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Walter M. X. Zimmer: Sonar systems and stranding of beaked whales

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Sonar systems and stranding of beaked whales

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There is increasing evidence that some military sonar operations coincide with mass stranding of beaked whales. Two of these stranding events were analyzed extensively and relevant sonar parameters disclosed.
Although the controversy around the National Marine Fishery Service permit for the SURTASS-LFA (US) continues to fuel public and legal interest, the focus on SURTASS-LFA is misleading in understanding the cause and effect between sonar systems and beaked whale mass stranding events.
This presentation summarizes information on the recent stranding events and the sonar systems involved. It addresses the need of appropriate acoustic risk assessment and mitigation and describes the approach taken by the NATO SACLANT Undersea Research Centre (SLC) to deal with this issue.

Stranding events

The following stranding events related to military sonar activities aroused considerable public interest.

Greece 1996

On May12 and 13, 12-13 *Ziphius cavirostris* stranded along 35 km of the coast in Kyparissiakos Gulf. During this period NATO SLC carried out low and mid-frequency active sonar trials. [1]

Findings:
No investigations of the whales' inner ear were carried out. [1]

Bahamas 2000

"On March 15 and 16,… a multi species stranding of seventeen marine mammals was discovered in the Northeast and Northwest Providence Channels on Bahamas Islands. The stranding took place within 24 hours of U.S. Navy ships using mid-range sonar as they passed through the Northeast and Northwest Providence Channels" [2]

Findings:
"All [specimens examined] showed cerebral ventricular and subarachnoid hemorrhages, small (petechial) hemorrhages in the acoustic fats of the jaw and melon, and blood in the inner ear without round window damage (that is, the blood may have either originated in the inner ear or diffused to it from hemorrhages sites in the subarachnoid space). No conclusion has yet been reached on whether these hemorrhages occurred before or after stranding." [3]

Madeira 2000

Three Cuvier's beaked whales stranded in Madeira archipelago coinciding with NATO Naval Exercises in the area surrounding Porto Santo Island, including the channel between Madeira and Porto Santo [6].

Findings:
The results showed hemorrhages at the inner ear and sub-rachnoidal spaces consistent with a temporary acoustic induced trauma [7].

Canary Islands 2002
"In September 2002, a massive stranding of 14 animals belonging to three different ziphiidae family species took place in the Canary Islands"[5]. This event coincided with a Spanish-led Navy maneuver.

Findings:
„The most remarkable feature were inner ear hemorrhages and edema starting in the VIIIth cranial nerve and extending into the spriral ganglion and the cochlear channels"[5].

Sonar types

Active sonars emit pulses ("pings") and time the arrival of returning echoes. The distance of the target from the sonar is then given by one-half the round-trip travel time multiplied by the speed of sound.

Based on the purpose, active sonar systems may be described as
Long-range detection sonar
LFAS
Tactical sonar
Short-range imaging sonar
Side-scan sonar
Multi beam sonar
Environmental sonar
Echo sounder
Acoustic Doppler Current Profilers (ADCP)
Acoustic tomography (e.g.: ATOC)

Sonar systems related or possibly relevant to beaked whale stranding events

Sonar Model	SURTASS LFA	SLC TVDS LF	SLC TVDS MF	AN/SQS-53C	AN/SQS-56
Reference	4	1	1	2	2
Stranding	nil	Greece 96	Greece 96	Bahamas 00	Bahamas 00
Frequency (kHz)	0.1-0.5	0.45-0.65, 0.7	2.8-3.2, 3.3	2.6, 3.3	6.8, 7.5, 8.2
Level (dB//uPa@1m)	240 (18*215)	214-228	223-226	235+	223
Pulse duration (s)	6-100	2+2	2+2	0.5-2	
max Bandwidth (Hz)	30	200	400	100	100
Repetition rate (s)	360-900	60	60	26	26
vert Beam width (deg)	5.5/11 ?	23	24	40	30
hor Beam width (deg)	360	360	360	360/120	360
Depth (m)	122	60-90	60-90	7.9	6.1
duty cycle (%)	10-20	7	7	8	8

These transmit systems are typical long-range detection sonar characterized by
- The (long) pulse repetition rate,
- Small vertical beam width,
- Large horizontal aperture (mostly omni-directional in azimuth).

