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DIVER DETECTION SONARS AND TARGET STRENGTH: REVIEW AND DISCUSSIONS

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Abstract

Recent concerns about underwater intruder attacks on ships in port and harbour infrastructure raised strong interests in detecting divers. This paper reviews current research and systems on diver detection using acoustic means and the factors affecting system performance. Previous published data on diver acoustic target strength is discussed and seem to be plausibly explained by considering the acoustic scattering from a diver's body and exhaled bubbles.

1. INTRODUCTION

Recent concerns about underwater intruder attacks on ships in port and harbour infrastructure raised strong interests in detecting divers. This paper reviews current research and systems on diver detection using acoustic means and the factors affecting system performance. One critical parameter for the design specification and performance prediction of such sonar systems is the target strength of divers. Recently some data has been published on the target strength of divers. We offer a plausible explanation of the observed target strength values in terms of simple quantitative modelling.

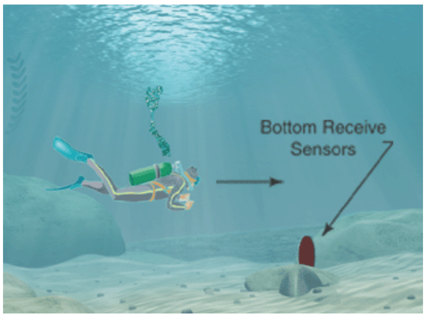
2. ACOUSTIC DETECTION OF DIVERS

2.1 Diver Detection by Passive Sonar

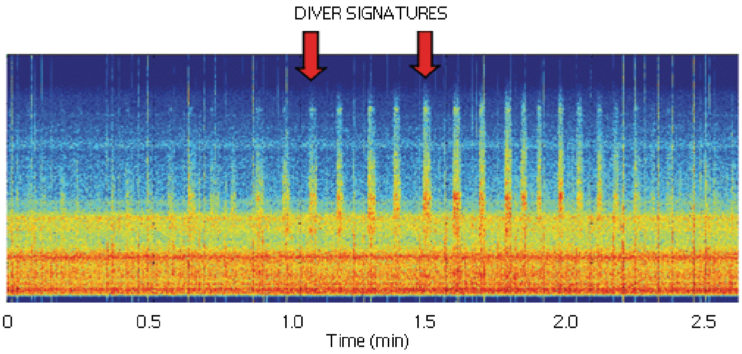
In 2002 the Naval Research Laboratory (NRL) conducted a series of detection measurements in San Diego harbour. Conventional and fiber optic hydrophone sensors were placed on the harbor bottom in 12 m of water to passively detect divers who were using open circuit breathing systems [1]. Figure 1 shows an example of the received signals as the diver approached the sensors at a height of 2 m above the bottom. The signals were first detected when the diver came within 24 m, and the levels increased as the diver approached the sensors and passed directly overhead. The acoustic emissions from the dive equipment and the diver's breathing patterns were clearly visible. The detections were made using individual hydrophones. Using multi-channel arrays and array processing would provide longer detection ranges and bearing information.

Passive fibre-optic sonar arrays were part of Northrop Grumman's "Centurion" harbour defence system, which was reported to detect divers with a battery-powered underwater propulsion device [2,3].

DRS Technologies' coastal and harbor surveillance system, Sea Sentry, employs passive acoustic sensors (or optional active acoustic and other sensor options) to detect intrusion into coastal and in-shore areas [2,4].



(a)



(b)

Figure 1. (a) Diver and bottom-mounted passive sensor. (b) Received acoustic emissions as the diver approached and passed over a hydrophone. The diver's breathing patterns are clearly shown. The figures are reproduced from Ref .[1].

