PERFORMANCE OF AN ENHANCED PASSIVE SONAR REFLECTOR SONARBELL: A PRACTICAL TECHNOLOGY FOR UNDERWATER POSITIONING

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Abstract

Commercial marine activity has driven the need for technological solutions for the positioning and relocation of equipment on the seabed. Traditional solutions often involve localisation through range measurements to several transmitters. However, these active devices contain batteries which require periodic maintenance. For this reason, the use of passive sonar reflectors as navigation and localisation aids is desirable. Fundamental to their practicality is their ability to reflect sonar energy, quantified as target strength. Recent advances in commercial passive reflector technology, as embodied by the SonarBell, have made them a practical technology for underwater positioning. In the present work, the acoustic characteristics of passive sonar reflectors and the SonarBell are introduced. Basic sonar equation analysis and target strength results from broadband calibration measurements in a water tank estimate the performance that could be achieved using SonarBell within localisation systems. Accounts of two in-field tests demonstrate SonarBell being used practically.

1 INTRODUCTION

Deployment of equipment onto the seabed entails high operational costs, while mistakes could result in acute financial and environmental impacts. This is important in particular for industries such as the oil industry, with an estimated total seabed pipeline installation of over 220,000 km (Westwood, 2009), and the submarine cable industry which is estimated to have installed over 1,800,000 km of submarine cable supporting communication and power distribution (Global Marine GeoCable website, 2012). For these reasons, technologies for underwater positioning and relocation are an essential tool.

Many technologies have been investigated and developed to provide underwater location systems. The majority of underwater location systems, or more broadly, positioning and navigation systems, use fields of transmitters and triangulation algorithms to determine the relative position of a receiver from range measurements to each transmitter. By geo-referencing several transmitters within the field, the absolute position of the receiver in global coordinates can also be determined. These techniques are used by Long BaseLine (LBL) systems (Gamroth et al., 2011). Other system configurations, such as Ultra-Short BaseLine (USBL) use a single transponder and a sophisticated transceiver in order to determine position. Simple systems also exist such as range finders where a single transmitter is relocated by moving a receiver in a direction that reduces the measured distance.

All of these systems rely on at least one transmitter, be it a pinger which continuously transmits, or more commonly, a transponder which transmits a signal when commanded to. These active devices use batteries for power, requiring periodic maintenance which can be costly and difficult to service. The alternative of using passive sonar reflectors then becomes attractive, since these devices do not require maintenance and therefore can remain deployed for longer periods without cost implications.

Many designs of passive sonar reflectors have been tried, but their use in positioning systems has been limited. For a passive sonar reflector to be of practical use, it is paramount that it is able to capture and return as much energy as possible. A measure of its ability to return the captured energy is called target strength. Recent developments in the design and manufacture of passive sonar reflectors have resulted in a practical solution suitable for use in underwater positioning systems. A commercially-available passive sonar reflector built around recent technology improvements is the SonarBell.

This paper provides evidence that the performance of this type of reflector, the SonarBell is at a level where passive sonar reflectors are a viable option as a positioning technology. Specifically, basic sonar equation analysis estimates the distance over which a location system operates for reflectors with different target strength. The performance of a location system using SonarBell is then estimated by comparing the measured target strength of a SonarBell to the basic sonar equation analysis. In addition, in-field tests are described demonstrating the use of SonarBell.

2 PASSIVE SONAR REFLECTORS

2.1 Spherical reflectors

The sound reflection from an underwater object is determined by factors related to the incident signal, the environment and the object itself. The challenge of passive sonar reflector design consists in optimising target characteristics, such as shape and composition, in order to maximize reflection. Another important feature of passive reflectors, which simplifies their application, is to have omnidirectional scattering characteristics, that is, a uniform return that is not dependent on aspect angle. For this reason, spherical targets have been a popular choice for reflector geometry for several decades, although other geometries such as cylinders and tri-planes have also been used (Malme, 1994).

In order to increase the target strength several modifications on the basic spherical reflector have been attempted. An early idea was to direct the incident energy to a common point in the target, in order to form a concentrated return. This is achieved by inducing refraction at the shell boundary, thus focusing the sound at the concave posterior section of the sphere (Folds, 1971; Folds and Loggins, 1983). This effect requires an internal medium with lower sound speed than that of the exterior shell. The selection of the shell filler material is crucial for performance, but also is constrained by other factors. For example, carbon chlorides were widely used as filler focusing agent for sonar target shells, until the banning of these hazardous materials drove the search for alternatives (Boehme and Stockton, 1990). Furthermore, some of the replacement components investigated were chemicals that could also be subject to changes in the environmental protection laws (Kaduchak and Loeffler, 1998). A simpler approach involving air-filled shells has also been pursued. In the field of medical ultrasound imaging, air-filled microbubbles are used as contrast agents (Allen et al., 2001) while ceramic thin shells have been used as sonar calibration targets (Atkins et al., 2007). This approach has the disadvantage of providing less control over the optimal frequencies of operation and often exhibiting problematic high buoyancies.

Ultimately, a successful reflector design for a given frequency band depends on a complex interplay of factors such as shell thickness, shell composition and internal fluid. A commercial product with an optimal combination of these parameters would ideally reach high target strength levels, while also being robust, low-cost and convenient to deploy. In this respect, the SonarBell is a commercially-available passive sonar reflector designed to achieve these characteristics, as described in the following section.

2.2 Enhanced passive sonar reflector: SonarBell

SonarBell was originally conceived by scientists in the UK Ministry of Defence's (MoD), Defence Science and Technology Laboratory (Dstl) in 2004 and later commercialised in 2007 by Subsea Asset Location Technologies Ltd (SALT) to be an omnidirectional high target strength passive sonar reflector. The SonarBell is a spherical reflector available in sizes from 50 mm to 275 mm in diameter that can be matched to a broad range of sonar operating frequencies.

Fundamentally a SonarBell, shown in Figure 1, is a shell-based reflector, as described in section 2.1, but with numerous improvements incorporated in order to produce a competitive commercial product. For example the SonarBell shell contains several small holes which allow the shell to free flood, thus avoiding pressurisation problems when recovering from depth, a common and potentially lethal problem with gas-filled spheres (Edwards, 2008).

Figure 1. 200 mm diameter SonarBell passive acoustic reflector with distribution box.

