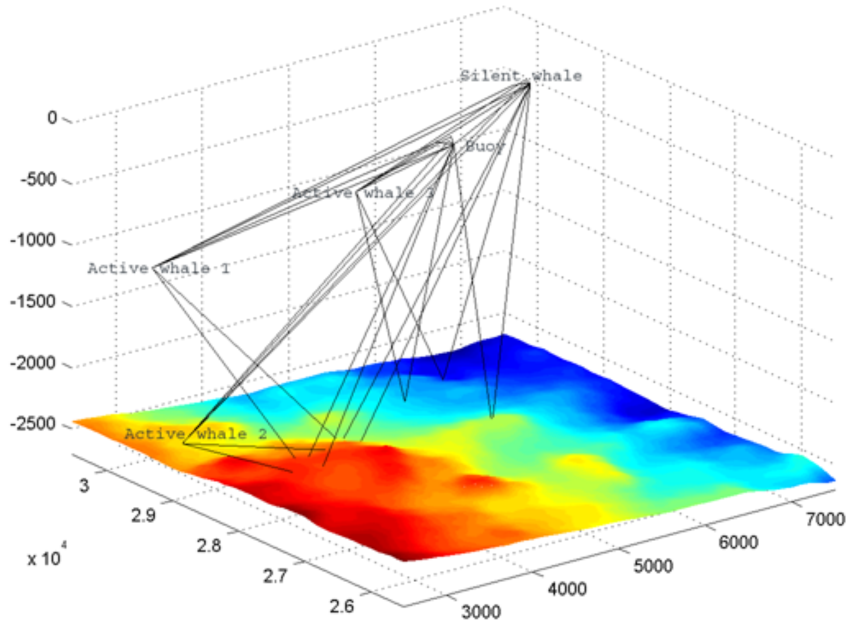
International Workshop on a Very Large Volume Neutrino Telescope for the Mediterranean Sea
VLVnT08 - Toulon, Var, France, 22-24 April 2008

Cetacean Sonar and Noise Pollution

Michel André
Laboratori d'Aplicacions Bioacústiques, Universitat Politècnica de Catalunya



www.sonsdemar.eu

Introduction

- Marine mammals: dependence on sound

- Recent introduction of man-made noise in the oceans

- Do man-made sounds lead to mortality? (Richardson *et al*., 1995; André *et al.* 1997).

- Cetacean mass mortality events linked to the use of military sonar (Evans & England, 2001; Jepson *et al*., 2003; Evans & Miller, 2003)

- Unpredictability in determining which sounds are to be considered dangerous for marine mammals: mitigation procedures.

-the biological properties of cetacean sonar

-the development of passive technologies to monitor the presence of cetaceans in areas of interest.

André, M., Kamminga, C. and Ketten, D. Are Low Frequency Sounds a Marine Hazard? 1997. *Journal of the Institute of Acoustics, ISBN: 1 901656 08*: 77-84.

Evans, D.L., and England, G.R. (eds.) 2001. *Joint Interim Report Bahamas Marine Mammal Stranding Event of 14-16 March 2000*. Unpublished report to US Department of Interior. 61pp.

Evans, P.G.H., and Miller, L. (eds.) 2003. *Active Sonar and Cetaceans*. ECS Newsletter no. 42 (Special Issue): 60pp.

Jepson, P.D., Arbelo, M., Deaville, R., Patterson, I.A.R., Castro, P., Baker, J.R., Degollada, E., Ross, H.M., Herráez, P., Pocknell, A.M., Rodriguez, E., Howie, F.E., Espinosa, A., Reid, R.J., Jaber, J.R., Martin, V., Cunningham, A.A., and Fernandez, A. 2003. Gas-bubble lesions in stranded cetaceans. *Nature*, Lond., 425: 575-576.

Richardson, W.J., Greene, Jr., C.R., Malme C.H., and Thomson, D.H. (eds.) 1995. *Marine Mammals and Noise*. Academic Press, San Diego, CA. 576pp.

the sperm whale sonar

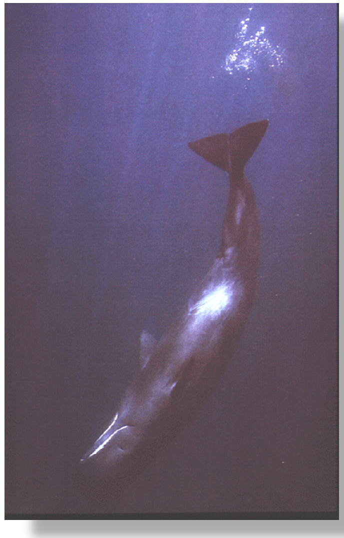
- Sperm whale forage at great depths where the light is scarce

- An adult SW ingests up to a ton of cephalopods per day

- Continuous production of usual clicks

- Until recently, differences in signal bandwidth and directivity index from other species: sperm whale sonar capabilities?

- Recent data on sperm whale on-axis recordings (Mohl *et al.*, 2003; Zimmer *et al.*, 2005) allowed to verify the sperm whale possible mid-range sonar function by performing simulations in controlled environments.



Møhl, B., Wahlberg, M, Madsen, P. T., Heerfordt, A., and Lund, A. The monopulsed nature of sperm whale clicks. J. Acoust. Soc. Am. 114, 1143–1154. 2003.

Zimmer, W. M. X., Tyack, P. L., Johnson, M. P. and P. T. Madsen. Three-dimensional beam pattern of regular sperm whale clicks confirms bent-horn hypothesis. J. Acoust. Soc. Am., 117, 1473-1485. 2005

The sperm whale diet

The sperm whale on-axis click

Scattering and Target Strength

Squid TS in the literature

Squid TS measurement: experimental approach

Modelling the sperm whale click propagation vs squid TS

Aggregation of squids

Conclusion

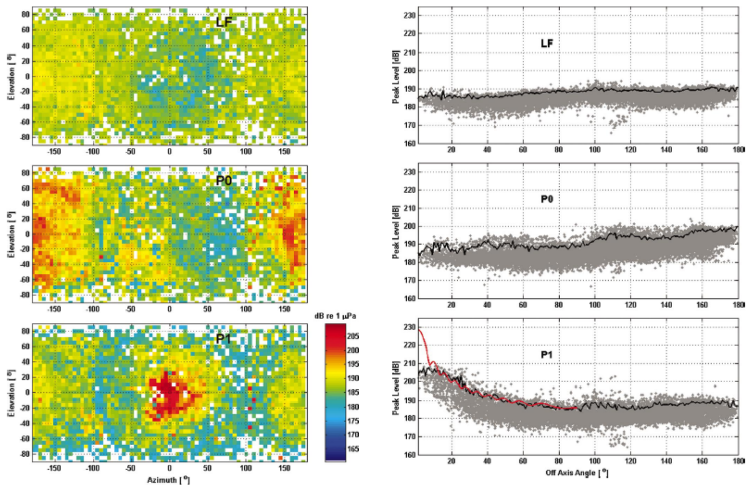
The sperm whale diet

- Mostly cephalopods: squids and octopuses
- Occasionally dwelling fish (0.3-3m in length)
- *Histioteuthiidae* mainstay of the sperm whale diet counting by numbers of individuals
- the size of the preys varies depending on the animal diving capacities, but usually < 1m
- on large scales squids aggregate and this amounts to an increase of the density over km^2

Family	*Mean percentage (by mass)*	*Median body mass (kg)*	*Mean percentage (comp. for body mass)*
Architeuthidae	5.1	24	0.2
Ommastrephidae	19.7	8	2.0
Octopoteuthidae	16.8	1	13.4
Histioteuthidae	23.6	0.8	23.6
Ancistrocheiridae	7.5	0.7	8.6
Onychoteuthidae	16.8	0.5	26.9
Cranchiidae	3.9	0.2	15.6

The sperm whale on-axis click

- broadband (0.2-30kHz)
- highly directional (DI=26dB)
- SL=230 dB_{peak} re 1 µPa (Møhl *et al.*, 2003; Zimmer *et al.*, 2005)
- centroid frequency: 15kHz (Møhl *et al.*, 2003; Zimmer *et al.*, 2005)
- components of a sperm whale click: P0, P1, P2, etc. + LF (Zimmer *et al.* 2005)



Beampattern of the three main components of the sperm whale click (Zimmer et al. 2005)

The questions:

- Scattering mechanism off a squid when insonified by a sperm whale on-axis click?

- Ranges at which prey targets are detected?

