Using marine mammals for making science education and science careers attractive for young people

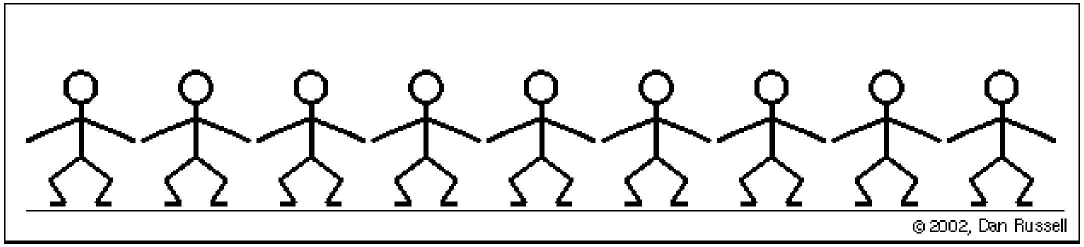
Acoustics teaching module

General information about acoustics

This project is funded by the Horizon 2020 Framework Programme of the European Union under Grant Agreement no 710708.

The biology of sound

A wave is a disturbance which propagates through a medium (solid, liquid, or gas) at a certain speed which depends on the inertial properties of the respective medium. The particles in the medium do **not** travel with the wave. There are two basic types of wave motion for mechanical waves: **longitudinal** waves and **transverse** waves.



Waves are caused by an object and sound is caused by vibrations

Sound is a wave that travels through air or water. Sound needs to travel through a medium - a liquid (such as water), a solid (such as the seafloor), or a gas (such as air). Sound cannot exist without a medium to travel through. Sound can be produced by vibrating an object and is characterized by intensity, frequency and wave length.

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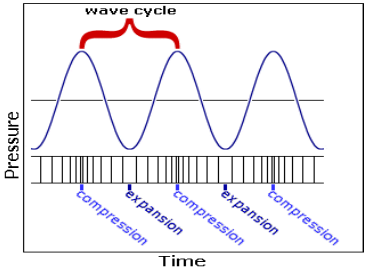
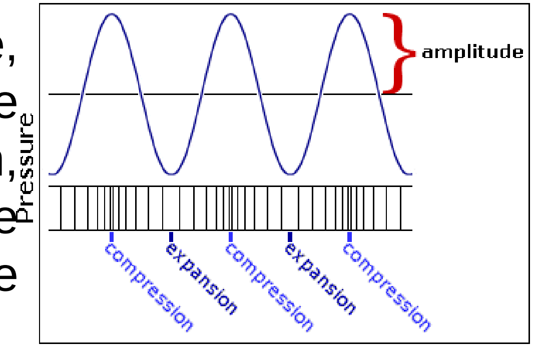
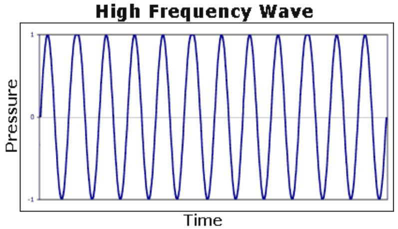
Sound characteristics

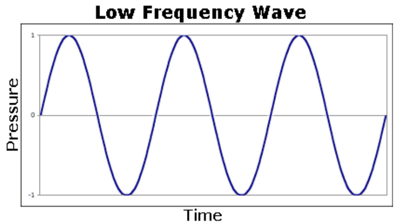


The length of one wave cycle, counted from a designated position of one wave to the same position of the next wave, is the **wavelength**. It is the distance that a sound wave travels in one cycle. The wavelength is related to the speed at which sound travels.

The typical amount of energy is the **intensity** of the wave, which is described by the **amplitude**. The amplitude gives the maximum distance a particle moves from its equilibrium, basically how much the medium is disturbed. It resembles the pressure change as the sound wave passes. Increasing the amplitude of a sound (increase the intensity) makes it louder.



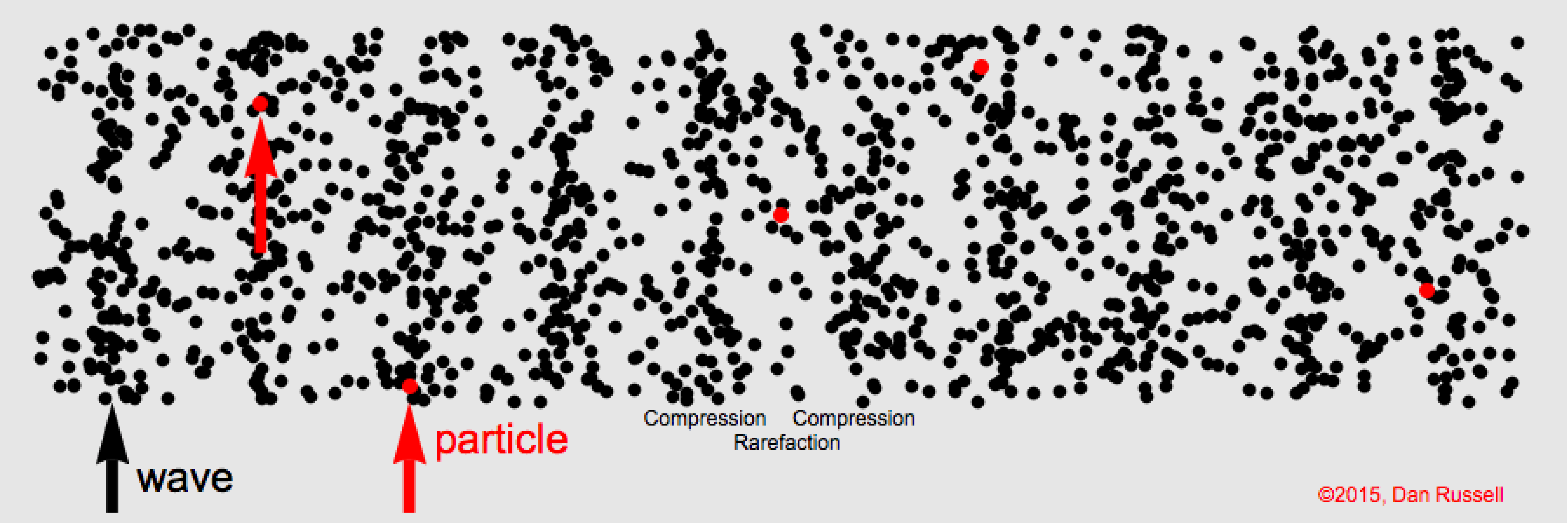




The **frequency** is the number of cycles of sound in a second. The high frequency wave has completed twelve cycles over the time shown, while the low frequency wave has completed only three cycles over the same time. The frequency makes high- or low-pitched tones, so when you decrease the frequency, you get a lower pitched sound.

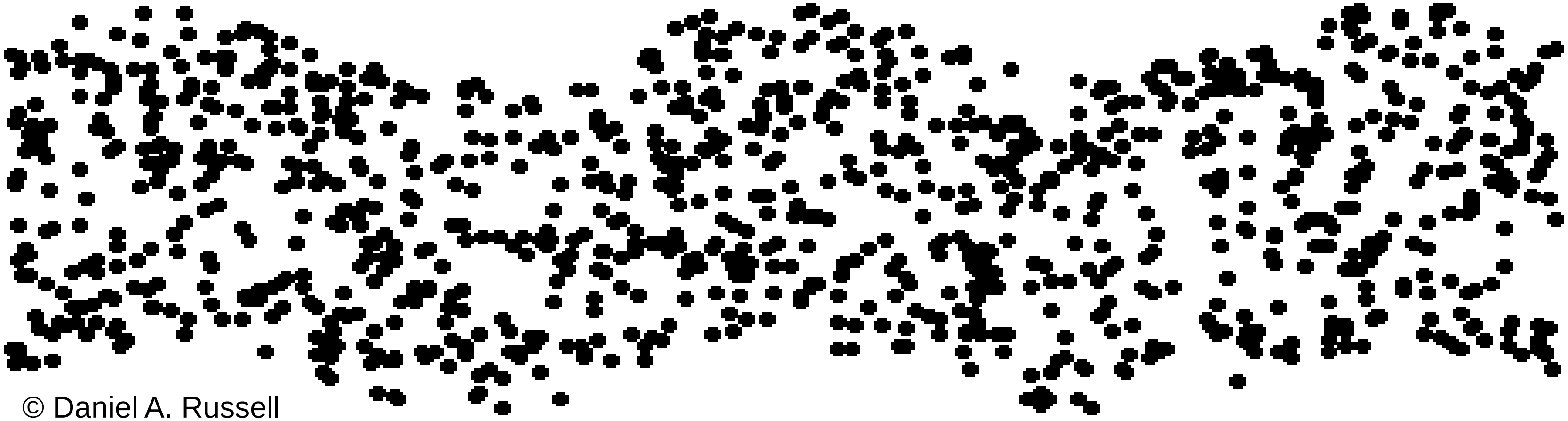
Longitudinal waves

There is a difference between the oscillatory motion of individual particles and the propagation of the wave through the medium.



