

# Estimating the risk of temporary acoustic threshold shift, caused by hydroacoustic devices, in whales in the Southern Ocean

ULRICH KREMSER<sup>1</sup>, PETER KLEMM<sup>2</sup> and WOLF-DIETRICH KÖTZ<sup>3</sup>

<sup>1</sup>Heinrich-Heine-Str.7, D-10 179 Berlin, Germany

<sup>2</sup>Hahns Mühle 5, D-12 587 Berlin, Germany

<sup>3</sup>Marinesteig 2, D-14 129 Berlin, Germany

**Abstract:** There is a potential threat to marine mammals from acoustic signals emitted by hydroacoustic devices. The impact on the hearing of marine mammals depends on the technical parameters of the instruments and on the exposure of the animal to noise pulses, as well as on the properties of the biological system, that is to say, on the anatomy and the audiogram of the animal. Here, the blue whale, the sperm whale and the beaked whale are taken as examples in an investigation of the potential exposure to noise pulses from the hydroacoustic instruments Hydrosweep and Parasound. Diving depths of the whales and relative speeds of the animals with respect to the survey vessels are taken into account, as well as the area impacted by the equipment, in estimating the level of sound needed to produce “temporary threshold shift” in an animal. The results suggest that auditory damage is only likely if animals pass the transducer at close range and that the impact on marine mammals can be mitigated by implementing prior detection and shut down procedures.

Received 20 January 2003, accepted 21 May 2004

**Key words:** Antarctic Treaty, environmental protection, Hydrosweep, mitigation measures, Parasound

## Introduction

The region of Antarctica, including the waters south of 60°S was declared a protected area by the Antarctic Treaty (Antarktisvertrag 1959) and the Protocol of Environmental Protection to the Antarctic Treaty (Madrid Protocol 1991). According to the Protocol, activities in this area must be planned and conducted so as to limit adverse impacts on the Antarctic environment. The Protocol requires the assessment of possible environmental impacts of any activity before it takes place, including scientific activities such as the use of shipborne hydroacoustic devices.

This paper seeks to develop an estimate of the risk posed to whales by two typical and widely used hydroacoustic instruments, the Hydrosweep multibeam swath mapping echo sounder and the Parasound sub-bottom profiler.

The risk of injuring a whale is estimated by:

- modelling the exposure of a whale to noise pulses, and
- assessing whether exposure will lead to damage to hearing in the form of temporary threshold shift (TTS).

Exposure to noise can significantly alter hearing in humans and animals. The level of damage depends upon the power spectrum of the signal in relation to the sensitivity of the animal (Kryter 1994, Wartzok & Ketten 1999) and may have a cumulative impact on hearing. TTS is recoverable but can be seen as a warning that extending the exposure to the signal or increasing the sound pressure might lead to physical damage within the ear and even to a permanent threshold shift (PTS).

The acoustic signal can be characterized by parameters of

sound pressure level, energy flux, frequency, pulse duration, repetition rate and rise-time. To understand the relation between exposure to noise and impact on hearing the acoustic characteristics of the animal also have to be taken into account. They vary with individual and species. There is evidence that peak pressure and energy flux are strongly related to threshold shift in humans and animals including marine mammals (Dierhoff *et al.* 1994, Richardson *et al.* 1995, Schlundt *et al.* 2000, Nachtigall *et al.* 2001, Finneran *et al.* 2002). However, research has yet to determine definitively the sound pressure level or energy level that will produce TTS and PTS.

## Modelling the exposure of a whale to noise pulses

### *The basic model*

The exact relation between the technical parameters of hydroacoustic devices such as Hydrosweep and Parasound and those of the hearing of whales (change in behaviour, temporary threshold shift, permanent threshold shift etc.) are not yet established. The investigation in this paper is based on a model which simplifies the relationships to allow assessments of possible potential damage.

The model will use:

- the technical data of Hydrosweep and Parasound
- data on whales and on whales hearing
- data on TTS measurements and assumptions on the relation between TTS and exposure to noise

The model relates TTS and exposure to noise, using

parameters like sound pressure level, energy flux and pulse duration. Other signal characteristics, like frequency and repetition rate, are taken into consideration when interpreting the results.

A whale that swims through the beam of a hydroacoustic device is exposed to the waves emitted from the device. Given the technical data of the device and the physical conditions regarding sound propagation, the exposure depends on the time the animal takes to swim through the beam. That exposure is calculated and compared with a threshold value which is estimated to be likely to cause TTS.

### *The hydroacoustic devices*

Multi beam echo sounders like Hydrosweep are used for studying seafloor geology and benthic habitats. These shipborne devices direct sound pulses to the seafloor and receive the echoes on the ship or a towed body. The transducers must not point sideways; all are flat and use beam forming. So they are able to map a swath with a width of 7.4 times the water depth. Multibeam surveys are normally conducted in parallel tracks with some overlap between swaths and at ship speeds up to 12 knots. Single beam echo sounders like Parasound are used as sub-bottom profilers. Their acoustic signals penetrate the sea bottom and the reflections received contain information on the structure of the bottom (SCAR 2002). The technical data for both Hydrosweep and Parasound used for calculations in this paper are listed in Table I. There are other versions available with different technical parameters as well as modes for working in shallow, medium and deep waters (personal communication, Hans Werner Schenke, Alfred Wegner Institute for Polar and Marine Research, 2004).

The horizontal area of high sound intensity at a depth  $D$  below the transmitter (the footprint of the beam) is defined by beam width. The maximum sound intensity is found vertically beneath the ship and is reduced by 3 dB at beam edge.

