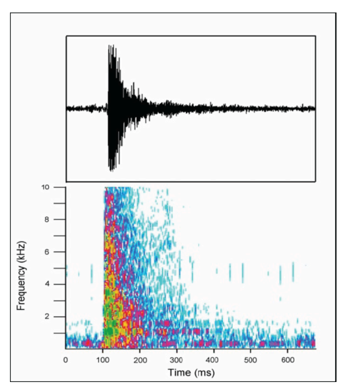
Underwater Acoustics: Webinar Series for the International Regulatory Community

Webinar Outline: Potential Effects of Sound on Marine Fishes
Tuesday May 10, 2016 at 12:00pm (US East Coast Time)

Part 1: Potential Effects of Sound on Marine Fish
Anthony D. Hawkins, Loughine LTD, Aberdeen, UK

There are many different types of underwater sound sources (all with different characteristics)

- Continuous sound sources
    - Shipping (large and small vessels)
    - Vibrating pile drivers
    - Dredging
    - Operational renewable energy devices (wind, wave, and tidal energy)
    - Fishing gears (especially those that come in contact with the sea bed)
- Pulsed (intermittent) sounds sources
    - Explosions
    - Percussive pile drivers
    - Seismic airguns (surveys for oil and gas)
    - Sonar systems (operate at a wide range of frequencies and pulse lengths)
- Pile driving is especially noisy (used to construct bridges, and wind farms- the wind farms can span extensive areas)
    - Each wind turbine is supported by multiple piles which can take several hours to drive into the sea bed; lots of pile driving going on, at multiple sites simultaneously
    - [pile driving sound played] Pile driving sounds have sharp onset, and this makes them particularly damaging or intrusive. There is also a wide spectrum of frequencies included in the sound.
        - Pile driving sounds are loud, wide band, and have a sharp onset.

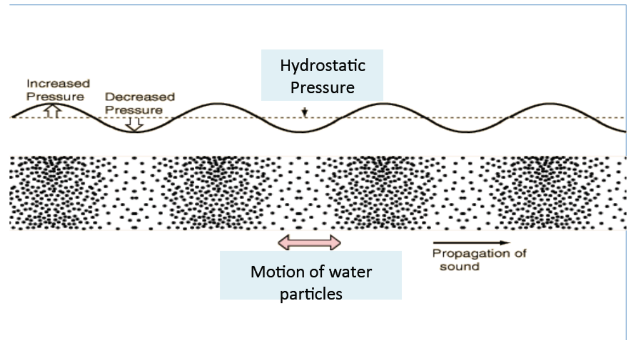


    - In addition to transmitting sound waves through the water, pile driving also transmits sounds through the seabed via compression waves and shear waves (and these interact to form interface waves at the boundary between the seabed and water). The interface waves are slower, low frequency waves, traveling slower than the speed of sound, but the magnitude of these waves can be quite large
        - Generating particle motion rather than pressure

Does noise affect fish?

- Need to evaluate the risk to fishes from exposure to noise
- Need to know the levels of sound that may have adverse consequences and those that do not
    - *Sound Exposure Criteria*

What is sound?



- Sound is generated by the movement or vibration of any object immersed in a medium
- Sound propagates through the medium at a speed that depends on its density and elasticity
    - It travels fast in water
- Sound consists of fluctuations in pressure (the sound pressure), but is also accompanied by back and forth motion of the water (the sound particle velocity)

Noise levels in the sea are changing dramatically as a result of human activity.

- Some of this noise is continuous, and lasts for a long time
- Other, louder sounds are present only for short periods
- How important are sounds to fish? How will exposure to noise affect them?

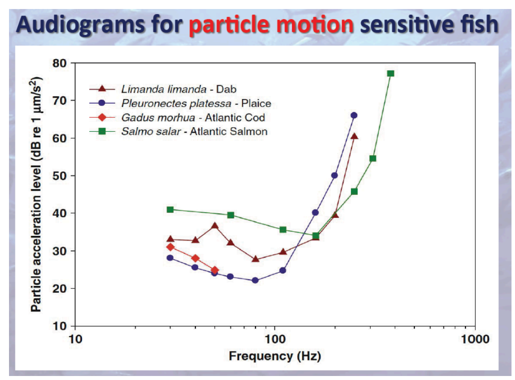
How well do fishes hear sounds?