Transverse waves

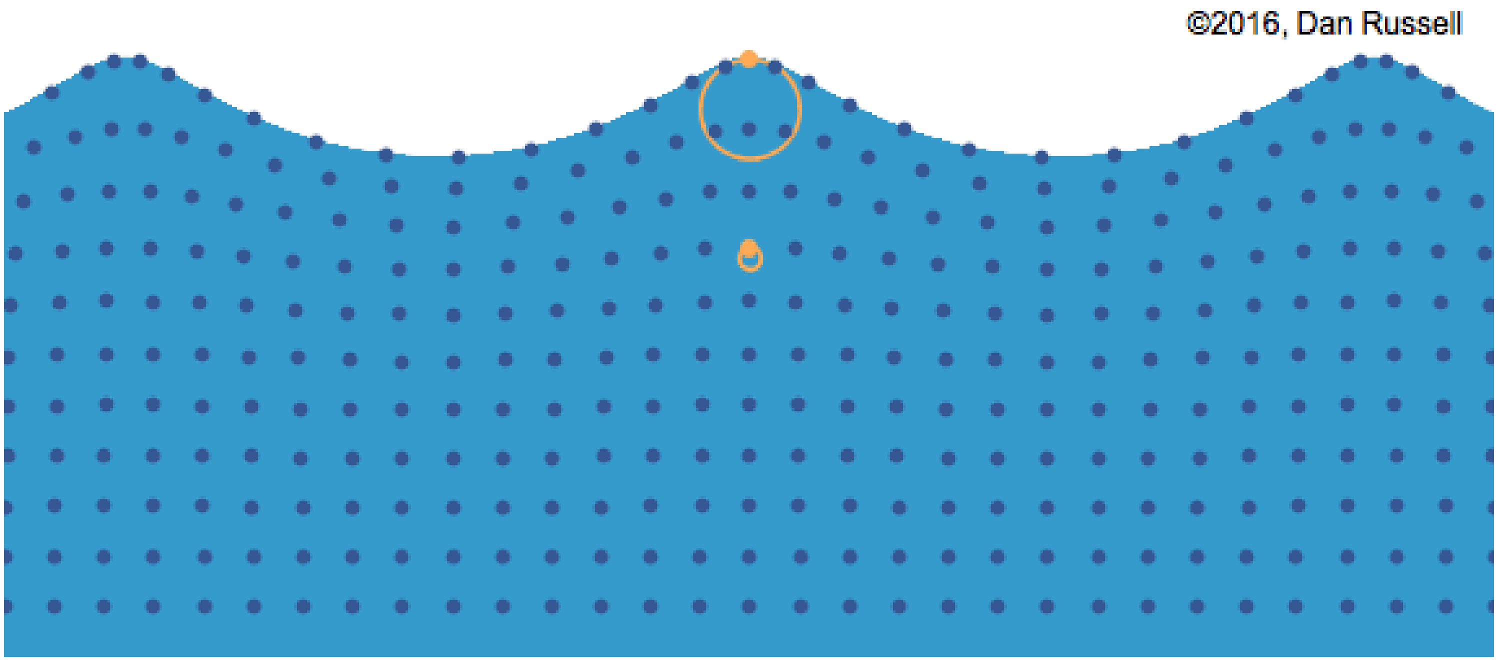
In a transverse wave the particle displacement is perpendicular to the direction of wave propagation. The particles do not move along with the wave; they simply oscillate up and down.



Water waves

Water waves: a combination of both longitudinal and transverse motions.

As a wave travels through the waver, the particles travel in *clockwise circles*. The radius of the circles decreases with increasing water depth.



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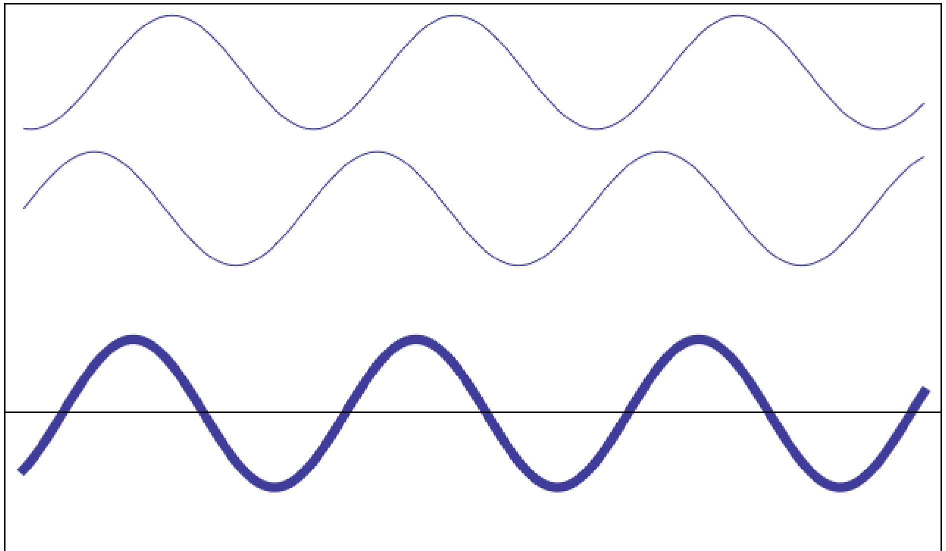
Constructive and Destructive Interference of waves

When two waves (with the same amplitude, frequency, and wavelength) travelling in the same direction are **in-phase**, they interfere **constructively** and the result has twice the amplitude of the individual waves. When the two waves have **opposite-phase**, they interfere **destructively** and cancel each other out.



→ Important for hearing underwater: sometimes sound waves can cancel each other out, thus animals present in those regions can't hear the sound

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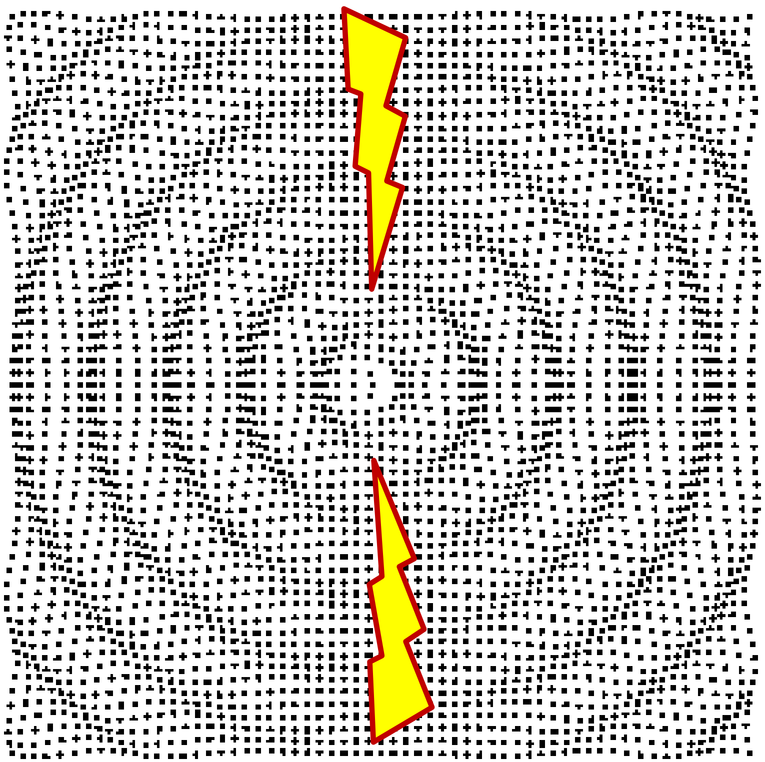
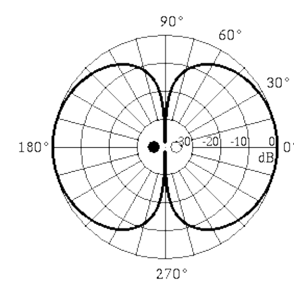
Radiation from a dipole source



The regions where sound is cancelled shows up along the vertical axes

A dipole source consists of two monopole sources of equal strength but opposite phase and separated by a small distance. While one source expands the other source contracts. **A dipole source does not radiate sound in all directions equally.**
The directivity pattern looks like a figure-8; there are two regions where sound is radiated very well, and **two regions where sound is canceled out**.



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Lloyd‘s mirror effect

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An acoustic source just below the water surface generates constructive and destructive interference between the direct path and reflected paths.

- The Lloyd mirror effect has been implicated as having an important role in explaining why **marine animals** such as whales and manatees have been repeatedly **hit by boats and ships.**
- Interference due to Lloyd's mirror results in low frequency propeller sounds not being discernible near the surface, where most accidents occur. *This is because at the surface, sound reflections are nearly 180 degrees out of phase with the incident waves. Combined with spreading and acoustic shadowing effects, the result is that the marine animal is unable to hear an approaching vessel before it has been run over or entrapped by the hydrodynamic forces of the vessel's passage.*

Reflection of waves from boundaries

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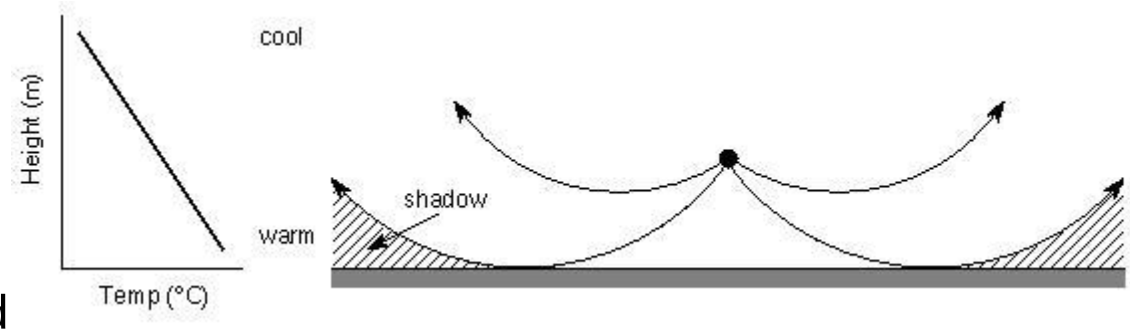
At sea level, air is 784 times less dense than water, therefore the two media form a boundary.

At a fixed (hard) boundary, the reflected wave changes its polarity (*undergoes a 180° phase change*)

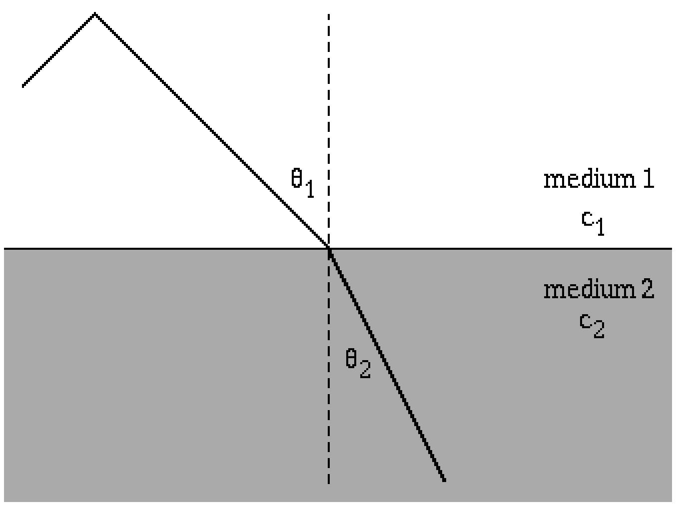
At a free (soft) boundary, the reflected wave has the same polarity (*no phase change*) as the incident wave

Due to the sound reflection at the surface boundary we often don't hear sounds from inside water on land, which is why oceans and lakes appear silent to us.

The speed of sound



The wave speed changes gradually over a given distance. The speed of a sound wave in air depends on the temperature in °C. Since temperature decreases with height, the speed of sound also decreases with height. This means that for a sound wave traveling close to the ground, the part of the wave closest to the ground is traveling the fastest, and the part of the wave farthest above the ground is traveling the slowest, which forces the wave to change direction and bend upwards.



