Particle Motion, Fishes, & Invertebrates: What We Know and Don't Know!

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Purpose

- Provide broad overview of issues needed to appreciate and understand PM
- Goals:
  - Introduce basic ideas about particle motion (PM)
  - Introduce the issue of substrate vibration (SV) and aquatic animals
  - Share *my thoughts* on gaps in understanding role(s) of PM, especially as related to tidal and wave energy
- While will primarily mention fishes, keep in mind that many aquatic invertebrates hear and even make sounds

Premise

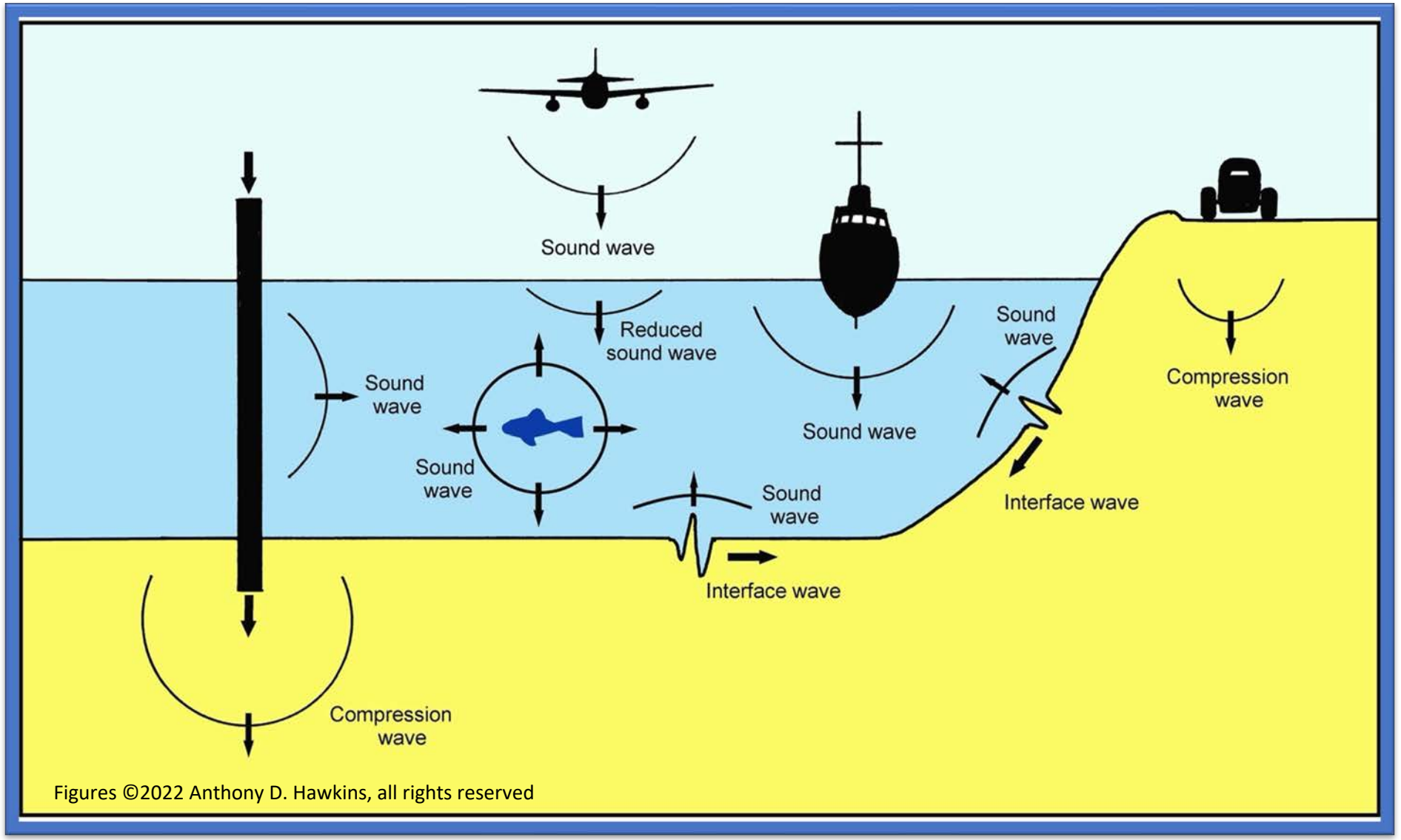
- Issues focus on potential impacts on animals
- Thus, critical to consider potential effects of anthropogenic sound from animal's perspective!
  - If animal detects the signal, or affected by it in any way, we need to understand the potential effects and the signal itself
  - If animal not affected by the signal, much less need to measure or mitigate
  - Analogy: many animals hear ultrasound, but from the perspective of humans, there is no need to mitigate ultrasonic signals since we cannot detect them
- This approach (Popper et al. 2020) is different than most often done – tendency is to mitigate even without evidence that the signal is detectable by the animal or has any potential effect!
- (note, all references are given at the end of slides)

Why the Concern About Anthropogenic Sound?

- Vertebrae hearing was “invented” by earliest fishes!
- Provides information from all directions around the animal – soundscape
- Sound is a very important source of information for aquatic animals:
  - High speed
  - Directional
  - Detectable when vision not useable
  - Perceived in all directions around animals
  - Detect distant predators and prey
- Many invertebrates, including crab, lobster, octopus, can hear
- *Moreover, many fishes and invertebrates make sound to communicate, find mates, etc.*