The beam widths, foot prints and beam volumes of Hydrosweep and Parasound used in this paper are as follows:

1. Hydrosweep: Beam width of  $\alpha = 90^\circ$  (perpendicular to the ship's axis) and  $\beta = 2.3^\circ$  (parallel to the ship's axis)

**Table I.** Technical data of Hydrosweep and Parasound (as used for calculations in the paper).

	Hydrosweep	Parasound
Sound pressure level	237 dB re 1 $\mu$ Pa@1 m	245 dB re 1 $\mu$ Pa@1 m
Pulse duration	20 ms	3.8 ms
Repetition rate	15 s	5 s
Frequency	15.5 kHz	18 kHz
Bandwidth	40 Hz, pulse duration 25 ms 1 kHz, pulse duration 1 ms	40 Hz, pulse duration 25 ms 5.5 kHz pulse duration 180 $\mu$ s

2. Parasound: Beam width  $\beta = 5^\circ$

The foot prints of the beams (Hydrosweep: rectangle with sides  $a$  and  $b$ ; Parasound: circle with the radius  $r$ ) as function of water depth  $D$  are calculated as follows:

$$\text{Hydrosweep: } F_H(D) = a \times b = 2 D \tan(\alpha/2) \times 2 D \tan(\beta/2) = 4 D^2 \times 0.02 = 0.08 D^2 [\text{m}^2]$$

$$\text{Parasound: } F_p(D) = \pi r^2 = \pi D^2 \times 0.0437^2 = 0.006 D^2 [\text{m}^2]$$

The volumes of the beams of Hydrosweep and Parasound as function of water depth  $D$  are as follows:

$$\text{Hydrosweep: } V_H(D) = 1/3 \times \text{foot print} \times \text{water depth} = 0.0267 D^3 [\text{m}^3]$$

$$\text{Parasound: } V_p(D) = 1/3 \times \text{foot print} \times \text{water depth} = 0.0020 D^3 [\text{m}^3]$$

It should be noted that the beam in reality has no sharp limits as suggested by the calculations above. Sound pressure levels of Parasound drop rapidly with angle away from the main beam axis, losing 20 dB at  $15^\circ$  and 40 dB by  $60^\circ$ . A similar decrease of sound pressure can be stated for Hydrosweep (SCAR 2002) but the beam is a broad fan.

The sound pressure level (SPL) as a function of distance from the source is calculated according to

$$\text{SPL [dB]} = \text{SL} - 20 \log_{10}(R/R_0) - B(R/R_0) \quad (\text{Gausland 1998}) \quad (1)$$

SL = source level at reference distance  $R_0$

B = attenuation factor (a function of frequency)

Attenuation factors of  $3.855 \text{ dB km}^{-1}$  (Hydrosweep, 15.5 kHz) and of  $5.088 \text{ dB km}^{-1}$  (Parasound, 18 kHz) were used corresponding to a water temperature of about  $^\circ\text{C}$  in the Antarctic waters (Wendt 2001).

This model (1) is appropriate for calculating the SPL for most distances involved in this study. Because of non-linear effects the SPL for the distance of less than 50 m to the transducer is taken from tables (Wendt 2001). Estimates over long ranges require more sophisticated models and real environmental data.

### *The hearing in whales*

Animal hearing is described by the audiogram of the animal. The threshold of hearing depends on the frequency of the signal. Audiograms are available for human beings, some terrestrial mammals (Ahroon *et al.* 1996, Lehnhardt 1986), toothed whales (including dolphins), but not for baleen whales (Gill & Evans 2002). Gill & Evans recommend caution when transferring experimental or observational results from one species to another.

Particular caution should be exercised in extrapolating threshold sound levels of terrestrial animals to aquatic animals (Gisiner 1998).

In this paper we estimate the risk of TTS for a whale exposed to sound of multibeam and sub-bottom profiling

echo sounders. The model uses real data. Blue whales, sperm whales and beaked whales are taken as examples. Information on swimming speed and diving depth is taken from the literature.

The blue whales belong to the baleen whales and are classified by the World Conservation Union (IUCN 2000) as 'Endangered A1'. They swim at a mean speed of about 4 knots and dive to around 200 m (Gill & Evans 2002).

Sperm whales are toothed whales and classified as 'Vulnerable'. They swim at speeds around 3–5 knots and dive down to 3000 m (Gill & Evans 2002).

Beaked whales belong to the toothed whales and are classified as 'Lower Risk' by the IUCN. They are described as deep diving animals (down to 600 m and more, Bahamas Marine Mammals Stranding 2001). Gill & Evans (2002) report that beaked whales are more sensitive to sound than other whales.

Audiograms for certain species of toothed whales have been measured (Gill & Evans 2002) and they show a hearing threshold of around 40 dB re 1  $\mu$ Pa. So far audiograms of sperm and beaked whales have not been measured but one could expect them to be similar to the audiograms of the other toothed whales.

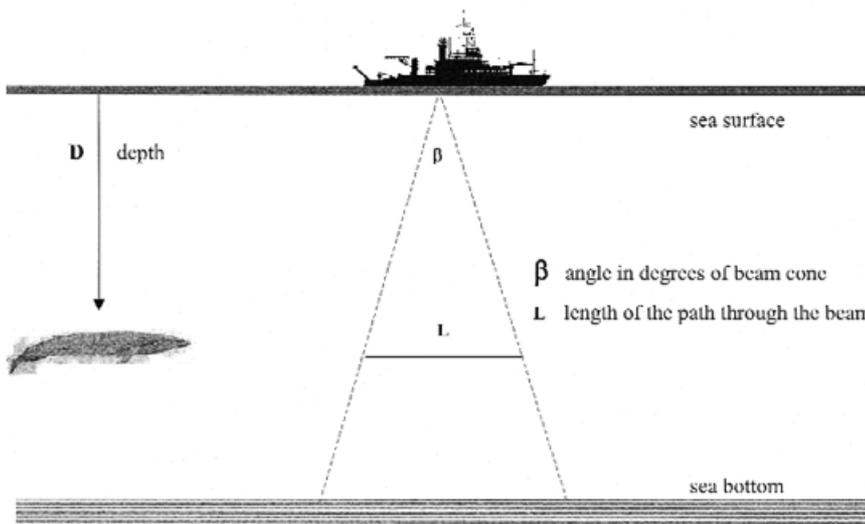
There are no audiograms available for baleen whales. But the main signals of communication between baleen whales cover a frequency range from 20 Hz to 20 kHz. In the absence of audiograms, it has been argued that whales have the greatest hearing sensitivity at the frequencies at which they communicate. Based on this assumption one would expect blue whales to be specially sensitive to low frequencies and in particular to about 10–70 Hz (Gill & Evans 2002, Mellinger & Clark 2003). This is in line with suggestions that the adaptation to living conditions under water lead to less sensitive hearing thresholds of about 80 dB at about 100 Hz in order to avoid interference by natural noise.