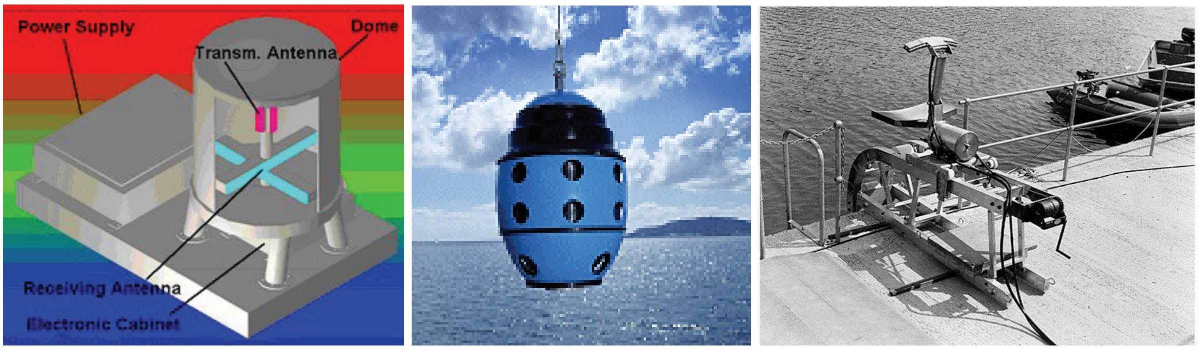
2.2 Diver Detection by Active Sonar

Sonar performance modelling studies have also been conducted to investigate detection of divers by platform-mounted ASW or mine avoidance sonars [5]. However, the majority of diver detection sonars are high frequency, active systems. There are many such systems that are in development or in service. We briefly list some examples to illustrate their operating frequencies and system characteristics. The list is not exhaustive. Listing a system in this paper constitutes neither endorsement nor verification of performances claimed by manufacturer.

The diver detection sonar from dsIT and ARSTECH operates at 60 kHz [6]. The transmitter uses 4 vertical-line arrays of 0.8 m length and the receiver has four horizontal line arrays of 1.25 m length, arranged as a cross, with every two arrays mounted back to back (Figure 2a). The sonar has narrow horizontal and vertical beamwidths, CW and FM pulses, and an embedded sonar performance model to predict expected detection range. The manufacturer describes the detection ranges as: 700 m against divers using closed-breather apparatus in high noise and reverberation; 1,200 m against divers using open-breather apparatus, and 1,400-2,000 m for swimmer delivery vehicles.

The Cerberus (Fig.2b) from QinetiQ operates around 100 kHz and has a wide bandwidth of 20 kHz for pulse compression processing [2,7,8]. The wide bandwidth is designed for fine range resolution and reverberation suppression [8]. The system uses narrow horizontal beamwidths for bearing accuracy, wide vertical beamwidths for water column coverage, and combined tracking/classification for reducing false alarms [8]. It was reported that divers were detected at ranges up to 800 m and distinctive human features were identified by the high resolution pulses at distances up to 500 m [9].

The Petrel from Thales Underwater Systems (TUS), a hull mounted three-dimensional sonar designed for Mine and Obstacle Avoidance, has been described to be able to detect divers using re-breather equipment [2,10]. The Sea Guardian (Fig.2c), also from TUS, operates at 100 kHz and uses acoustic mirrors to perform beamforming [11]. It was reported that the system can detect divers at 500 m [2,11].



(a) DDS(dsIT/ARSTECH) (b) Cerberus (QinetiQ) (c) Sea Guardian (Thales)
Figure 2: Some examples of diver detection sonar systems.

C-Tech's fourth-generation CSDS-85 Omni Active Surveillance sonar operates at 80 kHz [2,12]. A series of sea trials had been conducted for its earlier versions and the following maximum ranges were reported in different environment conditions: scuba divers were detected out to 600 to 960 m; divers using re-breathing apparatus detected out to 360 m, and surface swimmers detected out to 610 m [13].

Kongsberg's SM 2000 operates at 90 kHz with a bandwidth up to 20 kHz [2,14]. Multiple sonar heads can be installed and programmed for synchronized pinging from pierside, sea-floor tripods or mobile launch and recovery units.

Lockheed-Martin Canada's wideband, omni-directional sonar reports a detection range of minimum 500 m in high reverberation conditions [2,15].