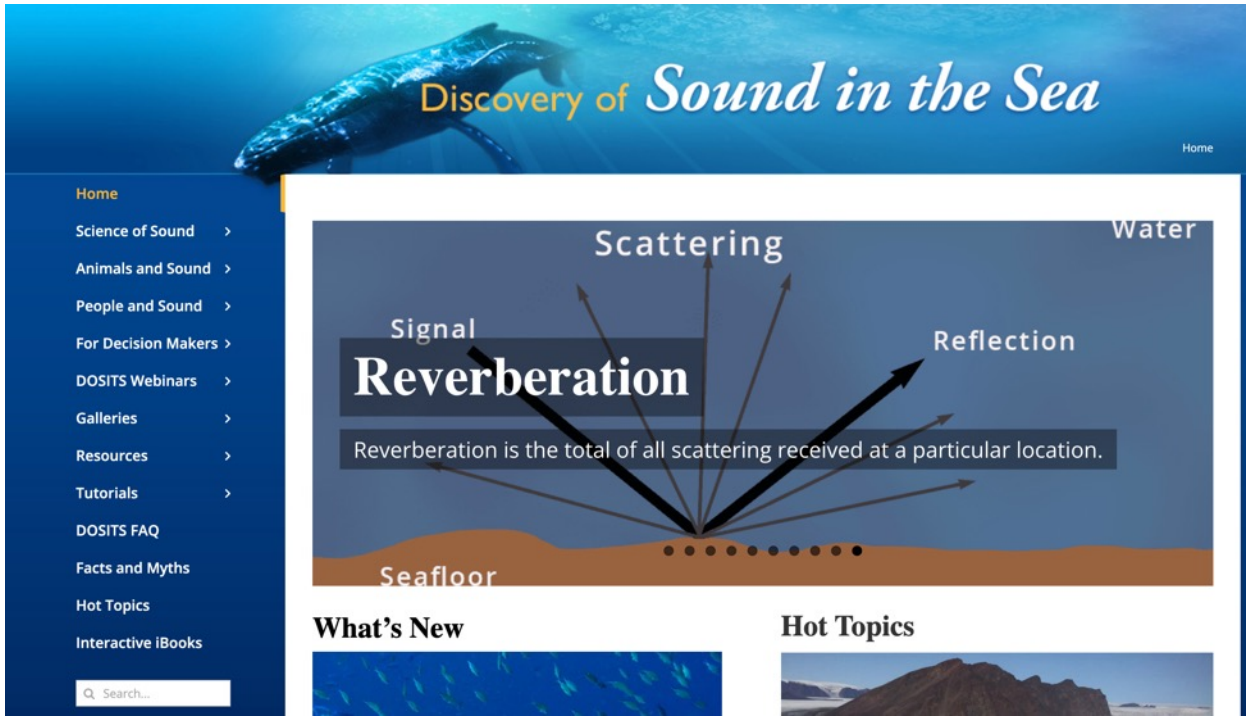
Thus, anything that interferes with detection of sound can affect animals' lives

Some Potential Anthropogenic Sources



Briefly Consider Underwater Sound

- Underwater sound follows same basic principles of sound in air
- Due to higher density of water, sound travels about 4.3 times faster than in air
- This means wavelength in water is about 4.3 times greater in water
- Speed of sound in air about 330 m/sec
  - Wavelength of 100 Hz signal about 3.3 m in air
- Speed of sound in water about 1,480 m/sec
  - Wavelength of 100 Hz signal about 14.8 m in water



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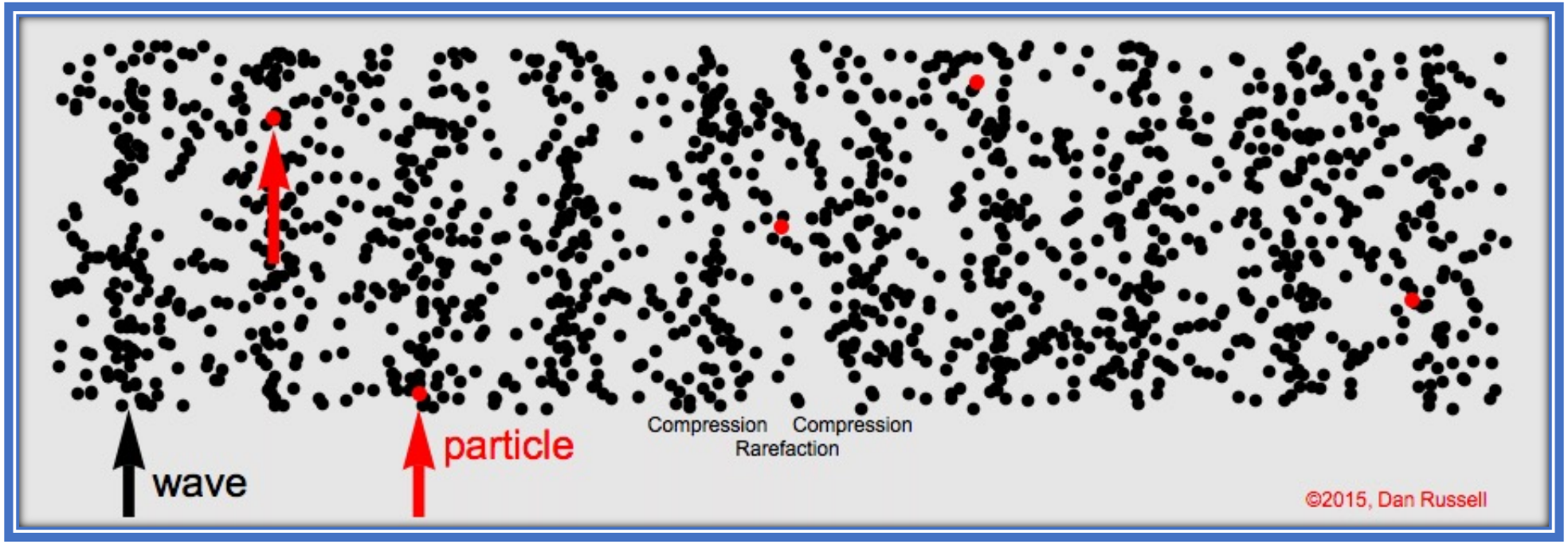
Lay-level, scholarly reviewed, information about underwater sound, effects of anthropogenic sound, bioacoustics, and related topics