*Calculating the exposure time of a whale to noise pulses emitted by Hydrosweep and Parasound*

The exposure time is the time a whale is exposed to noise pulses while swimming through the beam of the device. The figures used here are: the speed of a whale at 4 knots (which corresponds to about 2 m s<sup>-1</sup>) and a moving depth down to 1000 m and more (Fig. 1).

In a worst-case scenario, we assume whale and ship moving in the same direction (along the y coordinate) with the whale moving through the centre of the beam. The case of a whale that holds the position for a long time within the beam is considered rare or even unlikely by the authors. Regarding the case of a ship riding at anchor and allowing the whale to pass the longest possible way through the beam of Hydrosweep, the authors are of the opinion that the likelihood would be very low indeed. The speed difference between ship and whale  $v_{diff}$  may vary. In the case of Hydrosweep (index: y is the coordinate, H stands for Hydrosweep, b is one of the sides which determine the footprint of Hydrosweep, P stands for Parasound, r the radius of the circle of the footprint of Parasound) the maximum time for a whale crossing the beam is  $t_{yH} = b/v_{diff}$  or  $t_{yP} = 2r/v_{diff}$ . In the case of Parasound, the maximum time is given by  $t_{yP} = 2r/v_{diff}$ . From  $t_y$ , the number of pulses n the whale is exposed to is simply  $n = t_y/t_{pd}$ , with  $t_{pd}$  as repetition time of a pulse.  $t_y$ ,  $t_m$  (averaged time, for explanation see next paragraph), n and the corresponding exposure time ( $t_{expyH}$ ,  $t_{expmH}$  and  $t_{expyP}$ ,  $t_{expmP}$ ) are shown for different  $v_{diff}$  in Table II.  $n_H/n_P$  means the total number of pulses emitted by both Hydrosweep and Parasound working simultaneously (see later section).

The maximum exposure time at a fixed depth corresponds to the worst case as explained above. In reality a whale swimming through the beam moves in different directions and will rarely make its way through the beam centre. Mean values of time for crossing the beam (averaged crossing



**Fig. 1.** Schematic picture of a vessel using hydroacoustic devices like Hydrosweep or Parasound.

**Table II.** Maximum ( $t_y$ ) and averaged ( $t_m$ ) time for a whale crossing the beam of Hydrosweep ( $t_{yH}$ ,  $t_{mH}$ ) or Parasound ( $t_{yP}$ ,  $t_{mP}$ ) at a depth of  $D_1 = 150$  m,  $D_2 = 500$  m and  $D_3 = 1000$  m, the maximum possible number  $n$  of pulses received from Hydrosweep ( $n_H$ ) and Parasound ( $n_P$ ) while crossing the beam and the corresponding maximum and averaged exposure time ( $t_{\text{expyH}}$ ,  $t_{\text{expmH}}$  and  $t_{\text{expyP}}$ ,  $t_{\text{expmP}}$ ).

$v_{\text{diff}}$ (m/s)	$t_{yH}$ (s)	$t_{mH}$ (s)	$n_{yH}$	$n_{mH}$	$t_{\text{expyH}}$ (ms)	$t_{\text{expmH}}$ (ms)	$t_{yP}$ (s)	$t_{mP}$ (s)	$n_{yP}$	$n_{mP}$	$t_{\text{expyP}}$ (ms)	$t_{\text{expmP}}$ (ms)	$n_H/n_P$
a. $D_1 = 150$ m													
3	2.0		1	1	20	20	4.4		1		3.8		1/0
2	3.0	1.7	1	1	20	20	6.5	3.8	2	1	7.6	3.8	1/1
1	6.0	2.7	1	1	20	20	13	5.9	3	2	11.4	7.6	1/2
0.5	12.0		1	1	20	20	26		6		22.8		1/5
0.4	15.0	4.6	1	1	20	20	33	10	7	2	26.6	7.6	1/6
0.3	20		2	1	40	20	44		9		34.2		2/7
0.2	30	6.6	2	1	40	20	66	14	13	3	49.4	11.4	2/11
0.1	60	9.5	4	1	80	20	132	21	26	5	94.8	19.0	4/22
b. $D_2 = 500$ m													
3	6.7		1	1	20	20	14.6		3		11.4		1/2
2	10	5.7	1	1	20	20	21.6	13	5	3	19.0	11.4	1/4
1	20	9.0	2	1	40	20	43	19	9	4	34.2	15	2/7
0.5	40		3	1	60	20	87		17		64.6		3/14
0.4	50	15.3	4	2	80	40	110	33	22	7	83.6	27	4/18
0.3	67		5	2	100	40	147		30		114		5/25
0.2	100	22	7	2	140	40	220	47	44	10	167	38	7/37
0.1	200	32	14	3	280	60	440	70	88	14	334	53	14/74
c. $D_3 = 1000$ m													
3	13.3		1	1	20	20	29		6		22.8		1/5
2	20	11.4	2	1	40	20	43	25	9	5	34.2	19	2/7
1	40	18	3	2	60	40	86	39	17	8	64.6	30	3/14
0.5	80		6	2	120	40	174		35		133		6/29
0.4	100	31	7	3	140	60	220	67	45	14	167	53	7/38
0.3	133		9	3	180	60	294		59		224		9/50
0.2	200	44	14	3	280	60	440	93	90	19	342	68	14/76
0.1	400	63	28	5	560	100	880	140	180	28	684	108	28/152

time  $t_m$ ) can be calculated by dividing the length  $L$  of the whale track through the beam by the  $y$  component of the speed difference  $v_{\text{diff}}$ , i.e.  $t_m = L/v_{\text{diff}}$ .  $L$  varies with the distance to the beam centre on the way through the beam ( $0 \leq L \leq 2r$  (Parasound) and  $0 \leq L \leq a$  (Hydrosweep)).  $v_{\text{diff}}$  is a function of the angle  $\gamma$  between the directions of movement of the ship and the whale ( $0 \leq \gamma < = 360^\circ$ ).