Similarly to the shell reflectors previously described, the SonarBell reflects incident acoustic energy back towards the acoustic energy source. The reflection consists of two echoes. The first echo is the reflection of energy from the front face, referred as the specular reflection. The second echo is created by designing the SonarBell such that some of the acoustic energy incident on the shell is refracted at the shell boundaries to focus it towards a point on the back of the shell. The focused sound combines constructively with acoustic energy from other waves existing in and around the shell, in order to generate a second reflection. A pictorial representation of the generation of the second echo is shown as a sequence of diagrams in Figure 2. The incident energy travels from the right and on impact with the spherical reflector splits, with some energy travelling around the outer shell and some energy being refracted through the inner section. At the focus point on the rear of the shell the energy combines, generating the second echo. This second echo is directed back through the reflector, and exits the shell in a direction towards the original source of the incident energy.

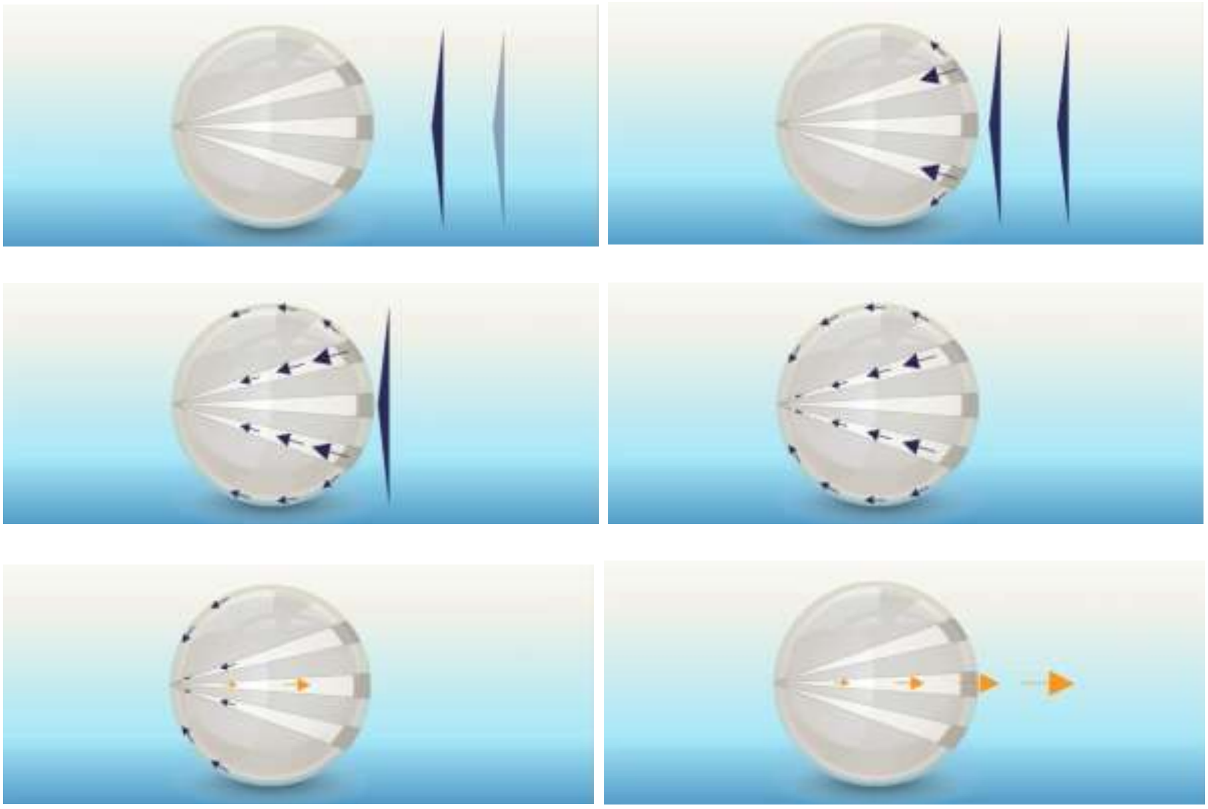


Figure 2. A sequence of diagrams showing the generation of the second echo by a SonarBell.

It is the second echo that contains the majority of the reflected energy when operated at its design frequency and hence it is the second echo that defines the target strength of the SonarBell. In general the target strength is affected by:

- the efficiency of the SonarBell to reflect energy;
- the size of the SonarBell, as this affects the amount of incident energy collected; and
- the frequency response of the SonarBell - designed for single or multiple frequency peaks, or for a broadband response.

When determining the target strength required from a passive sonar reflector the complete sonar system within which it is to operate needs to be considered. Basic analysis using the sonar equation provides a method of considering the sonar system and passive sonar reflector. Details of this approach are provided in the next section.

2.3 Target strength considerations

Target strength is the ratio of the intensity of the reflected energy to the intensity of the incident energy referred to a distance of 1 m from the centre of the reflector and is calculated as shown in Equation 1 (modified from Urick, 1967).

Equation 1 $$Target\ Strength\ (dB) = 10.\log_{10}\frac{Ir}{Ii}$$

where $Ir = sound\ intensity\ of\ return\ measured\ at\ 1\ m\ from\ the\ centre\ of\ the\ reflector$

$Ii = sound\ intensity\ incident\ on\ the\ reflector$

For a passive sonar reflector the amount of energy required to be reflected in order to be detected will vary from system-to-system and will be influenced by many factors associated with the system design. It is therefore impossible to specify a single passive sonar reflector target strength that would be suitable for use by all sonar systems. However, an indication of the performance of a sonar system using passive sonar reflectors for reflectors with different target strengths can be calculated using the sonar equation. Consider a sonar positioning system, the signal-to-noise ratio at the receiver expressed in dB for a signal reflected from a passive sonar reflector is calculated using Equation 2 (Urick, 1967).

Equation 2 $$SNR(dB) = SL - 2 * TL - NL + TS$$

where $SNR = receive\ signal - to - noise\ ratio$

$SL = projector\ source\ level$

$TL = one\ way\ transmission\ loss$

$TS = reflector\ target\ strength$

$NL = ambient\ noise\ level$

Assuming a source level of 200 dB re 1 µPa at 1 m, a noise level of 70 dB re 1 µPa and spherical spreading for a positioning system operating at 25 kHz in 500 m water depth, Equation 2 becomes:

Equation 3 $$SNR(dB) = 200 - 2 * (20.\log_{10} R + \alpha.R) - 70 + TS$$

where $R = range\ or\ distance\ between\ sonar\ and\ reflector\ (m)$

$\alpha = absorption\ loss\ of\ 4.904(dB/km)\ (National\ Physics\ Laboratory\ website, 2012)$

A graph of receiver SNR against distance is plotted in Figure 3 for passive sonar reflectors with different target strengths.