The sperm whale diet

The sperm whale on-axis click

Scattering and Target Strength

Squid TS in the literature

Squid TS measurement: experimental approach

Modelling the sperm whale click propagation vs squid TS

Aggregation of squids

Conclusion

Scattering and Target Strength (1/1)

- $ka = 2\pi/\lambda * a$

If *ka* >> 1, a geometric scattering applies

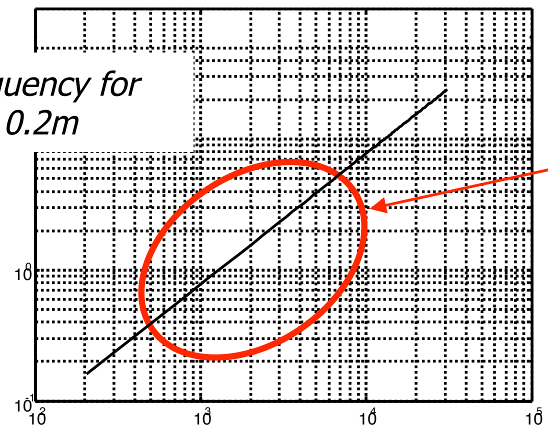
If *ka* << 1, the Rayleigh scattering occurs

At *ka* close to 1 there is a transition region where TS can change dramatically with frequency (hundreds of Hz-few kHz): do SW use the low frequency end of its spectrum to detect this transition region?

- Most caught squids have mantle lengths between 0.2-0.7m

- on-axis SW clicks occupies frequencies above 5 kHz, *ka >>1*: geometric scattering

Ka depends on frequency for an object of length 0.2m



Transition region

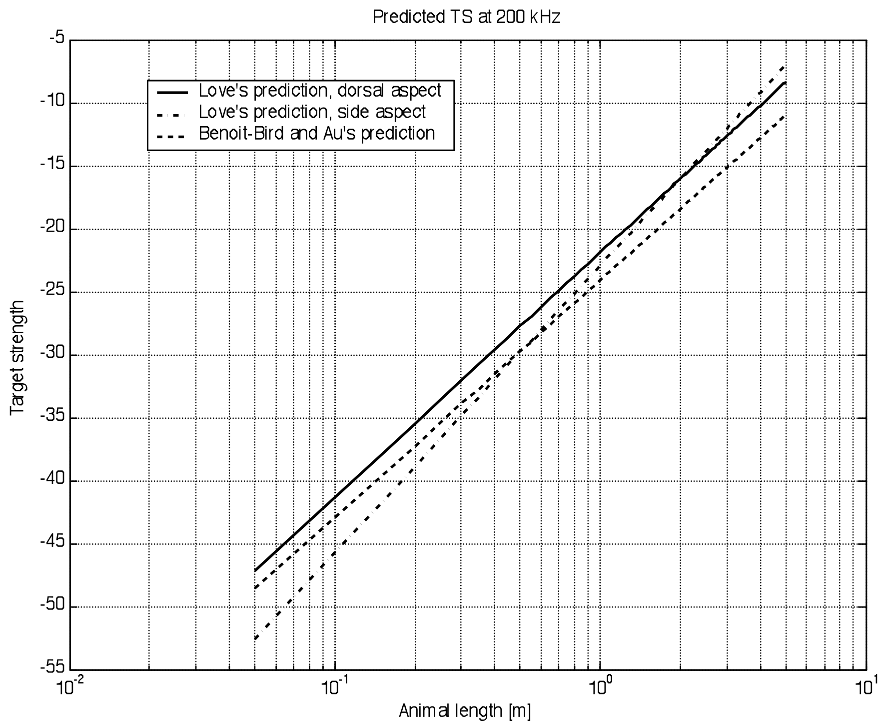
Squid TS in the literature (1/2)

- few measurements of TS pattern for live squids

- Love's relations:

TS [dB] = 19.4 log10 L [m] + 0.6 l [m] – 21.9 (dorsal aspect)
TS [dB] = 22.8 log10 L [m] – 2.8 l [m] – 22.9 (side aspect)

- Benoit-Bird and Au's prediction for organisms at 200kHz



Love, R. H., "Measurements of fish target strengths: a review", Fisheries Bulletin 69, 703-15, 1971

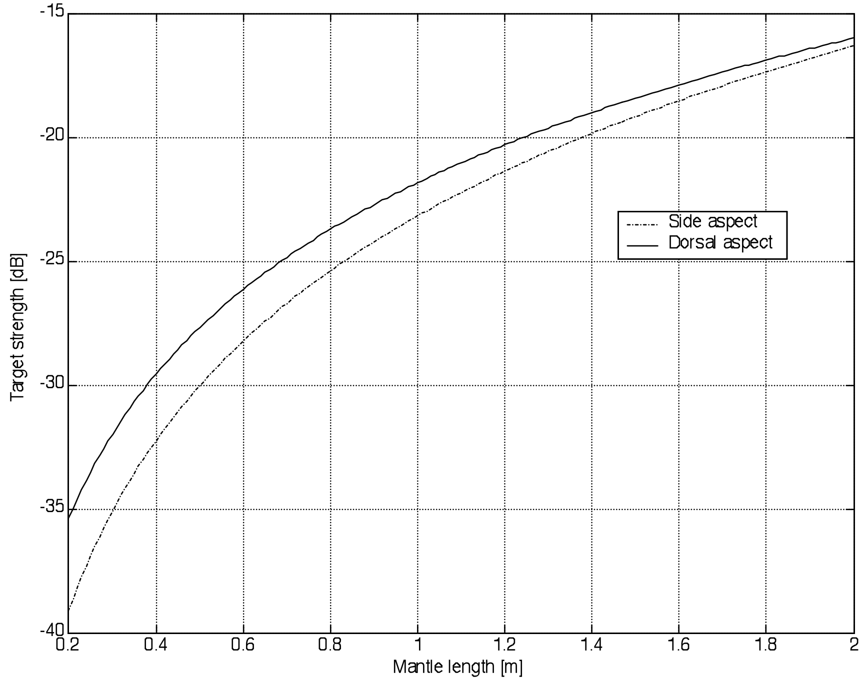
Benoit-Bird, K. J. and Au, W. W. L., "Target strength measurements of Hawaiian mesopelagic boundary community animals", JASA 110(2) 812-9, Aug 2001.

The target strength depends on animal length and geometric scattering applies. At any animal length, the difference is less than 6dB

Squid TS in the literature (2/2)

- applying Love's relations to predict the sperm whale prey TS (from side to dorsal aspects) at 15kHz for squids of mantle lengths between 20-200cm:

TS $_{\text{predicted range}}$ = -39 dB to – 17 dB



Squid TS measurement: experimental approach (1/5)

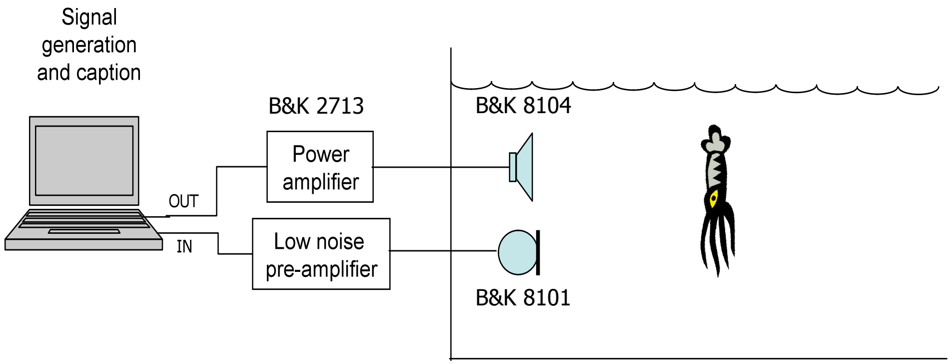
- TS of a *Loligo vulgaris* and *Sepia officinalis*

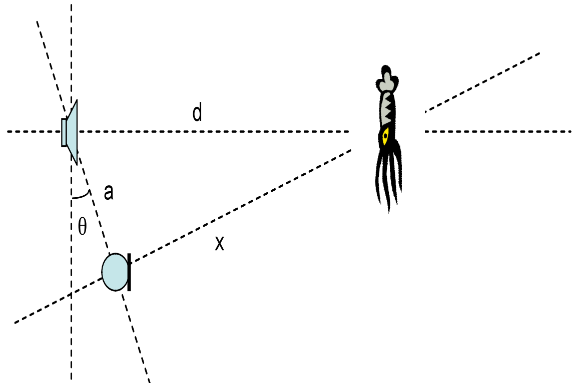
Dorsal mantle length	24,5 cm
Ventral mantle length	21,8 cm
Total length including tentacles	35,5 cm
Maximum body width (incl wings)	15,0 cm

Dorsal mantle length	15,6 cm
Ventral mantle length	13,4 cm
Total length including tentacles	27,3 cm
Maximum body width (incl wings)	11,2 cm

Squid TS measurement: experimental approach (2/5)

- 4-8m freshwater pool, 2m depth





d = 50 cm
a = 12 cm
q = 15°
x = 48.3 cm (x2 = d2+a2-2adcos(90°-q) = d2+a2-2adsinq)
Direct path: Start at 0.080 ms and end at 0.580 ms.
Target echo: Start at 0.656 ms and end at 1.116 ms.
Other echoes: Start later than 1.067 ms.

