Underwater Acoustics: Webinar Series for the International Regulatory Community
Science of Sound Webinar
Friday, November 13, 2015 at 12:00pm ET

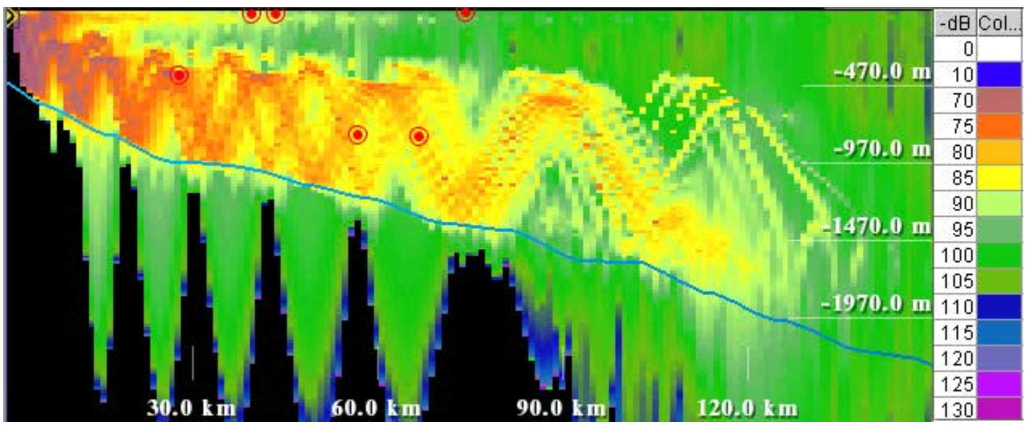
Summaries below combine the webinar outline (provided in advance) with each webinar presentation. Content from the original **outline** are indicated in **bold text**.

Presentation Summary: Sound Movement and Sound Measurement (Dr. Kathleen Vigness-Raposa, Marine Acoustics, Inc.)

Example shown of a complex propagation modeling output (what a regulator may get from a permitee assessing potential impacts of a sound source). This is the first step in determining if a sound might affect a marine animal: calculate the level of sound at different distances and depths from the source.

Complex propagation outputs: this example is one snapshot in space and time (one radial or look direction of the sound field)

- Across the top of the diagram (shown below) is the sea surface; turquoise line is the seafloor; sound source in upper left (yellow diamond); simulated animals are represented as red dots (with circles around them) within the sound field

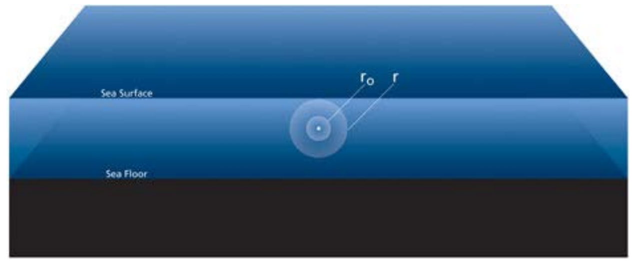


- Colors are individual pixels or grid cells in range and depth increments away from the source that correspond to the amount of transmission loss (TL) in decibels
- You are increasing in depth (m) as you go from top to bottom in the graphic; as you move left to right, you are going away, in distance away from the sound source (range)
- The model outputs give individual slices or radial bearings away from the sound source; you then need to decide how many radials you to create the full 3D sound field
- Important to understand both range and depth when considering potential impacts. Usually one would think that the closest animal will receive the highest sound level, but this is not necessarily the case depending on how the sound propagates or moves. In this example, the animals farther away from the sound source at deeper depths are actually getting higher received levels than the closer animals at the sea surface.
- To get a complex output, there are complex inputs that go into the model
  - Sound source
  - Sound velocity profile (how fast sound moves at that location in the water column, which varies with range)
  - Seafloor interactions with the sound
  - Bathymetry (in this example, a slope area)
- Models available at Ocean Acoustics Library (http://oalib.hlsresearch.com/)

- Not for the novice user, but nice background documents and good starting point for advanced practitioners

Some basic calculations to approximate received levels from a given sound source:

Spherical spreading:

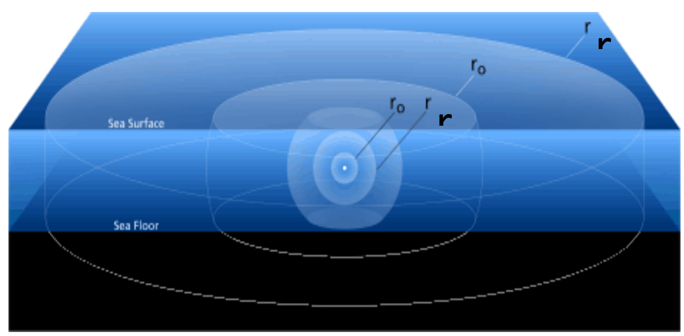


- Most simple approximation of sound movement
- Sound source (white circle) is at mid-depth in the water column
- Sound wave propagates from the source uniformly in all directions
- Sound level decreases rapidly: TL = 20 $\log_{10}$ r (where r=range in meters, TL=transmission loss)
- For example, source level (SL)= 240 dB rms re 1 µPa at 1 m, RL at a range of1000 m = 180 dB rms (the full calculation is that RL = SL-TL. TL=20 $\log_{10}$(1000)=20 x 3 =60. RL=240-60=180 dB rms)

Spherical and Cylindrical Spreading

Range, *r* (meters)	**Transmission Loss**, *TL* (dB)
1	0
10	20
100	40
1000	60

- Beyond some range, sound will hit the sea surface or sea floor. Propagation changes from spherical (moving uniformly in all directions) to cylindrical (moving uniformly only in horizontal direction).
- Sound levels decrease *less* rapidly, at a rate of 10 $\log_{10}$ r (where r=range in meters)
- In the transmission loss calculation, need to consider both spherical and cylindrical spreading, as in this equation:
  TL = 20 $\log_{10}$ rs + 10 $\log_{10}$ rc/rs
  rs= range of spherical spreading in meters; rc = range of cylindrical spreading in meters
  For example, 5,000 m ocean, source at 2,500 m: TL = 20 $\log_{10}$ 2500 + 10 $\log_{10}$ rc /2500

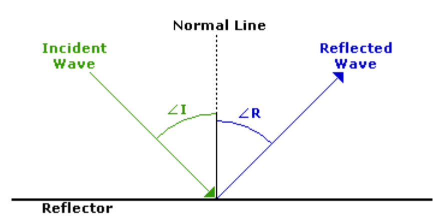


Sound doesn't just move in straight lines; it can change direction.

***Sound reflection, refraction, and scattering*. Rather than traveling in a straight line, sound can reflect, refract, and scatter as it moves away from a sound source. These processes have implications for whether sound might affect a marine animal.**

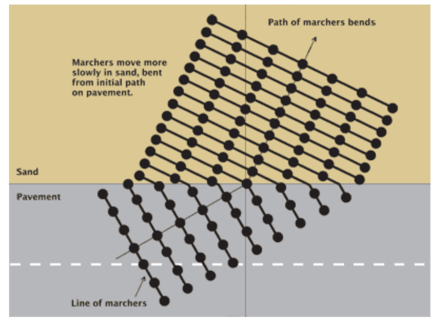
Reflection

- When sound hits a boundary (or reflector, such as the sea surface or the seafloor), it can change direction, and have an incident wave (incoming) and a reflected wave (outgoing).
- The characteristics of the reflector affect how *reflection* happens

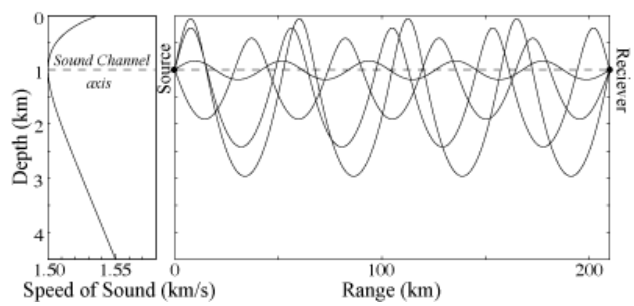


- The boundary between the ocean and the air (i.e., the sea surface) is a nearly perfect reflector under calm conditions. The amount of energy in the reflected wave = the incident wave.
- As the two media become more similar (e.g., ocean and a watery, sandy seafloor), the incident wave will come in, and less of it will be reflected because more energy is transmitted through that reflector and into the 2nd medium. When this happens, we then have something called *refraction*.