Short-range sonar system have a pulse repetition rate consistent with the water depth and comparable vertical and horizontal beam width (mostly pencil beams)

Sound exposure

The exposure of sonar systems is assessed with the passive sonar equation

$$RL = SL - TL$$

$$SE = RL - NL + DI - RD$$

where

RL is the received level
SL is the transmitted source level
TL is the propagation or transmission loss from source to target
SE is the signal excess or the level which exceeds the required level for the specific task
NL is the spectral ambient noise level
DI is the directivity index of the receiving system
RD is the 'recognition differential' required for detection/reaction

Sound source level

The sound source level is defined as the pressure level that would be measured at a reference distance of 1 m from an ideal point source radiating the same sound intensity as the actual source. It is a purely theoretical value.
In underwater applications, the source level is typically expressed as dB//uPa@1m, that is

$$SL = 20\log_{10}\left(\frac{pressure@1m}{1micoPa}\right)$$

Very close to the sound source, however, the so-called near field, the sound intensity does not follow simple relations as it is generated by an extended surface. The total sound intensity can be measured properly and described by a single number only at a certain distance. The maximum sound pressure level is also only measured in the axis of the transmit beam pattern. For example, the SURTASS LFA consists of an array of 18 sound sources. While it is correct to use 240 dB//uPa@1m as the maximum source level for long-range applications, the maximum received level close to the source may not exceed 215 dB//uPa@1m, which is the source level of a single source, as stated in the SURTASS LFA OEIS[4].
In practice the source level will be measured at distances, large enough to exclude near-field effects, but close enough to calculate the propagation loss between the reference and actual distance.
Direct comparison of source levels is only valid when the propagation media is not changed. The source level is not applicable to the comparison of effects of sound in water to effects in air. Sound intensity (W/m²) should be used instead.

$$Intensity = \frac{pressure^2}{density * soundspeed}$$

giving

$$I_{air} == \frac{p_{air}^2}{0.442} = \frac{p_{water}^2}{1575} = I_{water}$$

consequently for the same intensity, the sound pressure in air is less than in water

$$p_{air} = \frac{p_{water}}{61.6}$$

Sound propagation

An understanding of sound propagation is crucial to the performance assessment of long range sonar systems and consequently also required for the evaluation of the exposure of marine life to sound.

In general, propagation loss is composed of losses due to distribution of energy (spreading loss), absorption of energy in the water column and loss as a consequence of interaction with the bottom.

Spreading loss

Spreading losses reflect the principle of energy conservation and depend only on the sound speed gradient in the ocean (Snell's law).
The sound speed itself is a function of water temperature, salinity and hydrostatic pressure. In deep water these parameters vary only little, the sound speed close to the surface will depend heavily on the seasons (varying temperatures).

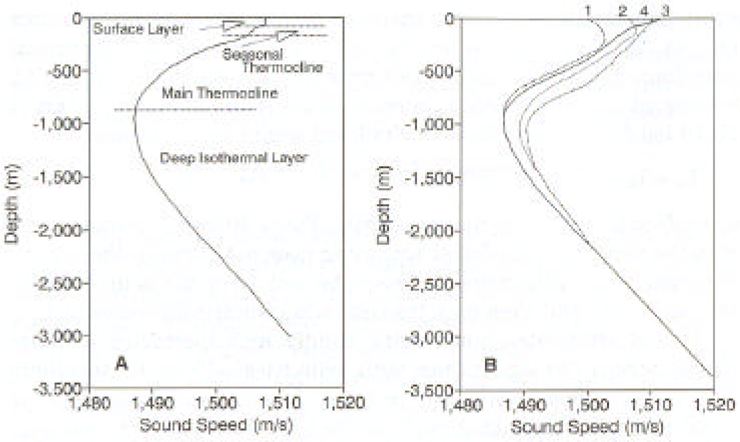

Figure 1 Typical deep sea sound speed profiles (1-4: winter, spring, summer, autumn) [8]

Spherical spreading occurs in uniform media (constant sound speed) unaffected by boundaries. The transmission loss due to spherical spreading is given by

$$TL = 20\log_{10}(R/\text{km}) + 60$$

Cylindrical spreading law applies when the sound energy is completely trapped in a thin layer. The transmission loss due to cylindrical spreading is given by

$$TL = 10\log_{10}(R/\text{km}) + 30$$

The difference between spherical and cylindrical spreading is significant. As an example, a transmission loss of 90 dB is reached at 31 km for spherical spreading and at 1,000,000 km for cylindrical spreading.
To be useful, cylindrical spreading law must be modified with loss due to absorption and boundary (bottom) interaction.