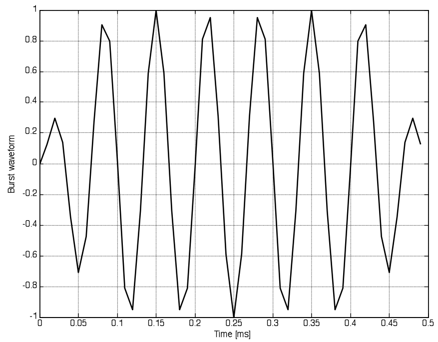
- we restricted the analysis to 0.7 to 1.0 ms after the pulse transmission.

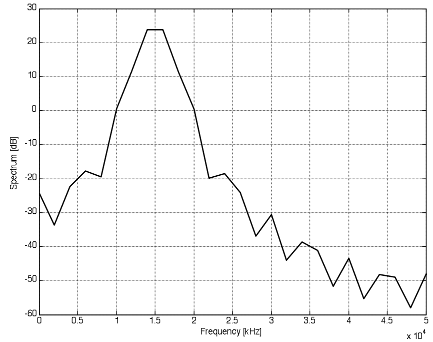
Squid TS measurement: experimental approach (3/5)

- calibration measurement without any target present and hydrophone at 1m distance from transducer

- transducer SL = 90.2 dB re 1µPa/V
- laptop amplitude generated signal 1V and the B&K power amplifier added 40dB
- SL = 130.2 dB re µ1Pa
- linear units: 3.24 Pa. Pre-amplifier set to 40dB, thus signal amplitude at hydrophone: 0.38mV
- the transduction ratio of our system: 3.24Pa/0.38mV = 8.53 kPa/V

- the transducer sent out a 0.5ms burst of a 15kHz sine wave every 100ms.

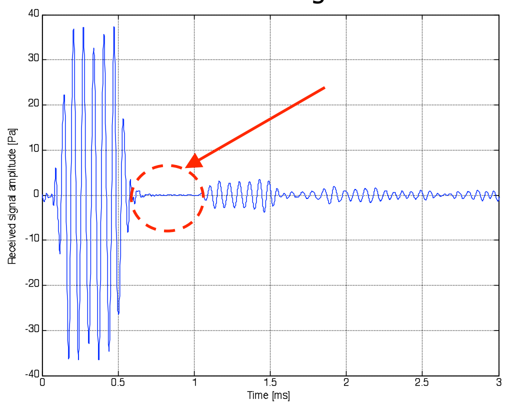


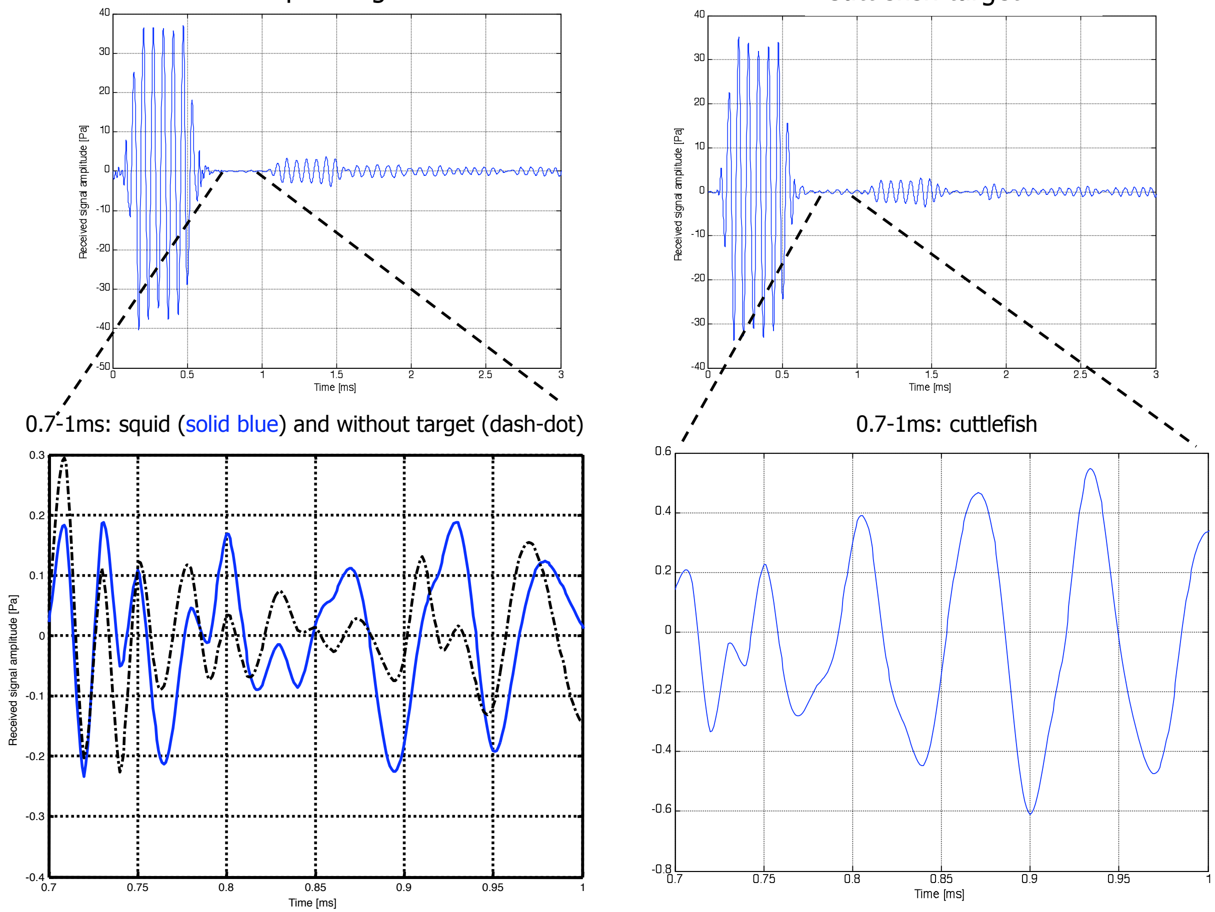


Transmitted burst and waveform spectrum (logarithmic scale, arbitrary reference)

Squid TS measurement: experimental approach (4/5)

- measurement were taken without a target, with the squid target and with the cuttlefish target





Between 0.7-1ms (waveforms averaged after 5000 returns), the greatest peak-to-peak amplitude is 0.41 Pa and 1.16 Pa for the squid and cuttlefish respectively

Squid TS measurement: experimental approach (5/5)

- Target strength estimation

$$TS = 10 \log Ir/Ii = 20 \log pr/pi$$

where Ir = the acoustic intensity of the scattered sound at a distance of 1 m and
Ii = the incident acoustic energy

$$TS = 20 \log pr/pi = 20 \log p_{measured}/p_{1m} + 20 \log xd$$

$p_{measured\ squid}$ = 0.41 Pa / 2
$p_{measured\ cuttlefish}$ = 1.16 Pa / 2
P_{1m} = 3.24 Pa
d = 50 cm
x = 48.3 cm