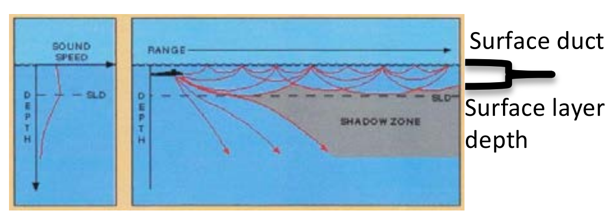
Refraction



- If sound moves into a new medium, or the sound speed in a given medium changes with changes in temperature, salinity, and pressure, sound can refract.
- Refraction is the bending of sound waves towards the slowest sound speed (sound is "lazy", it wants to go to the slowest speed)
- Example of marching band (to the right) moving from pavement (fast sound speed) to sand (slow sound speed); each dot represents a band member, their arms linked together (the thin black line) represents a sound wave moving forward. The marchers (sound waves) move quickly on pavement (large distance between adjacent lines/waves) and go straight, but they are slowed down in sand (adjacent lines closer togher). Refraction also occurs; the overall path bends as the marchers move into the slower area
- A *sound channel* exists in the ocean because sounds waves are bent, or refracted, towards the sound speed minimum. Sound speed profile- at one location, as move down in depth, what is the speed of sound? Lowest or minimum sound speed is at the sound channel axis (in mid-latitudes around 1000m).
- Sound waves leaving the source at specific angles will remain in the sound channel and not lose energy to interactions with the sea surface or sea floor. Sound can travel great distances in the sound channel



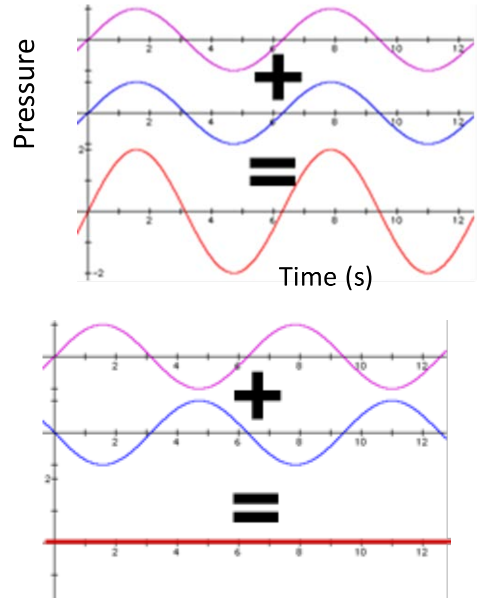
Final example of sound movement: with both reflection and refraction occurring, may observe a surface mixed layer (wind mixes water column to a certain depth, called the surface layer depth, so that temperature, salinity, etc. are constant)



- The surface mixed layer can cause sound to propagate as a surface duct. (reflection and refraction happening together)
- Sound refracts towards the surface, then reflects off the sea surface to be refracted back to the surface. Sound travel long distances in the surface duct.
- Some sound energy does get below the surface duct and is refracted towards the sea floor, creating a "shadow zone" between the surface duct and the deep layer, where little sounds propagates
    - Another reason why to know range and depth with a sound source

Interactions among sounds

A sound can be a tone at a single frequency or a combination of energy at many frequencies. It is important to understand the frequencies of which a sound is composed to determine its potential to affect various marine animals. Just as importantly, the phase of a signal, or really the difference in phase between two signals, determines how they will interact with each other, either adding or canceling each other out.