- Visibility is often poor underwater
- Sound provides an effective way for fish to communicate
- Hearing also gives fish knowledge of the surrounding world
- Sound is used for:
    - Communication and social interaction
    - Foraging and finding prey
    - Avoidance of predators (listening to sounds predators make)
    - Orientation and navigation (listening to sounds from natural sources and orientating to them)
    - Habitat selection

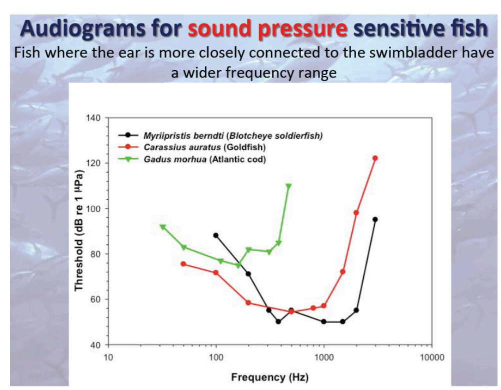
- Important to determine if a species responds to sound pressure or particle motion. Need to make sure conduct experiments carefully and can measure both of these parameters
    - Many experiments conducted in small tanks with sound generated in air (above the tank); very little particle motion being generated in the water, so for a particle motion sensitive species, it will appear to be insensitive to sound

- If immerse loud speaker in water, will generate a lot of particle motion, but little sound pressure; would favor a fish sensitive to particle motion
- Need to find an appropriate acoustic field, resembling the natural habitat, where you can monitor both of these things

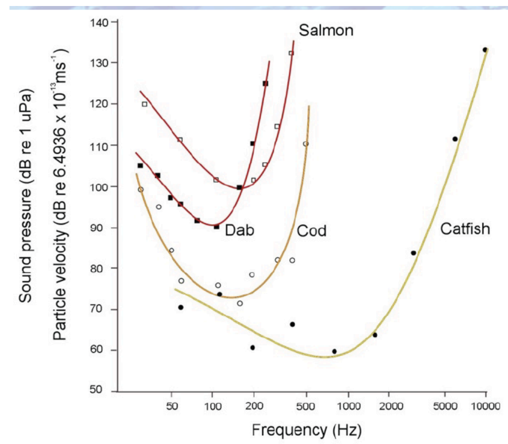
- It is difficult to reproduce sounds in shallow tanks and to measure particle motion components of sound. It is quite difficult to acquire sensors that measure particle motion- often have to estimate or model it
- Important to therefore carry out hearing experiments under good acoustic conditions (most successful experiments have been carried out in the sea or specially observed tanks)
    - Example of fish held in cage in midwater in the ocean; sounds played back to fish from loudspeakers at different distances; fish conditioned to respond to sound
        - Nearfield effect was used to vary the ratio of particle motion to sound pressure
            - As the speaker gets closer to the fish, the magnitude of the particle motion increases for a given sound pressure
    - By determining auditory thresholds at different distances, can determine which stimuli a fish is responding to (particle motion or sound pressure)
    - Audiograms generated; plot minimal level to which animal will respond at different frequencies
        - Audiogram for particle motion sensitive fish
            - These fish specialize in ultra-low frequencies
            - Cod included as at low frequencies respond to particle motion and at higher frequencies respond to sound pressure



        - Audiogram for sound pressure sensitive fish
            - Ear is connected to, or close to, the swim bladder
                - Extends the frequency range of the animal; those with a connection have a wider frequency range
            - Gas in swim bladder pulsates when exposed to sound pressure creating particle motion which then stimulates the ear; the ear itself is sensitive to particle motion



- Audiograms for different fishes under similar acoustic conditions (showing particle motion detectors and sound pressure sensitive fish with extended ranges)
  - A bit deceptive- in some circumstances, e.g. shallow water, magnitude of particle motion for a given sound pressure increases, and therefore, under those conditions, the sensitivity of the salmon and dab would appear to increase compared to other species. Wrong to describe these fish as "less sensitive"; it really depends on the circumstances under which they are living.
    - Possible some fish are able to detect airborne sounds rather than water born sounds.