The speed of a wave depends on the elastic and inertia properties of the medium through which it travels. When a wave encounters different medium where the wave speed is different, the wave will change directions.

Sound speed dependencies

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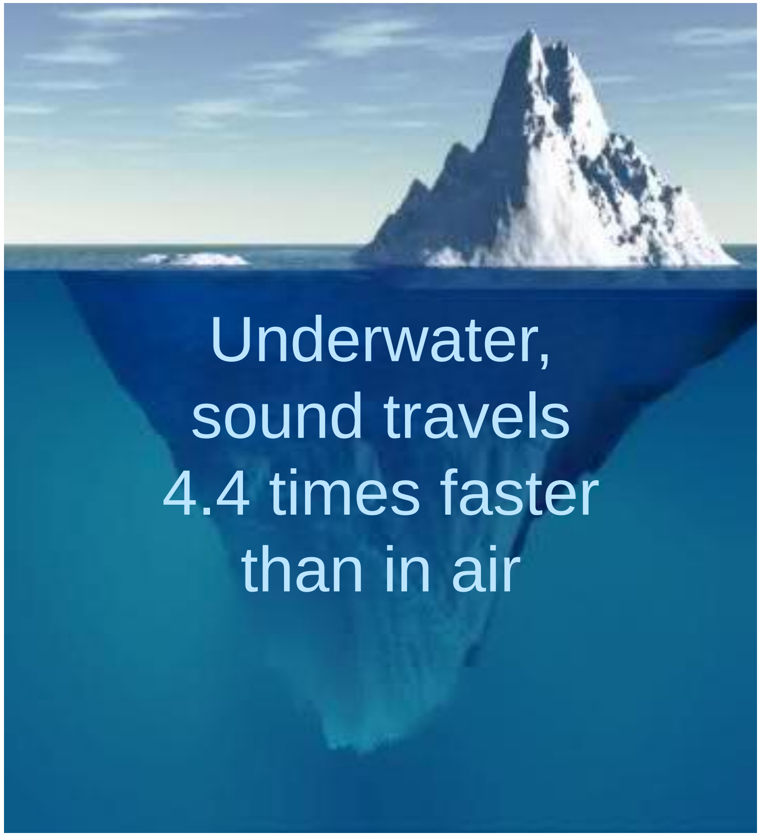
medium	c_s in m/s at 20 °C
air	343
water	**1484**
water (0 °C)	**1407**
seawater	**~1500**
ice	3250
gold	*3240*
diamond	*18000*

Influence of density $\lambda = \frac{c_S}{f}$

λ wavelength c_S sound-speed f frequency

Influence of pressure, salinity and temperature



The composition of Sound

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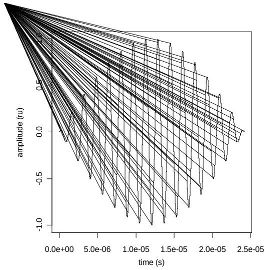
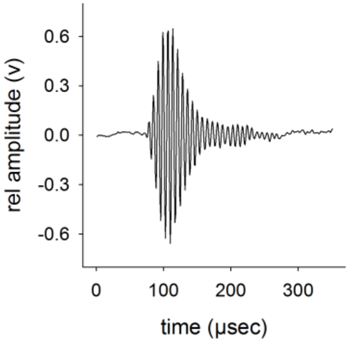
Pure tone

regular sine wave signal



artificial signal



porpoise click

(Verfuß et al. 2005)

Chimes

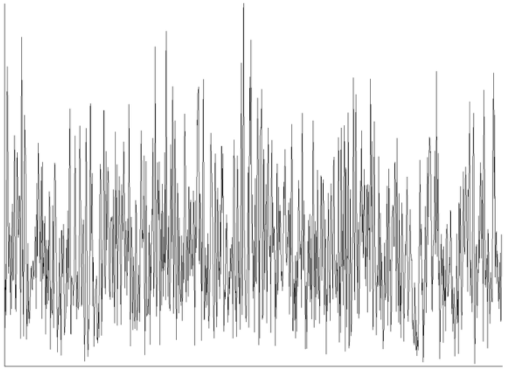
complex tonal sound

for instance a d-minor chord

Noise

unwanted data

different types



white noise

Sound = all of the above

Marine mammal vocalisations

Marine mammals produce vocalisations using mechanisms similar to those of land mammals. Pinnipeds (seals and sea lions), polar bears and sea otters have a larynx with vocal cords similar to that of humans and produce sounds in air and in water. Baleen whales also use their larynx to produce deep, low frequency sounds.

Sounds are produced by vibration of the vocal folds in the larynx by expressing air from the lungs. The sound produced by the larynx can be purposely modified by changing the position and form of the animal's buccal cavity, tongue, and lips.

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Marine mammal vocalisations

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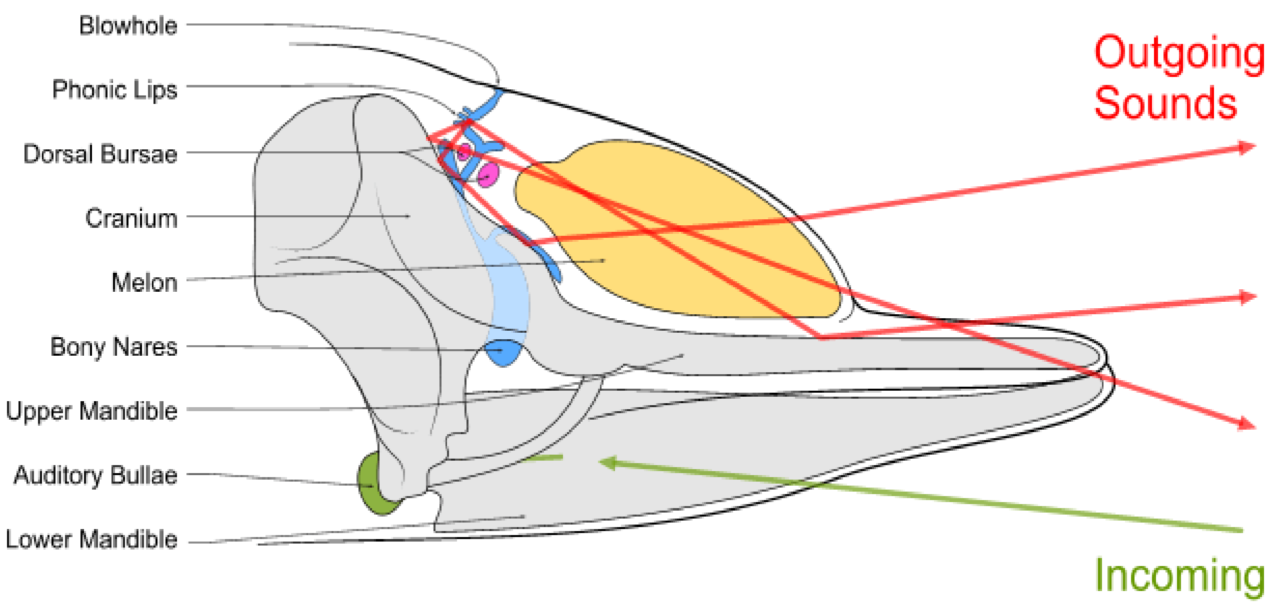

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Toothed whales can produce two different kinds of sounds: they produce whistles using their larynx, as well as high frequency signals for echolocation with the phonic lips and their specialized air sacs near the blowhole.

Marine mammals also produce other sounds by slapping parts or their entire body against the water surface. Tail and flipper slapping as well as breaching are commonly performed behaviours by some cetaceans, all producing sounds.

Adaptations for diving & an aquatic lifestyle: Odontocetes – Echolocation ("dolphin sonar")

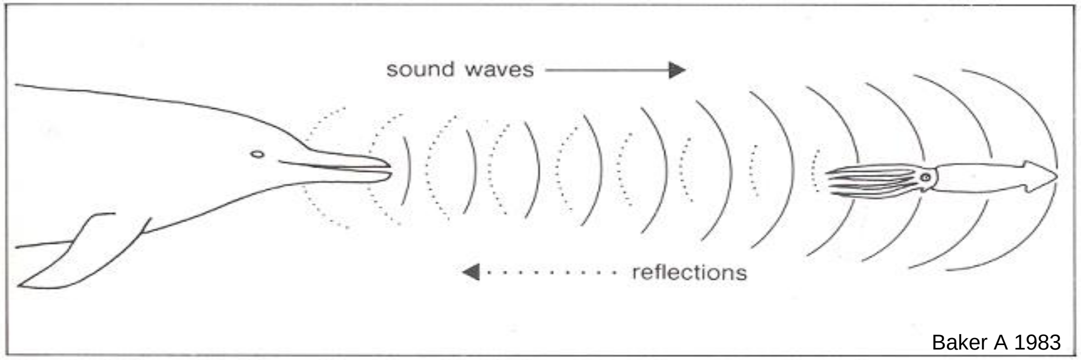


Fig. 6 Schematic illustration of a dolphin's echolocation system in action.

- **Orientation**
- **Obstacle avoidance**
- **Communication**
- **Foraging**

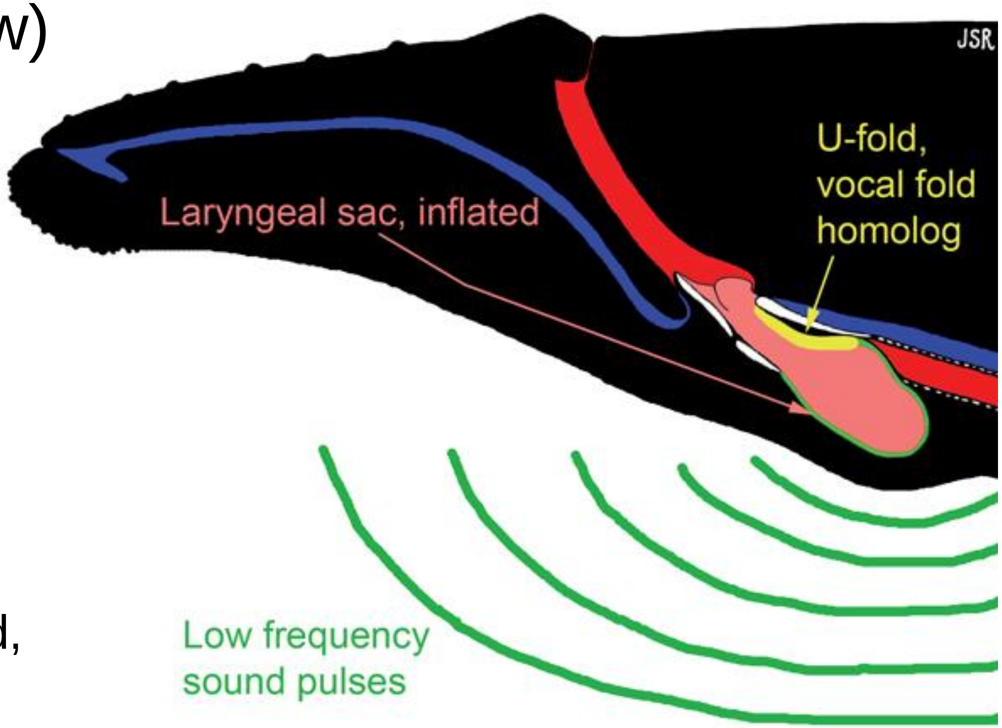
Many marine animals rely on sound for their survival and underwater sound is one of the primary triggers for behavioural reactions in cetaceans

A functional and healthy hearing system is of primary importance for cetaceans

Marine mammal vocalisations

It is believed that baleen whales produce their sounds by contracting their throat and chest muscles, causing air to flow between the lungs and the laryngeal sac (pictured in pink).