Credit: An Acoustics Primer, Chapter 8, URL: www.indiana.edu/~emusic/acoustics/phase.htm Copyright 2003 Prof. Jeffrey Hass, Center for Electronic and Computer Music, School of Music, Indiana University, Bloomington, Indiana

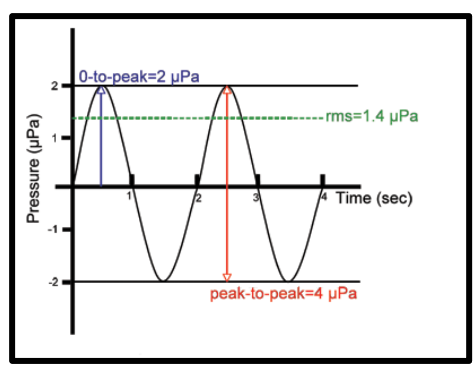
- Phase is really a *waveform* (graph of pressure vs. time); *phase* is the location of a point within a wave cycle of a repetitive waveform. This is where you look to see how waves will interact.
- When two (or more) sounds combine, their phase difference determines whether the amplitudes of the sounds will add or cancel each other out. For example, two sounds of the same frequency that are perfectly aligned are "in phase" and their amplitudes add (1st graph on right)
- If one of the two sound waves of the same frequency is shifted by one-half cycle relative to the other, they are "out of phase" and cancel each other out (2nd graph on right)
    - This is the principle behind noise-cancelling headphones and how they work
- Most sounds consist of many different sine waves at different frequencies (eg. Weddell seal call)
- Waveforms of all the sine waves are added together at each location along the wave cycle to create the sound; not just a simple tone.
- Also, when two or more sounds occur in the same region in the ocean, the resulting sound field is dependent on their phases. The sound field is not always louder (more sound energy); that only occurs if the sounds are in phase. Phase difference is an important consideration in masking.

***Sound measurement*. Sound is measured in units called decibels, which are *relative units*, just like degrees of temperature. Just as temperature is described in degrees Celsius or degrees Fahrenheit, the scale on which decibels are being measured (re 1 µPa in water or 20 µPa in air) or *reference pressure must be stated*.**

- **dB re 1 micropascal (µPa) for water; dB re 20 µPa for air**
- **Other complex factors but very simple generalization: subtract 61.5 dB from sound levels in water to obtain sound levels in air (but it is more complex than this)**
- **http://www.dosits.org/science/soundsinthesea/airwater/**

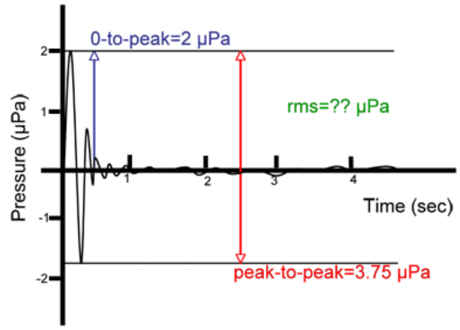
Also important to understand is how that pressure was measured.

- **Reference pressure and measured pressure**
- **There are several ways in which the amplitude of a sound wave (its signal level) can be measured:**
    - **peak pressure or 0-to-peak pressure**
        - range in pressure between zero and the greatest pressure of the signal
    - **peak-to-peak pressure**
        - range in pressure between the most negative pressure and the most positive pressure of the signal
    - **root-mean-square (rms) pressure**
        - The square root of the average of the square of the pressure of the sound signal over a given duration (work backwards through the name)



For example given here, 0-to-peak pressure is 2 µPa; peak-to-peak is 4 µPa; rms is 1.4 µPa (summed over a 0.5 second duration)

More complex calculations with more complex signals. With this picture (similar to an impulsive signal like an airgun), 0-to-peak pressure is 2 µPa, peak-to-peak is 3.75 µPA, and rms will vary depending on duration which the signal is being averaged. If average over 0.5 seconds, the pressure is 1.4 µPa; if over 1 second, get 1 µPa; if over 2 seconds, get 0.8 µPa. Compare these measured pressures to the reference pressure of 1 µPa to calculate the decibels. So not only is there a difference among 0-to-peak, peak-to-peak, and rms dBs, there may be a difference among dB rms values depending on the duration over which the signal is averaged.