- Good audiograms are only available for a few species of fish (there are lots of audiograms available but they have been conducted under poor conditions and should be considered invalid)
  - For plaice and salmon, know they are sensitive to particle motion (and have good audiograms)
  - For cod, have good audiogram and know it is sensitive to sound pressure
  - Even those that detect sound pressure use particle motion to determine sound direction
    - The difference between sound pressure and particle motion, where sound pressure acts in all directions (scalar property), particle motion is a vector quantity (acts in one direction)- it always provides cues back to the position of the source

- Fish can discriminate between different sounds.
  - Cod can discriminate between sounds of differing frequency and amplitude and filter out sounds from noise
    - Cod audiogram tracks sea noise at lower frequencies
    - As level of background noise changes, so do the thresholds for cod
      - "Masking"- reduces the range over which a fish can detect sounds of biological importance
      - There is a high risk that manmade noise will cause masking
      - Masking reduces the range fishes can detect sounds of biological importance (sounds fish make and sounds predators make)

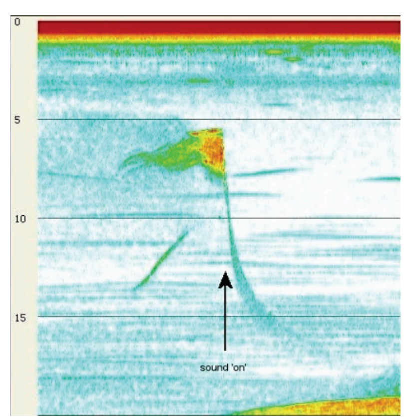
        - Cod can also discriminate between sounds coming from different directions and distances
    - Potentially, fish can locate and identify different sound sources with some precision

Potential effects on behavior of exposure to man-made sounds

- Many fish make sounds [sounds of a male haddock courting a female played] Male haddock produce low frequency, repetitive sounds and a single call can last for 20 minutes or so. Females select males based on sounds produced.
    - Thousands of fish together at a spawning ground produce a loud rumble; can locate spawning grounds by listening for these sounds
    - Man-made noise will impact fish communication and could impact their reproductive success
- Interference with communication (masking of biologically important sounds); like haddock example given
- Displacement (from feeding grounds and other preferred habitats)
- Interference with migrations (delay or prevent fish from reaching their destinations; migration is subject to specific timing; masking of cues for migration)
- Physiological stress (affect behavior, growth, and reproduction)

How do we decide whether sounds have an adverse effect on fish?

- *Sound Exposure Criteria* for different effects (death or injury close to a source, hearing impairment close to a source, masking, changes in behavior)
- Different effects occur at different distances; need to define these areas
    - Map areas that have adverse effects
    - Map the area likely to be affected by sound propagation models
- Define sound exposure criteria- those levels of sound that kill fish, injury them, or cause hearing damage
    - Have little information on behavioral effects and sound levels that cause behavioral effects.
        - These experiments are difficult to carry out. Need to conduct these experiments over a wide area, and captive fish are unlikely to behave in the same way as wild fish
        - Need to conduct this work in the sea
            - School of mackerel and sprat split up upon playback of pile driving sounds
            - Able to create response curves for both spray and mackerel and- provide sound exposure criteria
    - Most sound exposure criteria are a bit “dodgy”. They are more “assumed” rather than based on data (especially those used for regulation). There is new research coming out, but it takes a while for research to be integrated into legislation.



        - Metrics used are inappropriate- for fish, expressed in sound pressure, when fish/inverts are sensitive to particle motion
        - In investigating zones of effect, the propagation models have not been validated, are poor models, especially for shallow waters, do not take into account particle motion, and/or seabed transmission/ground propagation
        - Actual impacts on populations are often unknown and difficult to assess
- Can observe behavioral reactions or even death, but do not know greater impact on populations of animals
    - Can see behavior; estimate critical functions effected; and then guess population effects, and potential ecological effects. Right now, in process of observing response, actual effect. But need to look at impact on populations and ecological communities
- Need to regulation human sources to avoid effects on fish populations
    - Have some limited information on effects of acute exposure of fish to some sound, but do not know overall effects on fish populations
        - Know little about chronic effects of cumulative exposure (lots of sources of sound active all the time); do not know what the chronic effect is and impact to fish populations
- Need to conserve marine soundscapes

Additional information on the DOSITS website:

Science of Sound > What sounds can animals hear?
http://www.dosits.org/science/soundmeasurement/soundsanimalshear/

Science of Sound > How is hearing measured?
(http://www.dosits.org/science/soundmeasurement/hearingmeasured/)