Scientific Solutions' diver detection sonar uses a series of air-backed parabolic reflectors. The company states that a test in Singapore in November 2004 showed detection ranges of over 700 m [16].

The SeaBat sonar series from Reson operate at 100, 200, and 400 kHz. The manufacturer's website has a video clip that shows detected images of divers [17].

Echoscope from CodaOctopus operates at 375 kHz, with optional frequencies of 150, 250, and 500 kHz. The company states that the sonar provides three-dimensional images in real time at up to 200 m for diver detection and other purposes [18].

2.3 Factors affecting performance

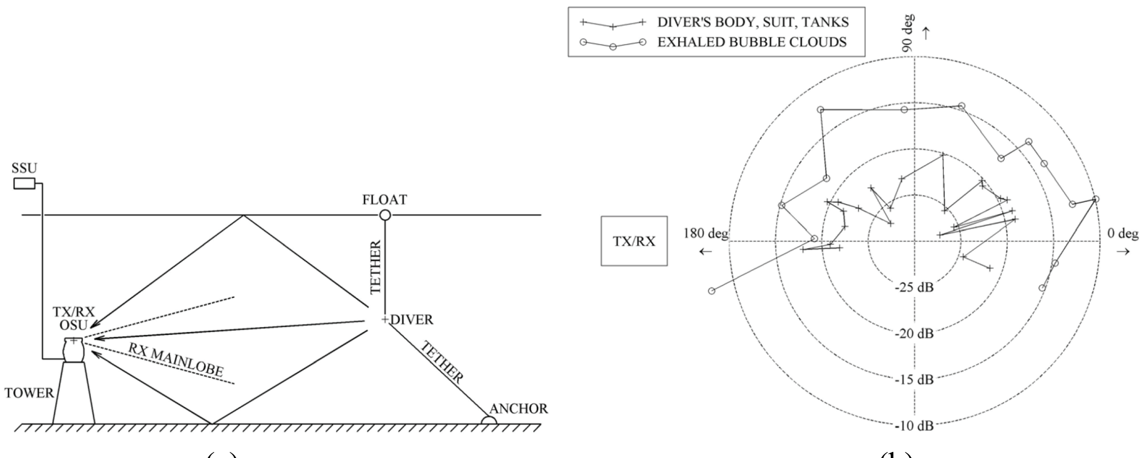
Experience from sea trials show that variable detection ranges, fluctuating echoes, and track fragmentation were the major performance limitations of current systems. They are mainly caused by variable environmental (sound propagation) conditions, presence of clutters such as rock outcroppings, buoys, and masking by wakes from boats [9].

Another factor of note is the high ambient noise levels in busy harbours. For example, at frequencies greater than 30 kHz, noise spectral levels from typical port environments can be 10 to 20 dB higher than predictions based on wind speed [19]. Noise levels also tend to increase with decreasing port latitude and are presumed to be associated with greater abundances of snapping shrimp [20].

3. ACOUSTIC SCATTERING STRENGTH OF DIVERS

One critical aspect for the design and performance prediction of diver detection active sonar is to understand and characterise the scattering mechanisms and the echo target strength.

Little published data exists on target strength of divers. For unsuited swimmers, Urick (1983) lists a value of -15 dB with no reference given about its origin [21]. Sarangapani et al (2005) tried to measure diver target strength at 60 kHz but no measurements were given [22]. Hollett et al (2006) measured diver target strengths using CW pulses of 100 kHz and 1-ms duration [23]. Their results, reproduced here in Fig. 3, show that scattering from diver-exhaled bubble clouds are the primary contributor with target strengths ranging from −10 dB to − 20 dB, averaging about −15 dB. Scattering from the diver's body, suit, and air tanks are secondary with target strengths ranging from −18 dB to −27 dB, averaging about − 23 dB.