The results (Table II) reflect the trends expected. The smaller the difference of speed between whale and ship, the greater the exposure time. At a speed difference of  $0.4 \text{ m s}^{-1}$  and at a depth of 150 m, the whale needs only 15 s to move through the beam of Hydrosweep and is therefore targeted by one pulse only. Regarding Parasound, however, the whale takes 33 s to swim through the beam and is exposed to seven pulses.

The maximum length through the beam increases with the depth and so does the exposure time. At the same speed difference of  $0.4 \text{ m s}^{-1}$  and in a depth of 500 m, the whale needs 50 s to move through the beam of Hydrosweep and 110 s to move through the beam of Parasound. A whale

would be targeted by 4 and 22 noise pulses, respectively. Swimming through the beam at a depth of 1000 m would increase the exposure time to 100s (Hydrosweep) and 220 s (Parasound) with a corresponding number of pulses (7 and 45).

However, when evaluating the impact on the hearing it has to be taken into account that the sound intensity decreases proportionally to  $R^2$  ( $R$  = distance from the source) as does the energy flux.

### Estimating whether exposure will cause a risk of TTS

#### *The dependence of TTS on sound pressure, energy flux and pulse duration*

The risk of a threshold shift in a whale due to the exposure to noise pulses depends on, inter alia, the technical parameters of the device and the properties of the mammal's ear. Despite progress in investigating the dose–impact relation and getting more valid information on hearing and physical damage to hearing (Glorig 1988, Ridgway *et al.* 1997, NIOSH 1998, Au *et al.* 1999, Schlundt *et al.* 2000, Finneran *et al.* 2000, 2001a, 2001b, 2002, Ketten *et al.* 2001, Nachtigall *et al.* 2001, Southall *et al.* 2001, Knust *et al.* 2003) one is still far away from the aim of defining generally accepted threshold values for TTS and PTS.

Experiments with white whales and dolphins (Finneran *et al.* 2002, fig. 10a) show that TTS depends on sound pressure level, energy flux and pulse duration. A relation between sound pressure level (peak pressure) and the pulse duration can be given approximately by

$$\text{SPL}_R \text{ (dB)} = 195 - 10 \log_{10} t \quad (2)$$

where the index  $R$  indicates the risk of threshold shift and  $t$  stands for pulse duration in seconds. The rise of this equation corresponds to the energy exchange rate of  $-3 \text{ dB}$  (NIOSH 1998). Equation (2) is “a good fit to watergun” generated values (Finneran *et al.* 2002).

Schlundt *et al.* (2000) exposed white whales and dolphins to 1 s signals (sound pressure level from 141 and 201 dB re  $1 \mu\text{Pa}$  with frequencies from 3 to 75 kHz) which induced (masked) TTS (signals at frequencies of 0.4, 3, 10, 20 and 75 kHz). Nachtigall *et al.* (2001) exposed a bottlenose dolphin to octave-band noise centred at 7.5 kHz. The frequencies of the signals used and the sound pressure generated are similar to those emitted from Hydrosweep and Parasound (15.5 and 18 kHz, respectively).

#### *Evaluation of TTS risk*

Equation (2) is based on experimental results (Schlundt *et al.* 2000, Nachtigall *et al.* 2001, Finneran *et al.* 2002) and relates peak pressure and pulse duration to MTTs (temporary shift of masked hearing threshold) or TTS.