Shadow zones develop for negative sound speed gradients.

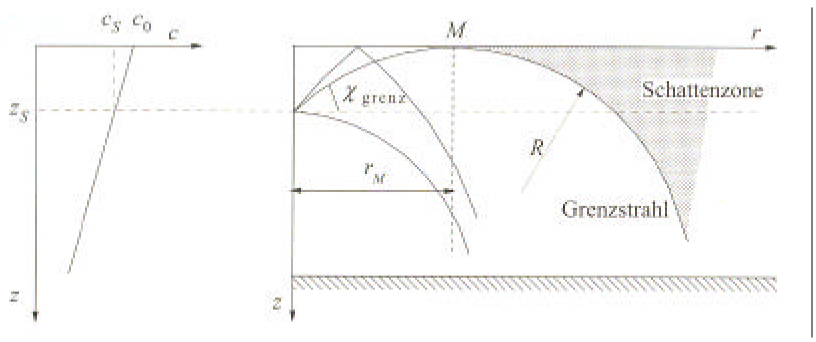

Figure 2 Shadow zone for downward reflecting sound speed profile [9]

This means that due to the onset of surface reflections there are areas where no sound enters (acoustic shadow).

Surface channel
If the water column can be described by two layers, where the surface layer has a positive and the lower layer has a negative sound speed gradient, sound energy may be trapped in this surface channel.

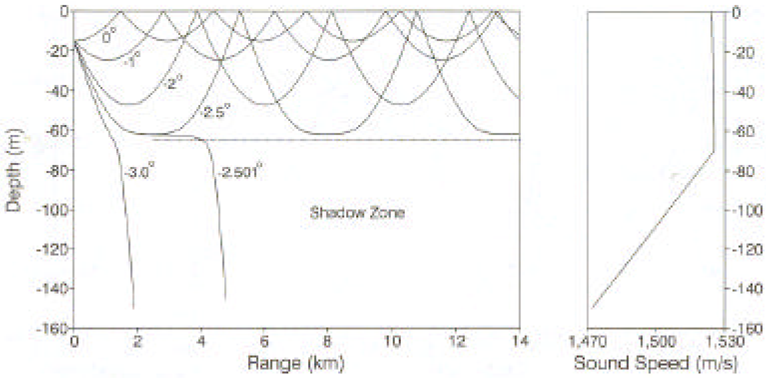

Figure 3 Surface channel for a source depth of 15 m in a 60 m mixed layer [8]

The amount of energy trapped in the surface channels depends on how large the positive sound speed gradient in the surface layer is. At very long distances the transmission loss follows more the cylindrical spreading. This scenario appeared to have played an important role in the Bahamas 2000 stranding [2].

Deep sound channel
Conversely, if the surface layer exhibits a negative and the lower layer a positive sound speed gradient, a deep sound channel develops.

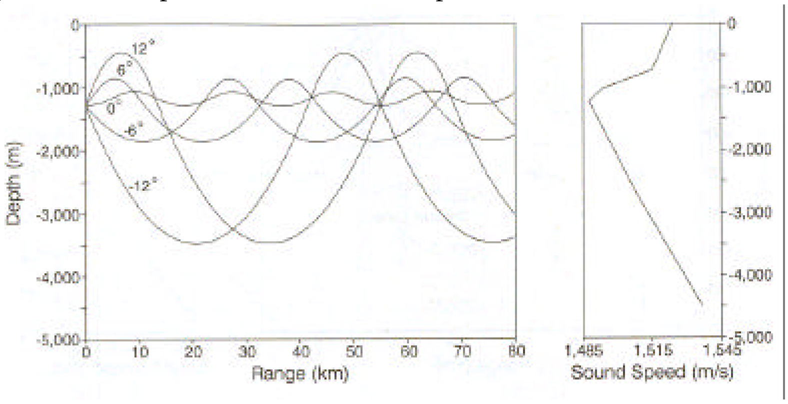

Figure 4 Deep sound channel with source on the axis [8]