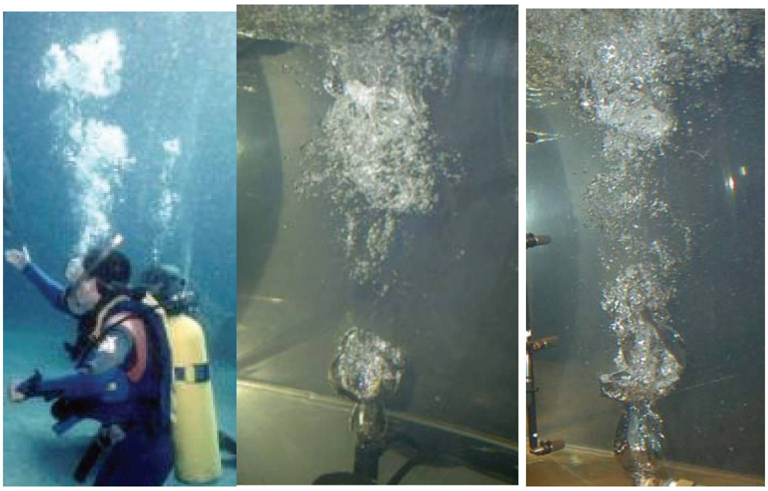
(a) (b)

Figure 3: (a) Experimental set-up; and (b) measured diver target strengths at 100 kHz, reproduced from Ref. [23].

No details were given in [23] about the shape and size of the air tanks used by the diver. Below we limit our discussion to scattering from the bubble clouds and the diver's body.

3.1 Scattering from Exhaled Bubble Clouds

Bubble formation from an underwater vent is a complex process that is affected by vent size, gas flow rate, buoyancy, viscosity and surface tension forces. The formation of a bubble at a nozzle at low gas flow rate can be calculated theoretically and has been used to size bubbles [24]. However, at high flow rate, multiple bubbles interact, coalesce and fragment, and the range of bubble sizes produced can be very wide [25]. Figure 4 shows some examples of air bubbles in water [26].



(a) (b) (c)

Fig.4: Examples of bubble clouds formed due to injection of air into water.

(a) Scuba diver (© Microsoft Encarta 2004)

(b) & (c) Bubbles from air jets, reproduced from Ref. [26]. The diameter of the orifice is 16 mm. The air flow rate is 0.53 litre/s in (b) and 1.4 litre/s in (c).

Air bubbles in water having an equivalent radius (i.e., the radius the bubble would assume if it were a sphere of the same volume) between roughly 0.5 and 7 mm tend to assume ellipsoidal shapes. Large bubbles, with an equivalent radius greater than about 9 mm in water, tend to undergo severe distortions and the shape approximates a "spherical-cap" [25].

As shown in Figure 4a, the bubbles exhaled by a diver have a distribution of different sizes. Further, the size distribution changes as the bubbles ascend. Determination of bubble size distributions requires further research. In this paper, we make the following drastic simplifications: (1) all bubbles are spherical; and (2) the distribution of bubble sizes is such that their acoustic effects can be approximated by bubbles with uniform mean radius.

First we consider the target strength of a single spherical bubble. Figure 5a shows the target strength of spherical bubbles of different radius. The bubble is at 5 m water depth and the incident sound is a plane wave at 100 kHz. We see that bubble monopole resonances occur at about 40 microns. At sea level, bubble monopole resonances occur at about 31 microns at 100 kHz [e.g., Fig.8.2.3 of Ref. 27]. The increased radius is due to the increased water depth.