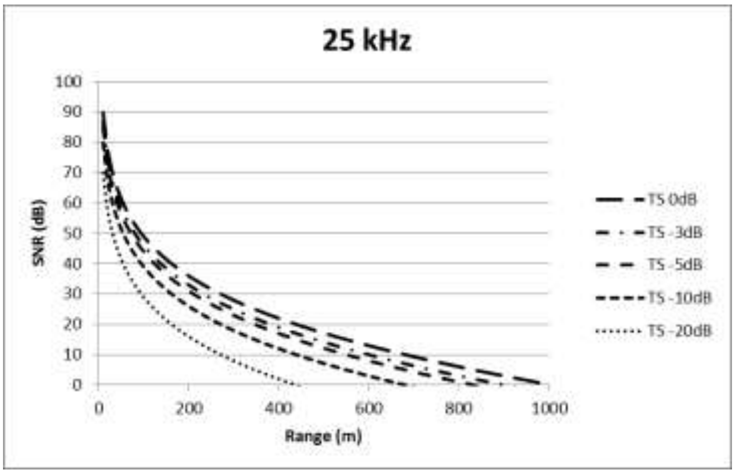


Figure 3. Plot of received SNR against operating distance for reflectors with different target strengths operating at a frequency of 25 kHz and NL = 70 dB re 1µPa.

For an ideal rigid spherical reflector isonified by a plane wave, completely backscattering in an isotropic manner, its target strength is defined by Equation 4 (Urick, 1967).

Equation 4 $$TS_{Rigid} = 10.\log_{10}\frac{a^2}{4}$$

where $a = radius\ of\ sphere$

For a sphere of radius 2 m the target strength is calculated to be 0 dB. From Figure 3 it can be seen that a reflector with a target strength of 0 dB is predicted to operate over distances of hundreds of metres, for a reasonable signal-to-noise ratio (SNR) at the receiver. As the target strength of the reflector reduces from that of the 0 dB reflector, the distance over which the sonar can operate also diminishes. Therefore, in general, reflectors with large target strength support operations over longer distances.

Similar analysis can be conducted for different operating frequencies. Figure 4 shows the SNR analysis for two more typical positioning sonar operating frequencies of 50 kHz and 120 kHz and demonstrates that as the operating frequency increases the distance over which the positioning system could operate reduces. (Note absorption loss values used to produce Figure 4 were

14.431 (dB/km) at 50 kHz and 33.866 (dB/km) at 120 kHz, (National Physics Laboratory website, 2012).)

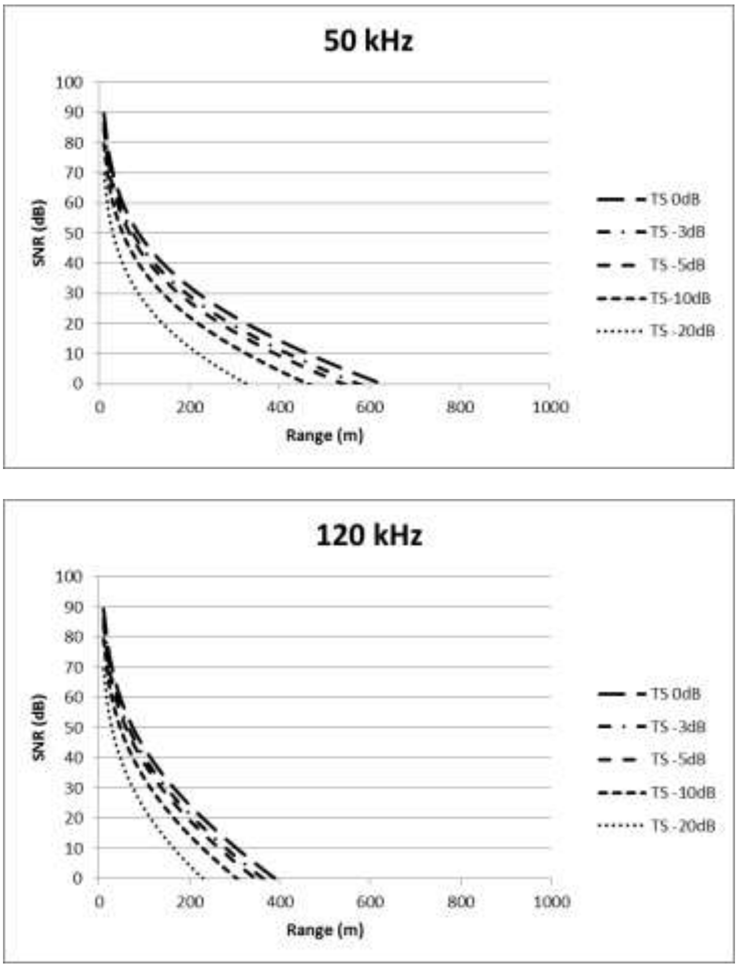


Figure 4. Plots of SNR against operating distance for reflectors with different target strengths for 50 kHz and 120 kHz and NL of 70 dB re 1µPa.

A typical sonar receiver will require a signal-to-noise ratio of 10 – 20 dB to achieve a reasonable compromise between the false alarm rate and the probability of detecting a target. Thus a detection range of the order of 200 m when using a simple sonar system operating at 120 kHz is appropriate.

It is typical for modern sonar manufacturers to improve system performance by utilising processing gains obtained from the size of the transducer array and use of frequency modulated pulses. The upper limit of processing gains for commercial sonar systems seems to be about 40 dB at 300 kHz and correspondingly lower when operating at lower frequencies. The SNR at the receiver of a modern sonar can be calculated by the inclusion of processing gain into Equation 2, as shown by Equation 5.

Equation 5 $SNR(dB) = SL - 2 * TL - NL + TS + PG$

where $SNR = receive\ signal - to - noise\ ratio$ $SL = projector\ source\ level$

$TL = one\ way\ transmission\ loss$ $TS = reflector\ target\ strength$

$NL = ambient\ noise\ level$ $PG = system\ processing\ gain$

Results for a system with different processing gains are plotted in Figure 5 when the system employs a reflector with a target strength of -5 dB. By comparing Figure 5 to Figures 3 and 4 it can be noted that the operating distance increases as processing gain is increased. These increased distances are more indicative of modern sonar systems. Thus a detection range of the order of 300 m when using a more sophisticated 120 kHz sonar system employing a frequency-modulated transmission and a larger transducer array is appropriate.

This analysis, albeit simple, highlights that passive sonar reflectors are practical technologies for use in underwater positioning systems supporting useful operating distances, if a reasonable target strength can be attained by the reflector. Verification of the target strength achievable by a SonarBell reflector was conducted by the University of Birmingham. The methodology and results are described in the following section.

