The Impact of Offshore Wind Turbines on Underwater Ambient Noise Levels

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Why is Offshore WT Noise a Concern?

1. With the current interest in offshore wind farm development there is concern about any negative environmental impacts caused by offshore developments
2. One concern that needs to be considered (Kochinski (2003), NRC (2003), and dismissed, is the impact of increased operational noise levels on the behavior, mating characteristics and migration of endangered species, including marine mammals
3. Since sound is key to underwater communication, navigation and foraging for marine mammals we need to demonstrate that wind farms will not create sound levels that interfere with the normal behavior of marine mammals (Richardson (1995)

Assessing the Impact (Richardson (1995))

To asses the impact of increased made made sound on marine mammals Richardson (1995) defines four zones:

Zone One: The zone of audibility
Zone Two: The zone of responsiveness
Zone Three: The zone of masking
Zone Four: The zone of injury

Zone Definition (Madsen et al (2006))

Zone One: The zone of audibility

Limited by the threshold of hearing or background noise TOL (1/3rd octave level).

If the signal has clearly defined characteristics then it can be detected at levels below the background noise, but not below the threshold of hearing

Zone Definition (Madsen et al (2006))

Zone Two: The zone of responsiveness

Defines the region where the animal responds to increased noise levels.

This is the most difficult to estimate, define and detect (Madsen (2006), Richardson (1995).

Zone Three: The zone of masking

Where the man made sound adds significant energy to the ambient noise such that the reception of the signal of interest is impaired.

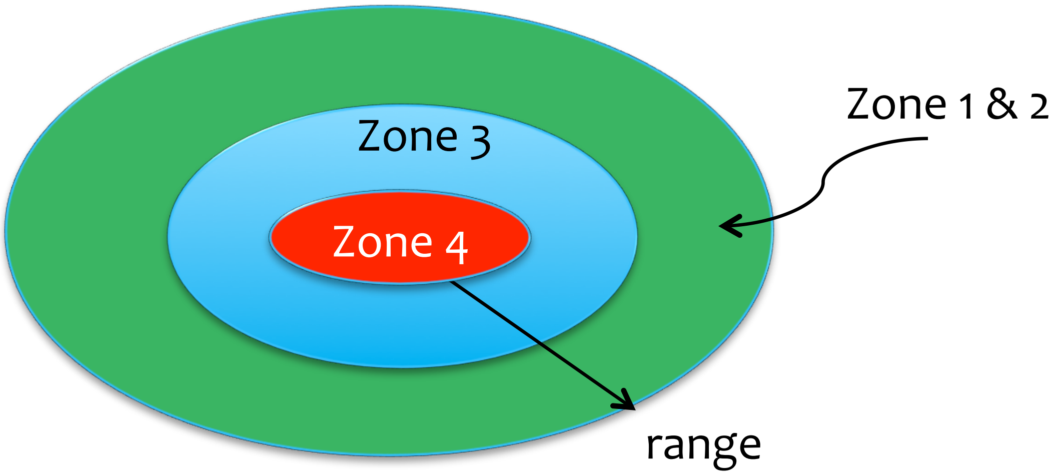
Madsen et al (2006) defines this as equal to the existing background noise

Zone Definition (Madsen et al (2006))

Zone Four: The zone of injury

Defines the region where the levels are so high that injury or hearing loss occurs

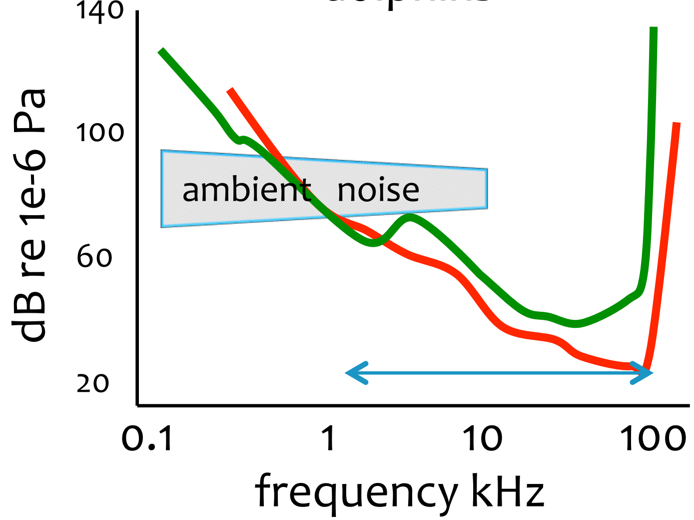
Usually indicated by temporary threshold shifts (TTS) (Madsen et al (2006), Richardson (1995). Depends on exposure time. NMFS (2003) set this limit using source levels of 180 dB re 1e-6 Pa for cetaceans and 190 dB re 1e-6 Pa for pinnepeds



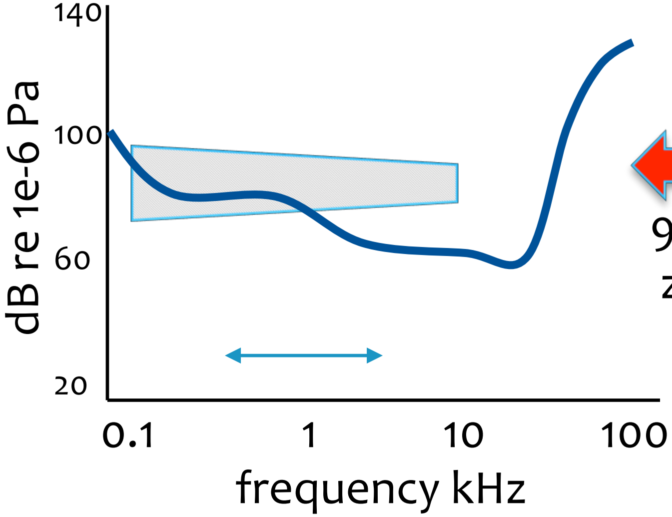
Threshold of Hearing

The affected species in shallow water are the Harbor Porpoise, the Bottle Nose Dolphin, the Northern Right whale, the harbor seal and maybe the Baleen whale for depths greater than 20m. Their hearing is based on 1/3rd octave bands (as with humans) and examples are given below. The whale species have low frequency hearing but threshold data not available (Madsen et al (2006)).