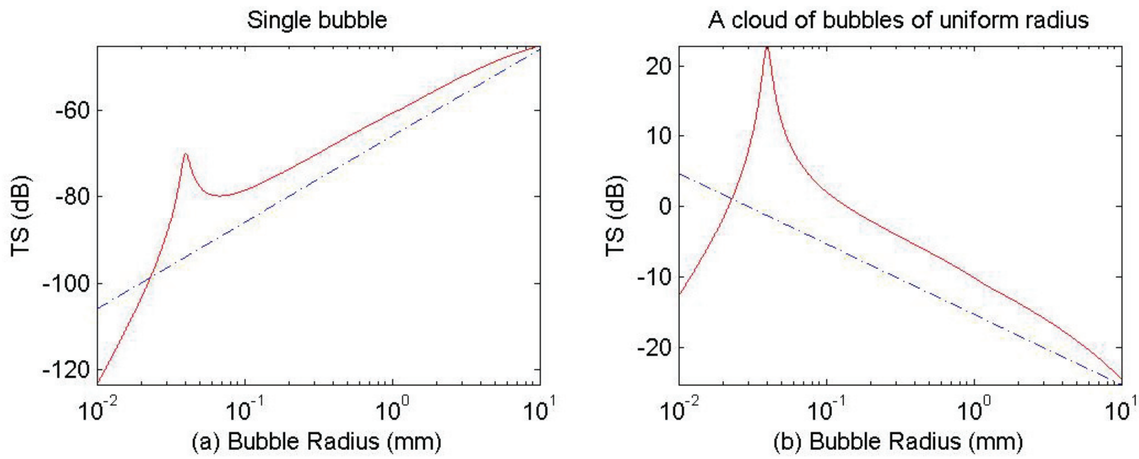


Figure 5: (a) target strength of a spherical bubble with radius from 10 micron to 10 mm. (b) target strength of a cloud of uniform-sized bubbles which collectively contain 0.5 litre of air. The dashed lines represent results of geometric acoustic approximation for large bubbles.

Next we consider the target strength of a bubble cloud exhaled by a diver. Up to 0.5 litre of air are usually inhaled and exhaled with each breath [28]. For a strenuous swimmer, we assume each exhalation contains 0.5 litre of air. Figure 5b shows the target strength of a cloud of bubbles which collectively contain 0.5 litre of air. The bubbles are assumed to be spherical and one size. Bubble movements, interaction between bubbles and multiple scattering are ignored.

Figures 5a and 5b are computed based on the work of Chapter 8 in Ref. [27]. The dashed lines represent results of geometric acoustic approximation for large bubbles.

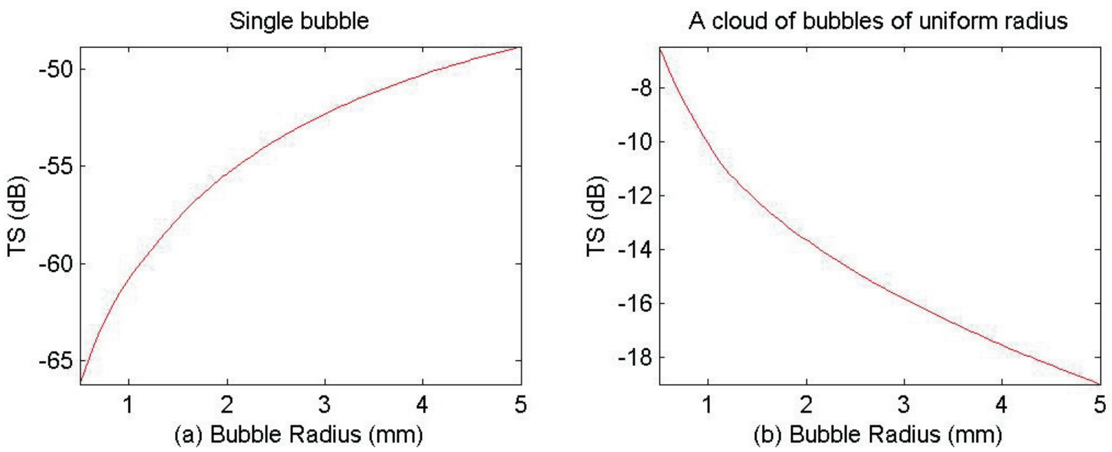


Figure 6: (a) target strength of a spherical bubble with radius from 0.5 mm to 5 mm. (b) target strength of a cloud of uniform-sized bubbles which collectively contain 0.5 litre of air.