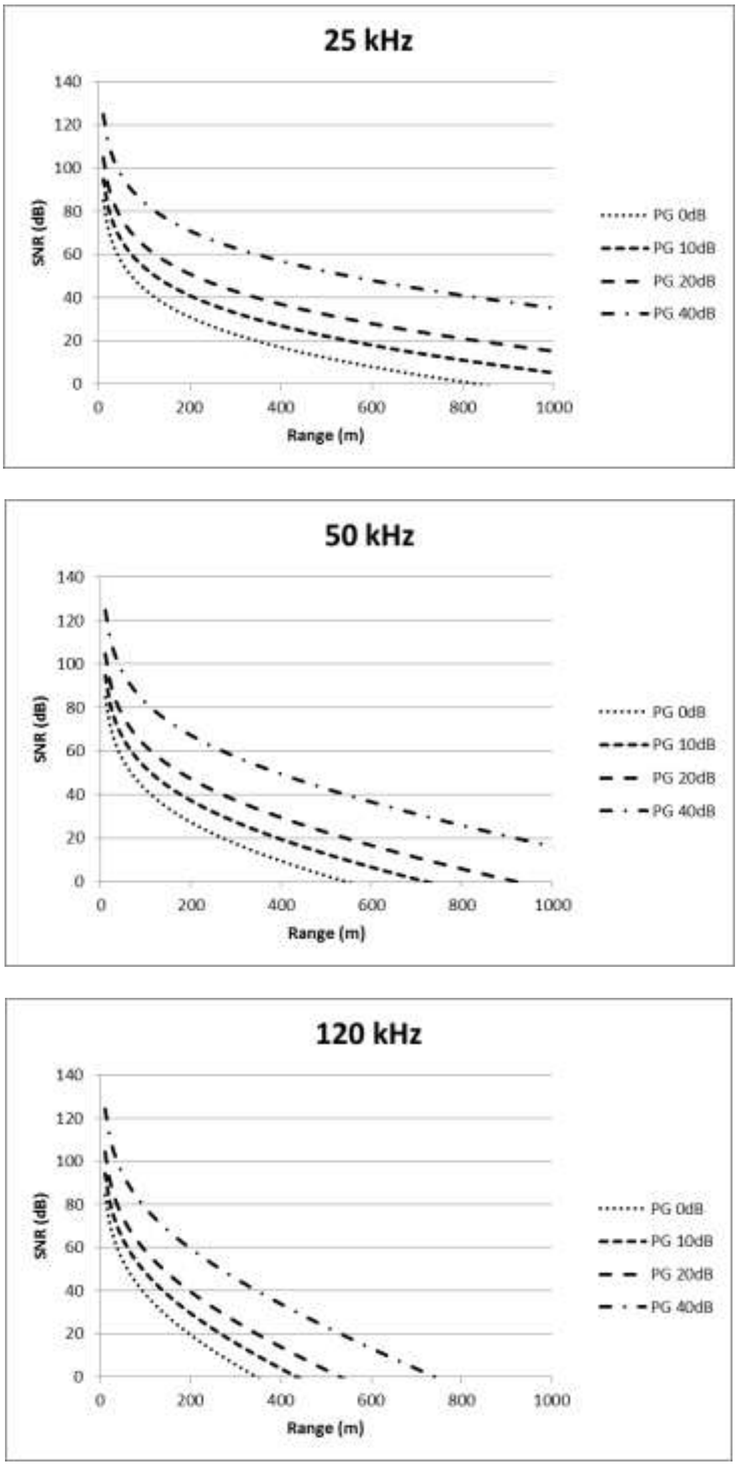


Figure 5. Plots of SNR against operating distance for a reflector with a -5 dB target strength for a sonar with different processing gains (PG) operating at a frequency of 25 kHz, 50 kHz and 120 kHz and NL of 70dB re 1µPa.

3 PERFORMANCE MEASUREMENTS

3.1 Laboratory water tank measurements

SonarBell performance was validated by means of extensive acoustic measurements executed in the water tank laboratory of the University of Birmingham. The experimental set-up was based on the methodology for standard-target sonar calibration. This involves backscattering measurements with the target located in the centre of the acoustic beam. The experiment geometry is depicted in Figure 6, with R as the range from the transducer to the target, and θ = 0º, for a monostatic arrangement.

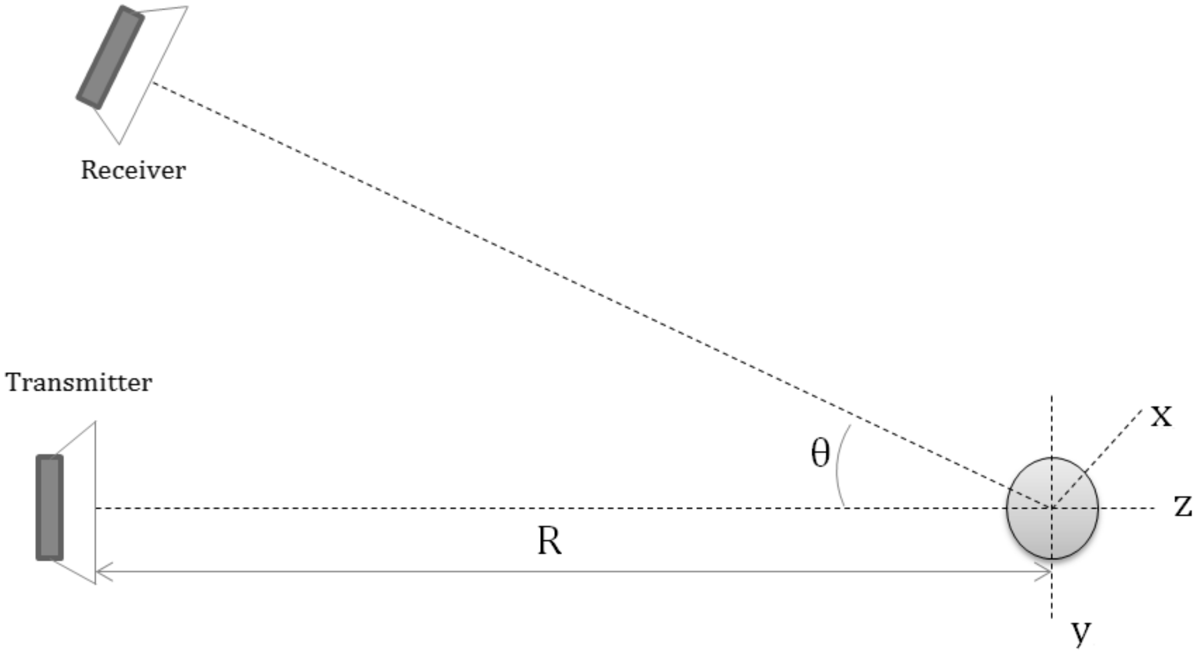


Figure 6. Geometry of the acoustic measurement, with θ = 0º for a monostatic setup.