The energy is in this case channeled around the depth of minimum sound speed. At very long distances the transmission loss follows more the cylindrical spreading.
The depth of the sound channel depends mainly on the minimum water temperature. The lower this temperature the deeper this sound channel will be. In the Atlantic and Pacific Ocean, the deep sound channel may be in the order of 1000 m (Figure 4). In the Mediterranean Sea, the sound channel is in the order of 100 m.
In the Greece 96 stranding the sound source was within the sound channel [1].

A *Convergence zone* develops in a deep sound channel when the source is close to the surface and the water depth is greater than the critical depth where the sound speed equal the maximum sound speed above this depth.

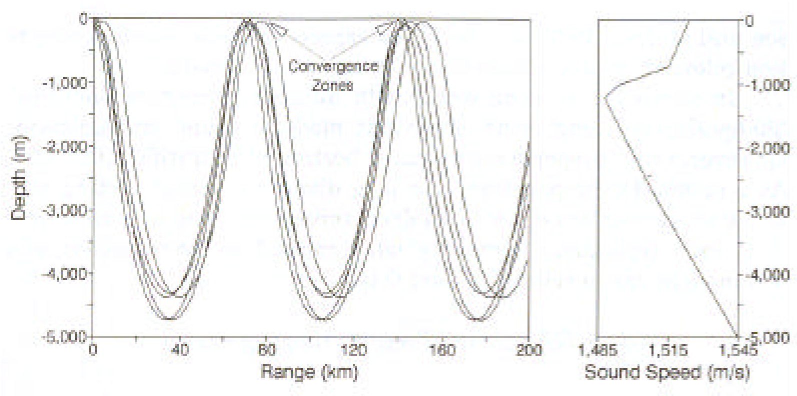

Figure 5 Convergence zones with source at 60 m [8]

In this case the acoustic energy will be first refracted from the surface and then back to the surface where a convergence zone develops. Shadow zones may develop between these convergence zones.

Considering the proposed depth of 122 m for the SURTASS LFA and its use in the Atlantic and Pacific Ocean with a deep sound channel at over 1000 m, one can assume that in most cases the sound propagation will develop convergence zones with embedded shadow zones and not follow the deep sound channel spreading. In special cases, sound propagation may occur in a surface duct.

Shallow water propagation is in principle cylindrical spreading with heavy bottom interaction. The transmission loss is determined primarily by the bottom characteristics (e.g.: the North and the Baltic Sea can be considered extremely shallow water). The ray theory approach to describe sound propagation usually fails in shallow water and should be replaced by mode-theory.

In most cases, the above characterization of spreading losses is too simplistic as in the real ocean, the sound speed profile is usually sufficiently complicated that only a combination of the above categories could describe the propagation. In general and for real applications, transmission loss is measured or estimated with mathematical models which take not only the actual sound speed measurements into account but also absorption and the complex bottom parameters. At reasonable close ranges, however, sound propagation is in close agreement with spherical spreading.

Absorption

Although different spreading preserves the total energy in the water, absorption removes acoustic energy from the propagation path. The absorption is frequency dependent and in sea water varies from 0.001 dB/km @ 0.1kHz to 30 dB/km @ 100 kHz

$$a_0 = 0.036(f / \text{kHz})^{1.5} \text{ dB/km} \quad [8]$$

For low frequencies and short ranges the effect of absorption may be neglected. At large ranges, however, transmission loss due to absorption becomes significant.
For example, we get a loss of 90 dB for 1kHz and a range of 2500 km.

Bottom Interaction

The bottom is for sound propagation a medium with significantly different parameters (higher sound speed, higher absorption, sheer speed, etc). Most transmission loss programs model the bottom as a medium in which sound propagates. In general, the bottom introduces into the sound propagation increased absorption and scattering. Urick gives for Baltic Sea a bottom absorption in the order of 0.5 dB/km [11].
Usually only the specular (forward) reflection is used in propagation models. Energy scattered in all directions contributes to reverberation, which reduces sonar performance.