Sound Pressure & Particle Motion



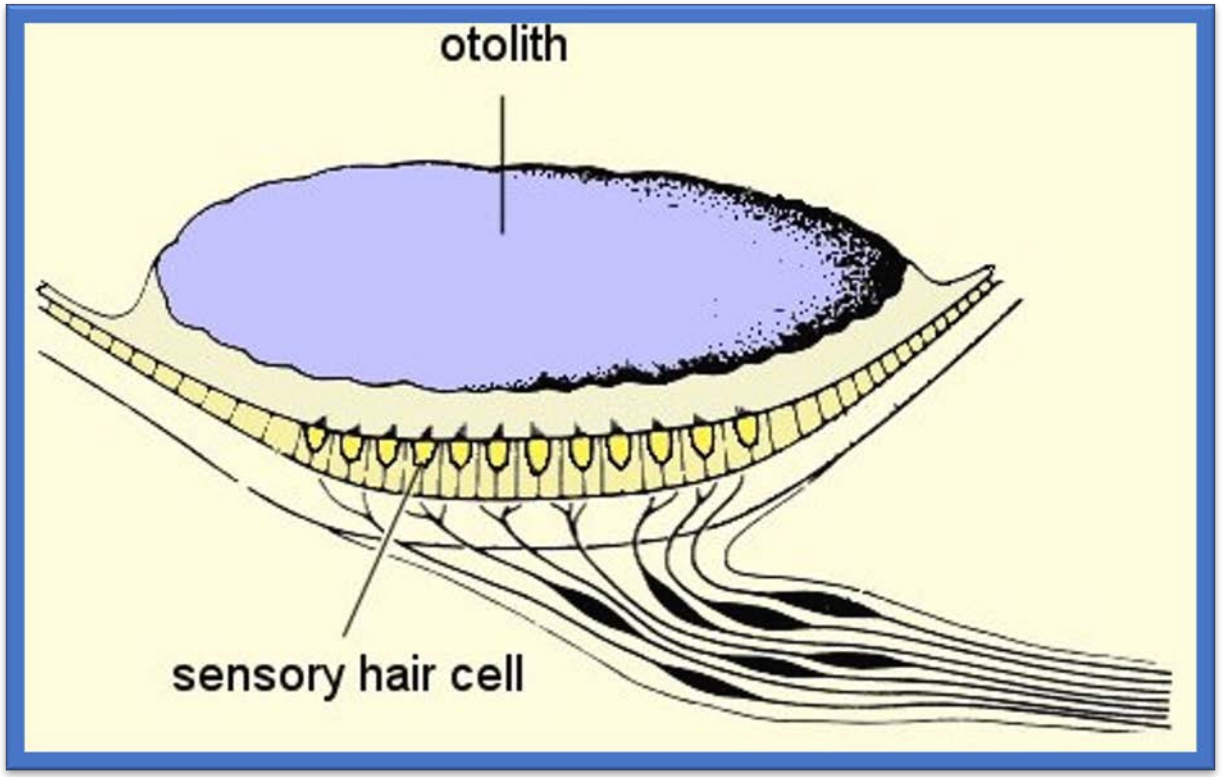
- All sound has both sound pressure and particle motion
- In air, due to low density, PM is not consequential very far from the source – terrestrial vertebrates primarily use SP!
- In water, PM travels great distances and is used in hearing by all fishes and invertebrates
- This is because the ears in fishes and invertebrates evolved to detect particle motion and not sound pressure!

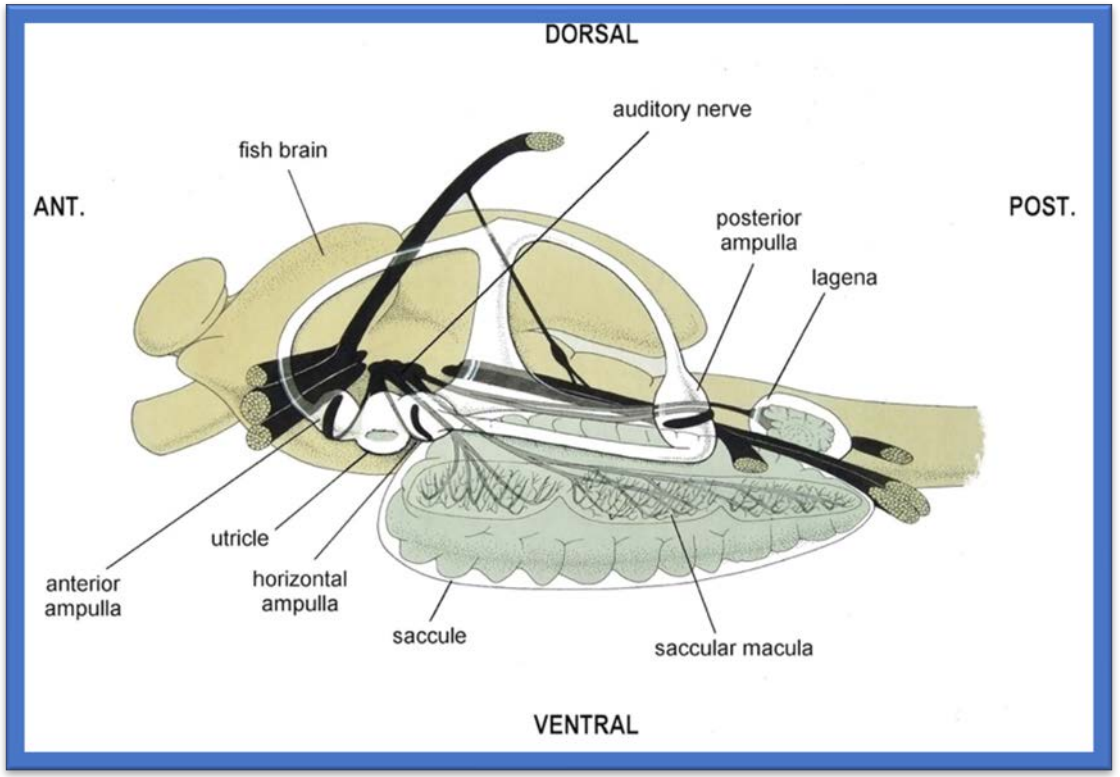
Sound Pressure vs. Particle Motion

- Sound pressure is scalar – does not have direction
- Particle motion is directional – it can be used to tell the position of a sound around an animal
- Fish (and invertebrate) ears are PM detectors!
- Thus, understanding PM is critical if we are to understand sound detection by fishes and invertebrates
  - Much data in the literature on hearing focused on SP
  - However, since fishes detect PM, most hearing studies were asking the wrong questions?
  - And getting wrong answers!

How is PM Detected?