The sonar system comprised a Reson TC-2130 broadband transducer connected to custom-made receiver and transmitter circuitry, based on a National Instrument NI-6251 data acquisition card. The complete system was previously calibrated using the standard-target method and tungsten carbide spheres. Essentially, the acoustic return of a known target is compared to its theoretically calculated value. The difference corresponds to the system response, which is compensated in subsequent experiments in order to show the true response solely related to the target. In this sense, the complete electro-acoustic instrumentation installed in the water tank laboratory of the University of Birmingham has been tested to a high degree of accuracy.

Initial calibration was performed using tungsten carbide spheres with nickel binder. These spheres are considered optimal standard targets due to their hardness, robustness and resistance to corrosion. The calibration frequency range spanned from 50 kHz to 180 kHz, an operation band that is relevant to several sonar application areas.

The achieved precision of the procedure is evaluated by comparing a predicted response to calibrated measurements. The system developed has been shown to reach an RMS error of approximately 0.1 dB across the band, when resonances are not present. This figure is the lowest, best-case scenario estimated from discrepancies between measured and theoretical values. The potential sources of error and variability are related to the system, the target and the medium, and the analysis of these root causes has been attempted elsewhere (Foote, 1983). Practical considerations of stability and repeatability of the experimental sonar system have been recently examined, showing parameters such as the variation coefficient to be as low as 0.28 % for long–term pinging (Islas-Cital and Atkins, 2012). Full descriptions of the calibration method and experimental settings can be found in Islas-Cital et al., 2011). This publication also discusses the addition of target phase to the calibration, a research line that is the main focus of the Ph D thesis of one of the authors (Islas-Cital, 2012) but not covered within this text.

Acoustic measurements of the SonarBell were completed both with stepped-frequency continuous wave (CW) pulses, and Linear Frequency Modulated (LFM) chirps. The chosen SonarBell was 200 mm in diameter and optimized for 120 kHz. It was held in a thin fibre net (Foote et al., 1987) during calibration, as shown in Figure 7.

Figure 7. Calibrated 200 mm diameter SonarBell and supporting net.

The size of this sphere allowed for clear time resolution of the echo components of the return, namely the specular part and the secondary part. A typical raw echo trace for a 100 µsec LFM pulse transmission is shown in Figure 8. The different arrivals are clearly separated in time (space), a capability that relies on system resolution and target dimensions. For smaller targets the echo components may be overlapped.

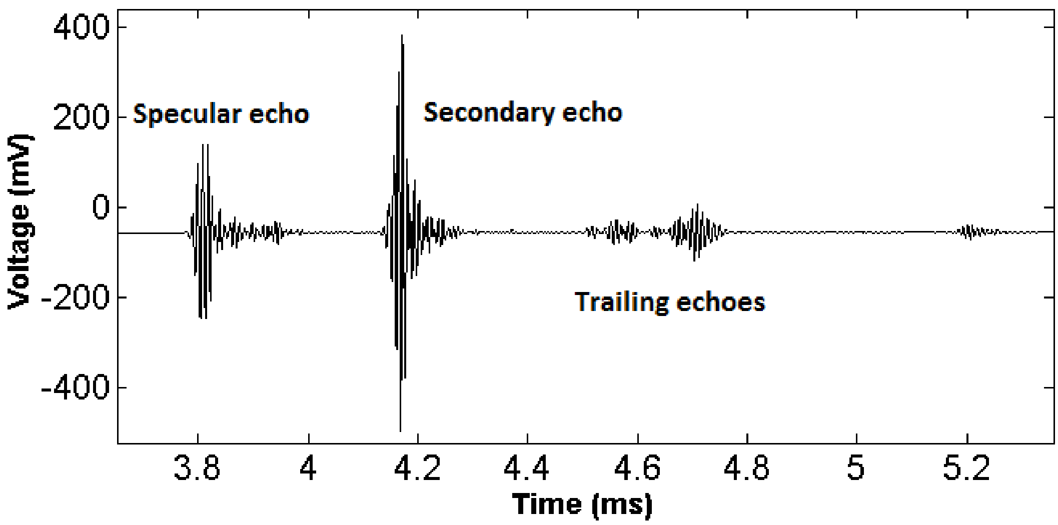


Figure 8. Raw received echo from a 200 mm diameter SonarBell using an LFM pulse.

The calibrated amplitude response of the 200 mm diameter, 120 kHz optimised SonarBell, is shown in Figure 9, for the specular and secondary echoes. The individual responses were obtained by means of temporal windows applied to the raw echo, and subsequent Fourier processing, as explained in detail in the reference literature.

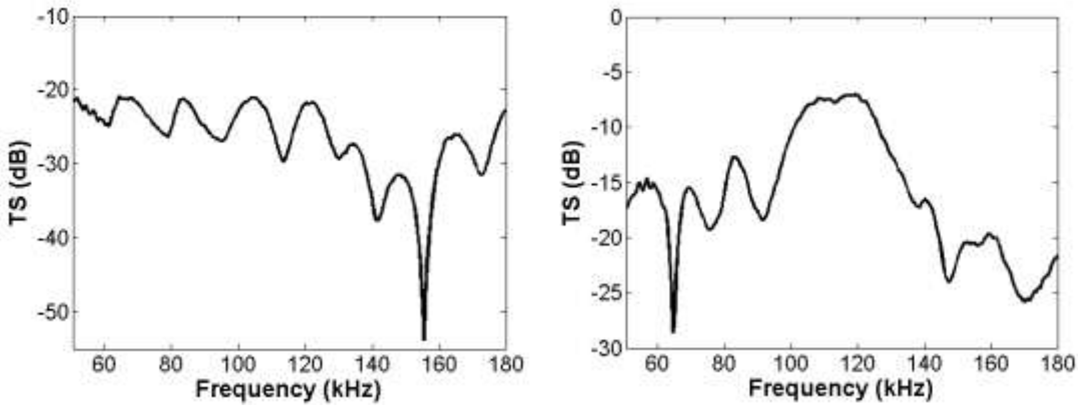


Figure 9. Calibrated amplitude response of a 200 mm SonarBell optimised for 120 kHz; (left) specular echo and (right) secondary echo.

It can be observed that the response due to the specular echo approximates the nominal TS value for a rigid spherical target, -26 dB, as given by Equation 4. However, an oscillatory behavior and deep notches are also present in the frequency response and deviate from this value. These additional features are found in the first and second responses. The echo formation mechanisms that generate these features are related to the interaction with other types of surface waves circumnavigating the sphere, but they are not covered in detail in the present work.