We simply assume peak pressure reduced by 10 dB not to

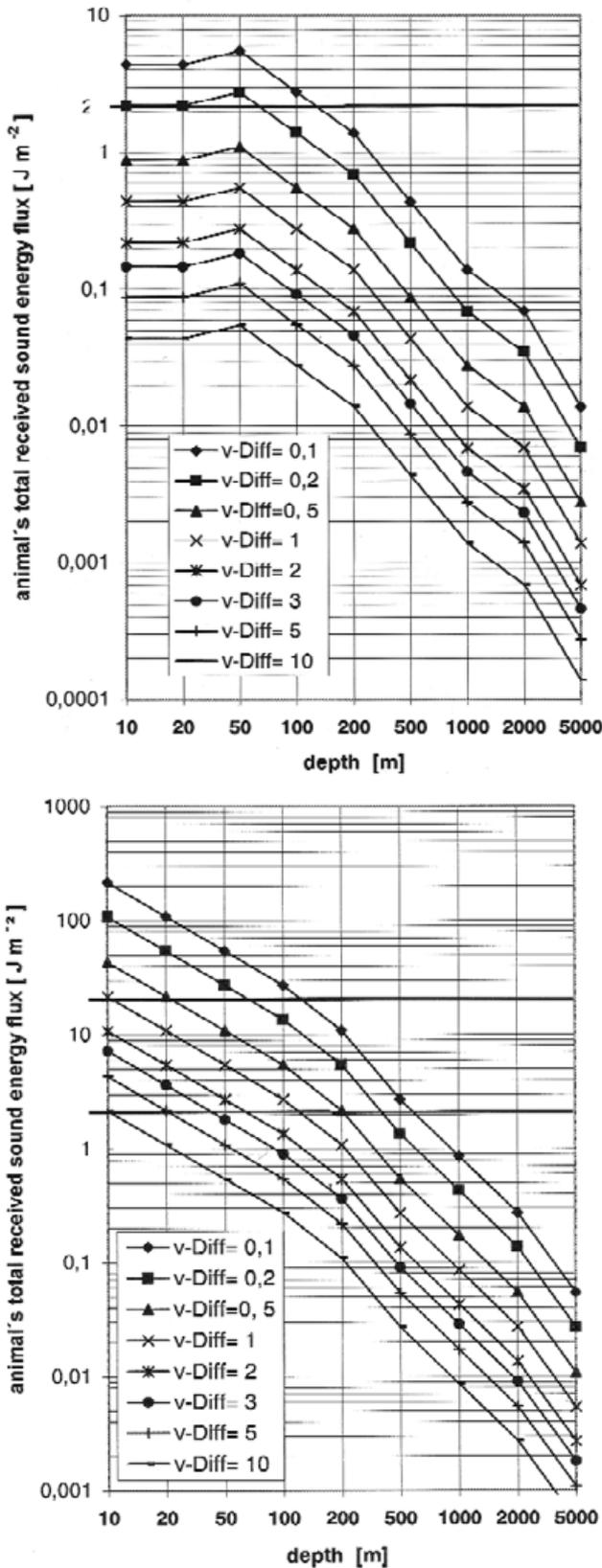


Fig. 2. Animal's total received energy flux as function of speed difference ( $v_{Diff}$  [m s<sup>-1</sup>]) and depth. **a.** Hydrosweep, **b.** Parasound. The bold lines indicate an energy flux of 2 and 20 J m<sup>-2</sup>.

induce TTS, e.g. we will use the equation

$$SPL_{mp} \text{ (dB)} = 185 - 10 \log_{10} t \quad (3)$$

for calculating a maximum permissible SPL ( $SPL_{mp}$ ) and assuming a risk of TTS when exposed to  $SPL \geq SPL_{mp}$ .

The SPL values to be used in Eqs (2) and (3) are peak pressures instead of the average values.

The energy flux is calculated by using the formula

$$I \times t = P^2 (t/\rho c) \text{ [Joule/m}^2\text{]} \quad (4)$$

$$\text{and } SPL = 10 \log_{10} (P^2/P_0^2)$$

with  $I$  = Intensity,  $\rho$  = seawater density,  $c$  = speed of sound propagation, and  $P_0 = 1026 \text{ kg m}^{-3}$ ,  $c = 1500 \text{ m s}^{-1}$ .

With  $SPL = SPL_{mp} = 185 \text{ dB}$  and  $t = 1 \text{ s}$  an energy flux of about  $2 \text{ J m}^{-2}$  results. If the energy flux exceeds this value we assume a risk of TTS

SPL for Hydrosweep and Parasound as function of distance from the source are calculated according to Eq. (1) (for depth < 50 m the SPL are taken from Wendt (2001), because non-linear effects need to be considered at such short range). The exposure time  $t$  (Table II) is calculated as sum of all pulse durations a whale is exposed to while crossing the beam. The exposure of the animal is defined as the total sound energy flux received by the animal (Fig. 2).

Figure 2a (Hydrosweep) shows a maximum exposure of about  $4 \text{ J m}^{-2}$ . The beam volume in which a whale could get exposed to an energy flux of  $2 \text{ J m}^{-2}$  and more is limited to small speed differences ( $0.2 \text{ m s}^{-1}$  and less) and short distances to the transducer ( $100 \text{ m}$  and less). According to our definition there is a risk of TTS. Due to non-linear effects the energy flux increases for depths down to  $50 \text{ m}$ .

Figure 2b (Parasound) shows a very large exposure for small depths and small speed differences. For  $v_{diff} = 0.1 \text{ m s}^{-1}$  exposures in excess of  $2 \text{ J m}^{-2}$  are confined to depths of less than  $500 \text{ m}$ . For  $v_{diff} = 3 \text{ m s}^{-1}$  (which might be more realistic with respect to the speed of the vessel when using the hydroacoustic device) limiting depth for whale passages with hazardous exposures is  $50 \text{ m}$ . Even closer to the device the animal's exposure increases further (while the likelihood of a whale passage decreases).

If both Hydrosweep and Parasound hydroacoustic devices are used simultaneously, the pulses must not overlap if additional disturbance of reflected signals from the sea bottom and from sediment layers are to be avoided. In practice, there is a shift between pulses emitted from both devices, and a series of pulses is assumed as follows (H stands for Hydrosweep and P for Parasound):

Pulse (H) 20 ms, after 5 s pulse (P) 3.8 ms, after 5 s pulse (P) 3.8 ms, after 5 s pulse (H) 20 ms and so on.

The exposure by Hydrosweep and Parasound working simultaneously is less than that by Parasound alone. The difference in SPL at a fixed depth is large very close to the source. (According to Wendt 2001, at a depth of  $10 \text{ m}$ , Parasound: Peak pressure 227 dB; Hydrosweep: Peak

pressure 211 dB; at the depth of 100 m: Parasound, 208 dB, Hydrosweep 199 dB). It means that the exposure by Hydrosweep even over a longer time (20 ms) contributes less to the exposure than a shorter pulse (3.8 ms) emitted by Parasound at a fixed depth.

### Discussion of assumptions and results

Although blue whales, sperm whales and beaked whales have been chosen as examples in this paper the calculations can be carried out for other marine mammals as well, as long as the required information is known, in particular, with respect to diving behaviour and speed.

