department of Trade and Industry
1 Victoria Street
London
SW1H 0ET

Tel:
Fax:
email:
website:

Submitted by:
Steve Parvin
Subacoustech Ltd
Chase Mill
Winchester Road
Bishops Waltham
Hants
SO32 1AH

Tel: +44 (0)1489 891849
Fax: +44 (0)8700 513060
email: steve.parvin@subacoustech.com
website: www.subacoustech.com

The Target Strength of marine mammals, and estimated performance of Active Acoustic Monitoring systems.

S J Parvin, E Harland and J R Nedwell.

02 February 2007

Subacoustech Report No. 565R0608

subacoustech
ACOUSTIC • RESEARCH • CONSULTANCY

Approved by Technical Director: Dr J R Nedwell

This report is a controlled document. The Report Documentation Page lists the version number, record of changes, referencing information, abstract and other documentation details.

List of Contents

1 Introduction

This report has been prepared by Subacoustech Ltd., for the UK Department of Trade and Industry under programme RDCZ/011/00018 entitled ‘A feasibility and demonstration study; active and passive detection of marine mammals’. This is the second report delivered as part of this programme aimed at ‘reporting the key parameter determining marine mammal active acoustic detection (Target Strength)’. The overall aim of the project is to identify the limits of performance of methods of acoustically detecting marine mammals during offshore activity such as construction and seismic survey.

The use of the seas and seabed as a natural resource has increased greatly over recent years, and consequently the number and scale of offshore activities has increased in proportion. Many of man’s offshore activities cause underwater noise, from the noise created by ship movements through to the extreme levels of sound generated during the use of explosives underwater, for instance for decommissioning of unwanted oil and gas installations.

The noise from offshore activity has the capacity to directly cause disturbance to marine mammals such as seals, whales, dolphins and porpoises. It may be noted, however, that secondary effects can occur, for instance by disturbance of the fish that are their food.

The effects of noise can include death or lethal injury, physical injuries that can have longer term consequences for the animal such as deafness, and sub-lethal behavioural effects such as the avoidance of an area. All of these may have significant consequences for individuals or stocks of a species.

Hence, it is generally a condition of consents issued for offshore activity that

1. the likely level of noise created by various activities is estimated prior to an operation being undertaken,
2. where the noise component of an activity may be significant, the noise levels are kept at the lowest reasonable level,
3. and that where the noise of an activity is sufficient to create an adverse effect, mitigation measures are introduced.

Of these, a primary measure where sensitive species inhabit a proposed area of activity is the monitoring of the area for the presence of the species. This enables the activity to be terminated if there are marine animals present. Generally, use is made of Marine Mammal Observers (MMOs) in an attempt to visually detect marine mammals. However, this approach is ineffective and in darkness or poor visibility detection is impossible. Under these circumstances acoustic detection offers significant advantages. There are three approaches for an Acoustic Detection System (ADS) that might be used, comprising

Passive Acoustic Monitoring (PAM). In this approach, a sonar-type system monitors for vocalisations or echolocation signals from the animals. The systems that have been fielded to date are of generally poor quality, have left-right ambiguity (i.e. cannot determine which side the signal is from) and have no range-finding ability.

Active Acoustic Monitoring (AAM). In this, a sonar “ping” is broadcast in the water and the system looks for a returning signal when it encounters a target. There are systems that have been well developed for military and other purposes, but they all suffer from the fact that they use a “beam” of sound and hence the area of water that is covered at any one time is small. In addition, the sonar may itself cause environmental effects, albeit at a low level.

Acoustic Daylight Monitoring (ADM). This class of sonar is new, and relies on detecting existing background noise being scattered from a target. It has significant potential advantages, including broad area coverage, lack of need for insonification and the ability to also act in PAM mode, but is “cutting edge” technology at the limits of achievability.