Figure 6 is a "zoom-in" of part of Fig. 5 for bubble radius from 0.5 mm to 5 mm. It shows that if most of the bubbles have radius from 0.5 mm to 5 mm, a bubble cloud that collectively contains 0.5 litre of air will yield a target strength that is consistent with the values shown in Figure 3b.

3.2 Scattering from Diver's Body

Measurements show that the target strength of a dolphin was dominated by reflections from the dolphin's lung [29]. We assume that this is also true for scattering from human body. Human tissues, except lung and bone, exhibit sound speeds close to that of water and exhibit sound attenuation close to 0.1 Np/cm-MHz [30, 31, 32]. The attenuation also varies nearly linearly with frequency [32]. Therefore the attenuation due to human issues (skin, fat, muscle) is close to 0.1 dB/cm at 100 kHz and can be ignored [1 Np = 20/ln(10) ≈ 8.686 dB].

Based on a gas sphere of 3 litres (typical human lung capacity), Hollett et al (2006) estimated that the scattering strength from a human lung is -27 dB [23]. Here we proposed an alternative calculation with a result similar to that of ref. [23].

If we assume that the cross section of the lung cavity is approximately 17 cm by 20 cm [e.g., Fig. 7 of Ref. 33] and the sound power reflected by this area is uniformly radiated into a hemisphere of solid angle 2π, we obtain a scattering strength of -23 dB.

Another factor to consider is that the lung is not a perfect reflector. A lung with 49% air content has a sound speed of 700 m/s and density of 0.54 g/cm^3 [34], which gives us a reflection loss of -4.5 dB. In total, we obtain a scattering strength of -27.5 dB, which is consistent with the lower bounds in Fig.3b.

It is interesting to note that the measured target strength of a 2.2 m long, 126 kg dolphin is -23±4 dB at 79 kHz [29]. This value is somewhat greater than the above estimations, possibly because the dolphin's lung is larger.

4. CONCLUDING REMARKS

We reviewed current research, development and existing systems on diver detection using acoustic means. We discussed factors affecting performance and in particular, published data on diver target strength from the diver's body and exhaled bubbles. Our modelling seems to offer a plausible explanation to the measured values.

We stress modelling of the diver target strength presented in this paper is a preliminary attempt at offering plausible explanations to measurements. Radical simplifications were used in the modeling.

1. All bubbles are spherical and of the same size.
2. Inter-bubble acoustic interactions and multiple scattering are ignored.
3. Sound attenuation due to bubble extinction cross section (summation of scattering cross section and absorption cross section) were not considered.

Besides target strength, the following diver echo characteristics also affect active sonar performance and are interesting areas for further investigation.

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1. The coherence quality of echoes from diffuse and irregular-shaped scatterers such as bubble clouds and human bodies. This echo characteristic affects the gain that can be achieved by beamforming and replica correlation processing of FM pulses.
2. The Doppler effects due to diver's forward motion and body movements such as breathing and moving fins. This echo characteristic affects the performance of CW pulses.

REFERENCES

[1] S. Stanic, C.K. Kirkendall, A.B. Tveten, and T. Barock, "Passive Swimmer Detection", NRL Review 2004, (http://www.nrl.navy.mil/content.php?P=04REVIEW97).

[2] Jane's Information Group, *Jane's Underwater Warfare Systems, 2006* and *Jane's Underwater Technology, 2006.*

[3] http://www.nsd.es.northropgrumman.com/Automated/products/Centurion.html

[4] http://www.drs.com

[5] D. Schneider and Corsten, A. "Combined performance of various sonar systems for own ship harbour protection against an asymmetric attack", *Turkish International Conference on Acoustics, 2005*. http://www.tica05.org/.

[6] www.dsit.co.il and www.arstech.de

[7] http://www.qinetiq.com/home/commercial/transport/marine/cerberus.html

[8] T., Clarke, A. Webb, C. Minto and D. Stanhope, "The Cerberus Wideband Swimmer Detection

Sonar", *Marine Technology Reporter*, November 2006, (www.seadiscovery.com).