TS_{squid} = -36.3 dB

$TS_{cuttlefish}$ = -27.3 dB

from Love's general relations

TS_{squid} = -34.7 dB

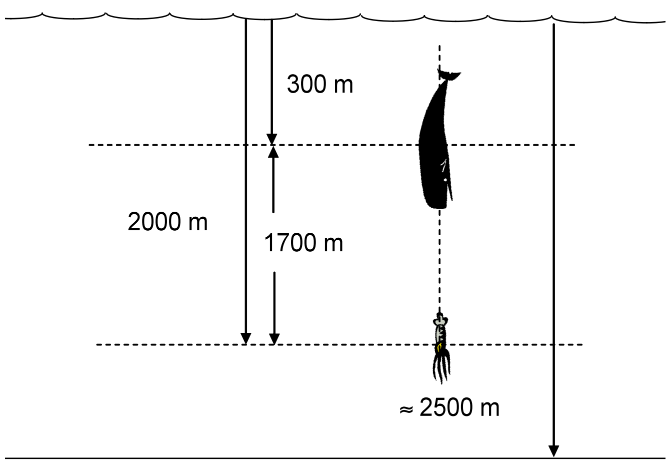
$TS_{cuttlefish}$ = -37.5 dB

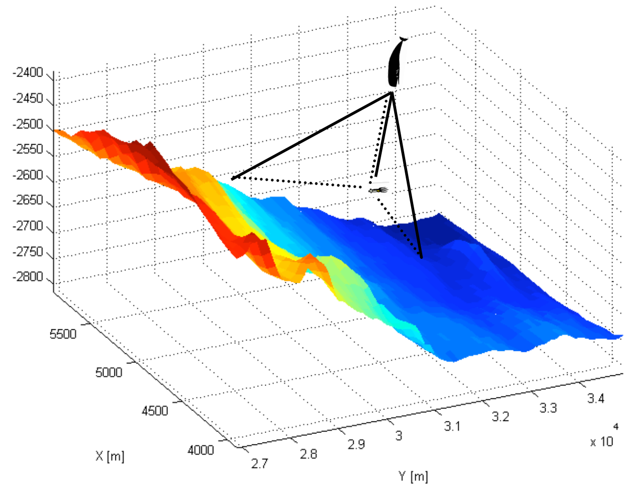
The transducer tolerance of 2.5 dB translates to the same tolerance on the TS. It leads to ranges of
TSsquid = -36.3 ± 2.5 dB = -38.8 to -33.8 dB
TScuttlefish = = -27.3 ± 2.5 dB = -29.8 to -24.8 dB

Modelling the sperm whale click propagation vs squid TS (1/5)

- at frequencies above a few kHz: ray tracing modelling option
- ray tracing software: Songlines for use in the WACS project

Scenario: diving sperm whale at a depth of 300m and a squid at 2000m (bottom depth: 2500m)

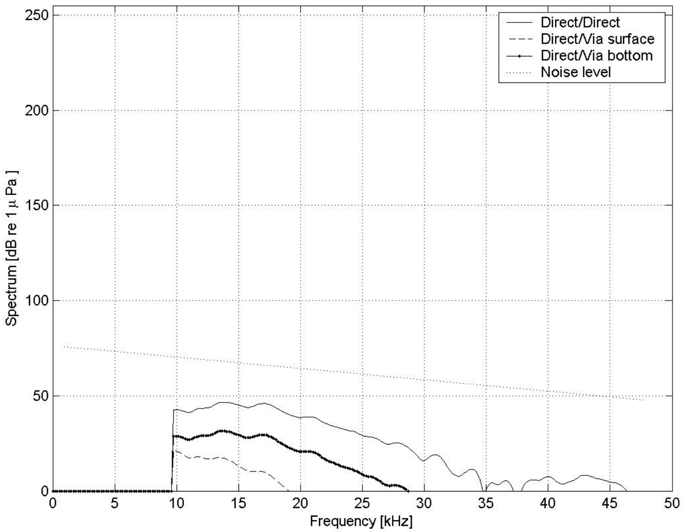




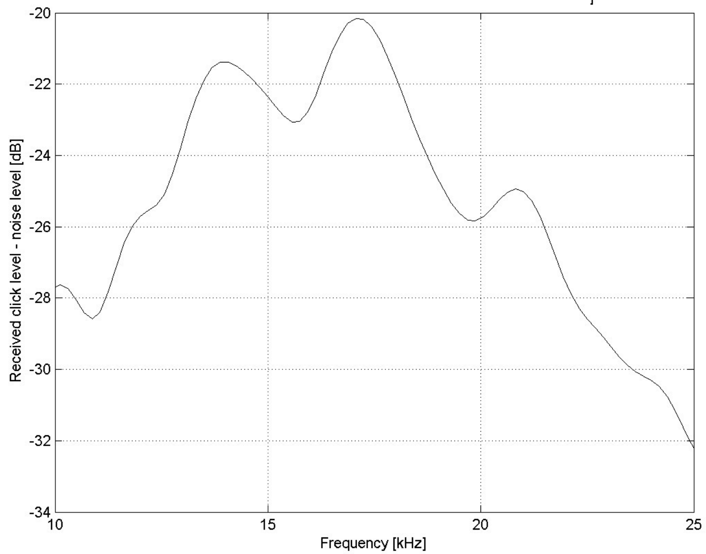
Modelling the sperm whale click propagation vs squid TS (2/5)

- SW click source level = 230 dBpeak re 1µPa
- Circular piston radiator of 0.8m (Mohl *et al.*, 2003)

Signals received from target + noise level.
Direct paths to target



Difference between direct/direct path
click level and noise level [dB]



Modelling the sperm whale click propagation vs squid TS (3/5)

- deep-sea state 1 noise level in the RMS bandwidth (4.1kHz; Mohl *et al.*, 2003) of the on-axis click is 70 dB re 1 mPa
- hearing directivity of 21-24 dB between 13 and 18 kHz

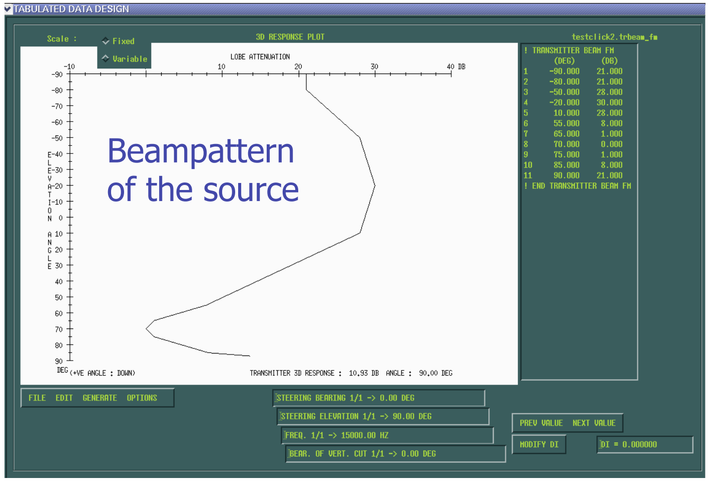
- sperm whale could detect a single small squid of around 25cm long at a range of 1.7 km

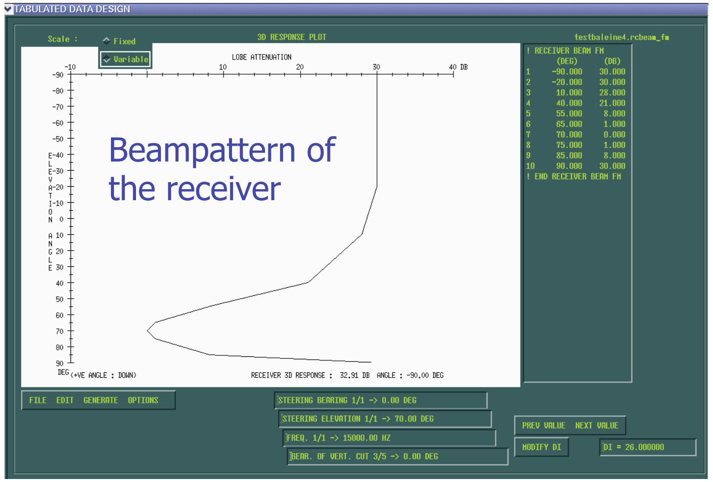
- Higher sea states would require a more directional hearing or a better signal processing by the sperm whale auditory system.
- The effects of reverberation from non-specular scattering at the sea surface and seabed were not included in these simulations.