The purpose of this report is to assess the feasibility of detecting marine mammals using Active Acoustic Monitoring (AAM). A key parameter when assessing the performance of active sonar is the ratio between the sound that strikes the marine mammal and that returning to the sonar system; this is known as the Target Strength and is the main subject of this report. The report also estimates detection ranges of several species using typical high frequency AAM sonar systems, and additionally evaluates the likely performance of an Acoustic Daylight system for detection during offshore seismic surveys using airguns.

2 Target Strength Measurement.

2.1 Introduction.

In active sonar systems, as shown in figure 2-1, an array of high frequency sound transducers is used to generate a beam of sound which is transmitted towards a target. The sound is usually a short "ping" of sinusoidal sound. The sound strikes the target, and bounces back to the array, which receives the returning signal, allowing the target to be detected.

The performance of the sonar system depends on the degree to which the beam of sound is focussed onto the target, and hence the directivity of the array generating the sound beam. It will also depend on the level of background noise, since the higher this is the more difficult it will be to detect sound.

2.2 Definition of Target Strength.

The performance of the system also depends heavily on the proportion of sound that is reflected by the target back to the array. This is formalised as the "Target Strength" of the target.

Figure 2-2 indicates the principle. A target is insonified by a wave from a distant sonar system. The wave insonifies the target with a pressure $P_{0.}$ Targets typically behave as a secondary point source, giving rise to waves that reflect spherically from the target with a nominal pressure of P_s at one metre. The Target Strength is defined in terms of the ratio between the pressure of the incident wave, and the reflected pressure at one metre from the target, and is given by

$$TS = 20 \log (P_s/P_0) \qquad \textit{eqn. } 2.1$$

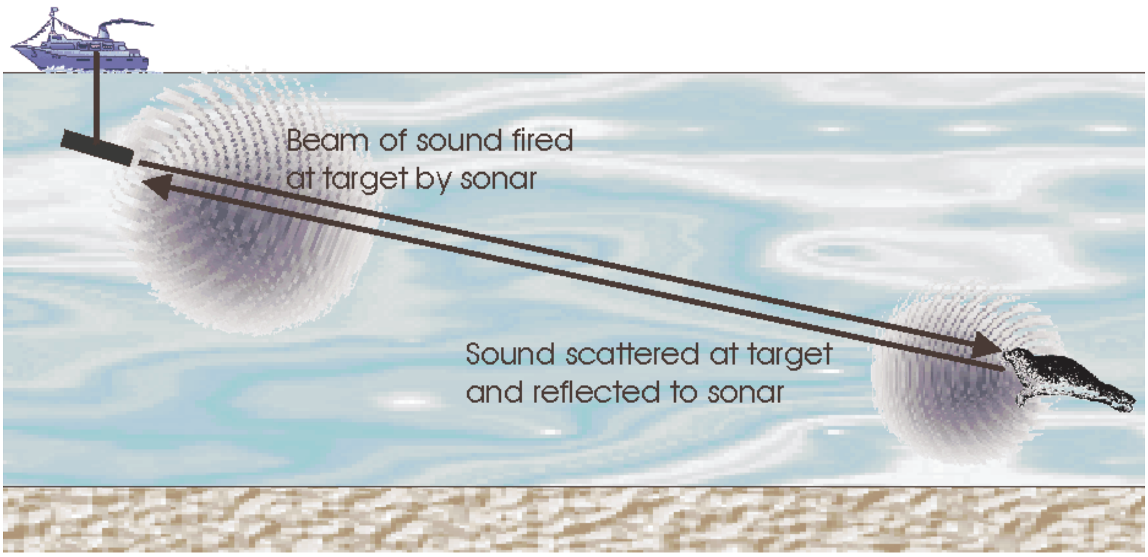

Figure 2-1. The principle of an active acoustic detection system, or sonar.