Pressure	Decibels
rms (0.5 sec): 1.4 µPa	2.9 dB re 1 µPa
rms (1 sec): 1.0 µPa	0 dB re 1 µPa
rms (2 sec): 0.8 µPa	-1.9 dB re 1 µPa
0-to-peak: 2 µPa	6 dB re 1 µPa
peak-to-peak: 3.75 µPa	11.4 dB re 1 µPa

Duration over which signal is averaged	rms pressure
0.5 sec	1.4 µPa
1 sec	1.0 µPa
2 sec	0.8 µPa

Additional information on the DOSITS website:

Science of Sound > How do you characterize sounds? (http://www.dosits.org/science/sound/characterizesound/)

Science of Sound > What happens when sound pressures are large? (http://www.dosits.org/science/sound/largesoundpressures/)

Science of Sound > Why does sound get weaker as it travels? (http://www.dosits.org/science/soundmovement/soundweaker/)

- Sound Spreading (http://www.dosits.org/science/soundmovement/soundweaker/spreading/)
- Advanced Topic > Cylindrical vs Spherical Spreading (http://www.dosits.org/science/advancedtopics/spreading/)
- Sound Absorption (http://www.dosits.org/science/soundmovement/soundweaker/absorption/)

Science of Sound > How does sound move? (http://www.dosits.org/science/soundmovement/soundmove/)

- Reflection (http://www.dosits.org/science/soundmovement/soundmove/reflection/)
- Refraction (http://www.dosits.org/science/soundmovement/soundmove/refraction/)
- Scattering (http://www.dosits.org/science/soundmovement/soundmove/scattering/)
- Advanced Topic > How does sound move? Wave Propagation and Huygens' Principle (http://www.dosits.org/science/advancedtopics/propagation/)

Science of Sound > How does sound travel long distances? The SOFAR Channel (http://www.dosits.org/science/soundmovement/sofar/)

- History of the SOFAR Channel (http://www.dosits.org/science/soundmovement/sofar/sofarhistory/)
- Sound Speed Minimum (http://www.dosits.org/science/soundmovement/sofar/speedminimum/)
- Sound Travel in the SOFAR Channel (http://www.dosits.org/science/soundmovement/sofar/sofartravel/)
- Sound Channel Variability (http://www.dosits.org/science/soundmovement/sofar/variability/)

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

Advanced Topic > Introduction to Decibels (http://www.dosits.org/science/advancedtopics/decibel/

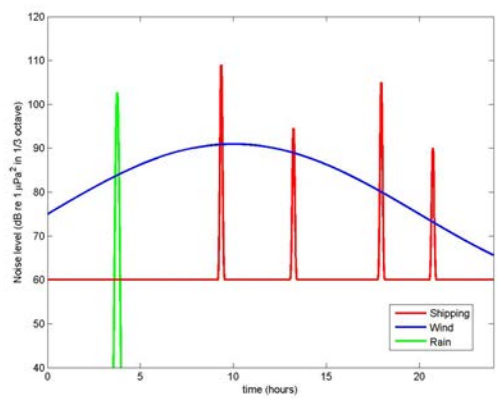
<u>Presentation Summary: Ocean Noise Variability and Noise Budgets (Dr. James Miller, University of Rhode Island)</u>

One way to think about noise in the ocean (noise budgets)
A lot of noise in the ocean- one animal's noise is another animal's signal.
Different examples of noise in the ocean were played.

A proper accounting of the *ocean noise budget* must include the background ambient noise component and the contributions from identifiable sources (National Research Council, 2003).

- What is an ocean noise budget? Think of it like a household budget with expenses being; tracked- track different sources of sound that contribute to the local *soundscape*.
    - Some sounds are short duration (e.g. air guns) and others are continues (e.g. ship noise, waves).
- A noise budget provides a listing of these sources and allows for comparison between sources, and the context for adding another potential source (e.g. adding a wind farm to an area that already has noise in it). Everything is range dependent. These sound sources may be biologically relevant (masking might be able to be measured using a noise budget, but don't know this yet)
- It is helpful as an outreach tool to explain noise sources to the public/media.