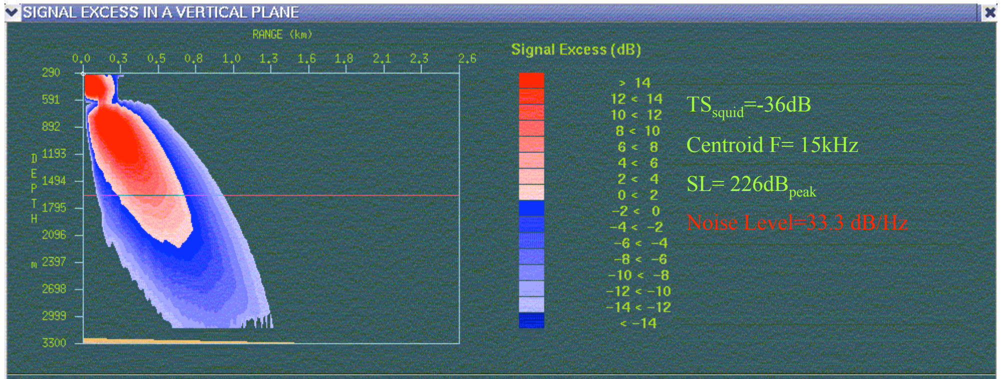
Modelling the sperm whale click propagation vs squid TS (4/5)

- Validation of these results taking into account the surface, volume (reverberation index = -100 dB/m3) and bottom reverberation: "*Venus* software" from *Thales Underwater Acoustics*

- location of simulations: Canary Islands: 28º20'35N, 15º51'49

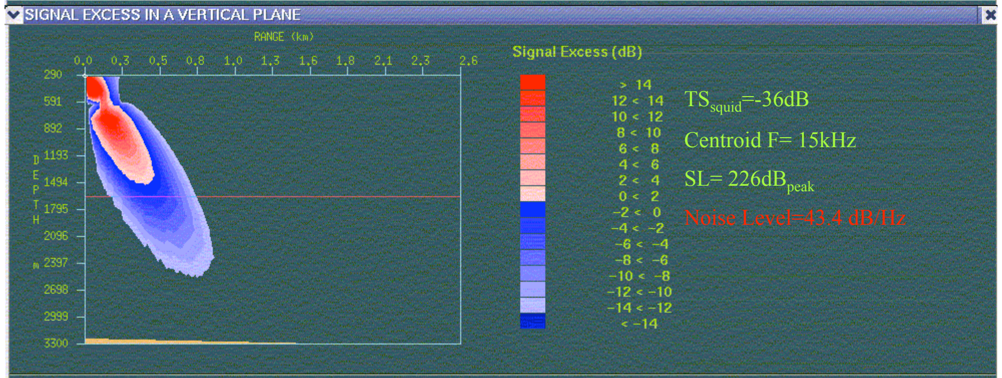






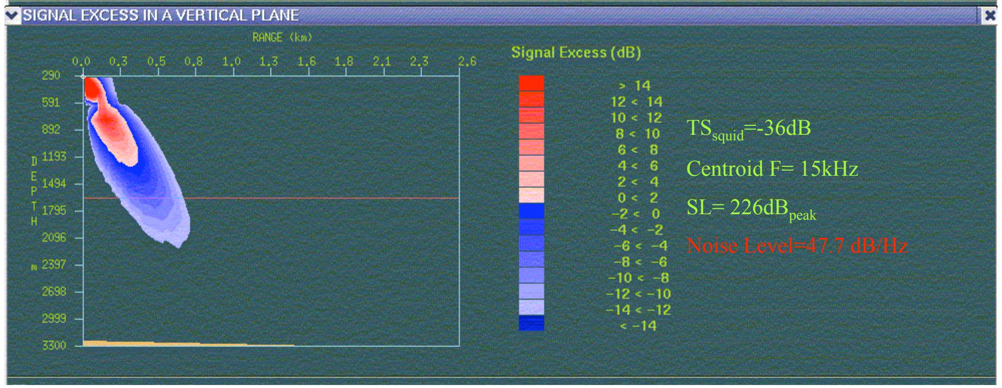
Sea state 1:

Detection of a 25cm squid at 2.2km



Sea state 3:

Detection of a 25cm squid at 1.5km

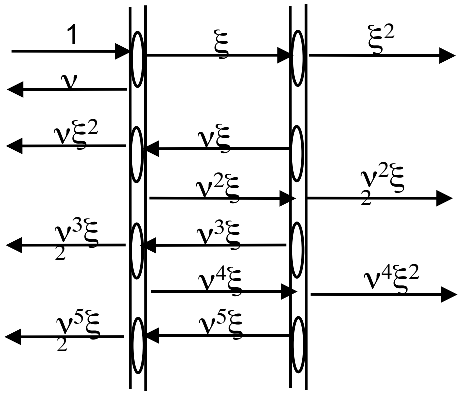


Sea state 5:

Detection of a 25cm squid at 1.2km

Aggregation of squids

- Squids form large aggregation when spawning
- n squid aggregation TS $\neq \Sigma$ TS $_{n\ individual}$
- the school is ellipsoidal in shape and elongated in the direction of travel (Nx = 2Ny = 3.25 Nz)



The number of fish/squid effectively insonified by multiple reflections, assuming that $\nu \ll 1$ is:

$F_{mult} = N_{\beta}\,\nu^2\,(\xi^2+3\xi^4+6\xi^6+10\xi^8+\ldots)$

$F = N_{\beta}\,[1 + \sum_{p=1:(N\infty-1)} (1+(1-\xi)^2 p(p+1)/2)\,\xi^{2p}]$

$TS_{school} = TS_{individual} + 10\log 10F$

packed ellipsoidal 1000 m3 school of *Loligo Vulgaris*, each of mantle length 24.5 cm, the target strength is

TS_{school} = -7.9 dB

- the target strength of a 1000 m3 school is between 28 and 43 dB above the TS of a single squid. Such a school would be detectable at ranges of several km even with low directional hearing and basic auditory processing.

Love, R. H., "A model for estimating distributions of fish school target strengths", Deep Sea Research part A 28(7) 705-25.

The sperm whale diet

The sperm whale on-axis click

Scattering and Target Strength

Squid TS in the literature

Squid TS measurement: experimental approach

Modelling the sperm whale click propagation vs squid TS

Aggregation of squids

Conclusion

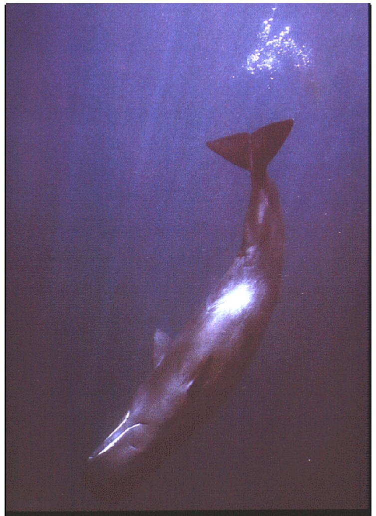
Conclusion (sperm whale sonar)

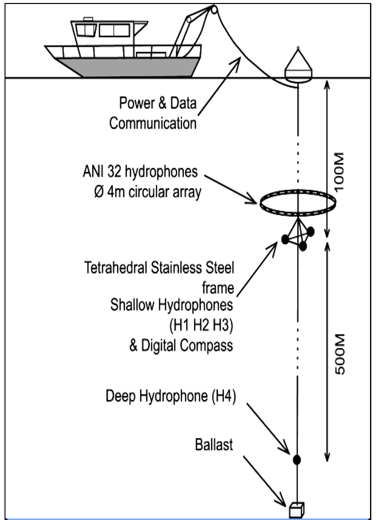
- TS experiments on small squids at 15kHz confirmed theoretical measurements and gave values of around – 36 dB for squid with a mantle length of 25cm.

- The sperm whale on-axis click would allow to detect a single 0.2m squid at a range of 1.2 to 2.2km depending on sea state noise levels, with a reasonable directional hearing.

- Large aggregation of squids would extend this range and allow the detection at several km

- Sperm whale usual clicks appear to be suited for mid-range echolocation on very low reflective and relatively small organisms like squids (< 1m), at ranges of at least several hundreds of meters.