Transmission loss modelling

More realistic transmission loss models are based on the wave equation, which is a differential equation relating the space and time variables in an acoustic field. Models may assume range independence of the propagation medium (sound speed, bottom parameters) or a variation of these values (range-dependent). An example of a model output is given in the next figure

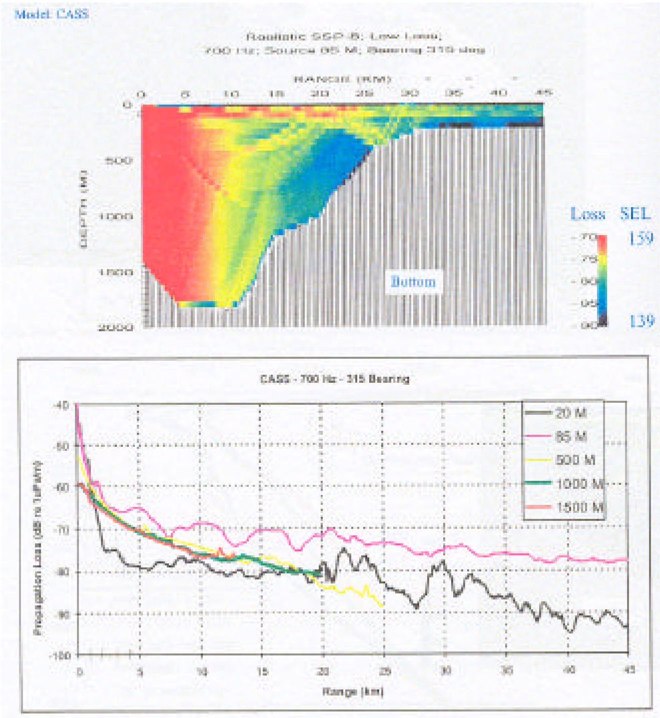

Figure 6 Transmission loss modelling for Greece 96 stranding [1]

Optimal frequency

Early sound propagation modelling and transmission loss measurements show that LF sounds around 300 Hz are characterized by minimum transmission loss, as indicated in the next figure.

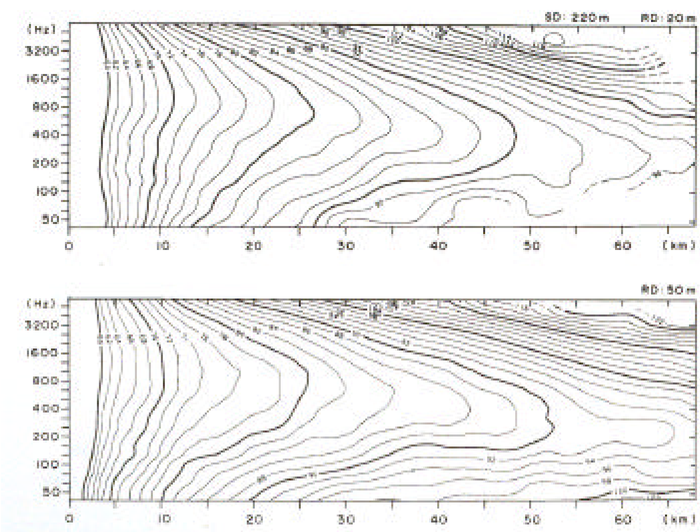

Figure 7 Measured transmission loss from an unspecified area and sound speed profile [9]

This observation explains the interest in using low frequencies for long-range sonar systems.

Ambient noise

Ambient noise is the term for underwater sound which in general cannot be attributed to individual sound source location, but is the statistical average of all possible sound sources and locations.

Natural background noise
Biological noise from 12 Hz to over 100 kHz
Earthquakes below 100Hz with a maximum around 10Hz
Shipping noise
Mainly Below 1 kHz with a maximum below 100Hz
Sea surface noise
Increases with sea state and is maximum between 300 an 500 Hz
Local noise
Mainly precipitation, lightning etc., with a spectrum including significant high-frequency components
In general, ambient noise may be considered omni-directional, i.e. noise from all directions with more or less equal intensity. Heavy shipping or ports produce a more directional noise field.