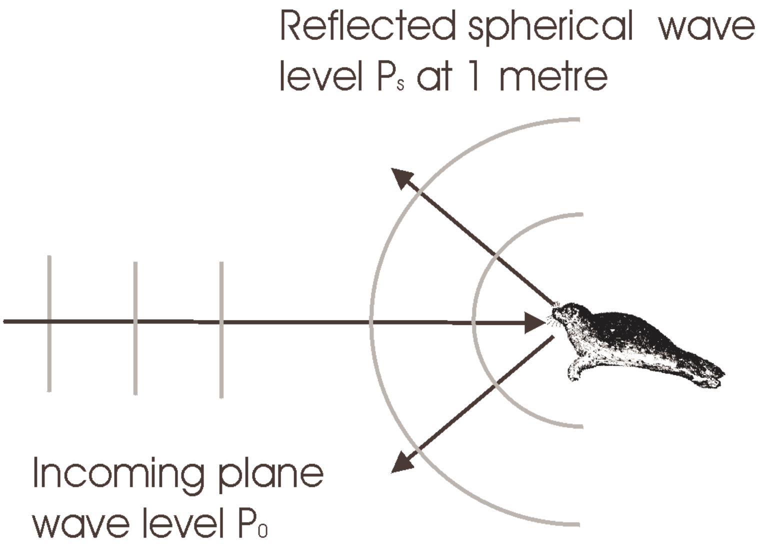

Figure 2-2. The principle of Target Strength.

Wheareas the array performance is in the hands of the designer of the system, and the background noise is well documented and can be allowed for in system design, the target strength of marine mammals is not under the control of the operator and is generally poorly documented.

3 Critical review: the Target Strength of marine mammals

3.1 Background

There has been very little information published on the target strength of marine mammals. It is a very difficult parameter to measure accurately and most of what little information there is has been obtained opportunistically so there is always a great deal of uncertainty in estimating the range and depth of the animals and the aspect that the animal presents. In addition, a number of these opportunistic measurements are bistatic measurements, which use a geographically separated transmitter and receiver pair. In particular, attempts to measure the target strength using sonobuoys and explosive sources have to be regarded with a high degree of suspicion because of uncertainties in the receiver frequency response, limited receiver dynamic range and uncertainties in the source level of the charge.

More recently, with increased interest from environmental pressure groups on the impact of high levels of sound on marine mammals, it has become increasingly difficult to carry out this type of experiment, and even when it has been carried out, there is a reluctance to publish the information for fear of attracting unwelcome attention.

This means that when trying to assess the potential performance of an active sonar to detect marine mammals it becomes necessary to estimate target strength based on models of the animals. Most workers have relied on the Love equations derived in the early 1970's from some very detailed work on fish. However, the physiology of marine mammals is somewhat different to fish and they are generally rather larger than fish, so the applicability of this equation is questionable. More recently, more detailed models have emerged, but as yet no workers have attempted to apply these models to marine mammals

3.2 Mysticetes

(Levenson 1978) reported on the sounds produced and reflected by humpback whales (Megaptera Novaeangliae). The paper was however an ASA conference abstract only, with no information on values obtained. The sounds were recorded from a colinear sonobuoy array deployed by an oceanographic aircraft. Source levels, target strengths, and frequency characteristics were analysed.

(Love 1973) measured humpback whales migrating past Bermuda. Measurements made at 10 and 20 kHz on 6 animals. Of these only three animals gave usable echoes. These measurements gave a range of target strengths from -4 to +8 dB (+/-4 dB), depending on aspect. He compared his measurements with Urick equations based on the external measurements of typical animals and showed that the measured target strengths are typically 2 dB less than predicted.

(Miller and Potter 2001) and (Miller et al. 1999a) described measurements made at 86 kHz on northern right whales and humpback whales. They found that for northern right whales (n=3) the TS varied between -12.4 and -1.4, depending on aspect. Measurements on a humpback whale suggest a TS of +4 dB for the broadside aspect. Discrepancies in the higher frequency measurements were attributed to losses in the skin and blubber (Miller et al. 1999b).

3.3 Odontocetes

(Anon 2000) presented measurements made during a SACLANTCEN SIRENA cruise of a group of striped dolphins. Measurements were made in open sea at 2.6, 3.8 and 8 kHz. The peak TS at 3.8 and 8 KHz was -8 and mean TS of -20.3 dB.