Science of Sound > What are common underwater sounds?
(http://www.dosits.org/science/soundsinthesea/commonsounds/)

Science of Sound > Why do sounds have different properties?
(http://www.dosits.org/science/soundsinthesea/properties/)

Science of Sound > How do people and animals use sound in the sea?
(http://www.dosits.org/science/soundsinthesea/peopleanimalsuse/)

Science of Sound > How does marine life affect ocean sound levels?
(http://www.dosits.org/science/soundsinthesea/marinelifeaffectoceansound/)

Science of Sound > Advanced Topics > What is intensity?
http://www.dosits.org/science/advancedtopics/whatsintensity/

Animals and sound > Why is sound important to marine animals?
(http://www.dosits.org/animals/importanceofsound/whyissoundimportant/)

Animals and Sound > How do marine animals use sound?
(http://www.dosits.org/animals/useofsound/animalsusesound/)

Animals and Sound > How do marine fish communicate using sound?
(http://www.dosits.org/animals/useofsound/fishcommunicate/)

Animals and Sound > How do marine fish and invertebrates use or make sound when feeding?
(http://www.dosits.org/animals/useofsound/fishinvertfeeding/)

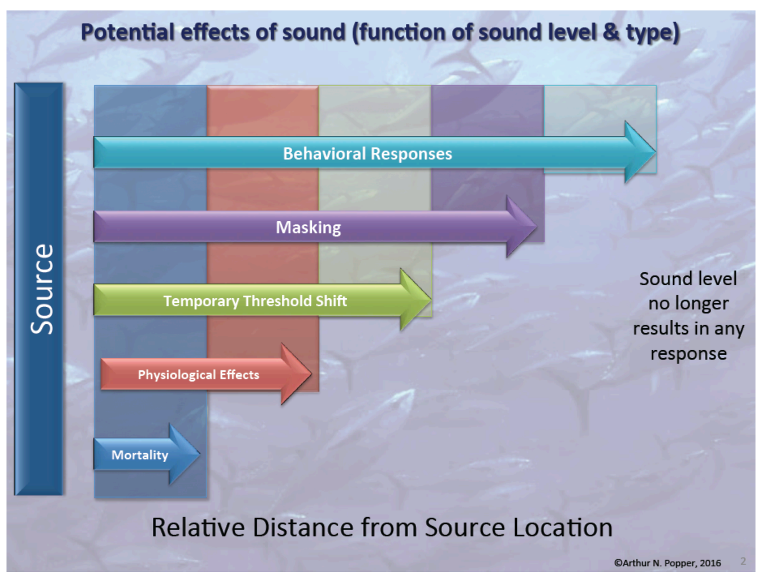
Animals and Sound > How do marine fish produce sounds?
(http://www.dosits.org/animals/soundproduction/fishproduce/)

Animals and Sound > How do fish hear?
(http://www.dosits.org/animals/soundreception/fishhear/)

Animals and Sound > Advanced Topic > What components of sound are used for hearing?
(http://www.dosits.org/animals/advancedtopics/componentsofsound/)

Part 2: Sound Exposure Criteria and Their Development
Arthur N. Popper, University of Maryland & Environmental BioAoustics LLC

- There are different possible effects of sound on animals, depending on the distance, sound level, and sensitivity (to a sound)
- In thinking about potential effects, one has to take into account that not every sound source to which a fish is exposed has the potential to cause problems.
    - Risk analysis
        - Mitigate, or assess that risk is acceptable



What are the issues?

- Mitigation is likely needed if a sound source impacts animals,but not if there are no effects
    - Need data on effects of sound on animals, and then use these data to set levels of mitigation
- Problems (in determining if need mitigation or not, and if so how much):
    - Few data on how fishes, turtles, or invertebrates are affected by man-made sounds
    - Getting data is often difficult and expensive
    - Effects may differ for different sound sources (e.g. effects from shipping vs. sonar)
    - Numerous species (>33,000 extant fishes and >>50,000 inverts that may be able to hear). This diversity in numbers and how they live in the marine environment is dramatic and results in requiring the study of many species
        - The ability to extrapolate to other species is difficult based on data for one or a few species

Current interim "criteria" for injury to fish (west coast, USA)

Peak SPL	208 dB re 1 μPa
Single Strike SEL	187 dB re 1 $\mu Pa^2 \cdot s$
Cumulative SEL	197 dB re 1 $\mu Pa^2 \cdot s$

- Note, SEL is total energy in a single sound and cumulative is sum of energy in all sounds (as in a sequence of pile strikes)
- Current interim criteria are NOT based on best available science!
    - Developed on west coast of US during pile driving operations
    - Numbers are rather far off from experimental data obtained over last several years.