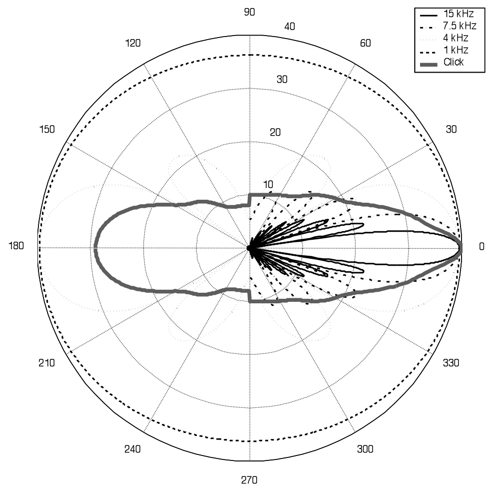




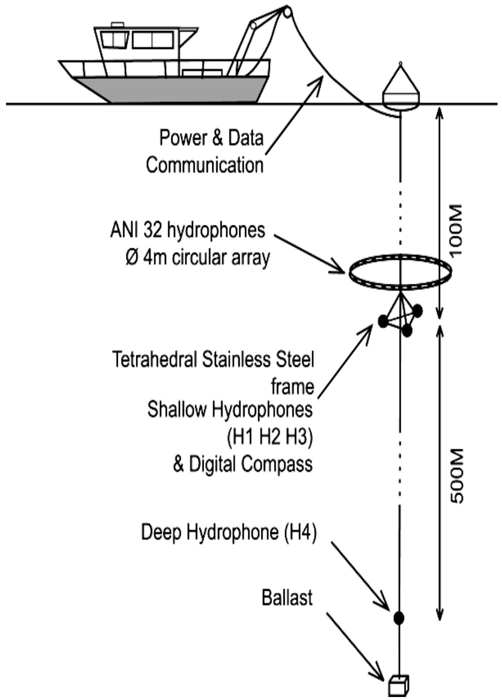
3D LOCALIZATION AND TRACKING OF WHALES

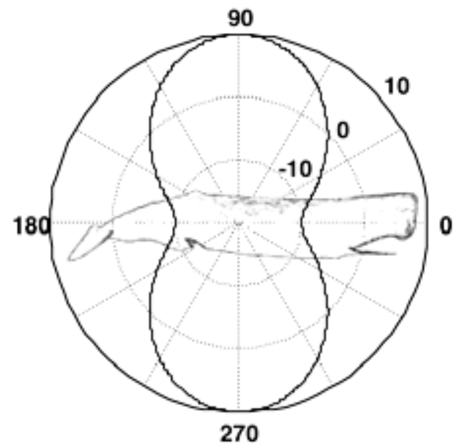
BIOLOGY

ENGINEERING

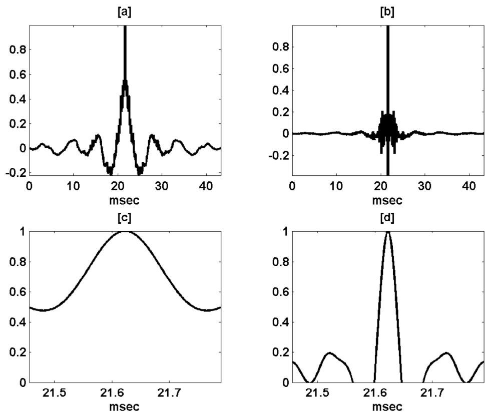


Composite beampattern of a click, created by applying its estimated power spectral density to a 0.8 m circular transducer that creates forward beams only from 5kHz upwards, and bidirectional beams downwards. The resulting click DI is 21.3 dB

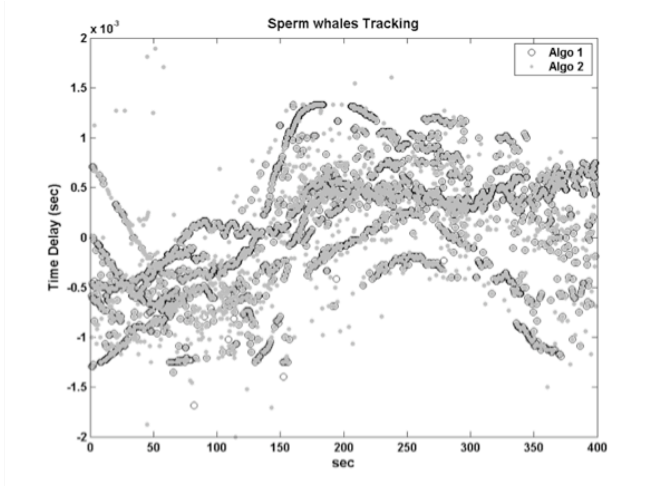




Sperm whale target strength values in dB, function of aspect angle to the source in the 1-16kHz bandwidth for a 10 to 15m adult. The model is assumed invariant by rotation around the 0° axis



Auto-correlation function of a sperm whale click, sampled at 48kHz and interpolated by 10: [a] low-pass filtered at 5000Hz, [c] is [a] zoomed 35μsec around the peak, [b] full spectrum (100Hz-24kHz), [d] is [b] zoomed 35μsec around the peak. Cross-correlation allow more precise time-delay estimates when the full bandwidth is used. Clearly, a time-delay measurement error of more than 20 μsec is unlikely except at very low SNR, which anyhow would prevent detection in most cases

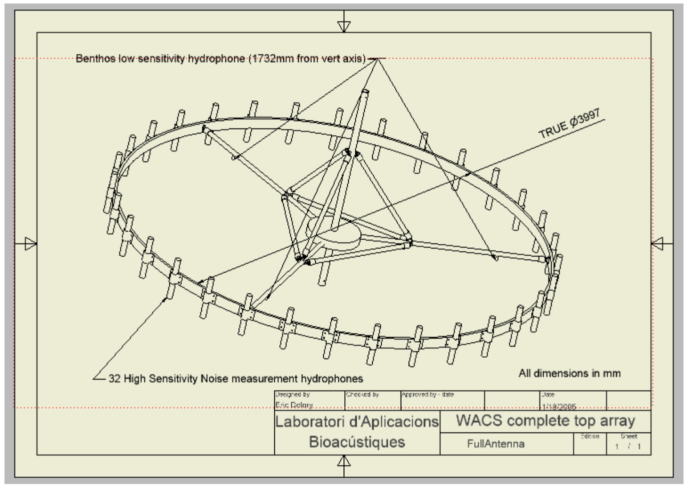


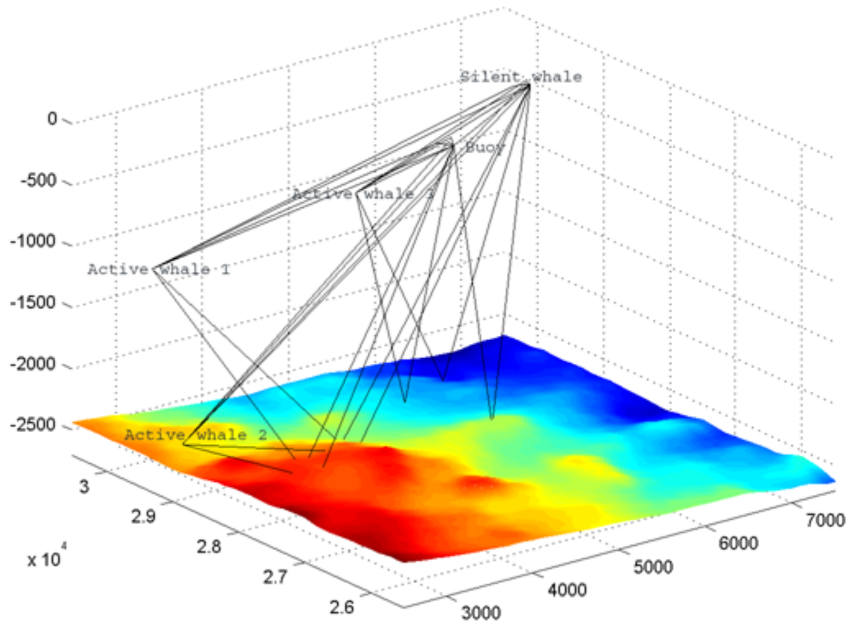
Tracked whales using the 3D localization algorithm. An automatic click detection and direction of arrival algorithm was first implemented, the results of which were compared to the same algorithm but with a much longer matching window in order to test how our simple algorithm would perform with our wider aperture array. Circled gray dots represent a perfect match between both algorithms, showing that the simulated wide aperture array is able to correctly track the detected whales.

Detecting silent whales from deep diving echolocating whales

Results of simulations under different scenarios where echolocating whales (sperm whales) are taken as illuminating source in a bistatic sonar approach (the active source position, i.e. an echolocating whale, is known by passive acoustics at a range of 3-5 km with an estimated distance error of 50m, the receiver is an array of acoustic sensors).