(Au 1994) and (Au 1996) presented measurements of the target strength of a bottlenose dolphin under controlled conditions. Measurements were made over the range 20-80 kHz using tonal and click type transmissions. TS figures varied between -10 and -30 dB. The angular plot of TS v aspect was also measured and showed peak TS on broadside and least TS at tail aspect (21 dB down). An attempt was also made to determine which part of the dolphin's body gave the highest TS and this showed that the area around the lungs were the dominant area with a TS up to 20dB higher than other areas.

(Dunn 1969) Measured the target strength of a sperm whale using a SUS charge transmitter and SSQ-41A sonobuoy receiver. Values obtained were between -7.3 and -8.5 for bow aspect. From this he inferred that beam aspect target strengths would be between 0 and +10 dB.

(Levenson 1974) measured the bistatic target strength of a sperm whale off Nova Scotia using SUS charges and SSQ-57 sonobuoy receiver. These gave figures of -2.5 dB in the 250-500 Hz band and 10.8 dB in the 8-16 kHz band.

Shot	Position	0.25-0.5 kHz	0.5-1 kHz	1-2 kHz	2-4 kHz	4-8 kHz	8-16 kHz
B	C	-3.8	2.3	9.8	7.5		8.6
C	B	-4.2	0.9	7	7.2	4.6	9.4
A	B		-3.9	3.1	5.3		
B	B		-5.4	2.2	0.3		
A	B		-0.4	6.7	2.9		
B	C			6.3	4.2		
C	A	0.5		7.7	6.5		
C	B	-2.6	-2.3	9.5	2.7		8.8
A	C		8.1	14.7	11.5	10.3	11.7
B	A		9.9	7	6.2		
B	C	-4.4	2.6	7.2	7.9		13.4
C	B	-0.3	10.8	13.8	7		14.4
C	B	-2.4	2.7	10.2	7.9		9.4
Mean		**-2.5**	**2.3**	**8.1**	**5.9**	**7.5**	**10.8**
Dev		**±1.9**	**±5.3**	**±3.6**	**±2.9**		**±2.4**

Table3-1. Sperm whale target strength

(Selivanovsky and Ezersky 1996) used a fish-hunting sonar operating at 20 and 140 kHz to look at the wakes left by dolphins hunting squid in the Sea of Japan. They estimated the target strength of the wake to be -12 to -18 dB when the animals were swimming at 4-6 m/s. The wakes were visible for 1.5 minutes. The species of dolphin was not given.

3.4 Target Strength for other species

(Foote 1980b) reviewed measurements on a number of fish species and found that the swimbladder contributes 90-95% of the scattering cross section for gadoid species. In (Foote 1980a) the effects of averaging the target strength was investigated and again data was compared with predicted values.

(Jaffe et al. 2004) was an ASA conference abstract only. Measurements were made on six captive. Transmissions were short CW pulses at a frequency of 171 kHz. An underwater video camera was aimed along the axis of the range direction of the sound transmission, permitting the co-registration of animal and acoustics. The camera and sonar were calibrated together by translating a 38-mm tungsten carbide sphere (TS=–39 dB@ 171 kHz) in a separate test tank facility. Results indicate that the reflectivity of the animals (not strictly target strength) is somewhat low, in the –49 to –40 dB range.

(Lillo et al. 1996) measured hake and jack mackerel and found TS values around -35 for hake and -38 for jack mackerel. (Penrose and Kaye 1979) looked at the target strengths of various squid and crustacean.

3.5 Comparison of calculated and measured Target Strengths

(Au 1996) measured the target strength of a bottlenose dolphin and then compared this with calculated values. He showed that the measured broadside values were close to those predicted by the Love equation (Love 1971) at 23 kHz, but progressively dropped at higher frequencies to be 12 dB lower at 80 Khz. He attributed this difference to attenuation in the blubber. His measurements were made in very shallow water but he pointed out that the lung volume will reduce from 6-7 litres near the surface to 0.25 litres at 300 metres depth and this will significantly reduce the target strength of the animal. The air will be increasingly compressed and a greater percentage will be found in the nasal and trachea regions, with unpredictable effects on the target strength.