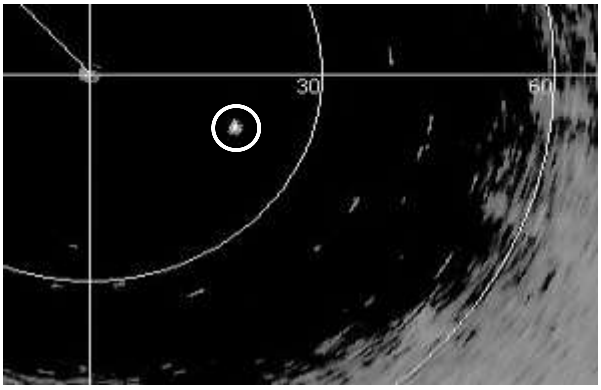
As expected, the secondary component presents higher target strength, since this effect has been enhanced by design. An increased response is found around the frequency range of 105 kHz to 125 kHz, which falls within the desired specifications for this sphere. Within this frequency range a maximum target strength of approximately -7 dB was measured for the second component. This value would correspond to a much larger, 1.8 m diameter, perfectly rigid sphere reflecting isotropically, according to Equation 4.

3.2 Field measurements

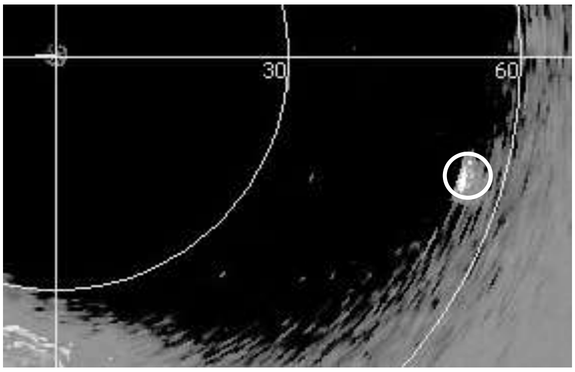
Several trials and demonstrations have been completed using SonarBell. Collectively they provide practical evidence of the performance and use of SonarBell in real situations. Two demonstrations are described in this text; the first demonstrates the performance of the SonarBell and the second demonstrates the ability of a Remotely Operated Vehicle (ROV) pilot to navigate along a course defined by a line of SonarBells.

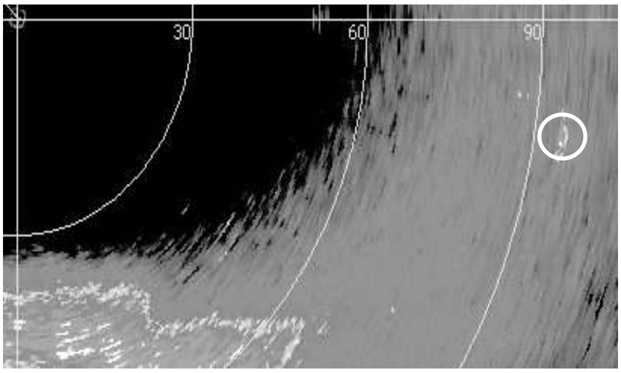
3.2.1 Lake Windemere performance demonstration

In 2010 a demonstration was completed in Lake Windemere in England. A 200 mm diameter SonarBell, selected for operating at 325 kHz, was deployed on a rope connected between a buoy and a seabed weight. Using a Tritech Super SeaKing mechanical scanning sonar operating at 325 kHz and deployed from a trials' vessel, the echoes from the SonarBell were logged whilst the distance between the sonar and SonarBell increased as the trials vessel drifted. Figure 10 presents a sequence of screenshots from the output of the sonar. Each screenshot has been annotated to show the position of the SonarBell (circle). In this demonstration the SonarBell was observed to a distance of 210 m.



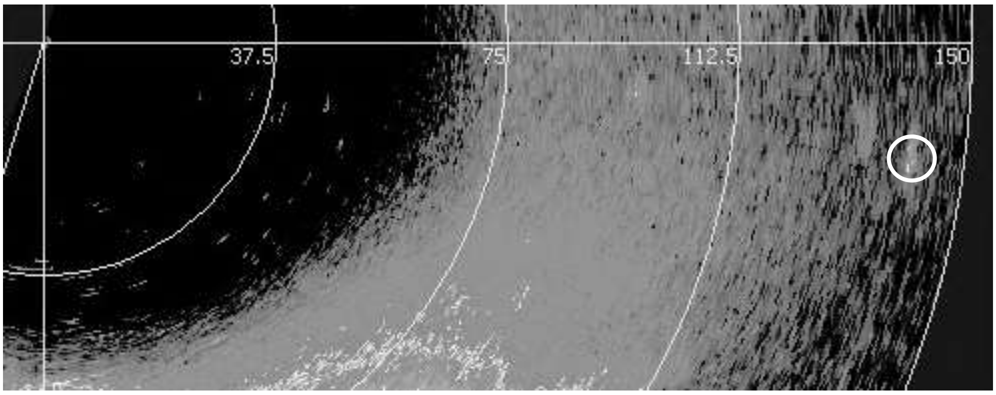
At 20 m



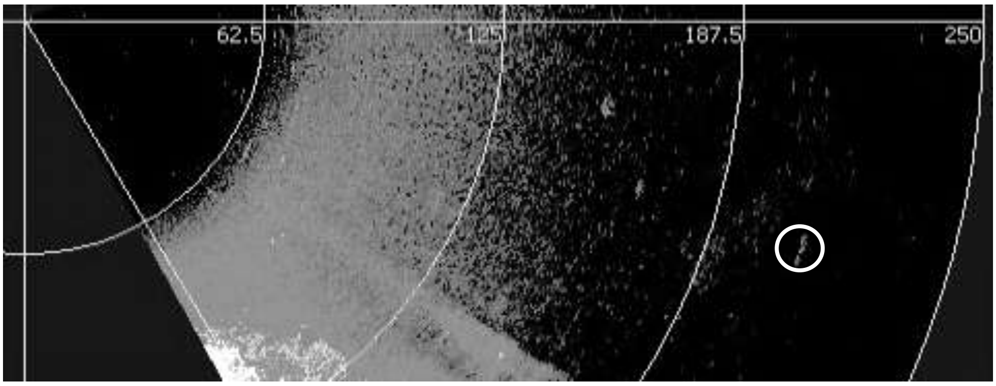


At 55 m

At 95 m



At 140 m



At 210 m

Figure 10. A sequence of sonar screenshots showing the SonarBell echo return as distance between the sonar and SonarBell increases (SonarBell positions highlighted with a circle).

An additional sonar screenshot from the Lake Windemere logged data is shown in Figure 11. This screenshot was taken when the distance between the sonar and SonarBell was 13 m. The screenshot clearly shows the double echo return from a SonarBell, that is, the specular and secondary echoes.