Simulated Array: 32 sensors on a ø4m ring – DI =15 dB at 10-30kHz





3D representation of rays with bottom, surface and objects reflections with varying bathymetry resulting from our simulation software *Songlines. Active Whales 1-3: 3 vocal whales, Silent Whale at 100m depth, Buoy: monitoring buoy, here located half-way between Gran Canaria and Tenerife Island (km28) on the maritime channel. Ray paths account for vocal whale to buoy, vocal whale to non vocal whale, silent whale to buoy, and their respective bottom and surface reflection paths. All dimensions in meters.*

Narrowband Simulations in 2D

Bi-static sonar equation:

$$SE = SL - TL1 + TS - TL2 - (RL + NL) + DI - DT \qquad (1)$$

Illuminating Source:

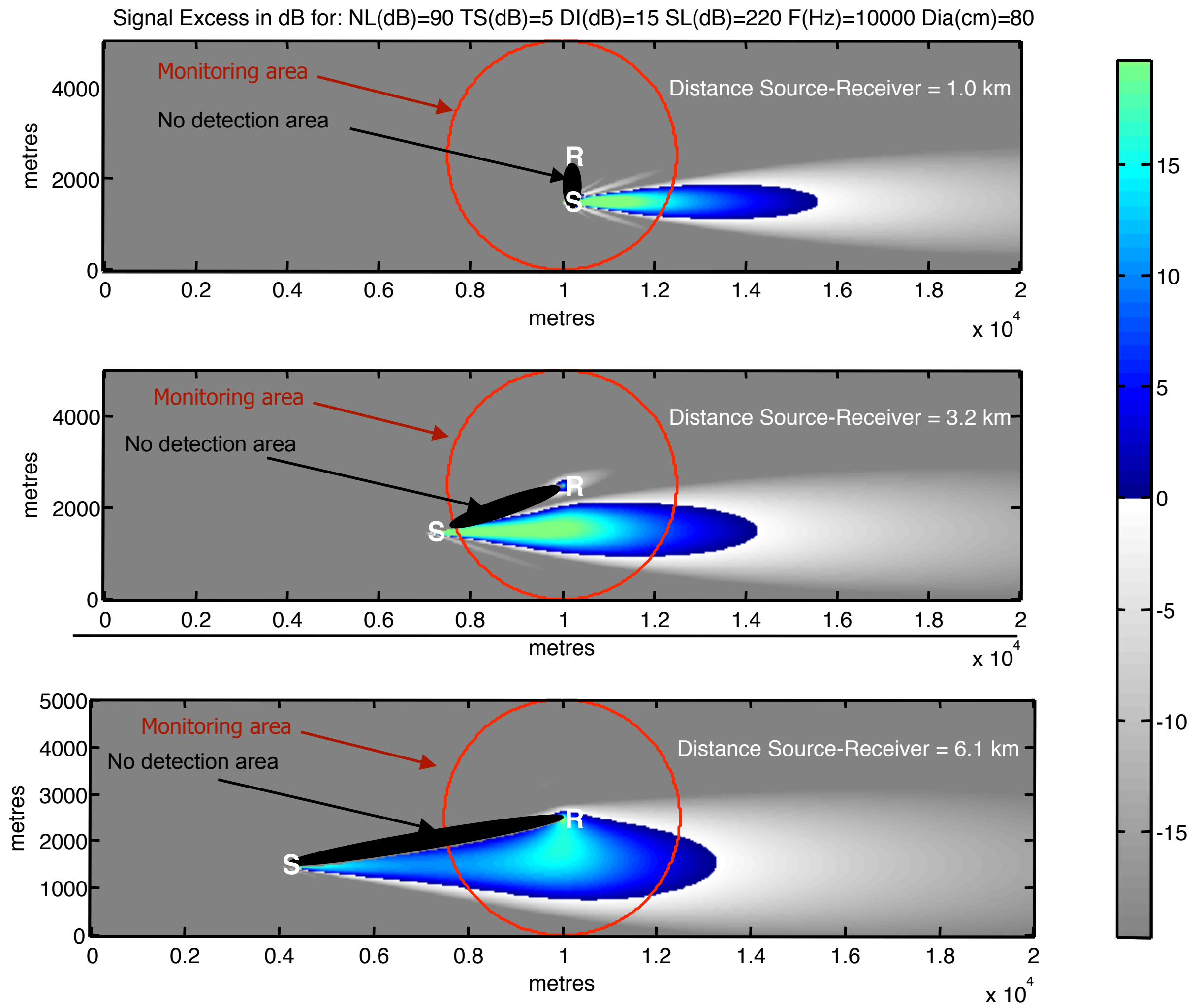
Adult sperm whale (BW=1-10kHz, sea state 2)

NL: Noise Level
TL: Transmission Loss
TS: Target Strength
DI: Antenna Directivity Index
SL: Source Level RMS
RL: Reverberation Level
F: Simulated Frequency
Dia: Piston Diameter as a transduction model for the animal 3D click beampattern

Expected Signal Excess (dB) from a 10-15m whale in a 2D plane illuminated by an adult Sperm whale

Sea state 2

BW = 1-20 kHz



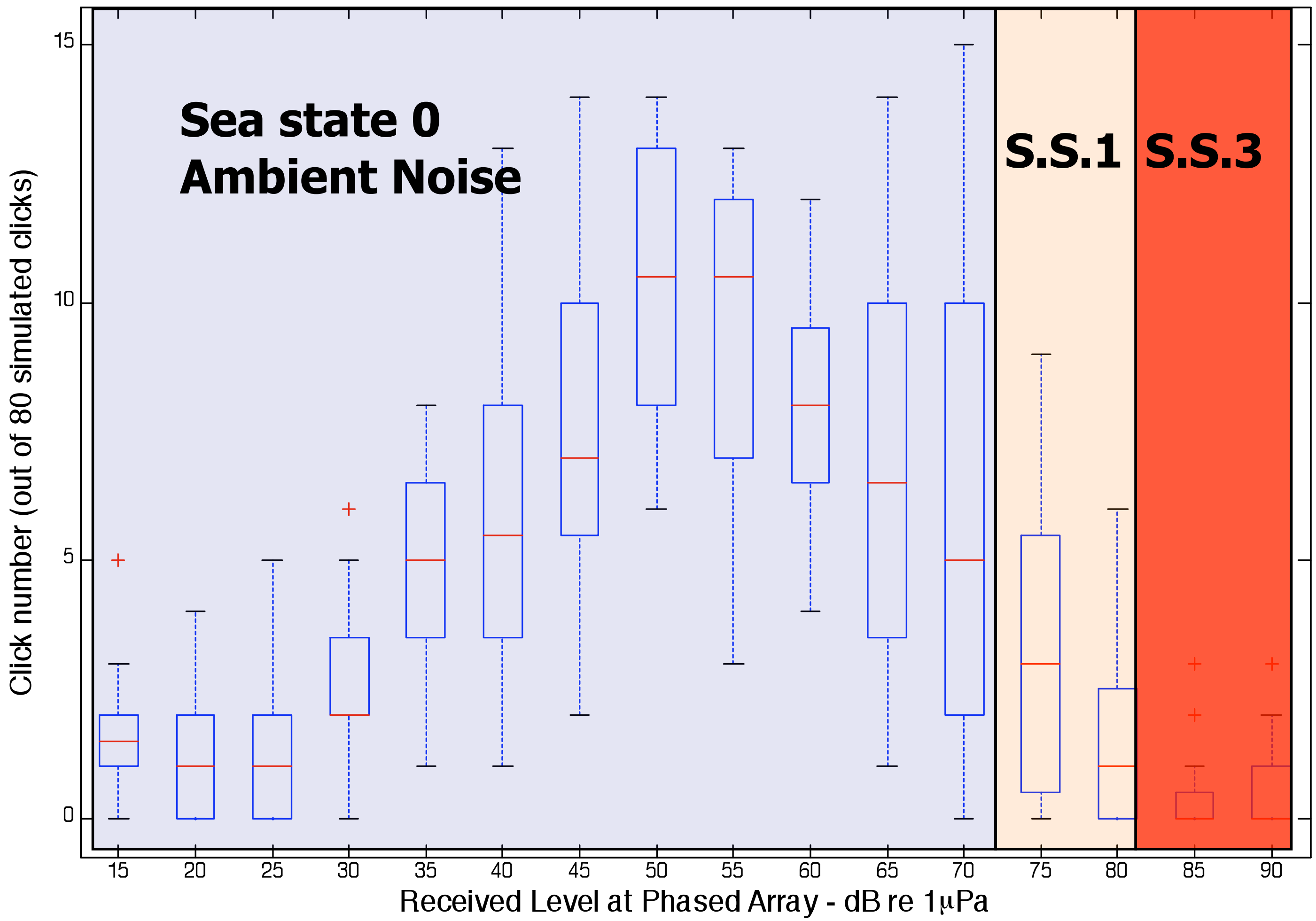
Broadband simulations in 3D

Illuminating Source:

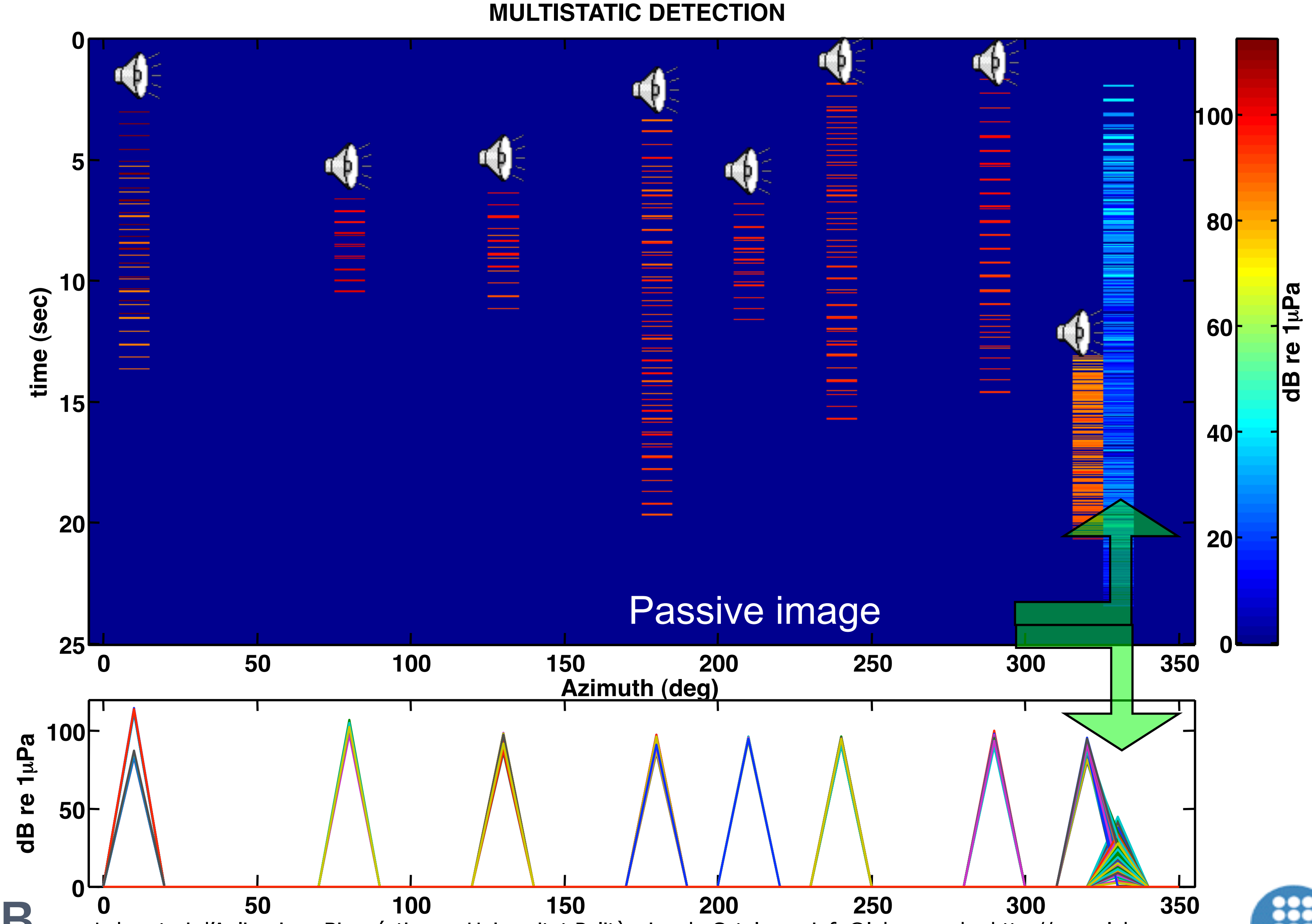
1. 8 sperm whales (BW=1-10kHz, sea state 0, 1 and 3), 500m from receiver
2. 8 sperm whales (BW=1-10kHz, sea state 0, 1 and 3), 1500m from receiver

Expected Signal Levels (dB) from a 10-15m whale in a 3D plane, 500m from receiver, illuminated by 8 Sperm whales with random position & heading – BW = 1-10kHz

8 Sperm Whales (random position & heading) illuminating one large whale at the surface 500m from receiver



8 active /1 silent /32 beams/No noise

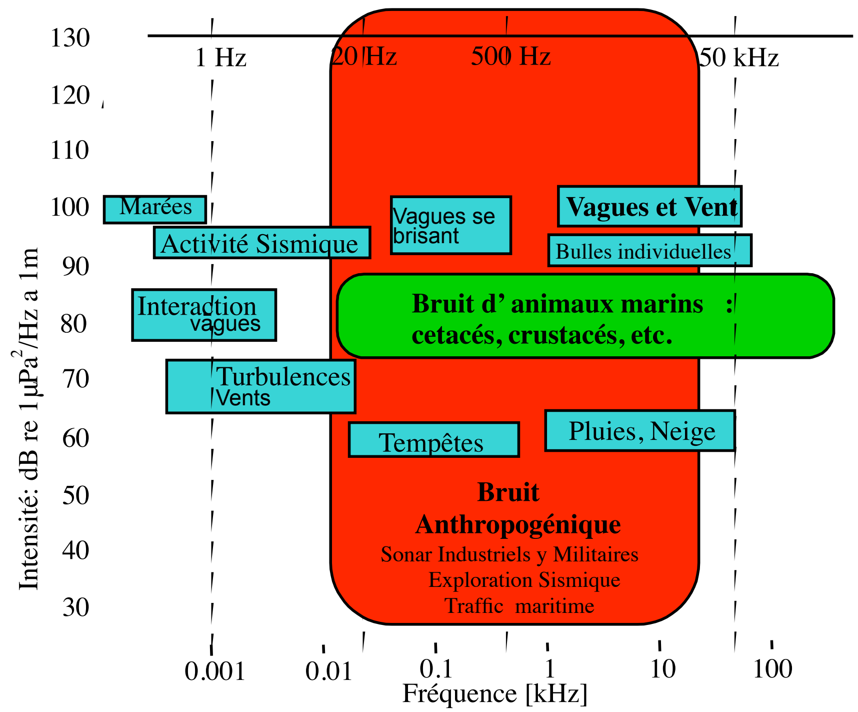


Conclusion (passive detection of silent whales)

1) The bistatic detection of echolocating and silent whales is possible through passive acoustics and ambient noise imaging
2) Sperm whales seem to be a good candidate as an illuminating source, due to a broader low frequency spectrum and a more powerful broadband beam
3) Above Sea-state 2, detection needs filtering and/or higher resolution array
4) Behavioural data are needed to build a proper 3D statistical model on whale positions and headings
5) Real conditions experiments are planned to validate these results

Partner Num.	Partner Institution Name	Principal Investigator (PI) for the Demo Mission	PI coordinates (Address, Email, Telephone, fax..)
1.	UPC Universitat Politècnica de Catalunya	Michel André	Michel.Andre@upc.edu
2.	UB* University of Bremen (Marum)	Christoph Waldmann	waldmann@marum.de
3.	FFCUL/ CGUL* Fundação da Faculdade de Ciências da Universidade de Lisboa Centro de Geofisica da Universidade de Lisboa	Jorge Miguel Miranda	jmiranda@fc.ul.pt
4.	INGV Istituto Nazionale di Geofisica e Vulcanologia	Paolo Favali	paolofa@ingv.it
5.	ISMAR Consiglio Nazionale delle Ricerche Istituto Scienze Marine, Dipartimento di Bologna	Nevio Zitellini	nevio.zitellini@bo.ismar.cnr.it
6.	Istituto Nazionale di Fisica Nucleare INFN*	Giorgio Riccobene	riccobene@lns.infn.it
7.	Consejo Superior de Investigaciones CSIC* Cientificas – Unitat de Tecnologia Marina - Centre Mediterrani d'Investigacions Marines i Ambientals	Juan Josè Danobeitia	jjdanobeitia@cmima.csic.es
8.	dBScale dBS*	Eric Delory	eric@dbscale.com
9.	Centro Interdisciplinare di Bioacustica e CIBRA Ricerche Ambientali, Università degli Studi di Pavia	Gianni Pavan	gpavan@cibra.unipv.it
10.	Technische Fachhochschule Berlin -FB VIII TFH* - Maschinenbau, Verfahrens- und Umwelttechnik - AG Tiefseesysteme	Hans W. Gerber	hwgerber@ism.tu-berlin.de hwgerber@tfh-berlin.de
11.	Tecnomare-ENI S.p.A. TEC*	Francesco Gasparoni	francesco.gasparoni@tecnomare.it

LIDO,
LISTENING TO THE DEEP-OCEAN ENVIRONMENT



130
120
110
100
90
80
70
60
50
40
30
Intensité: dB re 1 µPa²/Hz a 1 m
1 Hz
20 Hz
500 Hz
50 kHz
Marées
Activité Sismique
Interaction vagues
Turbulences Vents
Vagues se brisant
Vagues et Vent
Bulles individuelles
Bruit d' animaux marins : cetacés, crustacés, etc.
Tempêtes
Pluies, Neige
Bruit Anthropogénique
Sonar Industriels y Militaires
Exploration Sismique
Traffic maritime
0.001
0.01
0.1
1
10
100
Fréquence [kHz]