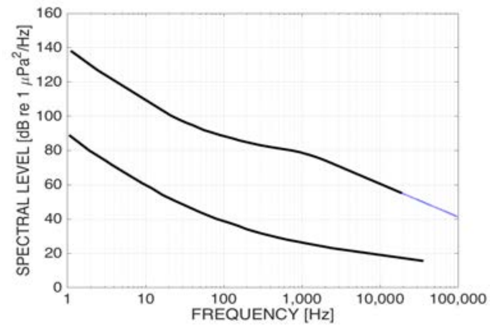
Example of a "hypothetical noise environment" (graph on right):



- Time on x-axis, and noise level in 1/3 octave bands on y-axis (1/3 octave bands are a biologically relevant bandwidth over which marine mammals integrate acoustic energy for hearing, so often use 1/3 octaves to measure noise).
- Three colored lines representing 3 hypothetical sound sources over a 24-hr period
- Red line is combination of a flat, constant at 60 dB noise level (referenced to 1 uPa^2 in 1/3 octave bands), and then every once in awhile a ship goes by (peaks in the red line). 4 ships went by that day in this particular location.
- Blue line is wind; in the middle of day, it got windy (wind comes up, noise gets higher, until get very high winds and so many bubbles are produced that sound levels actually go down). Later in day, wind died down (known from wind record) and noise went down.
- Green line is rain. Four hours into this 24-hr period, it rained. Rain can be very loud. (Acoustics provides an opportunity to measure rain at sea)

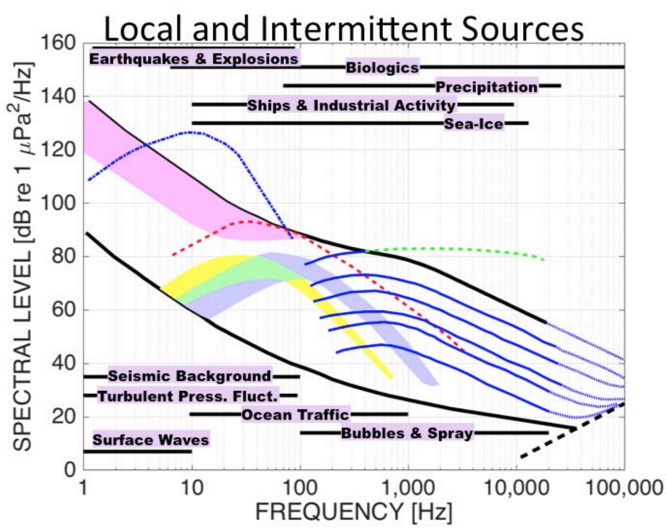
How can we compare the relative contributions from these three sources to the ambient noise field? Calculate an "average intensity". Then rate, or budget, these sounds.

The most fundamental understanding of the contributions of sources to background ambient noise is captured in what is called the Wenz curves (Wenz, 1961). Wenz bounded the range of prevailing noise levels, and identified the frequency and energy level in 1-Hz bins for prevailing and intermittent or local sources.



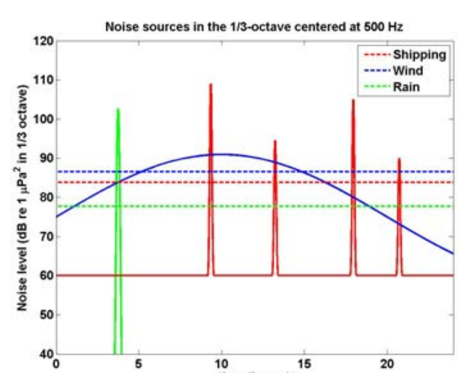
- Average spectral levels of noise (y-axis; spectral levels refer to amount of acoustic energy (dB) in 1-Hz bins, which is different from previous figure where it was dB in 1/3 octave bands), frequency in log scale on x-axis
- Usually noise in the ocean is below top line and above bottom line (if put a hydrophone in the ocean and measured for a certain time and averaged).
  - o At low frequencies, noise in the ocean is higher, and lower at high frequencies. This is due to absorption, which is frequency dependent.
  - o Noise sources do go above upper line (the black lines are just guidelines)