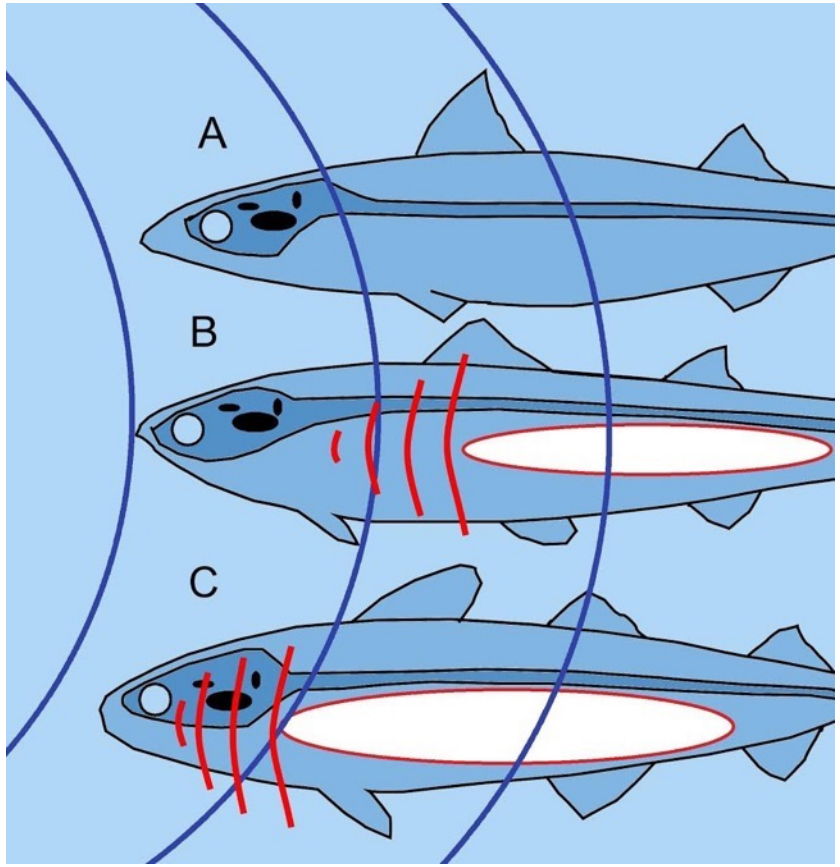
- The ears in fishes and invertebrates are accelerometers!
- The ear evolved to detect PM and *not* SP





PM Detection

- PM is detected by all fishes and probably by all invertebrates that hear
- SP only detected by fishes that have a “discontinuity,” such as swim bladder or other air bubble
  - Walls vibrate in response to the impinging sound
  - “Re-radiates” signal as PM, which potentially stimulates ear
- SP only detectable by a sub-set of fishes, and probably not by any invertebrate
  - Fishes without a swim bladder (flatfish, sharks) only detect PM (fig. A)
  - Fishes like tuna, salmon, sturgeon, have a swim bladder, but its response not detected at the ear (fig. B) since they are far apart - PM attenuates due to body tissues
  - Fish with special adaptations like carp, catfish, cod, may detect SP (fig. C)
  - Even if a fish detects SP, it also detects PM, but not reverse!
- Thus, when considering sound detection, it is imperative to understand how and what animals do regarding PM, and not SP

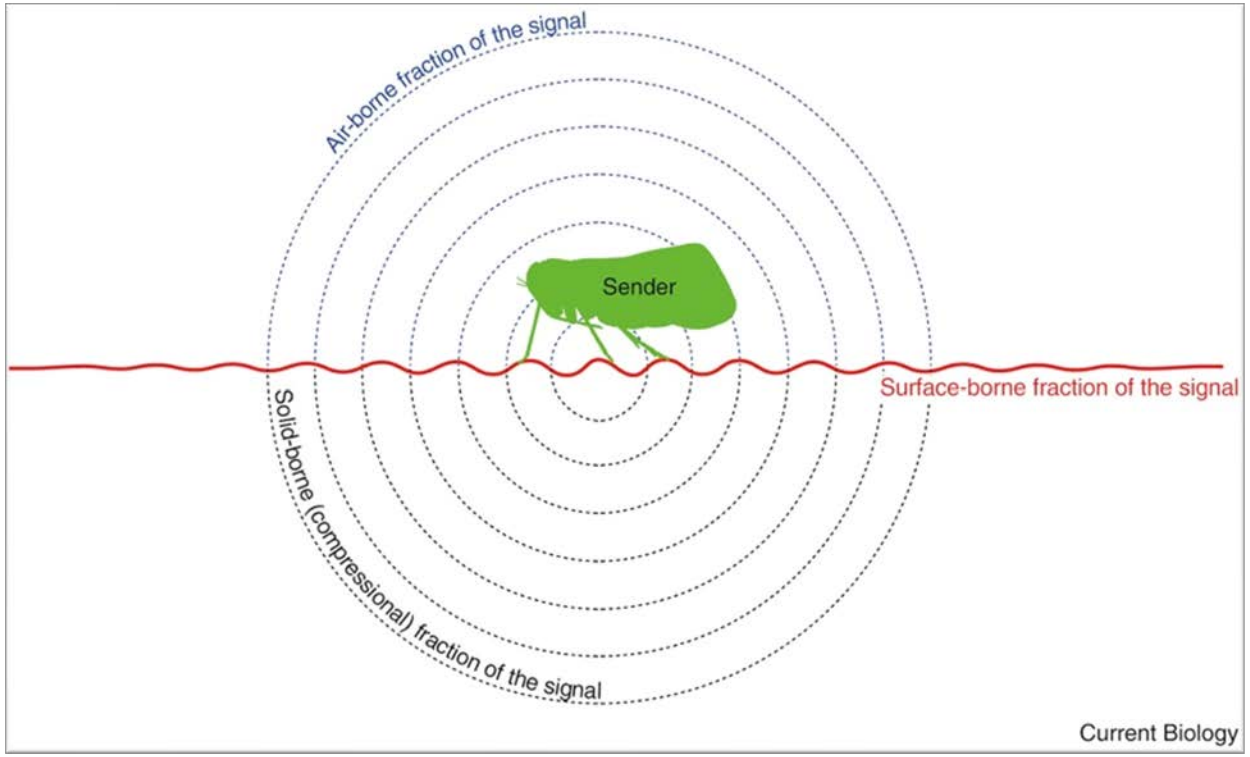


A Few Critical Points to Keep in Mind

- *In order to understand how fishes may react to anthropogenic sound, one must understand their responses to both PM and SP*
- BUT, even if a fish cannot detect SP, it may still have an effect by causing overstimulation of the swim bladder, and harm internal tissues
- Work in Popperlab showed this on several species that detect PM (salmon, sturgeon) (www.ahukini.net) (e.g., Halvorsen et al. 2012; Casper et al. 2016)
- Ear may not even be involved, but still get injury, especially to intense impulsive signals