This causes the u-fold (yellow) vocal folds to vibrate and produce sound. These vibrations propagate from the laryngeal sac into the surrounding water as sound waves (green lines).



Note: the respiratory tract is shown red, the digestive tract in blue

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Why is sound important to marine animals?

D•O•S•I•T•S

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Hearing is the universal alerting sense in all vertebrates

- Limited visibility in the marine environment
- Underwater, sound travels far greater distances than light
- Sound travels without much loss and there are many underwater surfaces that reflect sound

Marine animals rely on sound to acoustically sense their surroundings, to communicate at short and long distances and from all directions, protect themselves, locate food, navigate underwater, avoid predators, and/or understand their environment

Most marine animals rely on sound for survival

Underwater noise pollution

Potential effects of sound on marine mammals:

- Behavioral Changes
- Masking
- Hearing Loss
- Strandings

Means to measure marine mammal's reaction to sound:

- Hearing Sensitivity Studies
- Visual Observations
- Acoustic Monitoring
- Tagging Studies
- Controlled Exposure Experiments

Effects of sound

Range of impacts over a range of spatial & temporal scales

Individual level

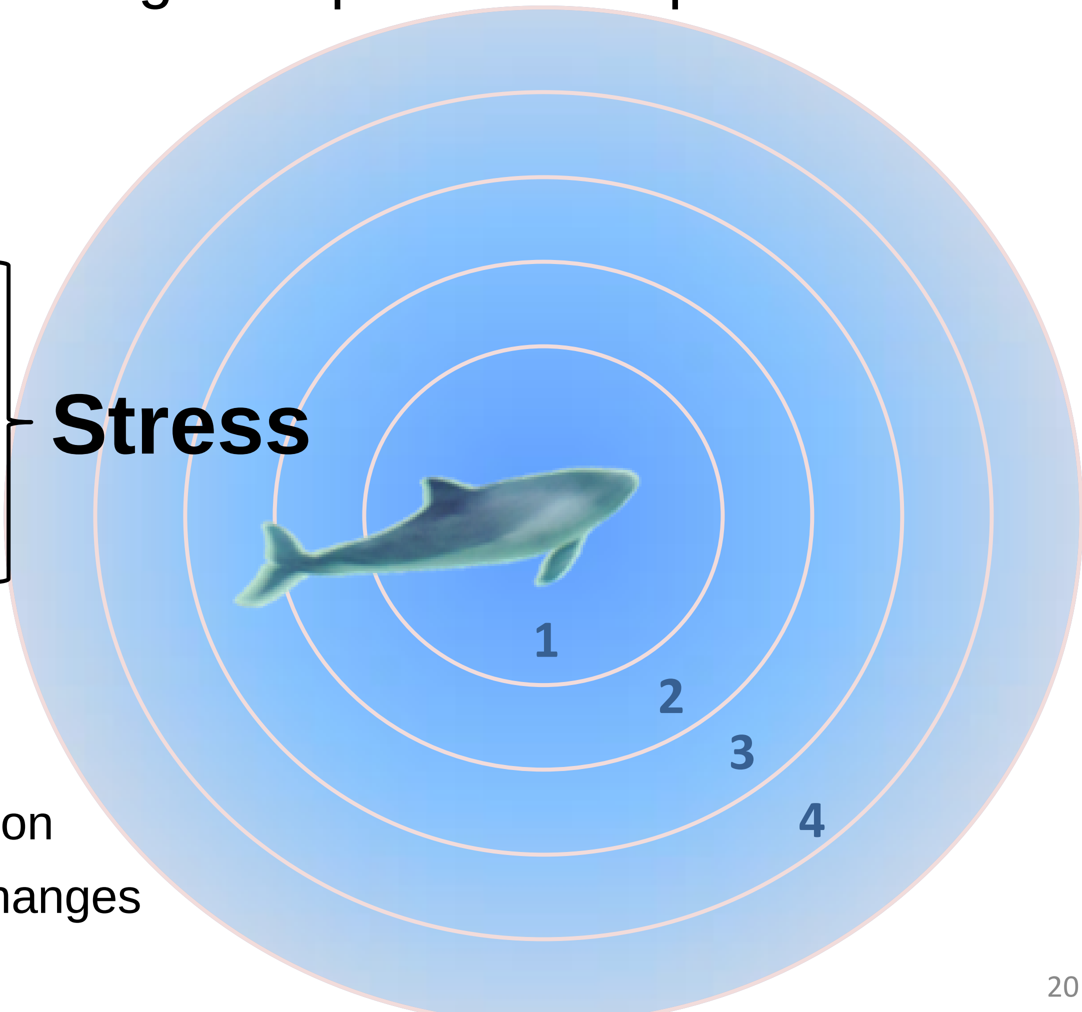
4: Audibility

3: Behavioural changes

2: Masking

1: Impairment, injury, death

Stress



Population level

- Stress
- Changes in spatial distribution
- Behavioural & population changes

(Richardsen et al. 1995)

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Behavioral Changes

D•O•S•I•T•S

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- Some sounds may not cause any response
- Minor to significant deviations observed
- Energetic costs of changing behaviour
- Some responses are momentary, others long lasting
- Changes in a variety of behaviours: diving, surfacing, vocalizing, stopping to vocalize, stopping to forage, stopping to feed, interrupting mating

Behavioural responses depend on a number of factors: individual's hearing sensitivity, tolerance to noise, previous/ continuous exposure to the same noise, behaviour at the time of exposure, age, sex, group composition

Animals can become accustomed to sounds that appear harmless by learning from previous experiences

Some marine mammals seem to have learned to use anthropogenic signals in their benefit: grey seals learned that acoustic deterrent devices indicate the location of a food source

Masking

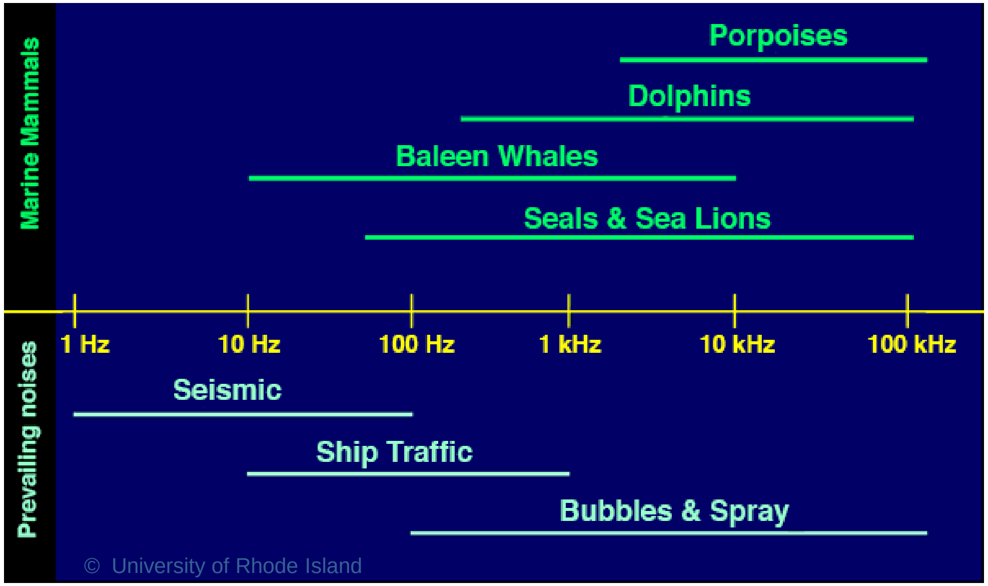
Masking occurs when noise interferes with an animal's ability to perceive (detect, interpret, and/or discriminate) a sound: elevated noise levels may mask important sounds for marine animals

The degree of masking is influenced by the level, frequency band, and the duration of the noise in comparison to the sound of interest. Masking has the greatest impact on animals when the noise is at frequencies similar to those of biologically important signals, such as mating calls (*Figure*: compare frequency ranges of sounds & ambient noise)

<u>Reactions to masking noise</u>:

- stopping vocalizations
- raising the intensity of vocalizations to above the noise (Lombard Effect)
- changing the frequency of their vocalization

→ **Due to dispersal of anthropogenic activities, masking may be one of the most extensive and significant effects on the acoustic communication of marine life today**