Presented different types of sound sources that are included on a traditional Wenz curve:



- Pink/purple area: low-frequency, very-shallow-water- winds that interfere with one another, producing pressure fluctuations that are measureable
- Blue dashed line: earthquakes and explosions (1-100 Hz)
- Man-made sounds dominate above 10 Hz
  - o Shipping traffic: blue/purple and yellow shaded curves (different colors for deep and shallow water, respectively). 10 Hz-1,000 Hz, band has a lot of shipping noise (dominate band 100-300 Hz); heavy traffic noise can get higher than this (red dashed line)
  - o Remember that these are average numbers, and if close to a ship, these numbers could be even higher

- Blue, sloping lines at frequencies above 100-200 Hz: as go up in wind speed and sea state, noise gets higher, primarily due to wind noise, bubbles. Sources are breaking waves usually
- Green dashed line: Heavy precipitation (can be one of the highest sources of natural sounds)
- Black dashed line above 200 kHz: at very high frequencies (think of echolocation),, molecular agitation contributes to the noise environment



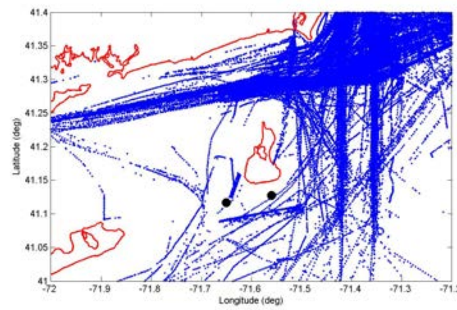
Back to the hypothetical environment: the dashed, colored lines are average noise levels in the environment over the 24-hr period.

- Wind is highest and then shipping is next highest, and rain is least important
- This is one way to compress calculated data into a few numbers people may be able to use/understand

Archival acoustic recorders are being used around the world to measure the acoustic environment and then compute the noise budget for a region.

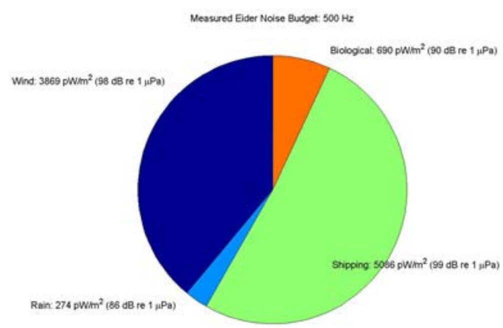
- Many different types of recorders
- Easy to record, but challenging to identify noise sources

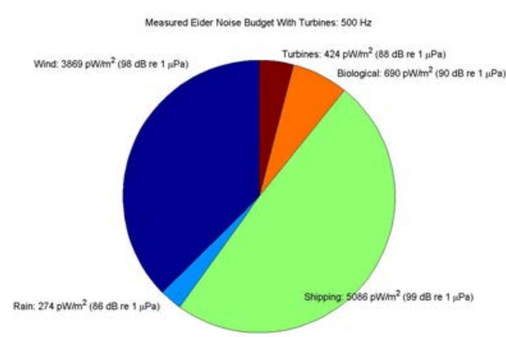
Results from a study that measured and computed the baseline noise budget and projected the impact from operation of the first offshore wind farm in the United States (off Block Island, RI)



- Block Island in center of graphic (red outline); Deepwater Wind is putting offshore wind turbines in this area.
- Question asked, what is the noise before the turbines go in?
- The 2 black dots show where 2 passive acoustic recorders were placed
- Each blue dot, in the graphic to the right, is a ship reporting its location. Can see a lot of shipping in the area (period for ~ 6 weeks in Fall 2008).
- Passive monitoring results reviewed

- With passive acoustics data, derive a measured noise budget in the 1/3-octave band centered at 500 Hz (pie chart to the right) for Block Island Sound in the fall of 2008 without turbine noise:
    - Green is shipping: ½ of noise in this band is dominated by shipping (which makes sense). Blue is wind (not surprising either). What was surprising were the biological signals (orange; dolphin vocalizations). And then it rained a few times (light blue)
    - Measurements of wind turbine (operational) noise from an existing structure in Europe: take these data as estimates of projected noise for Block Island, ran calculations, and insert in budget (maroon). Adding 5 turbines is projected to make a contribution to the noise budget similar to that of rain.