Current criteria for behavioral effects (USA)

- One number for onset of behavioral effects, for all species (from NMFS): sound pressure level (SPL) of 150 dB re 1uPa (conservative number) as indicator of the noise level at which there is the potential for behavioral effects
- Problem- it is not likely that exposure to this noise level will always result in behavioral modifications for all species
    - The level that will result in behavioral modification will vary by species, time of day, behavioral state, etc. Setting one number is not a realistic way to approach this issue
- No one is certain of the origin of this value, but it not based on experimental studies

Criteria for behavioral effects (some UK agencies)

- Specified (Nedwell et al. (2007)) as weighted levels, above the dB_{ht}*(Species)*-sound level above presumed threshold of a fish:
    - 90 dB (above the threshold): strong avoidance by almost all fish
    - 75 dB (above the threshold): ~ 85% of fish react but there may be some habituation
    - < 50 dB (above the threshold): mild reactions in a minority of fish
- No data to support these levels. These levels assume that all species behave in the same way and respond in the same way to the same sound levels
    - Work has never been calibrated against actual behavioral responses of fish
    - dB_{ht} based on ABR recordings, which are not valid measures of hearing sensitivity (show response of ear, but do not show how an animal will respond)

What do we actually know about effects of human-generated sound on fishes?

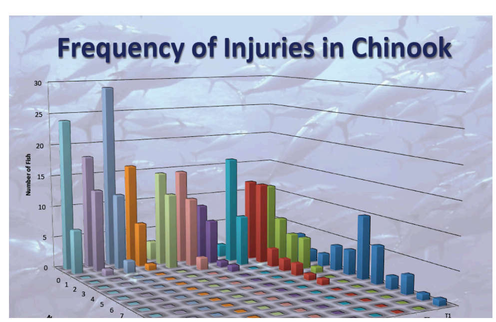
- Very little! Why?
    - Not many experiments
    - Hard to produce very loud sounds in the lab (to test behavioral responses)
    - Do not know if we can extrapolate between sound sources and between different species
    - Caged fish studies are not appropriate to give needed information on behavior

Experiments on the effects of sound on fishes

- Effects of seismic air gun exposure on fishes (Popper, Hawkins et al. 2016)
    - Lake Sakakawea, North Dakota (artificial lake); seismic studies for oil and gas
    - Work is typical of a lot of studies, where it is conducted in lakes as opposed to open ocean
    - Did not look at behavior, looked at physiological effects (fish in cages, exposed to seismic blast)
    - Looked at paddlefish and lake sturgeon (both considered engendered)
        - Examined body tissues (necropsies)
    - Cages at different distances from sound source
        - Hope to get dose/response curve; there was no effect at all, so could not derive a curve
    - Results:
        - Most intense sound, peak 231 dB re 1uPa, SEL_{SS} 208 dB re 1 uPa^2•s
        - No animals died during sound exposure or 7 days after exposure
        - No physical injury at any distance from the sound source
    - Conclusions:
        - Exposure sound level was higher than any SEL_{SS} in recent pile driving studies
        - The likelihood of tissue damage is low unless the fish is very close to an airgun of much greater power than ones used in this study (and in a lake)

- Effects of seismic exposure on hearing (Popper et al, 2005; Song et al, 2008)
    - Investigated effects of hearing in several species in Mackenzie River Delta (northern part of Canada)
    - Looked at hearing of several species: broad whitefish, lake chub, and northern pike
    - Also examined effects on ear tissues to see if there was damage
    - Fish expose to 5 or 20 seismic blasts
    - Examined hearing changes right after exposure and 24 hours later; also measured for temporary threshold shift (TTS)
    - Results:
        - Found some species experienced TTS (lake chub) but not others (broad whitefish)
        - Hearing recovered 18-24 hours after exposure
        - No tissue damage
    - Caveats:
        - Fish were captive, and therefore could not move between seismic shots (if fish are exposed to seismics, may move, which would reduce exposure)
        - Need data from other species before conclusions reached