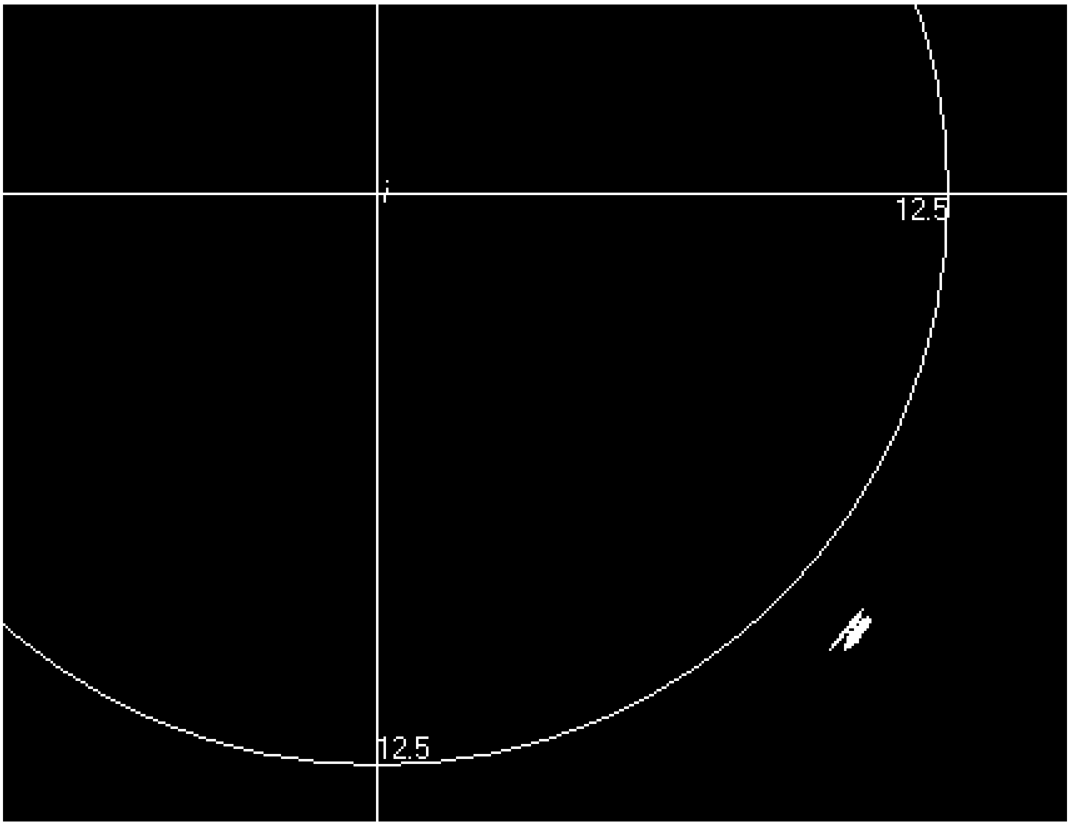


Figure 11. Double echo return from a SonarBell at 13 m distance.

3.2.2 Fort William ROV navigation demonstration

Operating at the Underwater Centre at Fort William in Scotland provided an opportunity to demonstrate the ability of an ROV pilot to navigate along a predefined track marked by a line of SonarBells.

A line of SonarBells was deployed to the seabed and consisted of twelve 100 mm diameter units and one 200 mm diameter unit. The SonarBells were spaced 10 m horizontally and floated 0.5 m above the seabed. A downward sloping seabed gradient was present resulting in the SonarBells lying in depths between 30 m and 60 m. Using an ROV fitted with a Tritech Super SeaKing mechanical scanning sonar the sonar echoes from the line of SonarBells were captured. A sonar screenshot recorded during the demonstration is shown in Figure 12 (left). It can be seen that the sonar picture is complex and it is difficult to identify the position of the line of SonarBells within it.

However, by reducing the sensitivity of the sonar to reduce the false alarm rate, the image becomes clearer and seven SonarBells from the line are clearly visible, as shown in Figure 12 (right, SonarBell positions annotated with circles). Operating with the sonar sensitivity reduced, an ROV pilot was able to navigate a vehicle along the line marked with SonarBells; which provided an easy and intuitive method of determining and correcting the direction of travel.

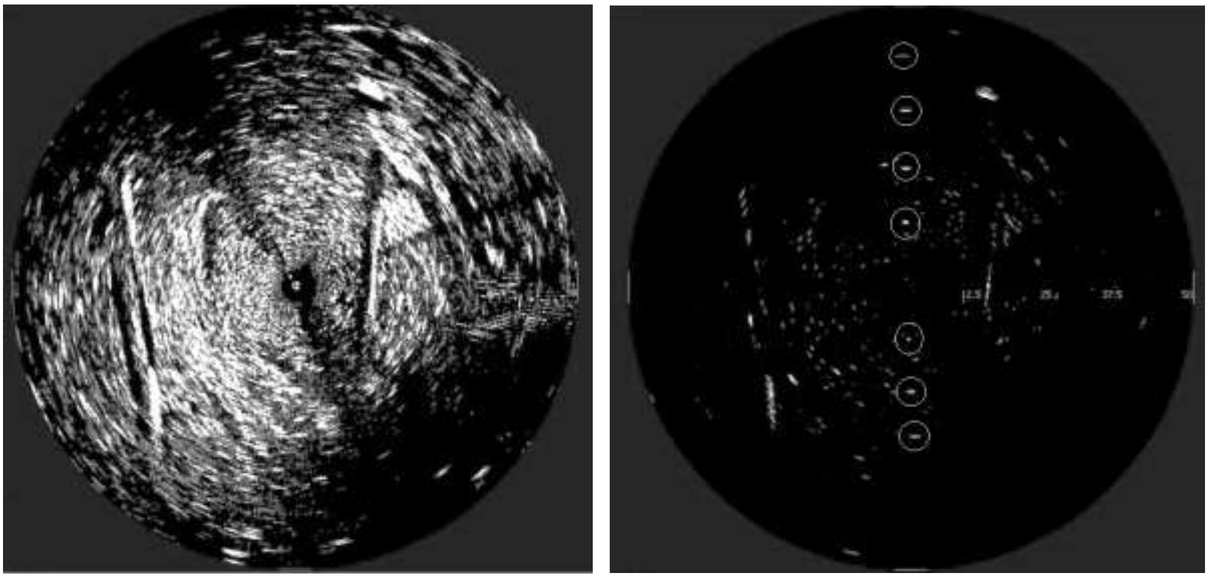


Figure 12. An example of the sonar picture of the line of SonarBell; (left) image of line of SonarBell and (right) same image with sonar sensitivity reduced, positions of SonarBell highlighted by circles.