(Reeder et al. 2004) looked at the high resolution target strength of the alewife, a swimbladder fish, over the frequency range 40-100 kHz. The measurements were compared with two models, the Fourier Matching Model (FMM) and the Kirchoff Ray Mode (KRM) model. These models offer greater resolution than the simple Love model and better predict the target strength of fish. How applicable these models are to ceteaceans and pinnipeds is not clear and further work is recommended.

(Sarangapani et al. 2005) calculated the target strength of human divers at 60 kHz using simple cylinder models and the FMM model. He suggested the target strength will be between -3 and -10 dB, depending on angle of incidence.

4 Target Strength of UK Species

4.1 Introduction

The purpose of this section is to suggest values of Target Strength that might be suitable for calculating the performance of AAM systems in detecting marine mammals in UK waters. From the literature search, data has been collected on just five species of UK whale: humpback whale, northern right whale, sperm whale, bottlenose dolphin and striped dolphin. Of these three are found regularly in UK waters: Humpback whale, sperm whale and bottlenose dolphin. No data has been found on any pinnipeds species.

Of this data, the only reliable measurements were those made by Au on the bottlenose dolphin, all the other measurements were made at sea with many uncertainties including range and aspect. However, they do give a good guide to the range of values likely to be encountered. With such a small measurement set it becomes necessary to extrapolate the values based on limited methodology. The technique mostly used is to use the method proposed by Love for fish (Love 1971) which assumes the animal can be represented by an air-filled sphere. The equation for TS is:

$$TS(f) = 22.8 * Log(L) - 2.8 * Log(\lambda) - 22.1 \qquad \textit{eqn. 4-1.}$$

Where L is the length of the animal in metres and λ is the wavelength in metres

This method is acceptable for frequencies below 20 kHz and when the animal is close to the surface so the lungs are fully inflated. Newer models, such as the FMM model, give a better representation of the animal and are likely to be applicable to a range of species, but are more difficult to run.

Based on this limited information, it is suggested that the following target strengths are used for a representative range of UK species:

Species	100 Hz	1 kHz	10 kHz	100 kHz
Fin whale	-6.8	-4	-1	1.5
Humpback whale	-10.5	1.5	-4.8 *(-2 to -6)*	-2.1 *(0 to-10)*
Minke whale	-16	-13	-10	-7.5
Sperm whale	-11 *(-2.5)*	-8.8 (8)	-6 *(10)*	-3 *(12)*
Bottlenose dolphin	-18	-14.5	-12 *(-9)*	-3.2 *(-23)*
Harbour porpoise	-29	-26	-23	-20
Grey seal	-25	-23	-20	-17

Table 4-2. xxxxxxxxxxx-

Note that the figures are calculated; the figures underlined in italics are real measurements included for comparison.

5 Calculated detection ranges

5.1 Active sonar detection

This section uses the information in the preceding section, in association with typical parameters for sonar systems, to calculate the range at which marine mammals might be detected.

Calculation of detection range is based on two sonars. One is a representative fish-finding sonar using a SL of 220 dB re. 1 µPa on a frequency of 100 kHz. The other is at 20 kHz and a SL of 230 dB re. 1 µPa and representative of a dedicated whale finding sonar. Assuming an ambient noise level for sea state 2 and no rain or wind noise, a receive DI of 10 dB and a threshold of +10 dB, the detection ranges are:

Species	20 kHz	100 kHz
Fin whale	4900 (1250) m	2600 (570) m
Humpback whale	4300 m	2200 m
Minke whale	3400 m	1700 m
Sperm whale	4100 m	2100 m
Bottlenose dolphin	3200 (730) m	1600 (330) m
Harbour porpoise	1150 (400) m	850 (170) m
Grey seal	2200 m	950 m

Table 5-1. Calculated detection range for species of UK marine mammal

Note that these represent the best that can be achieved, under ideal circumstances. In the real world the animal aspect can be worst case, dropping the TS by 20 dB, there is likely to be significant wind and rain noise and there is likely to be entrapped air bubbles near the surface attenuating the signal. There is typically likely to be an additional 30 dB less signal excess compared with the above. The reduced performance figures that result from these more pessimistic assumptions are shown in brackets in the above table.