Substrate Vibration: A Critical New Issue

- To date, we think about sound traveling in water from source to animal
- Now understanding that sound from many sources may enter substrate
- Sound travels in substrate and comes out, and this has potential to be detected (called Biotremology)
  - Most work to date in terrestrial environments
  - But same issues underwater (Louise Roberts)
- Particularly an issue for sources that are near or contact substrate – pile driving, seismic airguns, etc. ***And likely tidal energy!***
- A clear issue for animals living in, on, or near substrate: lobster, crab, flatfish, sturgeon, many others



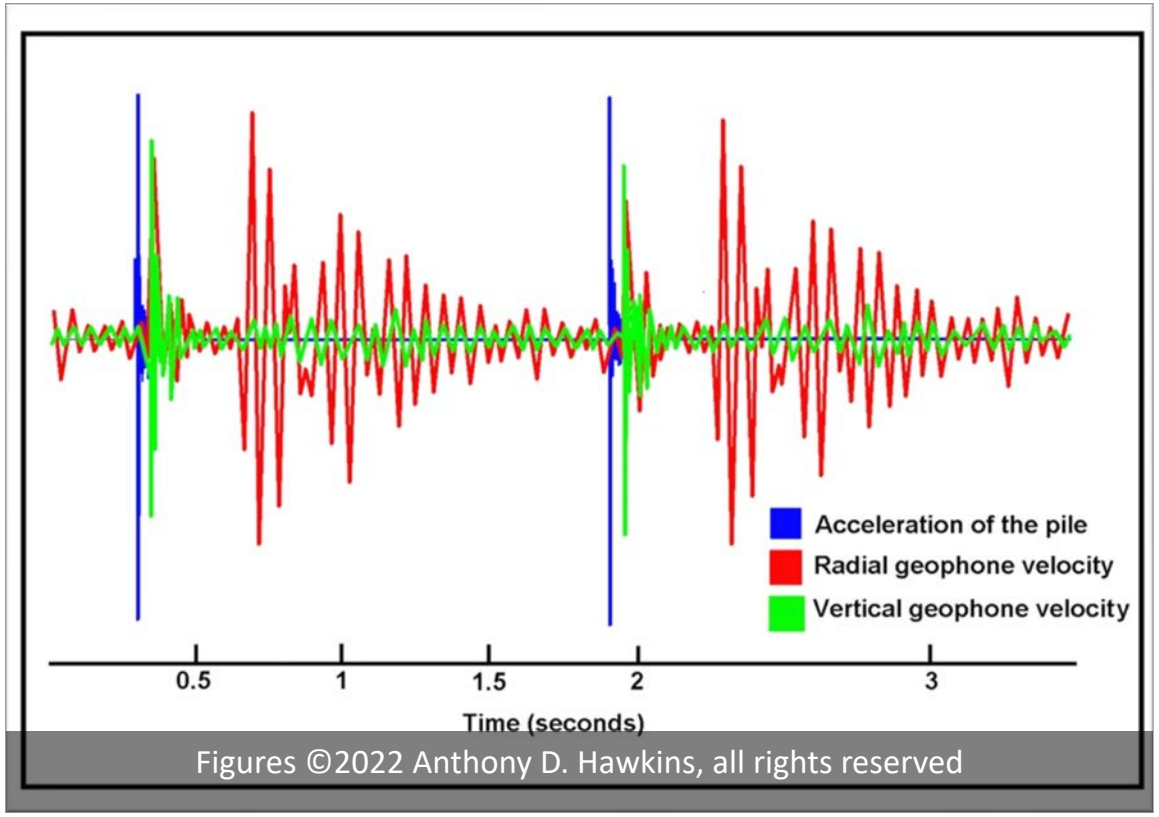
Hill, Peggy SM, and Andreas Wessel. "Biotremology." *Current Biology* 26.5 (2016): R187-R191.

Sources of Substrate Vibration

- Any source that puts energy into substrate
  - Pile driver, struck by a vertical hammer creates
  - Seismic airgun for geological exploration
  - Explosions
- These produce sound in water and vibrational waves within the substrate
- Energy can travel great distances in the substrate
  - Affect animals within the substrate
  - Also, animals living on or just above substrate
  - Energy leaving substrate travels through water as sound, and can affect animals at distances from source
  - See Roberts and Howard (2021); Hawkins, A. D., et al. (2021)