#### *A whale very close to the acoustic source*

The time  $t_y$  a whale takes to swim through the beam increases in a linear fashion with the distance  $D$  from the transceiver while the sound pressure level decreases with the square of the distance. Therefore, the exposure of the whale is highest close to the source of sound. This is reflected in Fig. 2 which shows a big risk of TTS at short distances to the source and for small speed differences. According to Wendt (2001, p. 72) the highest sound pressure level of Parasound is found to be 227 dB (peak pressure 230 dB) at a distance of 5 m from the source because of non-linear effects. A whale very close to the source will move quickly through the beam, e.g. the time passing through the beam will be rather short. At a depth of 10 m for example the path through the beam is 0.4 m only (H) or 0.87 m (P) and depending on the speed it will take only 4 s (H), 8.7 s (P) for small speed difference ( $v_{\text{diff}} = 0.1 \text{ m s}^{-1}$ ) and 0.13 s (H), 0.3 s (P) for a speed difference of  $3 \text{ m s}^{-1}$ . The ear of the whale can be exposed to one single pulse only but the probability is small that the whale will swim through when the device emits a pulse. Additionally the probability for a whale to swim into the beam very close to the acoustic source is very small (of the order of collision with a ship).

#### *Sound pressure levels outside the beam*

The sound pressure level outside the vertical lobe (beam) decreases rapidly with the distance  $R$ . According to measurements (Richardson 2004) the sound pressure close to the sea surface is almost negligible. The sound pressure within the horizontal lobes and close to the beam is about 20 dB less than the value found in the centre of the beam (Wendt 2001) and the sound intensity decreases according to the physical law proportional to  $1/R^2$  with the distance  $R$ . If the whale is exposed to a sound pressure of 20 dB less than the maximum over a distance twice the length through the beam the additional energy by this exposure is about 2% of the energy the whale is exposed to while passing through the beam.

As has been observed baleen whales do avoid patches of strong noise. Based on that observation the horizontal lobes could serve as warning to any whale approaching the beam (Gordon *et al.* 1998).

#### *Risk of TTS*

The evaluation of whether the exposure to noise pulses emitted by Hydrosweep or Parasound is likely to lead to TTS is based on experimental results by Schlundt *et al.* (2000), Nachtigall *et al.* (2001) and Finneran *et al.* (2002). These experiments were carried out on dolphins and white whales. The extrapolation of these results to other individuals of the same species or even individuals of other species is of speculative nature.

Our investigation shows a high risk of TTS if a whale moves very close to the hydroacoustic device through the beam. For a full understanding of what it really means one has to take into account the following facts and assumptions:

- the assessment “risk of TTS” is based on the assumption, that an exposure of more than  $2 \text{ J m}^{-2}$  may lead to TTS (Finneran *et al.* 2002, found a value of about  $20 \text{ J m}^{-2}$ )
- the time a whale take to cross the beam is calculated as a worst case, i.e. it is assumed the whale always takes the longest track and thus uses the longest time possible.

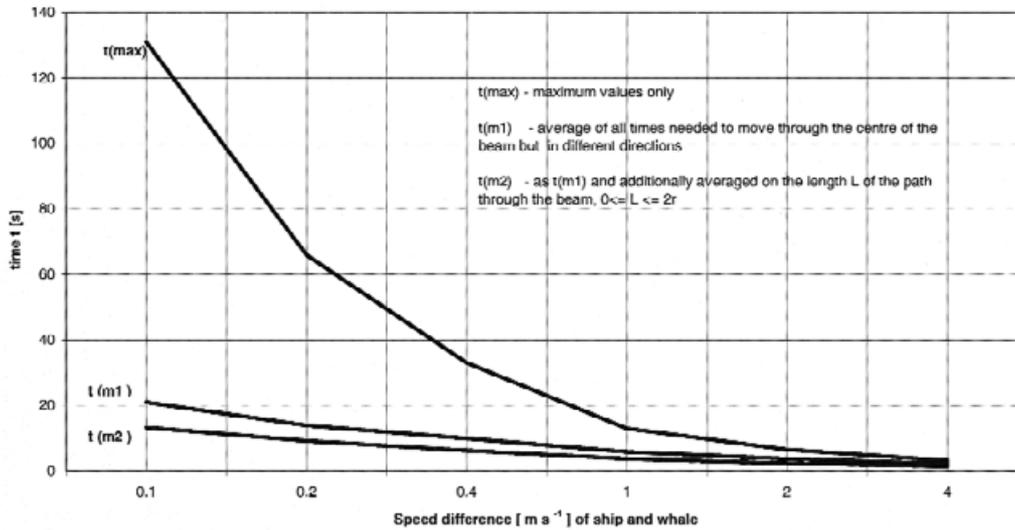
As indicated by Finneran *et al.* (2002) the recovery of TTS takes some minutes, e.g. the repetition time of these devices (15 s and 5 s) is too short for full relaxation of the hearing. Therefore, the exposure time is calculated by taking the sum of all signals and does not take into account the gaps between the signals. We do not attempt to estimate the probability of how often a whale is likely to enter the beam of a hydroacoustic device.

Apparently the assessment “risk of TTS” starts with  $2 \text{ J m}^{-2}$  and contains a large buffer zone until the whale might suffer a TTS (at about  $20 \text{ J m}^{-2}$ ). The difference alone between the “longest possible time” a whale takes to cross the beam and an averaged time makes clear how large the buffer really is (Fig. 3). In an earlier section the maximum and average times are explained and tabled (Table II). The animal’s exposures based on average beam crossing times are much smaller than those based on maximum beam crossing times (Fig. 4).

Another question not dealt with here concerns the additive effects of noise pulses emitted by Hydrosweep and Parasound. It is not known if any adverse effects are caused by superimposed pulses of different frequencies.