[9] R.T. Kessel and R.D. Hollett, "Underwater intruder detection sonar for harbour protection: state of the art review and implications", *The Second IEEE International Conference on Technologies for Homeland Security and Safety*, Istanbul, Turkey 9-13 October 2006.

[10] C. Ellis (2001), "Adaption of PETREL USM 5424 mine avoidance sonar for divergent operational requirement", *UDT Hawaii 2001*, paper 12A-1.

[11] B., Garnier and R. Woodall, "MAPS: the ultimate harbour protection system", *Turkish International Conference on Acoustics 2005*. http://www.tica05.org/.

[12] www.c-techltd.com

[13] R. Horodeczny and G. Boszormeny (2002), "Development program - Active sonar for security applications", *UDT Korea 2002*, paper 9A-3.

[14] www.kongsberg-mesotech.com

[15] http://www.lockheedmartin.com/data/assets/10867.pdf

[16] www.dawnbreaker.com/vas05/docs/SciSol-Brief.pdf

[17] http://www.reson.com/sw1493.asp

[18] http://www.codaoctopus.com/3d_ac_im/index.asp

[19] P.H. Dahl, J. H. Miller, D. H. Cato and R. K. Andrew, "Underwater ambient noise", *Acoustics Today*, **3,** 23-33, January 2007

[20] A.L. Anderson and G.L. Guber (1971), "Ambient Noise Measurements at 30, 90, and 150 kHz in Five Ports," *J. Acoust. Soc. Am.* **49**, 928-930.

[21] R. Urick, *Principles of Underwater Sound* (McGraw-Hill, New York, 1983), 3rd Ed.

[22] S. Sarangapani, J.H. Miller, G.R. Potty, D.B. Reeder, T.K. Stanton, and D. Chu, "Measurements and modeling of the target strength of divers," *Oceans 2005 - Europe* , **Vol. 2**, pp. 952- 956, 20-23 June 2005

[23] R.D. Hollett, R.T. Kessel, and M. Pinto, "At-sea measurements of diver target strengths at 100 kHz: measurement technique and first results", *UDT-Europe 2006*, Hamburg, Germany, 27-29 June 2006.

[24] M.S. Longuet-Higgins, B.R. Kerman and K. Lunde (1991). "The release of air bubbles from an underwater nozzle", *J. Fluid Mech*., **230**: 652-661.

[25] T.G. Leighton (1992), *The acoustic bubble*, Academic Press (London, England).

[26] C. Norwood and L. Chen (2004), "Water Injection for Bubble Noise Reduction", *Proceedings of Australian Acoustical Society Conference 2004*, 3-5 November, Gold Coast, Australia.

[27] H. Medwin and C.S. Clay, *Fundamentals of Acoustical Oceanography* (Academic Press, San Diego, California, 1998).

[28] *Microsoft Encarta*, 2004.

[29] W. W. L. Au (1996), "Acoustic reflectivity of a dolphin," *J. Acoust. Soc. Am*. **99**, 3844-3848.

[30] S.A. Goss, R. L. Johnston, and F. Dunn, "Comprehensive compilation of empirical ultrasonic properties of mammalian tissues," *J. Acoust. Soc. Am.* **64**, 423-457 (1978)

[31] S.A. Goss, R. L. Johnston and F. Dunn, "Compilation of empirical ultrasonic properties of mammalian tissues. II," *J. Acoust. Soc. Am.* **68**, 93-108 (1980).

[32] F. Dunn, "Introduction", in *Encyclopedia of Acoustics,* ed. Malcolm J. Crocker, (John Wiley, New York, 1997). pp. 1699-1701.

[33] A.H. Leung and S. Sehati, "Sound transmission through normal and diseased human lungs", *Engineering Science and Education Journal*, February, 1996.

[34] P.C. Pedersen and H. S. Ozcan, "Ultrasound Properties of Lung Tissue and Their Measurements", *Ultrasound In Med. & Biol.* **Vol. 12.** No. 6, pp. 483—499, 1986.