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Hearing Loss

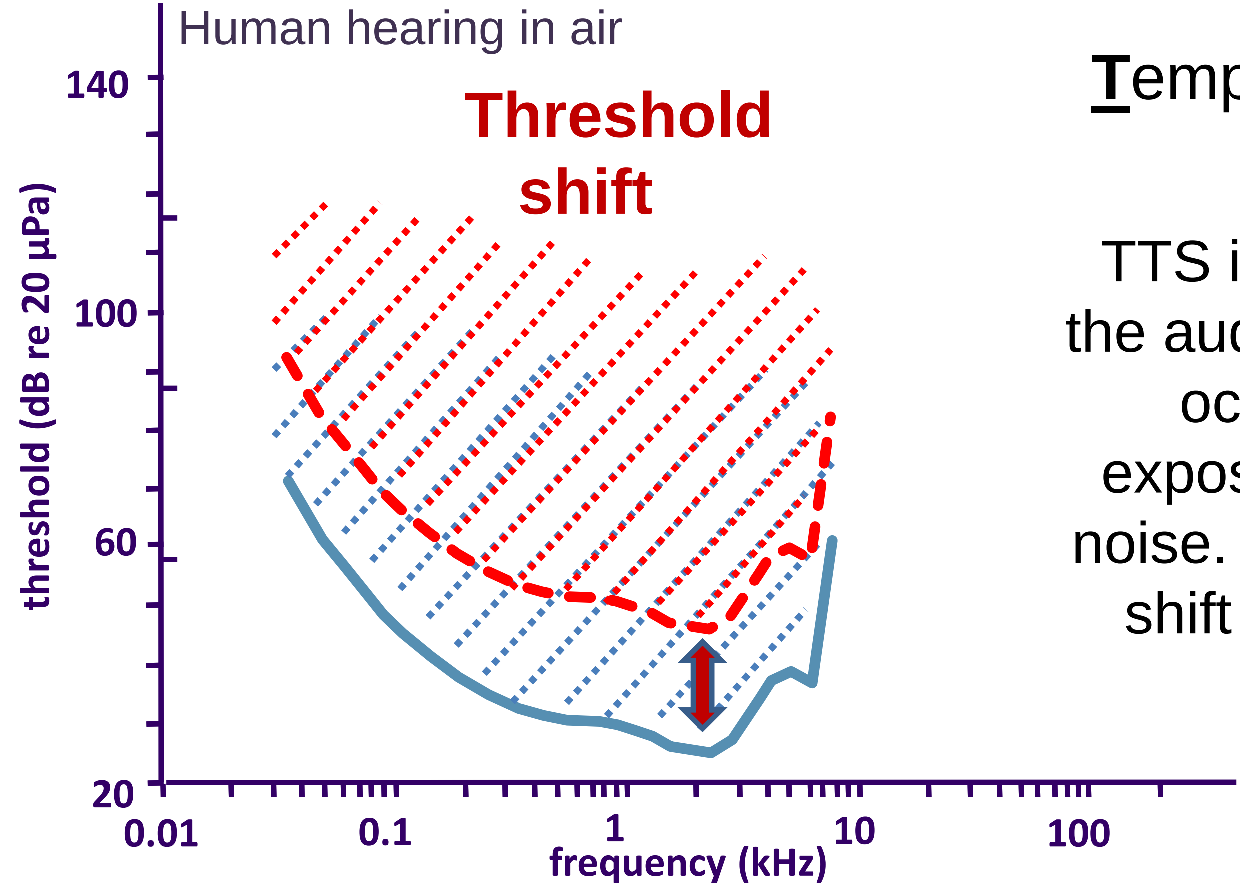
Hearing loss in mammals depends on many factors, including the hearing sensitivity of the animal in comparison to the intensity of the sound, the frequency of the sound, and the duration of exposure to the sound

Exposure to extremely loud sounds (in humans e.g., rock concerts, impulse noise from gunshots, etc.) leads to temporary or permanent hearing impairment

Hearing damage can also be caused by exposure to less intense but continuous noise over long periods of time. Hearing impairment does not occur if the frequency of the encountered sound is outside the individuals hearing range

Photos © ITAW

Hearing Loss



Temporary**T**hreshold**S**hift = "Disco effect"

TTS is a temporary shift in the auditory threshold. It may occur suddenly after exposure to a high level of noise. A temporary threshold shift results in temporary hearing loss.

Permanent Threshold Shift (PTS) can occur as a result of repeated TTS occurrences, or as a result of a single exposure to a very intense sound

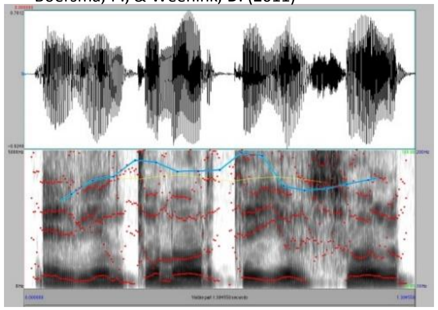
Determining the cause of a stranding or death of a stranded animal can be difficult and often remains without clear results

- It is known that military sonar exercises have contributed to mass strandings of beaked whales

In five well-documented cases, there is sufficient information about the military exercises and the times and locations of the strandings to determine that multi-ship exercises with sonar contributed to the strandings. These events occurred in Greece (1996), the Bahamas (2000), Madeira, Portugal (May 2000), and the Canary Islands, Spain (2002 & 2004)

Underwater noise Pollution

Boersma, P., & Weenink, D. (2011)



Anthropogenic causes

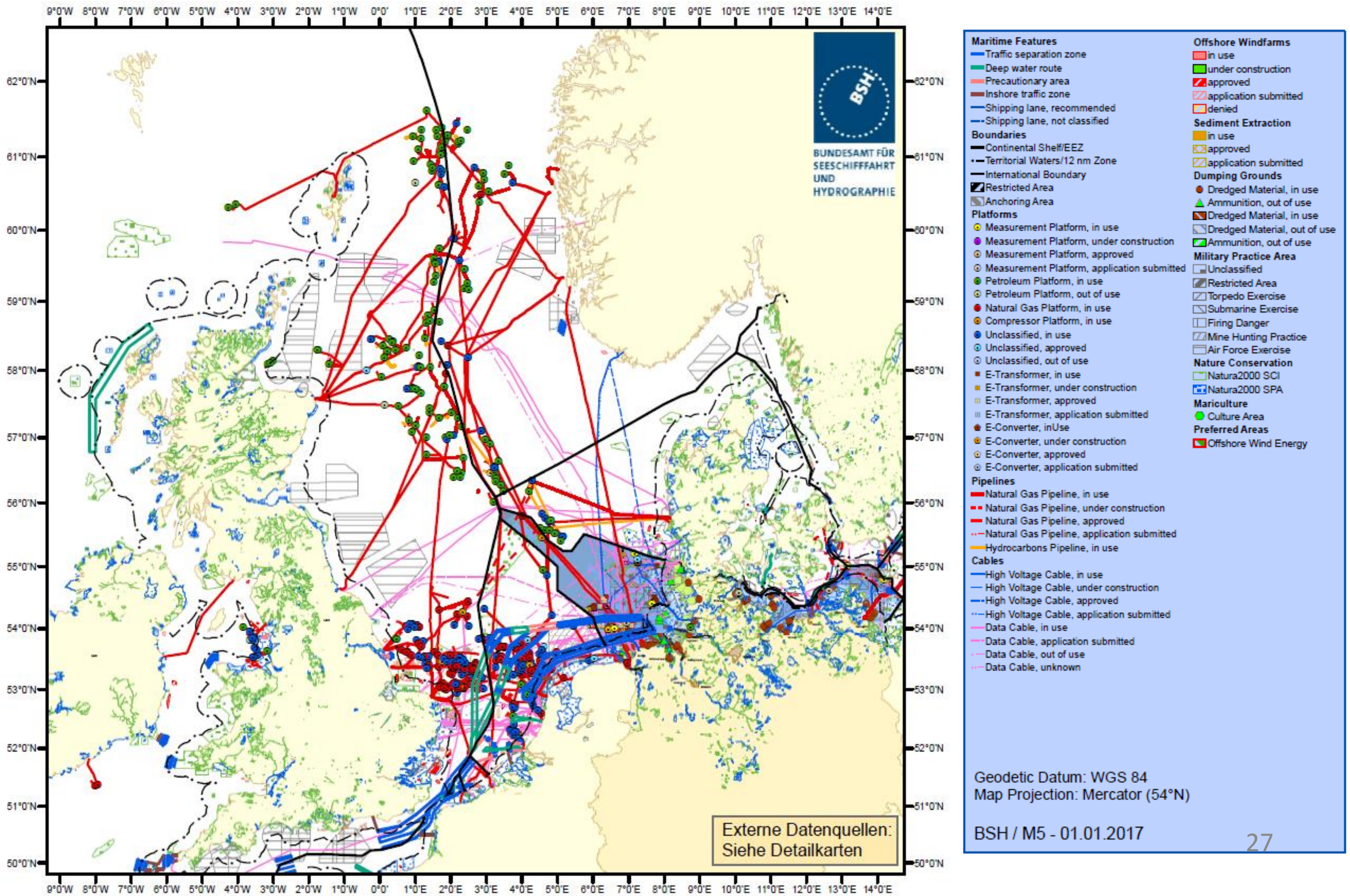
- Shipping
- Pile driving & offshore installations
- Military activities
- Exploration of natural resources
- Underwater explosions

Natural sound sources

Underwater noise Pollution

The North Sea is a heavily industrialized habitat!

North Sea: Existing and Perspective Uses and Nature Conservation



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Examples of underwater noise pollution