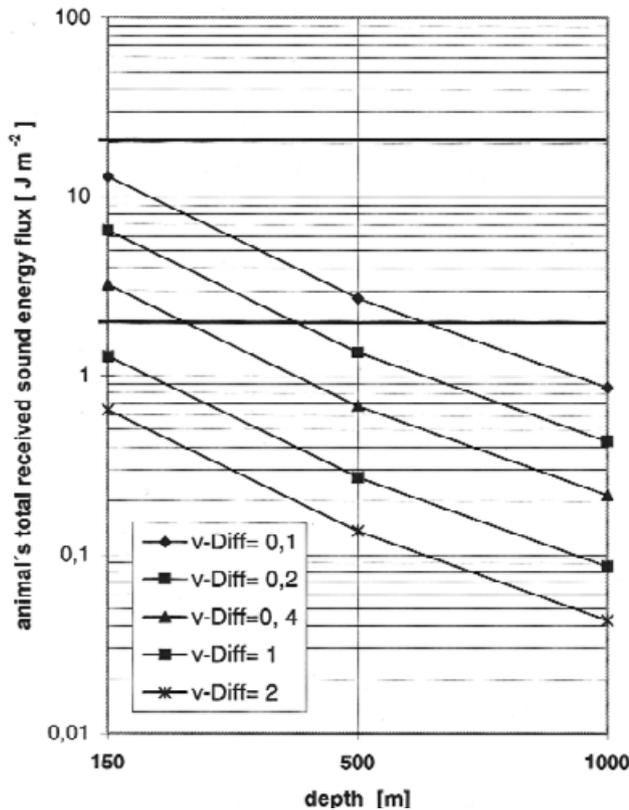
### Summary

On the evidence of current knowledge the risk of TTS is correlated to the total sound energy flux a whale receives



**Fig. 3.** Maximum  $t(\text{max})$  and averaged  $t(\text{m})$  times  $t$  of a whale moving through the beam of Parasound at a depth of 150 m.

from hydroacoustic devices. The animal's exposure can be modelled as a function of difference in speed between ship and whale and of depth at which a whale moves through the beam of the device. An exposure in excess of  $2 \text{ J m}^{-2}$  is defined to pose a risk of TTS to whales.



**Fig. 4.** Parasound: Animal's total received sound energy flux as function of speed difference ( $v_{\text{Diff}}$  [ $\text{m s}^{-1}$ ]) and depth. Exposure times are based on averaged times a whale is crossing the beam. The bold lines indicate an energy flux of  $2$  and  $20 \text{ J m}^{-2}$  respectively.

The beam volume in which the exposure of a passing whale exceeds  $2 \text{ J m}^{-2}$  is rather large for Parasound. Even for large speed differences that volume extends from the surface down to 500 m. For Hydrosweep the beam volume in which the exposure exceeds  $2 \text{ J m}^{-2}$  is smaller. For speed differences of  $0.2 \text{ m s}^{-1}$  and less that volume is limited to a depth of 100 m and the probability of a ship hitting a whale might be of the same order as the probability of a whale entering the small beam volume (e.g. the beam volume of Hydrosweep with  $D = 100 \text{ m}$  is  $26\,700 \text{ m}^3$ , the under water volume of the German research vessel *Polarstern* is between  $11\,000$  and  $17\,000 \text{ m}^3$ ).

The interpretation of main results of our investigation fit to the findings on risk evaluation by experts of an SCAR workshop (ATCM 2004).

It should be taken into account that our calculations are based on worst case assumptions for the exposure time. The consideration of average exposure times results in a much reduced risk of TTS.

Since the exposure is a function of difference in speed between a whale and a ship, long exposure could be avoided by ensuring a ship speed of about 8–10 knots. Under conditions where the vessel has to slow down - e.g. in shallow waters - to minimize the residual risk, whale monitoring should be carried out.

**Acknowledgements**

Thanks are due to Dipl.-Geogr. Ellen Roß-Reginek who contributed to this paper. We thank referees, especially Dr Phil O'Brien for his considerable help improving this paper.

**References**

AHROON, W.A., HAMERNIK, R.P. & LEI, S. 1996. The effect of reverberant blast waves on the auditory system. *The Journal of the Acoustical Society of America*, **100**, 2247–2257.