- Effects of pile driving (Halvorsen et al, 2012 a, b; Casper et al, 2012, 2013 a,b)
    - Pile driving used in construction of bridges, piers, wind farms, etc.
    - Sounds can be very loud (<250 dB re 1 uPa in water), but there are few data on effects
    - Regulators limit the amount of sound fish can be exposed to before pile driving operations are shut down. The levels of sound proposed were not based on the “best available science” when they were put into place
    - Current criteria are not based on best available science
    - Fundamental question explored through this research: How much sound energy can fish be exposed to before there is the onset of a physiological effects that could result in death or reduced fitness?
        - Issue is accumulation of sound energy over the course of exposure to a source:
            - Exposure to one sound is likely not to have an effect
            - Exposure to repeated sounds may have an effects (cumulative effect)
            - Question: how much repeated energy will result in onset of harm?
    - Replicated high intensity sounds in the laboratory; exposed fishes to various strikes and sound levels
    - Results:
        - Mild effects (non life threatening, fish would survive and recover, e.g. eye hemorrhaging)
        - Moderate effects (fish would survive, e.g. bruised swim bladders, damage to liver)



        - Mortal effects (fish wouldn't survive, e.g. hemorrhaging of intestine and bleeding of kidneys)
        - Look at effects across different exposures. At lowest level of exposure, very few effects; at higher level of exposure, get substantial number of different effects on different individuals
    - Overall findings:
        - Onset of physiological effects at about SEL_{cum} of 207-210 dB re 1 $uPa^2 \cdot s$
        - Mortality does not occur until about SEL_{cum} of above 215 dB re 1 $uPa^2 \cdot s$
        - Effects are generally the same for all species tested (5 different species) with very different morphologies, except in fish without a swim bladder
        - Recovery from non-mortal injuries takes less than 10 days (demonstrate this in several species)
        - No post-exposure injuries
        - Ear damage (and presumably hearing loss) only at sound levels well above those that result in other effects
            - Could not measure effects on hearing, but impacts on ear that were observed would affect hearing
    - Implication of findings:
        - Pile driving data show that onset of effects starts almost 20 dB higher than current standards
            - Means fish not harmed at regulatory levels
            - Pile driving activities can be conducted without harm (to fishes)
            - If sound levels get too high, mitigation needs to take place, or activities need to stop
        - Results applicable internationally

- Field studies on seismic airguns
    - Norwegian fisheries groups examined effects of seismic studies on fish catch rate
    - Indication that catch rate declines in presence of airgun exposure and lasts for several weeks post exposure, and then returns to normal
    - Slotte et al. (2004) showed that rather than swim away, fish dive to greater depths
    - Lokkebord et al. (2012) showed opposite results- increase in catch rate during seismic exploration
        - Different species (than Slotte et al.), different locales, times of year, sound sources
    - This points out the difficulty in understanding data and extrapolating results within and between species

Future approaches for mitigation

- Guidelines based on the best available science and guidelines that evolve as knowledge improves
- Understanding of what we know and do not know to guide future research (gap analysis)
- Funding for research to fill in the gaps in our knowledge
- Developing guidelines (Popper et al. 2014)
    - Interim guidelines to determining amount of mitigation required for any particular project
    - Accounted for different sound sources, species, types of responses
    - Based on best available science (and need constant updated based on new science)
    - Created tables [example shown]
        - Based on literature predicted which levels would cause an effect

What are the gaps in what we know?

- "Information gaps in understanding the effects of noise on fishes and invertebrates"
- There are a tremendous number of gaps; there is far more we don't know, than we do know
- Areas of high research priority:
    - Understanding aquatic soundscapes
    - Main characteristics of sound fields generated by human activities
    - Effect of man-made sounds on fishes and invertebrates
    - Do mitigation measures reduce sound exposure and reduce and/or eliminate detrimental effects?
    - Describe experimental sounds properly and conduct experiments under controlled acoustic conditions
- Most critical data gap: behavior
    - Physiological responses, such as mortality and tissue damage, of limited importance (not many fish are close enough to a source to be impacted this way)
    - BUT, how is (or is not) behavior altered by exposure? At any distance, behavioral effects, TTS, etc. are more likely to take place, and know little about these effects
    - Behavioral response in the lab or enclosed area are not representative of responses in the wild
    - Very hard to conduct behavior experiments in the field due to problems in observing animals as they move around (observing behavior and keeping track of individuals).