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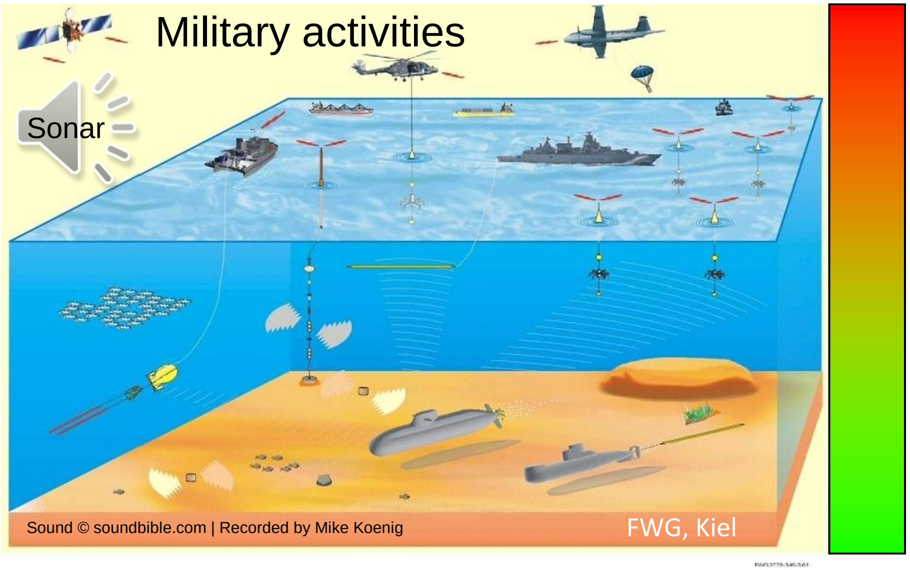
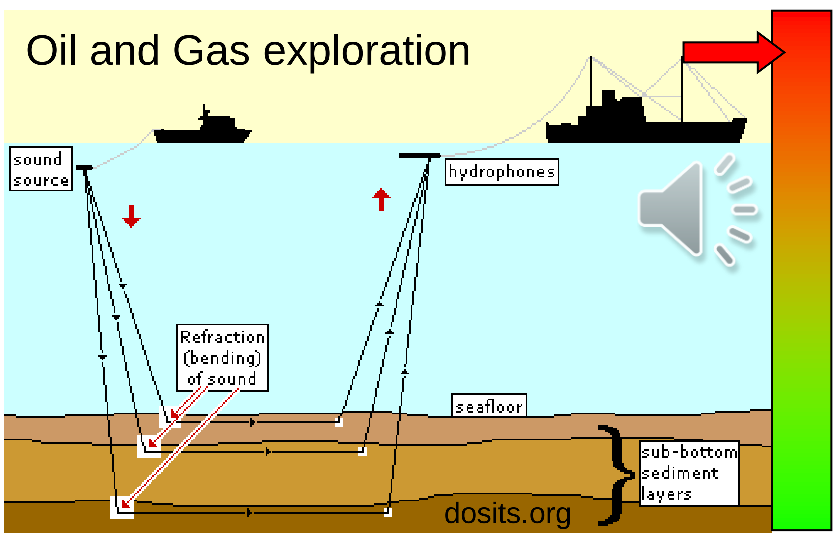
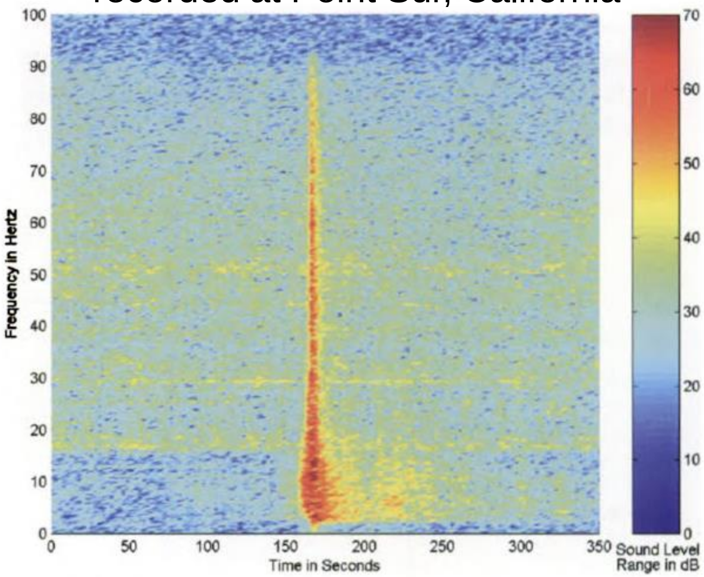
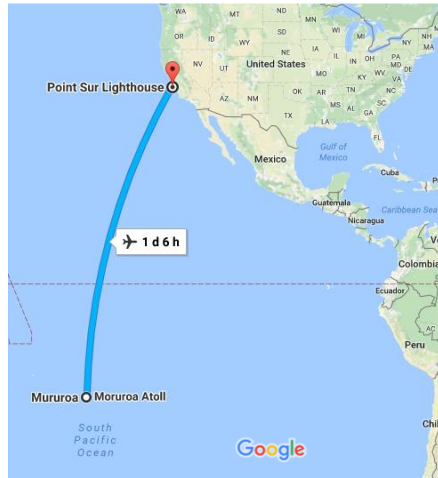




Examples of underwater noise pollution

Sonogram of a submarine nuclear test on the Mururoa Atoll on Oct. 21st 1992: recorded at Point Sur, California





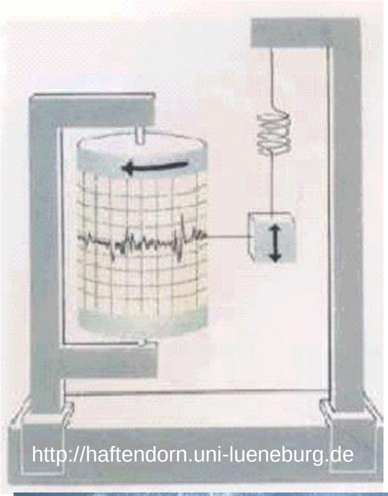
280 dB

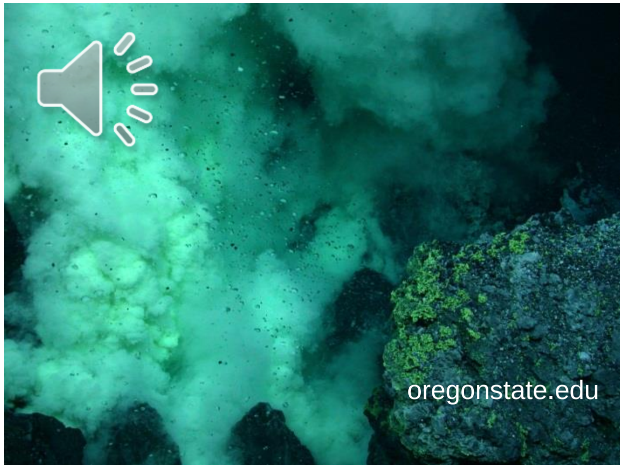
Underwater sound file of a nuclear explosion at the Mururoa Atoll on 27.10.1965

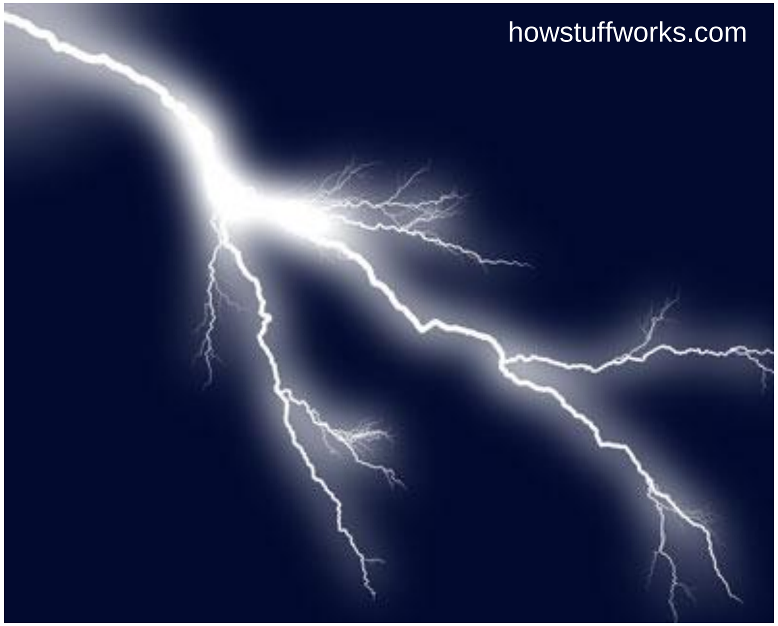
Recorded at a distance of

6600 km

Natural sound sources

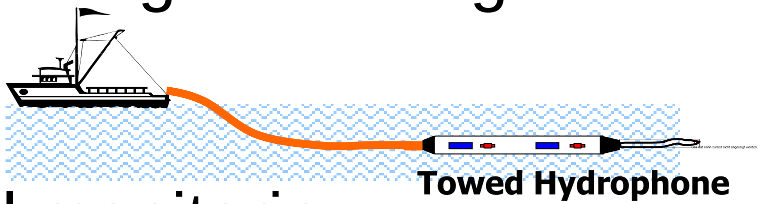






Bioacoustics

- Study of sound communication and related behaviour
- Study of sound production, hearing & learning
- Impacts of noise



- Bioacoustics in environmental monitoring
- Identification techniques and applications
- Recording & analysis equipment and techniques
- Underwater sound (ultrasound, infrasound)
- Bioacoustical sound structures, patterns, variation and repertoires

Bioacoustics & the marine environment

- ❖ The marine fauna lives & communicates underwater
- ❖ Acoustics crucial for survival & wellbeing
- ❖ Communication on different ranges: ⬇ frequency – ⬆ frequency
- ❖ Noise disturbance quick & detrimental

Measuring hearing sensitivity

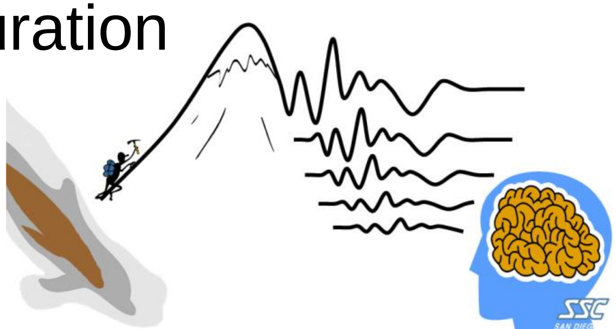
AEP measurements in human new-borns

Auditory Evoked Potentials (AEP)

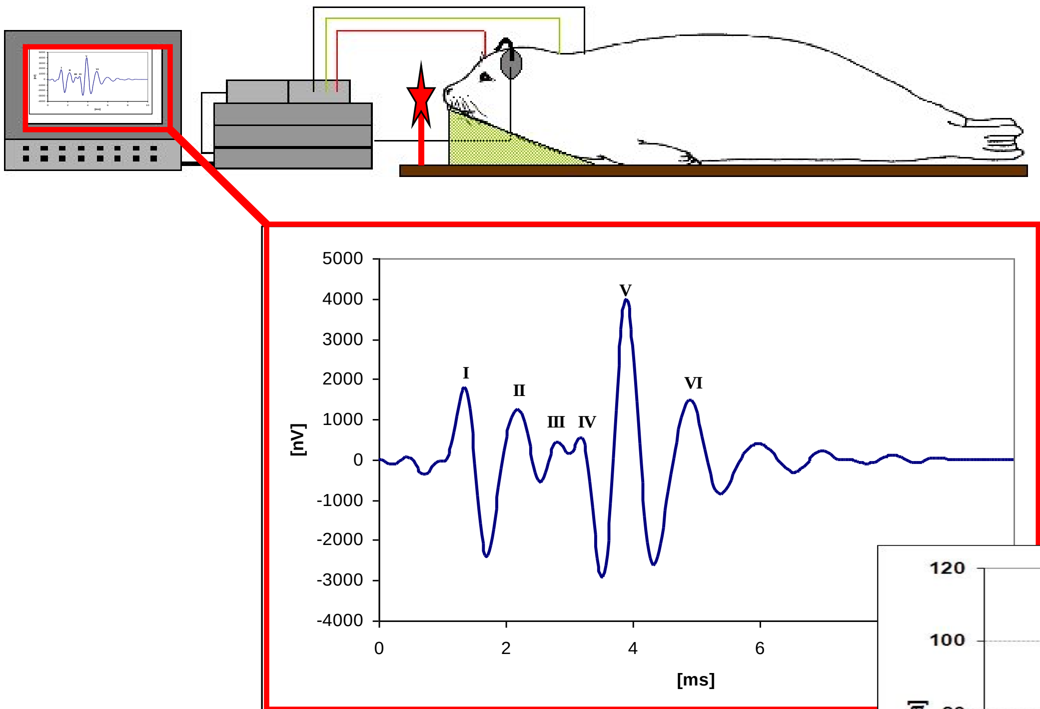
AEPs are very small electrical voltage potentials originating from the brain recorded from the scalp in response to an auditory stimulus