Substrate Vibration from Driving Pile

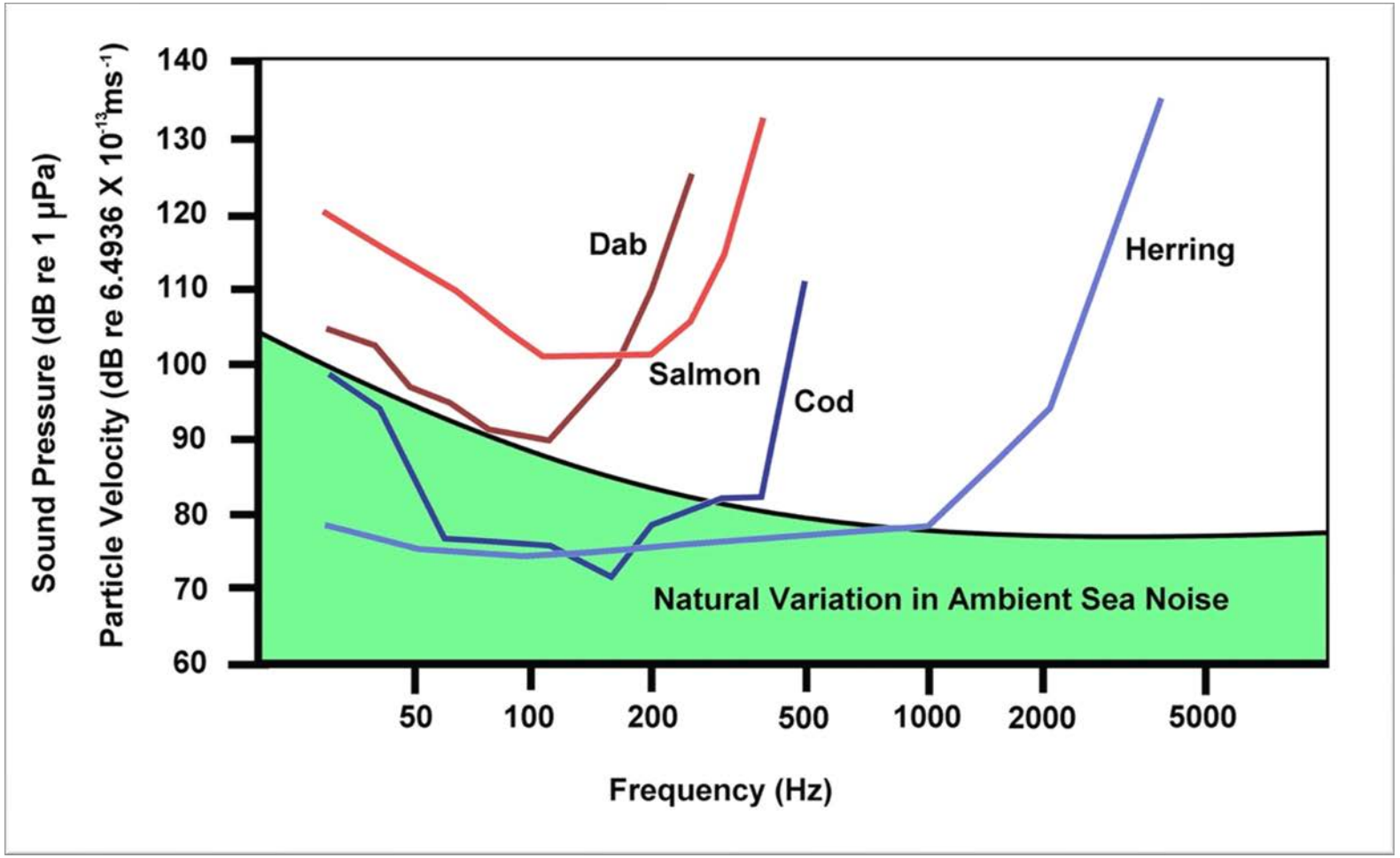
- Recordings from pile strike
- Blue is accelerometer on pile, showing sharp acceleration
- Substrate vibration from accelerometers at 68 m mounted on substrate
  - Red – radial geophone
  - Green – vertical geophone



What is Known about Sound Detection by Fishes & Invertebrates?

- Very little!
- Several issues (Popper & Hawkins, 2021):
  - Sound fields calibrated in SP, even when the fishes only detect PM – this means that we have no idea of signal levels to which fish were responding
  - Work done in tanks where sound fields are very complex and cannot easily even measure PM
  - Most recent studies done using physiological measures (ABR, AEP) that measures ear responses – but that is not hearing!!!!
  - Very variable, even for same species, from different labs
- Only a very small amount of usable data on detection of PM
- Minimal data on detection of sounds on or near substrate

Hearing by Different Fishes – PM Data Done in the Field



Consider What We Don't Know, and Need to Know (Data Gaps!)

- Most knowledge gaps re PM (and SV) are similar to those identified in general for fishes and invertebrates and anthropogenic sound (Hawkins et al. 2015)
- Moreover, the gaps associated with Tidal and Wave projects are likely to be similar to those for other sources such as seismic, pile driving, shipping, etc.
- Quite similar issues to Offshore Wind (Popper et al. 2022)
- Thus, following suggestions may seem familiar, but they provide good guidance

Data Gaps: Broader Issues to Consider

- There are 34,000 fish species & many more aquatic invertebrates
  - All fishes likely can hear, but data on perhaps 100, and most data not good!
  - There is extensive diversity in morphology of the auditory system
  - Thus, very hard to extrapolate data on hearing or effects of sound between species in many cases
  - Issue: Need to decide “representative” species to study as done for fish criteria analysis (Popper et al. 2014)
- Need data on PM as well as SP, and possibly also SV for select species
- Lack of tools to easily measure PM – far more complex and expensive than tools for SP

Possibly Most Important Data Gap!

- BEHAVIORAL RESPONSE to anthropogenic sources
  - Mortality/physical damage is measurable, but most fishes do not die from sound exposure, just as humans do not die from most sound exposure
  - Far bigger issue is how animals respond behaviorally to the sound, no matter if PM or SP!
  - These can happen on a far larger distance from source than physical effects
- Very few good data on behavioral effects
  - Most studies done in lab where behavior not easily extrapolatable to wild animals
  - Very hard to do in field – but see Hawkins et al. (2014)
- Some behavioral effects of anthropogenic sound:
  - None – but even then, could affect stress levels
  - Small responses (e.g., startle) that does not really alter fitness
  - Temporarily leaving feeding or breeding site – but return quickly
  - Permanently leaving sites
  - Changes in migration routes
  - Not hearing sounds of potential mates or predators or food

Hearing Data Gaps

- Masking – lessening likelihood of detection of biologically important sounds
  - Sounds from potential mates
  - Sounds of nearby predators
- Temporary decrease in hearing sensitivity (TTS – Temporary Threshold Shift)
  - Similar effects to masking
  - Decreases fitness
  - No evidence of permanent hearing loss in fishes
- Impact on PM detection has never been studied
- VERY CRITICALLY: Hearing is not just threshold or bandwidth
  - Much more important issues are discrimination, localization, detection of signals in noise
  - Sensitivity and bandwidth are not very informative of how an animal uses sound, or how use of sound can be impaired