- ANTARKTISVERTRAG. 1959. Deutsche Übersetzung nach Deutscher Bundestag. 8. Wahlperiode – Drucksache 8/1824 (1978).
- ATCM XXVII. 2004. *SCAR Report on Marine Acoustic Technology and the Antarctic Environment. Information Paper IP 078*, 17 pp.
- AU, W.W.L., NACHTIGALL, P.E. & PAWLOSKI, J.L. 1999. Temporary threshold shift in hearing induced by an octave band of continuous noise in bottlenose dolphin. *The Journal of the Acoustical Society of America*, **106**, 2251.
- BAHAMAS MARINE MAMMALS STRANDING. 2001. *Joint Interim Report, Bahamas Marine Mammal Stranding Event of 15–16 March 2000*. Washington, DC: NOAA.
- DIERHOFF, H.-G. *et al.* 1994. *Lärmschwerhörigkeit*. Jena: Gustav Fischer, 512 pp.
- FINNERAN, J.J., CARDER, D.A. & RIDGWAY, S.H. 2001. Review of marine mammal temporary threshold shift (TTS) measurements and their application to damage-risk criteria. *142nd Meeting of the Acoustical Society of America, Fort Lauderdale, Florida, 3–7 December 2001. The Journal of the Acoustical Society of America*, **110**, 2721 [Abstract].
- FINNERAN, J.J., CARDER, D.A. & RIDGWAY, S.H. 2001. Temporary threshold shift (TTS) in bottlenose dolphins (*Tursiops truncatus*) exposed to tonal signals. *142nd Meeting of the Acoustical Society of America, Fort Lauderdale, Florida, 3–7 December 2001. The Journal of the Acoustical Society of America*, **110**, 2749 [Abstract].
- FINNERAN, J.J., SCHLUNDT, C.E., CARDER, D.A., CLARK, J.A., YOUNG, J.A., GASPIN, J.B. & RIDGWAY, S.H. 2000. Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. *The Journal of the Acoustical Society of America*, **108**, 417–431.
- FINNERAN, J.J., SCHLUNDT, C.E., DEAR, R., CARDER, D. & RIDGWAY, S.A. 2002. Temporary shift in masked hearing thresholds in Odontocetes after exposure to single underwater impulses from a seismic watergun. *The Journal of the Acoustical Society of America*, **111**, 2929–2940.
- GAUSLAND, I. 1998. Physics of sound in water. In TASKER, M.L. & WEIR, C., eds. *Proceedings of the seismic and marine mammals workshop, London, 23–25 June 1998*. [www.smub.st-and.ac.uk/seismic/seismicintrc.htm](http://www.smub.st-and.ac.uk/seismic/seismicintrc.htm).
- GILL, A. & EVANS, P.G.H. 2002. *Marine mammals of the Antarctic in relation to hydroacoustic activities*. Oxford: German Federal Agency for Nature Conservation/Bundesamt für Naturschutz, 216 pp.
- GISINER, R.C. 1998. *Proceedings of the Workshop on the effects of anthropogenic noise in the marine environment, 10–12 February 1998*. Arlington, VA: Office of Naval Research 141 pp.
- GLORIG, A. 1988. Damage-risk criteria for hearing. In BERANEK, L.L., ed. *Noise and vibration control*. Washington, DC: INCE, 537–553.
- GORDON, J.C.D., GILLESPIE, D., POTTER, J., FRANZIS, A., SIMMONS, M.P. & SWIFT, R. 1998. The effects of seismic surveys on marine mammals. In TASKER, M.L. & WEIR, C., eds. *Proceedings of the seismic and marine mammals workshop, London, 23–25 June 1998*. [www.smub.st-and.ac.uk/seismic/seismicintrc.htm](http://www.smub.st-and.ac.uk/seismic/seismicintrc.htm).
- IUCN. 2000. *The World Conservation Union, The IUCN Species Survival Commission, 2000 IUCN Red List of Threatened Species*. Gland, Switzerland and Cambridge, UK: IUCN.
- KETTEN, D.R., MOORE, P.W.B. & RIDGWAY, S. 2001. Aging, injury, disease, and noise in marine mammals ears. *142nd Meeting of the Acoustical Society of America, Fort Lauderdale, Florida, 3–7 December 2001. The Journal of the Acoustical Society of America*, **110**, 2721 [Abstract].
- KNUST, R., DALHOFF, P., GABRIEL, J., HEUERS, J., HÜPPOP, O. & WENDELN, H. 2003. *Untersuchungen zur Vermeidung und Verminderung von Belastungen der Meeresumwelt durch Offshore-Windenergieanlagen im küstenfernen Bereich der Nord- und Ostsee, Forschungsbericht zum F/E Vorhaben 20097106*. Berlin: Umweltbundesamt, 454 pp.
- KRYTER, K.D. 1994. *The handbook of hearing and the effects of noise*. San Diego, CA: Academic Press, 673 pp.
- LEHNHARDT, E. 1986. *Clinical aspects of inner ear deafness*. New York: Springer, 172 pp.
- MADRID PROTOCOL. 1991. *Protocol on environmental protection to the Antarctic Treaty*. Umweltschutzprotokoll zum Antarktisvertrag. Bundesgesetzblatt, Jahrgang 1994, Teil II, Nr. 45, 2478–2531.
- MELLINGER, D.K. & CLARK, C.W. 2003. Blue whale (*Balaenoptera musculus*) sounds from the North Atlantic. *The Journal of the Acoustical Society of America*, **114**, 1108–1119.
- NACHTIGALL, P.E., SUPIN, A., PAWLOSKI, J.L. & WHITLOW, W.L. 2001. Measuring recovery from temporary threshold shifts with evoked auditory potentials in the bottlenose dolphin *Tursiops truncatus*. *The Journal of the Acoustical Society of America*, **110**, 2749 [Abstract].
- NIOSH. 1998. *Criteria for a recommended standard: occupational noise exposure, revised criteria 71998*. DHHS (NIOSH) Publication No. 98–126 (NIOSH, Cincinnati, OH).
- RICHARDSON, W.J., GREENE, C.R.J., MALME, C.I. & THOMSON, D.H. 1995. *Marine mammals and noise*. San Diego, CA: Academic Press, 576 pp.
- RICHARDSON, W.J. 2004. Marine mammals vs. seismic and other acoustic surveys: Introduction to the noise issues. *Conference on impact of acoustics on marine organisms, 17–19 June 2002, Berlin, Germany. Polarforschung*, **72**, 63–67.
- RIDGWAY, S.H., CARDER, D.A., SMITH, R.R., KALMONICK, T., SCHLUNDT, C.E. & ELSEBERRY, W.R. 1997. Behavioral responses and temporary shift in masked hearing threshold of bottlenose dolphin, *Tursiops truncatus*, to 1-second Tones of 141 to 201 dB re 1  $\mu$ Pa. *Technical Report 1751, Naval Command, Control and Ocean Surveillance Center RDT&E Division, San Diego, CA*. 17 pp.
- SCAR. 2002. SCAR *ad hoc* Group on Marine Acoustic Technology and the Environment. The Impact of Marine Acoustic Technology on the Antarctic Environment. Version July 2002.
- SCHLUNDT, C.E., FINNERAN, J.J., CARDER, D.A. & RIDGWAY, S.H. 2000. Temporary shift in masked hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones. *The Journal of the Acoustical Society of America*, **107**, 3496–3508.
- SOUTHALL, B.L., SCHUSTERMANN, R.J., KASTAK, D., REICHMUTH KASTAK, C. & HOLT, M.M. 2001. Pinniped hearing and anthropogenic noise. *142nd Meeting of the Acoustical Society of America, Fort Lauderdale, Florida, 3–7 December 2001. The Journal of the Acoustical Society of America*, **110**, 2722 [Abstract].
- WARTZOK, D. & KETTEN, D.R. 1999. Marine mammal sensory system. In REYNOLDS, J.E. & ROMMEL, S.A., eds. *Biology of marine mammals*. Washington, DC: Smithsonian Institution, 117–175.
- WENDT, G. 2001. *Sondergutachten Schallsausbreitung und Berechnung der Reichweiten von Schallsignalen verschiedener hydroakustischer Geräte*. Berlin: Umweltbundesamt, 139 pp.