5.2 Air gun detection ranges

Air guns produces a broadband pulse with peak energy around 100 Hz and source levels up to 260 dB re 1uPa@1m. The arrays are normally configured to direct the energy downwards so the sound travelling sideways is from the beam sidelobes or by scatter off the seabed. In most water depths there is also considerable dispersion which, even at ranges below 1 km, converts the short pulse into a sweep. In most areas this is a down sweep. The very low frequencies can enter the substrate and emerge back into the water column ahead of the main direct path arrival. The signal at ranges beyond 500 metres from an operating air gun array in shallow water can be very complex and is unsuitable for use in detecting animals by active sonar.

In deep water the acoustic environment is more benign and it is possible to consider the achievable performance when detecting animals. However, with much higher ambient noise levels, very little directivity on both transmit and receive, and lower effective target strengths, the performance is much lower than with the high frequency sonars. It should also be remembered that the pulse length in the water is much greater at these low frequencies. A perfect signal source should achieve a pulse length around 15mS, corresponding to a dead range of 50 metres. However, the time sidelobes are likely to extend this by at least a factor of 4 to around 200 metres. It would mean that any animal within 200 metres would not be detected.

There are no measured target strength values at air gun frequencies so using the predicted values from table 2 shows that a harbour porpoise could be detected out to 260 metres, while a fin whale could be detected out to 1600 metres. Because of the dead range, the harbour porpoise could only be detected in the range band 200-260 metres. Note also that this performance is only achievable in a limited arc looking straight down from the source. Once out of the main beam, performance will drop very rapidly. However, it is beyond the scope of this study to predict a coverage diagram of a typical air gun array as this would require detailed knowledge of the acoustic field around such a source. The figures included here should be considered as best achievable figures, with typical figures well below this. It is likely that the smaller animals will not be detected at all.

6 Conclusions

The feasibility of detecting marine mammals using Active Acoustic Monitoring (AAM) has been assessed. It has been found that:

1. A key parameter when assessing the performance of active sonar is the Target Strength of the marine mammals. The review summarised in this report indicates that while the data available is rather limited, values given for Fin whale, Humpback whale, Minke whale, Sperm whale, Bottlenose dolphin, Harbour porpoise and Grey seal are generally adequate for estimating the performance of AAM systems.

2. This information has been used to calculate the range at which marine mammals might be detected by a representative fish-finding sonar and a dedicated whale finding sonar. Assuming optimistic parameters, the detection ranges span from 850 metres for a harbour porpoise using a fish finding sonar, to 4900 m for a fin whale using a dedicated system. However, using more pessimistic assumptions these ranges drop to 170 and 1250 metres respectively.

3. The range is probably sufficient for detecting marine mammals during many offshore activities. However, a major disadvantage of AAM systems is that they use a “beam” of sound and hence the area of water that they cover at any one time is limited.