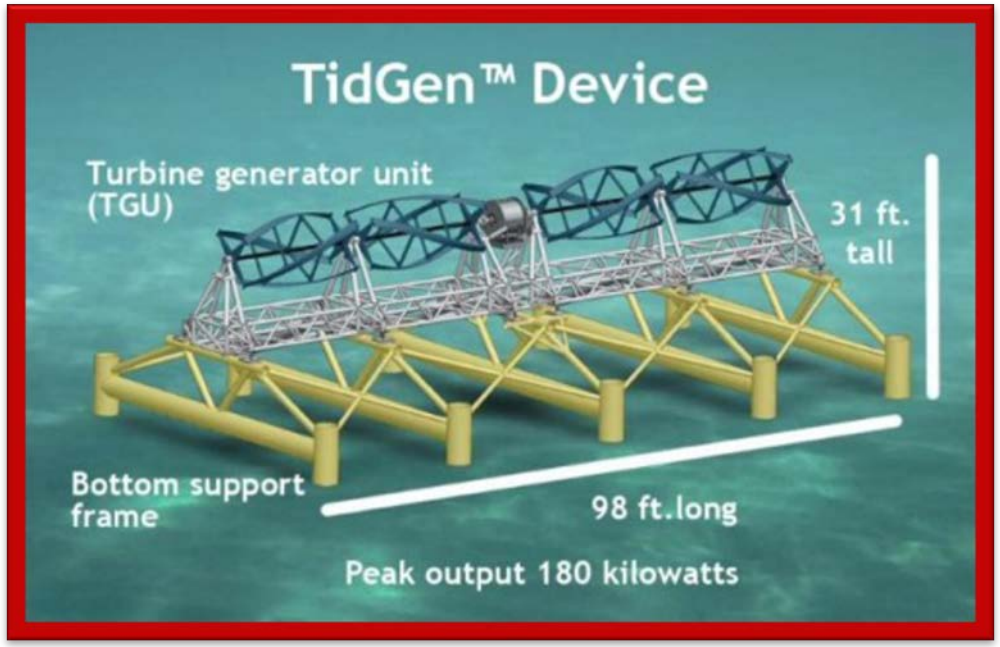
Other Critical PM Data Gaps (and for SV)

- Hearing (need improved methods such as experimental tanks, etc.)
  - Comparative (decide on appropriate species)
  - Age, size, season
  - Thresholds, bandwidth
  - Detection in presence of masker
- Potential effects of PM on development (e.g., of eggs an larvae; growth)
- Behavioral responses to PM to determine the levels that will have an impact on the animals
- Dose/response data and before/during/after data! Cumulative effects
- Physiological effects such as stress, endocrine levels, etc.
- Many more

Data Gaps for Sound-Producing Devices

- Also need:
  - More acoustic data (SP, PM, SV) for devices
  - Ambient sound levels in device locations with and without operations
  - Data on preconstruction, construction, and post construction sounds (levels, frequencies, etc.)
- Need common approaches to measures, measurement approaches, and terminology so data can be compared between sites and devices (same as for OSW)

Potential Sound Issues with Tidal Generation

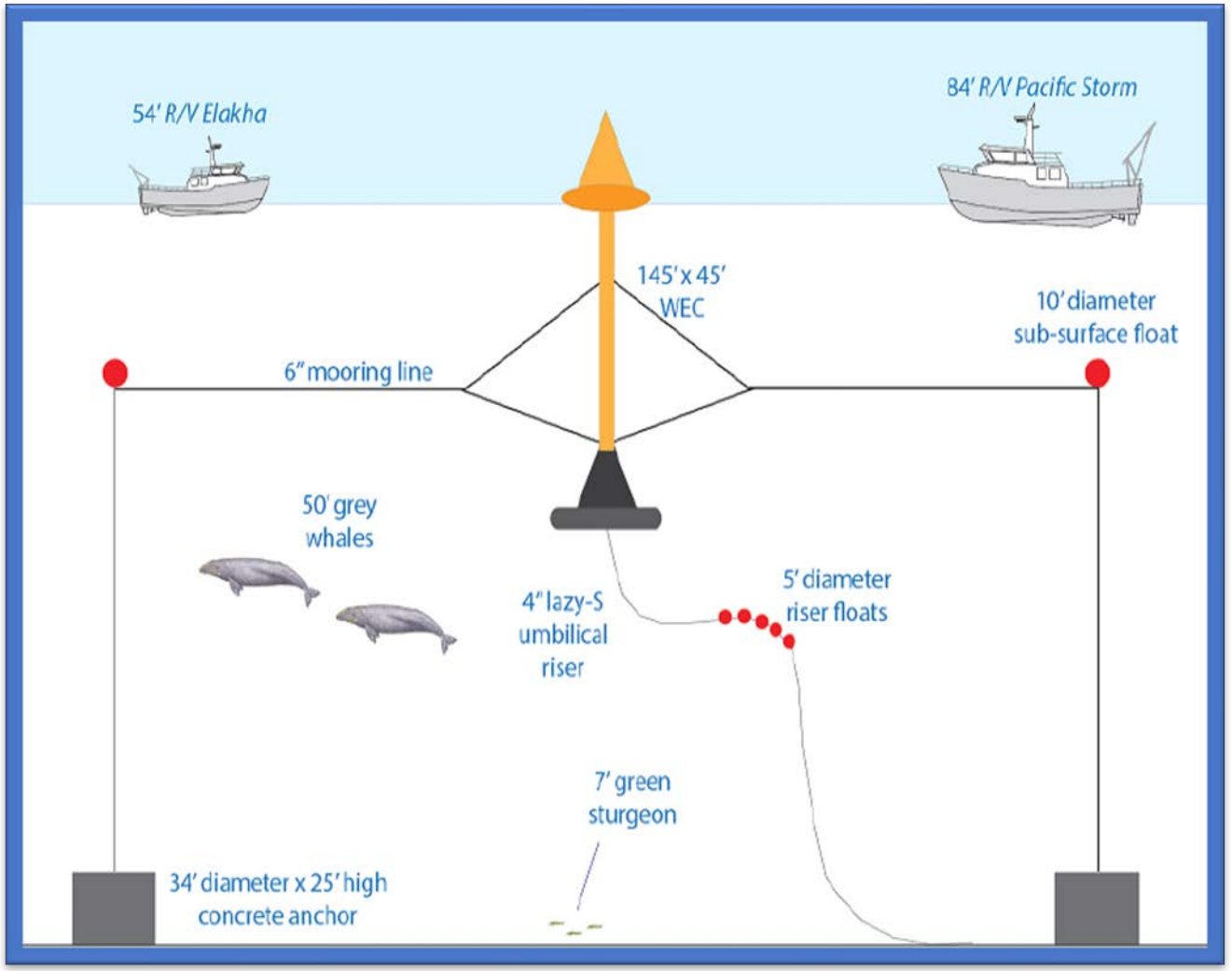


https://www.reinforcedplastics.com/content/other/hall-spars-rigging-manufactures-composite-components-for-orpc-s-tidgen-tidal-turbine