In this example navigation of the ROV along a predefined track was only possible because the SonarBells achieve high target strengths, staying visible even when the sonar sensitivity was reduced in order to suppress the noisy background.

4 DISCUSSION

A commercially available enhanced passive sonar reflector has been presented and the target strength of a 200 mm diameter SonarBell measured. It was demonstrated that this particular SonarBell can reach a maximum target strength of approximately -7 dB provided by the second echo at its design frequency, which is controlled carefully by the choice of construction materials and dimensional parameters. A passive sonar reflector with this target strength level is considered useable as part of an underwater positioning system. From basic sonar equation analysis presented in this work, it can be seen that with a modest processing gain a position system using SonarBell reflectors will be able to operate over hundreds of metres, which the authors believe is sufficient performance for many underwater positioning applications.

The target strength responses of the 200 mm diameter SonarBell also display other interesting features. Besides the intended return enhancement other characteristics are observed in both the specular and secondary echoes. These characteristics, as well as others not described herein, may also be of use in improving the performance of underwater positioning systems using passive sonar reflectors. These are the subject of further work.

In-field tests are presented which provide examples of using SonarBell. Both tests show SonarBell to be a passive sonar reflector that can work in different real-life situations.

5 CONCLUSIONS

It has been shown that a passive sonar reflector, SonarBell, is capable of achieving a target strength which is equivalent to that of a much larger object thus presenting a device which is easier to deploy and use, resulting in significant operating cost benefits. The SonarBell is an underwater reflector with high acoustical visibility, its characteristics have been described and its performance has been demonstrated in experiments in the water tank and in the field.

It has been shown that the target strength achieved by a SonarBell allows it to be used by a variety of sonar systems. In particular it has been shown by simple sonar performance analysis that SonarBells are suitable for use within underwater positioning sonar systems.

REFERENCES

Allen JS, Kruse DE, and Ferrara KW (2001). Shell waves and acoustic scattering from ultrasound contrast agents. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **48**, 409-418.

Atkins PR, Francis DTI, and Foote, KG. (2007). Broadband ultrasonic target strengths of hollow ceramic flotation spheres. In: *Proceedings of OES/MTS Oceans 2007*, Aberdeen, Scotland, 18-21 June 2007, 1-4.

Boehme H and Stockton JE. (1990). Alternate focusing fluids for passive acoustic targets. *Journal of the Acoustical Society of America* **88**, 2484-2486.

Edwards I. (2008). The Grimsby Myth, Subsea 7. Available at: http://www.cesalt.co.uk/downloads/ (Accessed: 30th October 2012).

Folds DL. (1971). Target strength of focused liquid-filled spherical reflectors. *Journal of the Acoustical Society of America* **49**, 1596-1599.

Folds DL and Loggins CD. (1983). Target strength of liquid-filled spheres. *Journal of the Acoustical Society of America* ***73, 1147-1151.***

Foote KG, Knudsen HP, Vestnes G, MacLennan DN, Simmonds EJ (1987). Calibration of acoustic instruments for fish density estimation: a practical guide. Cooperative Research Report Const. Int. Explor. Mer, 144, 69pp.

Foote KG. (1983). Maintaining precision calibrations with optimal copper spheres. *Journal of the Acoustical Society of America* **73**, 1054-1063.

Gamroth E, Kennedy J, and Colin B. (2011). Design and testing of an acoustic ranging technique applicable for an underwater positioning system. *International Journal of the Society for Underwater Technology* **29**, 183-193.

Global Marine GeoCable (2012). Available at http://www.globalmarinesystems.com/Capabilities/Charting_GeoCable (Accessed 24th October 2012).

Islas-Cital A (2012). Amplitude and phase sonar calibration and the use of target phase for enhanced target characterisation. Ph.D. Thesis, Dept. of Electrical, Electronic, and Computer Engineering, University of Birmingham.

Islas-Cital A, Atkins PR, Foo KY, and Picó R (2011). Phase calibration of sonar systems using standard targets and dual-frequency transmission pulses. *Journal of the Acoustical Society of America* **130**, 1880-1887.

Islas-Cital A and Atkins PR. (2012). Practical considerations in the amplitude and phase calibration of sonar systems in laboratory water tanks using the standard-target method. *Proceedings of Meetings on Acoustics* **17, 1-9.**

Kaduchak G and Loeffler CM. (1998). Relationship between material parameters and target strength of fluid-filled spherical shells in water: calculations and observations. *IEEE Journal of Oceanic Engineering* **23**, 26-30.

Malme CI. (1994). Development of a high target strength passive acoustic reflector for low-frequency sonar applications. *IEEE Journal of Oceanic Engineering* **19**, 438–448.

National Physics Laboratory (2012). http://resource.npl.co.uk/acoustics/techguides/seaabsorption/, Francois and Garrison 1982 model implementation, accessed 24th October 2012.

Urick RJ (1967), Principles of Underwater Sound for Engineers, McGraw Hill Book Company, 342 pp.

Westwood, D. (2009). The world offshore operations and maintenance market report 2010-2014, Douglas-Westwood Limited, Report number: 478-09.

List of Figures and Captions

Figure 1. 200 mm diameter SonarBell passive acoustic reflector with distribution box.

Figure 2. A sequence of diagrams showing the generation of the second echo by a SonarBell.

Figure 3. Plot of received SNR against operating distance for reflectors with different target strengths operating at a frequency of 25 kHz and NL = 70 dB re 1µPa.

Figure 4. Plots of SNR against operating distance for reflectors with different target strengths for 50 kHz and 120 kHz and NL of 70 dB re 1µPa.

Figure 5. Plots of SNR against operating distance for a reflector with a -5 dB target strength for a sonar with different processing gains (PG) operating at a frequency of 25 kHz, 50 kHz and 120 kHz and NL of 70dB re 1µPa.

Figure 6. Geometry of the acoustic measurement, with θ = 0º for a monostatic setup.

Figure 7. Calibrated 200 mm diameter SonarBell and supporting net.

Figure 8. Raw received echo from a 200 mm diameter SonarBell using an LFM pulse.

Figure 9. Calibrated amplitude response of a 200 mm SonarBell optimised for 120 kHz; (left) specular echo and (right) secondary echo.

Figure 10. A sequence of sonar screenshots showing the SonarBell echo return as distance between the sonar and SonarBell increases (SonarBell positions highlighted with a circle).

Figure 11. Double echo return from a SonarBell at 13 m distance.

Figure 12. An example of the sonar picture of the line of SonarBell; (left) image of line of SonarBell and (right) same image with sonar sensitivity reduced, positions of SonarBell highlighted by circles.