Advantages:

- No training necessary
- Non-invasive
- Short duration



Measuring hearing sensitivity

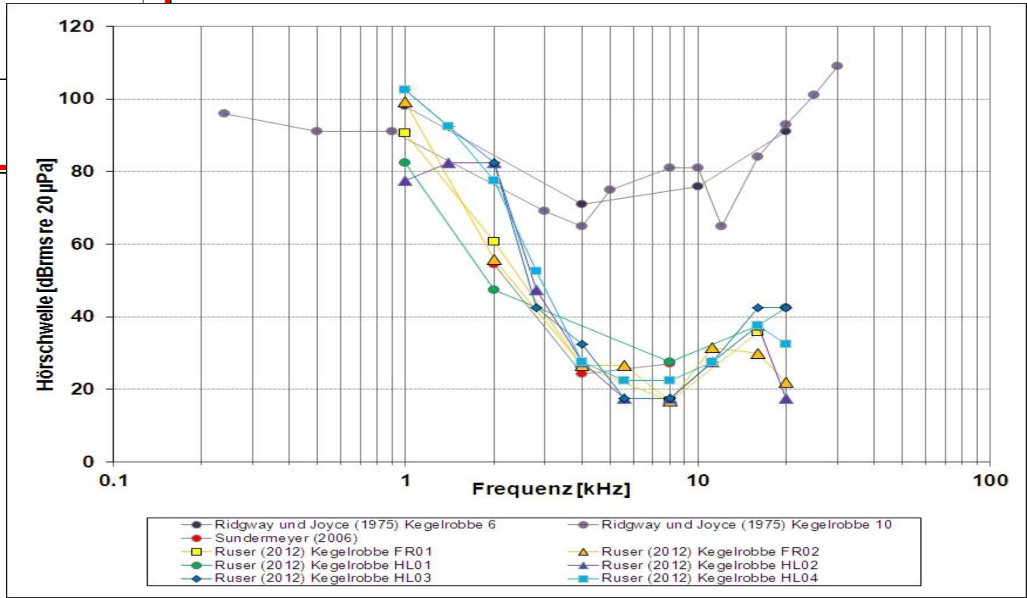


In-air hearing ability:
≥ 2.8 kHz

→ clearly better than previously known

(Ruser et al. PloS One 2014)

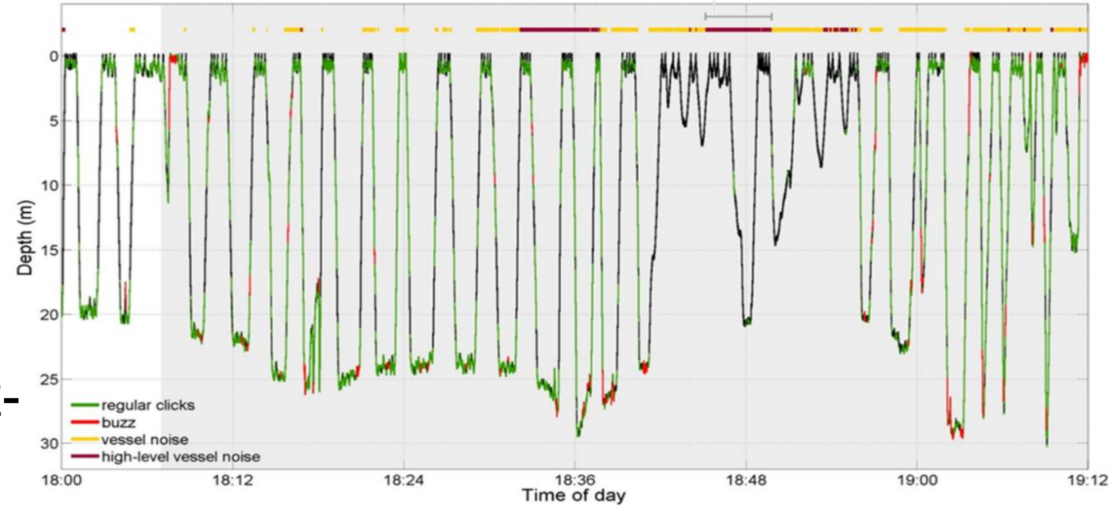
Measurements of underwater hearing ability using AEPs in progress



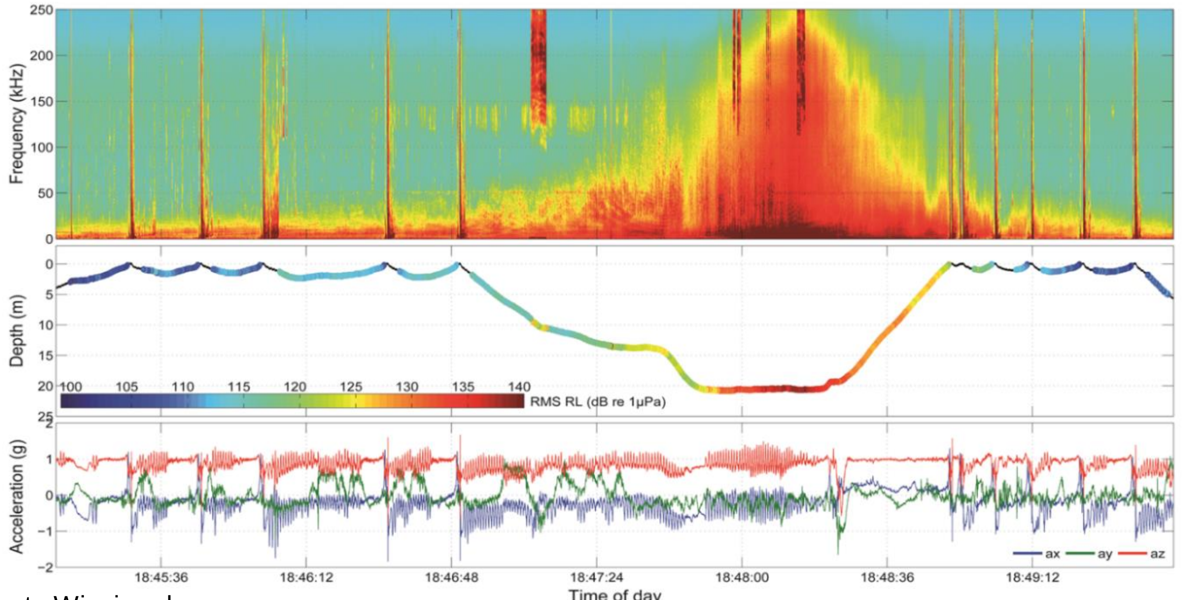
Bioacoustic research

Photos © ITAW

→ Behavioural and acoustic profile of a porpoise, pre-disturbance, during and post-disturbance



Audiograms of University of Aarhus, University St. Andrews: High-frequency D-Tag (50Hz – 160kHz)



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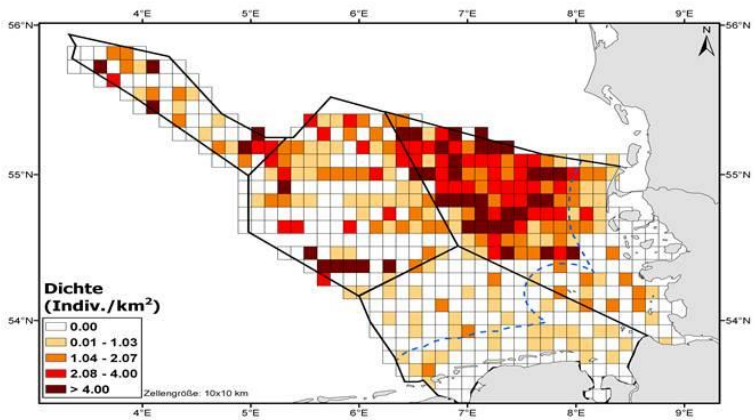
Measuring the effects of noise

- Self contained ultrasonic detector
- Detection of toothed whales, such as dolphins and porpoises by identifying the trains of their echolocation sounds, “clicks“
- Selection of tonal clicks and recording of time, duration and other features of these clicks

Influences:

- presence patterns (yearly, diurnal,…)
- impacts of pile driving
- **behavioural changes?**

Spacial distribution research



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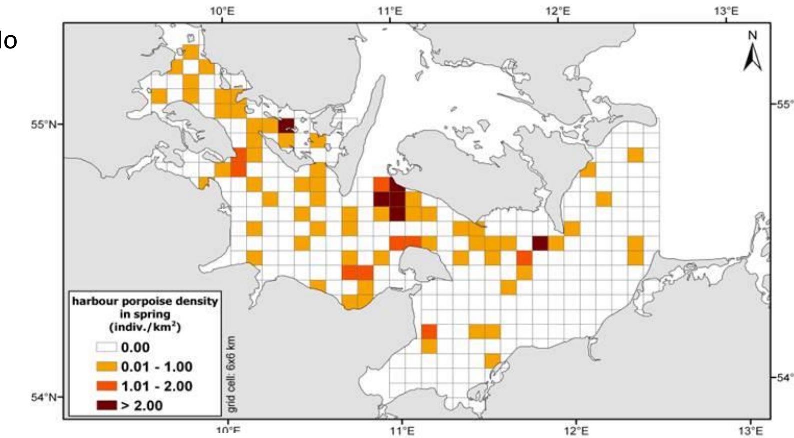
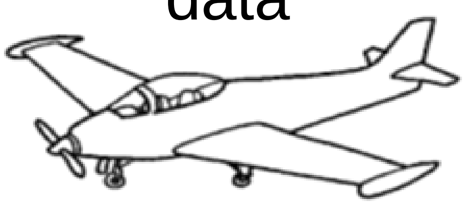
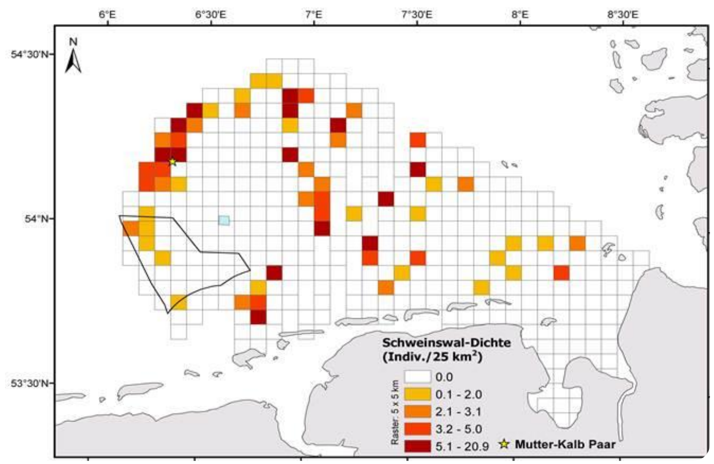