Additional information on the DOSITS website:

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

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

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

Science of Sound > How will ocean acidification affect ocean sound levels?
(http://www.dosits.org/science/soundsinthesea/oceanacidification/)

Advanced Topic > Ocean Noise Variability and Noise Budgets
(http://www.dosits.org/science/advancedtopics/noisebudget/)

People and Sound > How is sound used to measure rainfall over the ocean?
(http://www.dosits.org/people/studyweather/measurerainfall/)

People and Sound > How is sound used to measure wind over the ocean?
http://www.dosits.org/people/studyweather/measurewind/

People and Sound > How is sound used to research wind energy?
(http://www.dosits.org/people/examineearth/windenergy/)

Hot Topic: Ocean-Based Renewable Energy
(http://www.dosits.org/hottopic/renewableenergy/)

Technology Gallery > Archival Marine Acoustic Recording Units
(http://www.dosits.org/technology/observermarineanimals/archivalmarineacousticrecordingunits/)

Questions (asked and answered during webinar):

During the first presentation, RMS, peak-to-peak, zero peak were mentioned. Could you say a few words on SPL (sound pressure level) and SEL (sound exposure level) values and how they are measured/calculated?

Sound pressure level (SPL) relates to those decibel measurements where pressure is used to calculate sound level, which is reported in units of decibels (dB). It is important to understand whether it is dB rms or dB peak, because they can all relate to a sound pressure level (SPL). For *SEL, sound exposure level,* the units are dB re 1 $\mu Pa^2/s$. It's an integration over time or summation of the square pressure over time. SPL can vary, again, over that time summation. SEL is a cumulative exposure; it can be over a single signal, over a pulse, or over a full 24 hour period (or much longer). Need to be careful of stating what that time summation is when SEL values are provided.

Can Kathy talk a little about how the rms calculation [she discussed] relates to NOAA's 190, 180, & 160 dB (rms) thresholds? How many seconds are those averaged over?

The criteria themselves have been developed as criteria for common use in estimating potential impacts. Because there are no standards for the time integration of dB rms, the way those rms are calculated can vary. Typically what is done for rms measurements is to look at 90% of the energy of the pulse, so that you are capturing the energy of the pulse, and not summing over time when the pulse doesn't have energy. You are trying to focus on a time duration that is not too n; looking at 90% energy of what pulse is. Summation time is really an issue with impulsive sounds (air guns, explosions, etc.). For sonar sources or other types of traditional, continuous sources of sound (generally sine waves), the waveform looks the same throughout the pulse, and the rms time summation isn't that big of a deal. It is harder/a bigger deal with impulsive sounds since you have a "quiet time" in between pulses, and need to be careful with rms (also important when looking at SEL).

How did [Jim] calculate the percent contributions of the different sound sources within a band?

It is relatively straight forward: calculated the average intensity of the signals that were identified on the acoustic recorders. Once the signals were identified, the average intensity could be computed. If it was ship noise, it was on a lot, even though at a lower level, the average intensity would be high. Rain was a loud noise, but didn't last very long. Average intensity takes those levels and their duration into account. It would give a big value for a loud signal that was on a long time, and a lower value for a less intense signal on for a short time. A noise budget collapses all of that data into a few numbers that can be explained.

How does one deem the addition of noise from a source to an existing noise budget (as you presented) to be significant or not significant? Are there physical or biological criteria for that determination?

What is the biological relevance of the noise budget? Scientists are struggling with those issues associated with masking, etc. [Jim] gets to the limit of his knowledge so works with biologists; he can do the measurements and the math. The pie charts speak for themselves, but what does that mean? If the slice of the pie is small, would guess it would be less important because affecting the noise budget by a small amount. And if it was a big slice, or the pie changed a lot, then could say that sound source affected the noise budget a lot so has a greater chance of being a significant change. But as for specific numbers, haven't gotten that far yet.