7 References

1. Anon (2000) Sirena 00: Active cetacea detection. SACLANTCEN, La Spezia, Italy
2. Au W. W. L. (1994) Acoustic backscatter from a dolphin. The Journal of the Acoustical Society of America 95: 2881
3. Au W. W. L. (1996) Acoustic reflectivity of a dolphin. Journal of the Acoustical Society of America 99: 3844-3848
4. Dunn J. L. (1969) Airborne measurements of the Acoustic Characteristics of a Sperm Whale. Journal of the Acoustical Society of America 46: 1052-1054
5. Foote K. G. (1980a) Averaging of fish target strength functions. Journal of the Acoustical Society of America 67: 504-514
6. Foote K. G. (1980b) Importance of the swimbladder in acoustic scattering by fish: A comparison of gadoid and mackerel target strengths. Journal of the Acoustical Society of America 67: 2084-2089
7. Jaffe J. S., Roberts P. L., Simonet F., Bowles A. E. (2004) Acoustic reflectivity measurements of sirenia (Florida manatees) at high frequencies. The Journal of the Acoustical Society of America 116: 2556
8. Levenson C. (1974) Source level and bistatic target strength of the sperm whale (Physeter catadon) measured from an oceanographic aircraft. Journal of the Acoustical Society of America 55: 1100-1103
9. Levenson C. (1978) Source level and bistatic target strength of the humpback whale(Megaptera Novaeangliae) measured from an oceanographic aircraft. The Journal of the Acoustical Society of America 64: S97
10. Lillo S., Cordova J., Paillaman A. (1996) Target-strength measurements of hake and jack mackerel. ICES Journal of Marine Science 53: 260-271
11. Love R. H. (1971) Dorsal-aspect target strength of an individual fish. Journal of the Acoustical Society of America 49: 816-823
12. Love R. H. (1973) Target strengths of humpback whales Megaptera novaeangliae. Journal of the Acoustical Society of America 54: 1312-1315
13. Miller J. H., Potter D. C. (2001) Active high frequency phased-array sonar for whale shipstrike avoidance: Target strength measurements. In: Holland RC (ed) OCEANS 2001. Marine Technology Society, Washington, pp 2104-2107
14. Miller J. H., Potter D. C., Weber T., Felix J. (1999a) The target strength of the northern right whale (Eubalaena glacialis). The Journal of the Acoustical Society of America 105: 992
15. Miller J. H., Weber T., Tuttle A., Potter D. C. (1999b) The dependence of target strength of the northern right whale (Eubalaena glacialis) on the acoustic properties of blubber. The Journal of the Acoustical Society of America 106: 2163
16. Penrose J. D., Kaye G. T. (1979) Acoustic target strengths of marine organisms. Journal of the Acoustical Society of America 65: 374-380
17. Reeder D. B., Jech J. M., Stanton T. K. (2004) Broadband acoustic backscatter and high-resolution morphology of fish: Measurement and modeling. The Journal of the Acoustical Society of America 116: 747-761
18. Sarangapani S., Miller J. H., Potty G. R., Reeder D. B., Stanton T. K., Chu D. (2005) Measurements and modeling of the target strength of divers Oceans 2005 - Europe, pp 952-956 Vol. 952
19. Selivanovsky D. A., Ezersky A. B. (1996) Sound Scattering by Hydrodynamic Wakes of Sea Animals. ICES Journal of Marine Science 53: 377-381

Report Documentation Page

1. This is a controlled document.
2. Additional copies should be obtained through the Subacoustech Librarian.
3. If copied locally, each document must be marked "Uncontrolled Copy".
4. Amendment shall be by whole document replacement.
5. Proposals for change to this document should be forwarded to Subacoustech.

Issue	Date	Details of changes
565 R 0601		Initial draft
565 R 0602		Internal circulation and amendment
565 R 0603		Internal circulation and amendment
565 R 0604	18/12/2006	Internal circulation and amendment
565 R 0605	19/12/2006	Internal circulation and amendment
565 R 0606	20/12/2006	Internal circulation and amendment
565 R 0607	20/12/2006	First Issue
565 R 0608	02/02/2007	Minor amendments to First Issue following review.

1. Originator's current report number	565R0608
2. Originator's Name & Location	S J Parvin, Subacoustech Ltd
3. Contract number & period covered	565.
4. Sponsor's name & location	Dave Foskett, Department of Trade and Industry.
5. Report Classification & Caveats in use	UNCLASSIFIED
6a. Date written	
6b. Pagination	Cover +i + 13
6c. References	
7a. Report Title	The Target Strength of marine mammals, and estimated performance of Active Acoustic Monitoring systems
7b. Translation / Conference details (if translation give foreign title / if part of conference then give conference particulars)	
7c. Title classification	UNCLASSIFIED
8. Authors	S J Parvin, E Harland and J R Nedwell.
9. Descriptors / Key words	.
10a. Abstract	
10b. Abstract classification	UNCLASSIFIED; UNLIMITED DISTRIBUTION.