- Sits on bottom
- Need data on acoustic energy in form of:
  - Sound Pressure
  - Particle Motion
  - Substrate Vibration
- Also, data on:
  - Signal levels including in water, on, and in substrate
  - Sounds during construction and operation
  - Ambient levels
- How fishes and invertebrates react behaviorally to the signals
  - (Distinguish between responses to “sound” and other stimuli, such as vision)

Potential Issues with Wave Generation

- Same types of information as for tidal generator
- Needs substrate signals if any bottom contact
- Since variety of different approaches in different devices, need characterization of each
- First “guess” is that fewer sound issues than for tidal, but this could vary by device



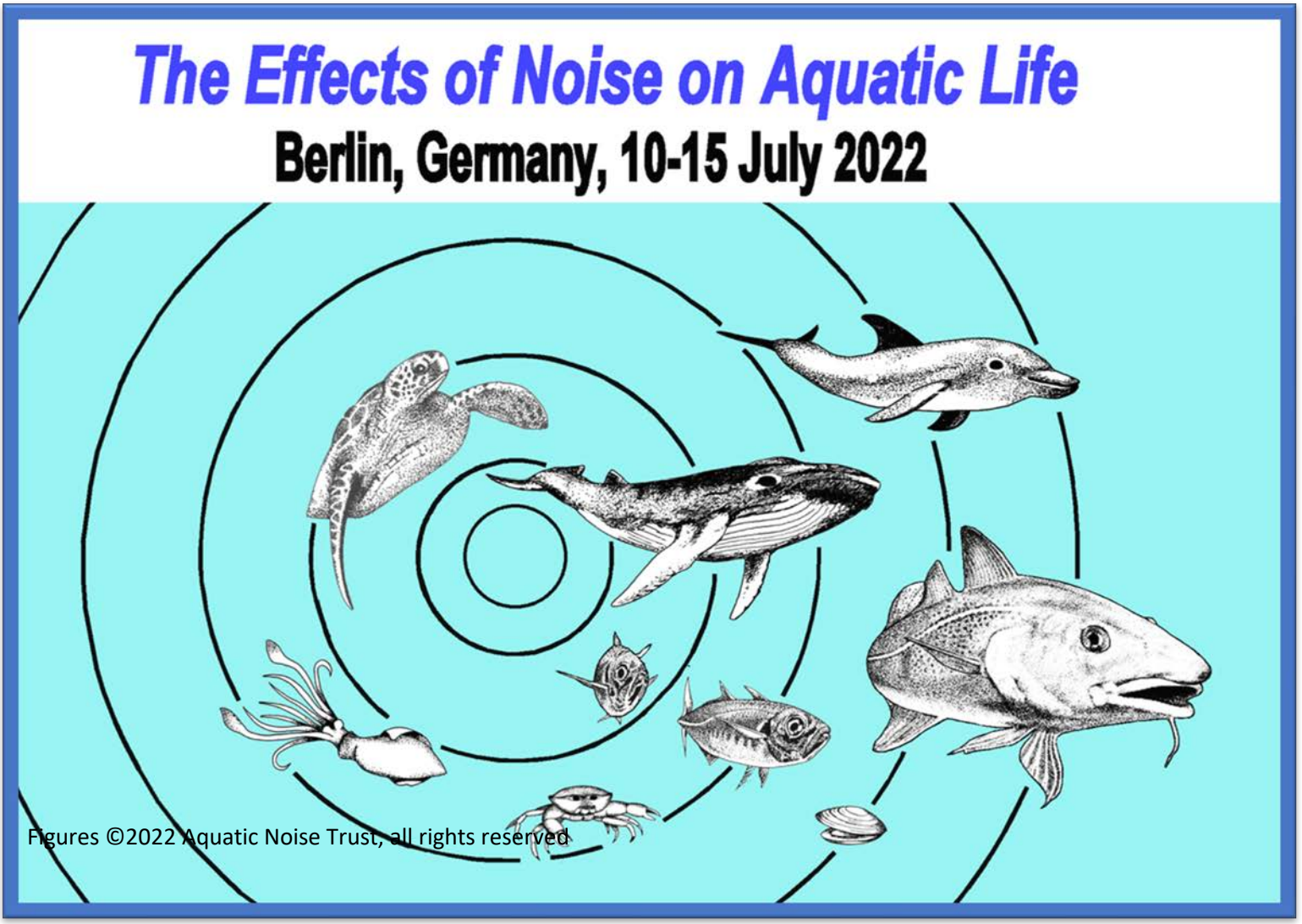
Mitigate: But First Ask Animal What Needed!

- To develop mitigation, first need to know what the animals can detect, and how they respond to the sounds
- If there is no response, do we need to mitigate?
- If the response is minimal and the animal goes back to doing "it's thing," do we need to mitigate
- Developing "criteria" for when one needs mitigation to PM is critical
- Also need ways to mitigate PM and substrate vibration!

Thanks to several Participants who Collaborated with Me on Anthropogenic Sound

- Michele Halvorsen
- Anthony Hawkins
- Joseph Sisneros
- Brandon Southall

- Others (not here)
  - Tom Carlson
  - Brandon Casper
  - Richard Fay (collaborator of >50 years!)
  - Michael Smith
  - Frank Thomsen



- AN2022.org
- >180 papers
- Focus on networking across species, techniques, regulatory issues, mitigation, etc.
- Sixth in series since 2007
- All papers published in a book (online) by Springer Nature

Some Suggested Readings

- Bevelhimer, M., et al. (2017). Hydroacoustic assessment of behavioral responses by fish passing near an operating tidal turbine in the East River, New York. *Transactions of the American Fisheries Society 146*(5), 1028-1042. 10.1080/00028487.2017.1339637
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Additional Articles

(all open access at www.acousticstoday.org!)

- Ballard, M. S., and Lee, K. (2017). The acoustics of marine sediments. *Acoustics Today 13*(3), 12-20.
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