Aerial surveys support acoustic data



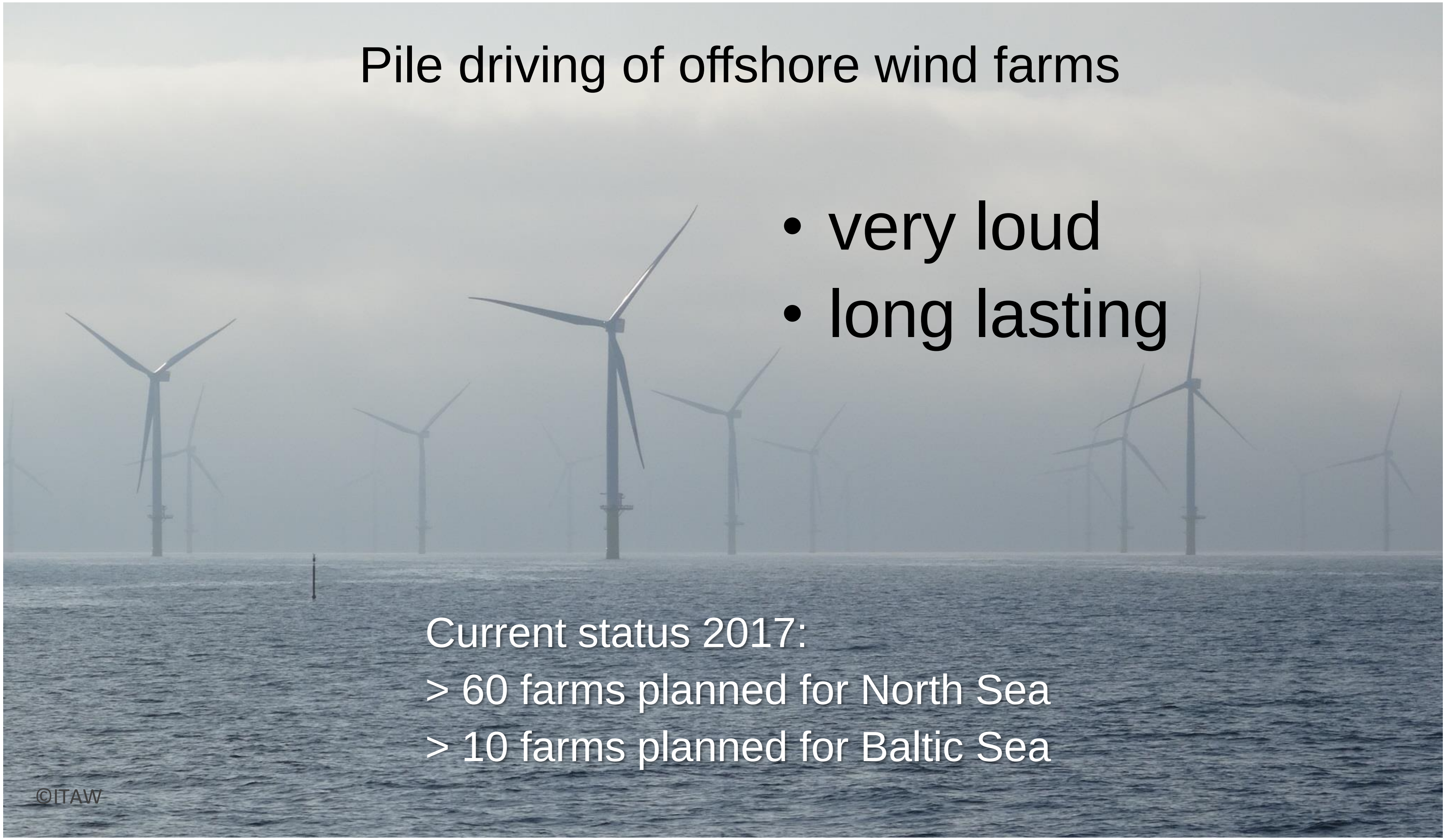


Clear change in porpoise distribution after a pile driving event in the North Sea

Porpoise distribution in North and Baltic Sea

(Gilles, A., Scheidat, M. and Siebert, U. 2009; Herr, H., Fock, H. and Siebert, U. 2009; Scheidat M., Kock K.H. and Siebert U. 2004; Scheidat, M., Gilles, A. and Siebert, U. 2008; Siebert U., et al. 2006)

Example of underwater noise pollution



Pile driving of offshore wind farms

- very loud
- long lasting

Current status 2017:
> 60 farms planned for North Sea
> 10 farms planned for Baltic Sea

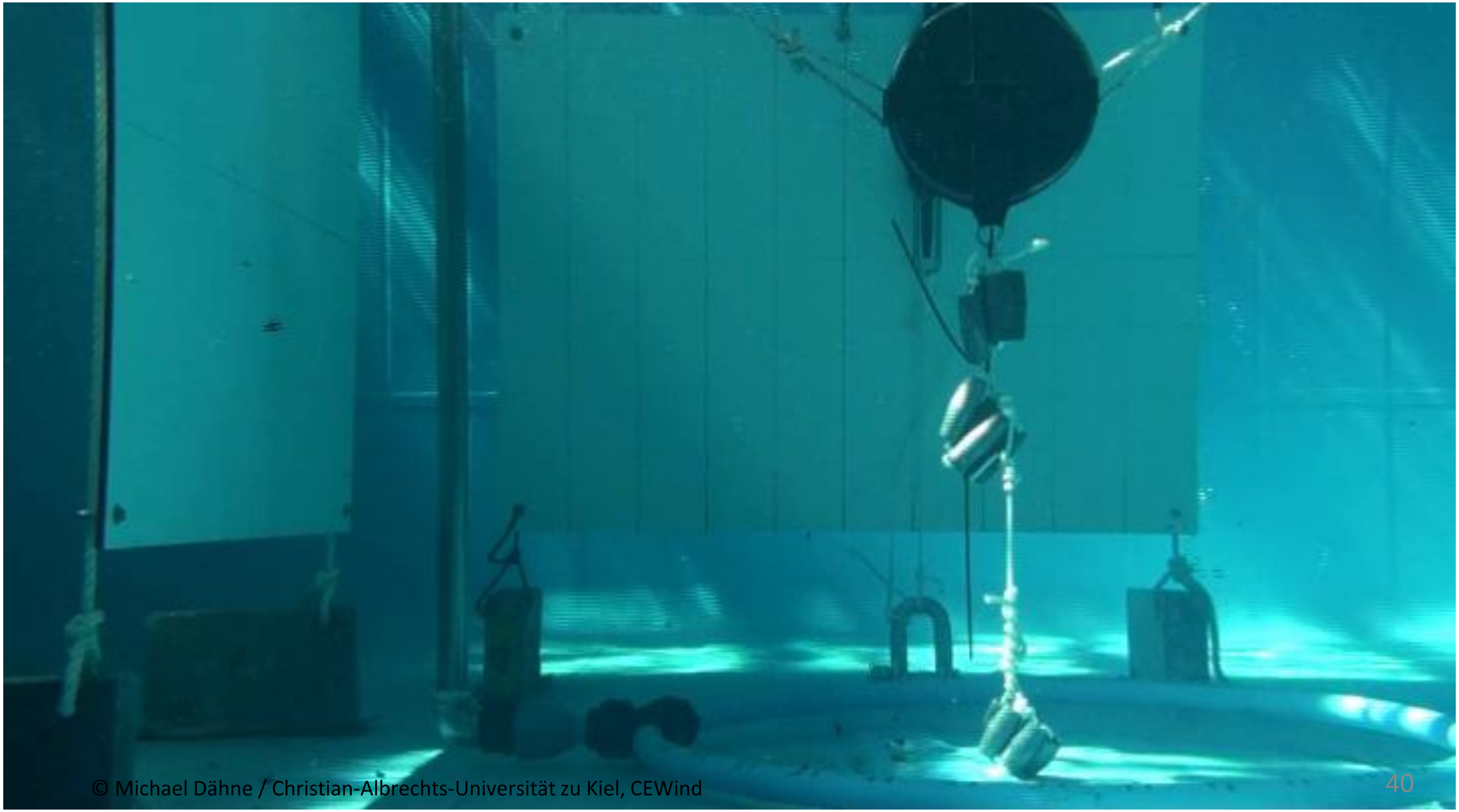
Noise pollution mitigation measures

What can be done?

1. Develop different, not/less noisy procedures
2. Use noise sources only in times of low animal abundance / avoid areas with high concentrations of marine mammals
3. Muffle sounds
   - Air bubble curtain (large/small)
   - Air sleeves
4. Keep animals away from noise
   - Only **temporary**!!! → you may keep them away from their prey as well
   - Most efficient method: other noise (deterrent devices, harassment devices), thus questionable
   - Ramp up of the sound signal intensity (pile driving)

Noise pollution mitigation measures

Test design for air bubble curtains



MARINE MAMMALS science education

Thank you for your attention

Nine scientific and educational research institutes plus NGO’s from Germany, Poland, Sweden, Belgium and Denmark joined forces for this project:

Project coordination: Kieler Forschungswerkstatt (ozean:labor)

Project partners:

Kiel University (CAU); Foundation for the Development of the University of Gdansk (FRUG/Poland); Havets Hus in Lysekil (Sweden); Institute for Terrestrial and Aquatic Wildlife Research (ITAW) at the University of Veterinary Medicine Hanover Foundation (TiHo); Leibniz Institute for Science and Mathematics Education (IPN); Meeresmedien Hamburg; University of Liège (ULg/Belgium); Marine Biology Research Center, University of Southern Denmark (SDU/Denmark); WWF Poland

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