A summary of ambient noise values is given by the so-called Wenz curves. Strictly speaking, these values are only valid for the deep open ocean. The values are also spectral values, i.e. dB//uPa²/Hz. The use of these values for *NL* in the sonar equation requires also the use of *RD* the Recognition Differential or a correction for the receiver bandwidth.

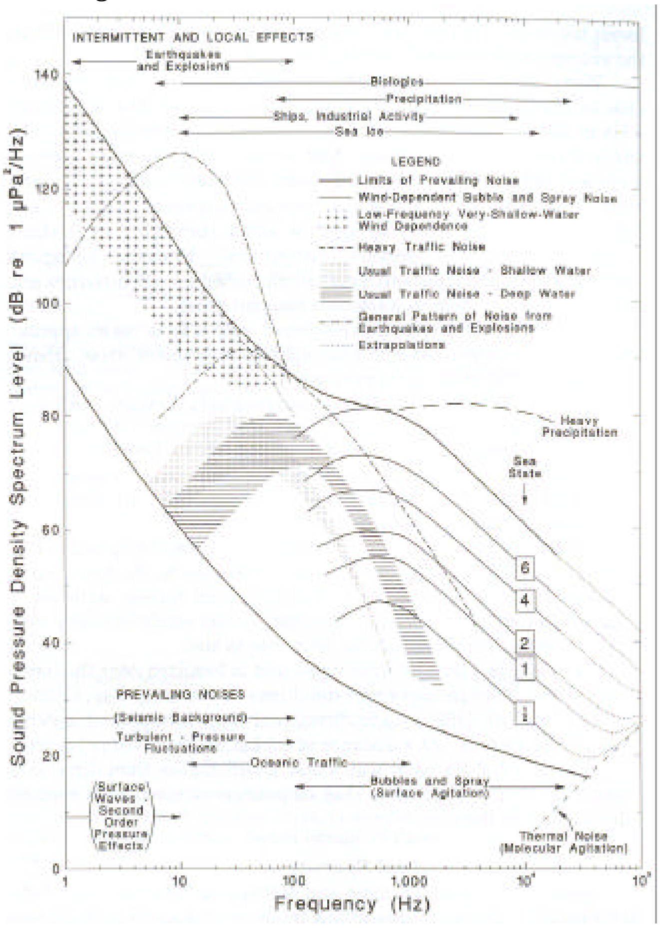

Figure 8 Wenz curves [7]

Recognition differential

The recognition differential is the ratio of signal power in the receiver bandwidth to the noise power in a 1 Hz band, required for detection at a preassigned level of correctness of the detection decision. For a probability of detection of 90% and a false-alarm probability of 0.01% and other assumptions on noise and processing, the recognition differential of an energy detector becomes [9]

$$RD = 7 + 5\log_{10}(B) - 5\log_{10}(T)$$

where

T is the pulse length

B if the receiver bandwidth

To estimate the receiver bandwidth of a marine mammal it may be assumed that the animal auditory system is a bank of constant-Q filters [10].

$$B = \frac{f_0}{Q}$$

Critical ratio tests with dolphins indicate that Q=15 may be a reasonable assumption [10].

Sound exposure, revisited

To estimate the sound exposure the sonar equations

$RL = SL - TL$

$SE = RL - NL + DI - RD$

are used with

SL=228 dB//uPa@1m (SLC TVDS LF),

NL=60 dB//uPa²/Hz (Wenz curves sea state 2 , ~600 Hz)

DI=0 dB omni-directional receiver

T=2 s

B=40 Hz constant Q filter with f0=600 and Q=15

Assume, without comment on the validity, an expected receive level of 140 dB, the lower limit, where the SURTASS LFA OEIS expects "immediate obvious avoidance responses"[4], then the necessary transmission loss becomes *TL=SL-RL,* or *TL*=88 dB.

To relate the transmission loss to distance from the sound source, we consider 4 cases

Spherical spreading:	R=25 km
Cylindrical spreading:	R=630,000 km
Modeled (20 m/figure 6):	R=38 km
Measurements (figure 7):	R=45 km

It appears from measurements and modelling that cylindrical spreading would give totally erroneous results.

In order to know if the animal can detect (hear) the sound, the second equation is used, which gives:

SE=66.5 dB.

The received sound is therefore 66.5 dB above the masking level of the ambient noise.