Putting mitigation into context

- Purpose of sound source mitigation is to lower the sound levels produced by man-made noise (such as pile driving)
- The fundamental question is, "how much mitigation is needed?"

- Two approaches to mitigation:
    - Set an arbitrary level
    - Only mitigate if an animal is affected by the sound
        - If no physiological and/or behavioral effects, then no need to lower the sound level
        - If there are physiological and/or behavioral effects, the goal should be to provide mitigation so that the sound level is below the level that causes the effect

Additional information on the DOSITS website:

Science of Sound > Advanced Topic > Sound Pressure Levels and Sound Exposure Levels (http://www.dosits.org/science/advancedtopics/soundpresslevelsandsoundexplevels/)

Animals and Sound > Potential Effects > How do you determine if a sound affects a marine animal? (http://www.dosits.org/animals/effectsofsound/howdoyoudetermineifasoundaffectsamarineanimal/)

Animals and Sound > Potential Effects, Marine Fishes (http://www.dosits.org/animals/effectsofsound/effectsofsoundonfish/)

Animals and Sound > Potential Effects, Marine Fishes > Behavioral Changes (http://www.dosits.org/animals/effectsofsound/effectsofsoundonfish/behavioralchanges/)

Animals and Sound > Potential Effects, Marine Fishes > Masking (http://www.dosits.org/animals/effectsofsound/effectsofsoundonfish/fishmasking/)

Animals and Sound > Potential Effects, Marine Fishes > Hearing Loss (http://www.dosits.org/animals/effectsofsound/effectsofsoundonfish/hearingloss/)

Animals and Sound > Potential Effects, Marine Fishes > Physiological Stress (http://www.dosits.org/animals/effectsofsound/effectsofsoundonfish/physiologicalstress/)

Animals and Sound > Potential Effects > How can we moderate or eliminate the effects of human activities? (http://www.dosits.org/animals/effectsofsound/howcanwemoderateoreliminatetheeffectsofhumanactivities/)

Questions asked and answered during the webinar

You mentioned shallow water vs. deep water effects, how do you define shallow water? Is it species dependent, or would you give a definition based more on the properties of sound?

The important thing is to relate the depth to the frequency of the sound and the nature of the sound. Shallow water is water that is less than the dimensions of a wavelength of a sound. At 100 Hz, that is 15 meters, so at 15 m depth means that if you try to generate sound pressures at those types of depths at 100 Hz, you are going to generate a huge amount of particle motion. It depends on the frequency of the sound you are transmitting, and also depends on the position of the loud speaker, and so on. It is important to realize that many of those fish that have great sensitivity to sound pressure, live in ditches and ponds. These areas are really shallow. If try to generate underwater sound pressures in water that shallow, because of the pressure release effect at the water surface, generate a huge amount of particle motion. We have just come to realize how important sensitivity to particle motion is; always measuring sound pressure, tend to forget that in fact, in different environments, the ratio of sound pressure to particle motion is very, very different. Also, close to the seabed, with things like pile driving and air guns, the seabed itself is vibrating. For many fish or invertebrates the sound particle motion is more important than the sound pressure.

If neither of the available regulatory thresholds are based on the best available science, particularly for behavior, given the need for industry to select thresholds to apply for impact analysis, and deciding when and how to mitigate, what would you suggest in the interim for assessing the impacts on behavior, in light of the amount of data gaps?

It seems that at the moment, most environmental impact assessments are “fictional.” They are based on criteria that are inappropriate, based on assumptions about fish behavior that are incorrect… This is bad for industry and regulators and reflects the need for more science to be done. For example, with pile driving EIS’s in the North Sea, they ignore the impacts in shallow water (because of low sound pressures, they assume that fishes are unlikely to be affected). But for a fish like the salmon migrating along the coast, something like pile driving is generating a huge amount of particle motion, which will be detected by the animal. Yet this is ignored in the EIS’s. When preparing the guidelines paper, we struggled with what to suggest as criteria for behavior and masking. It is almost impossible to come forward with criteria at the moment, simply because we do not have sufficient information. So the important thing is to do more science.

Anything that [a scientist] says in terms of a number, almost becomes “gospel” (e.g. 150 dB mentioned earlier in webinar). Saying any number, even during this webinar, could get out, and they could be accused of giving a number that they do not have any basis for distributing. Very difficult situation because of the lack of data.