The knowledge of the received level or signal access is not sufficient to asses the impact of sound exposure on marine mammals. It is necessary to include the biological significance of the sound on the target species, which is expected to depend also on frequency, bandwidth, signal duration and on the activity in which the animal is found (resting, foraging, etc). Richardson [7] suggests that biological significance depends on

- Area affected *versus* available habitat
- Auditory interference by masking
- Behavioural disruption
- Habituation *versus* continued responsiveness
- Long term exposure
- Cumulative exposure

In view of the pathological findings of the beaked whale mass strandings one should add to this list:

- Recovery from acoustically introduced traumas
- Cooperative reaction

The biological significance of sonar impacts and responses to sonar sound should be quantified in the same way as sound propagation is expressed, by a number. It may not be possible to address all relevant topics conclusively, but without being quantified (scientifically or politically) they may not be useful for risk assessment.

Risk assessment

The final assessment of acoustic risk is the responsibility of the decision-makers. To facilitate the assessment process, in which the risk is related to competing requirements and politically weighted, it would be useful to base the assessment on a well-defined risk assessment procedure, which also allows quantification of the residual risk ("Restrisiko"). To reduce this residual risk further, special, on-scene, risk mitigation tools could and should be developed. This risk assessment procedure should be comprehensive and must include the assessment of biological significance. The procedure should also be robust enough to allow minor uncertainties in the knowledge applied.

Similarly, as the sonar equation may be used to assess the performance of sonar systems, risk assessment procedures should allow a proper decision, but as with the sonar equation, its use should be accompanied by scientific knowledge and support.

SACANTCEN research for acoustic risk mitigation

Despite the fact that the analysis of the 96 Greece stranding failed to establish the causal relationship between the deployed sonar and the stranding of beaked whales, the NATO Undersea Research Centre (SLC) responded by implementing an acoustic risk mitigation policy. This risk mitigation policy applies to all SLC at-sea experiments and will be revised at regular intervals to reflect the advance of scientific knowledge. Since 1998, SLC has not been involved in any marine mammal stranding.

To support this risk mitigation policy, SLC initiated a research program SOLMAR (Sound Oceanography and Living Marine Resources). The objectives of this multi-national research program are to collect information relevant to acoustic risk mitigation for use by SLC and participating partners. Due to its scientific background the SLC activities concentrate mainly on oceanographic and acoustic research. To complement its own expertise, SLC seeks collaboration with research institutes, universities and NGO in all NATO countries.

A major activity within the SOLMAR project is to carry out yearly sea trials denominated Sirena and Zifio, which focus on specific scientific questions. So far these sea trials have focused on the Ligurian Sea, within and outside the cetacean sanctuary, and on the Genoa canyon, a known Cuvier's beaked whale habitat. Integrated data from the Sirena and Zifio trials will allow correlation of cetacean locations with oceanographic, biological and hydrographic parameters. They support the SOLMAR project by seeking to establish a paradigm for monitoring and conservation of marine species by,

- Determining regions of high and low cetacean density through oceanographic, biological and historical means and using this information as a basis for selecting regions for the conduct of acoustic trials where the likelihood of cetacean presence is low,

- Employing visual and acoustic monitoring techniques during acoustic trials to establish a marine mammal free zone,
- Establishing an acoustic methodology to determine the baseline behaviour of cetaceans prior to exposing them to sound.

To address the interaction between sonar and cetaceans, a series of carefully planned controlled exposure experiments have and will be carried out.

Open Questions

A number of questions should be addresses

1. Tactical mid-frequency (1-10 kHz) sonar has been used by navies during the last two decades: why have so few mass stranding of beaked whales been reported?
   - Lack of temporal-spatial coincidence
   - Interaction more often but
     - No stranding occurred
     - No stranding observed
2. Is sound directly or indirectly the cause of the stranding?
   - Trauma due to sound impact
   - Trauma due to reaction to sound
3. Which characteristics in the sonar sound are causal to stranding?
   - Sound pressure
   - Signal waveform (type, bandwidth, duration)
   - Signal usage (repetition rate, operational context)
4. Is there a gradual interaction or a sudden onset of mass stranding?
   - Is there a linear relationship between cause and effect
   - Do animals panic when disturbed by sound
5. …
6. …

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