harbor porpoise and bottle nose dolphins



pinnepeds (seals)



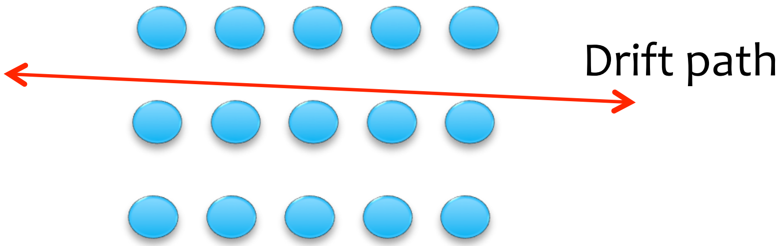
90-100 dB
zone 1 and 2

Measured Offshore WT Noise

COWRIE Report (2010)

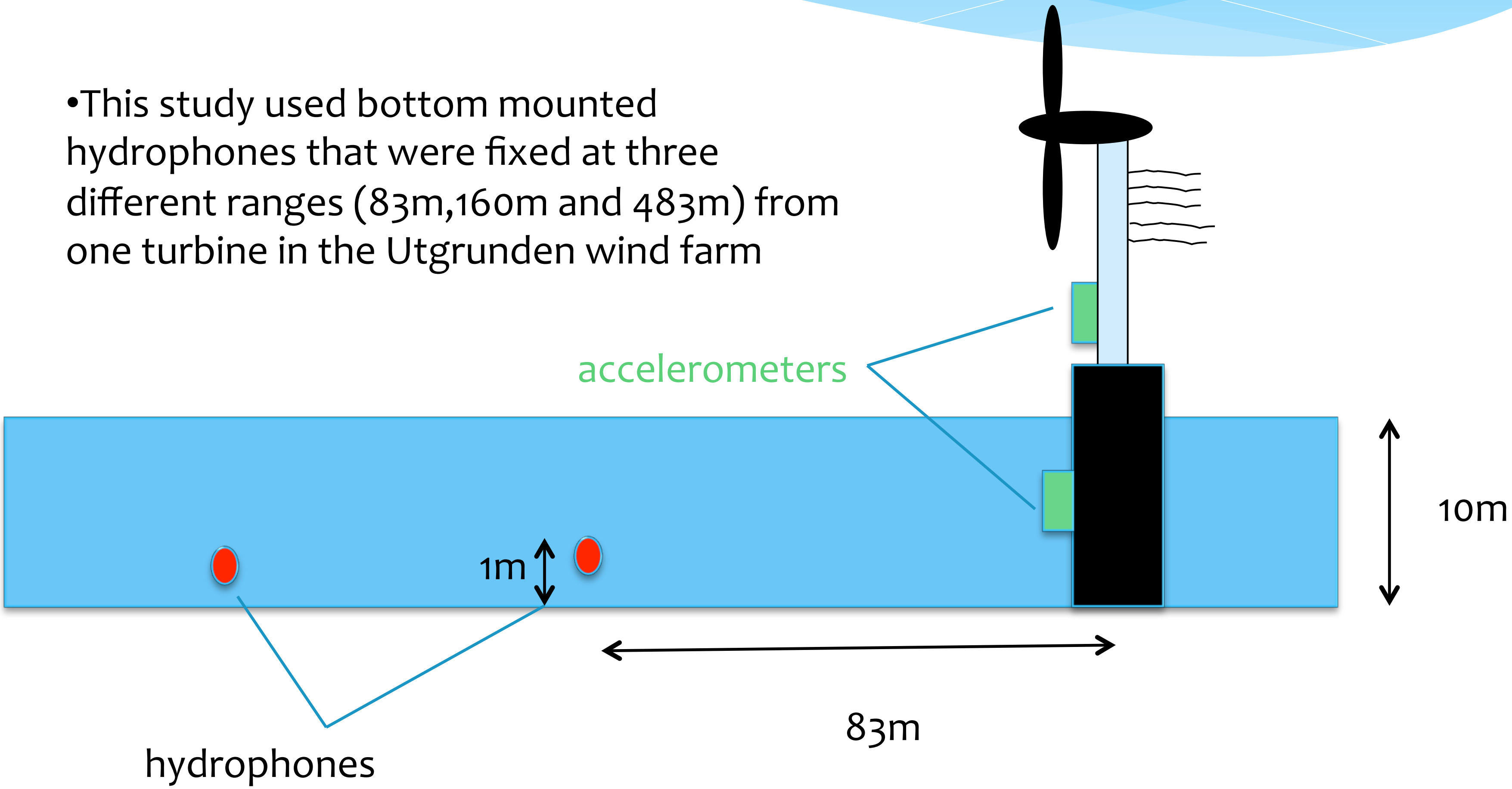
- This report published the measurements of Nedwell et al (2006) for four different wind farms in the coastal waters of the UK
- The main concern of the report was the construction noise caused by pile driving that caused source level of ~250 dB re 1e-6 Pa
- In general there was difficulty in separating wind turbine noise from the background noise apart from in one case where OASLs of 122-147 dB were reported and separated from the background noise by 20 dB.
- In general all the wind farms were located in very shallow water (5m or less). Water depth varied from 4-12m during the measurement period.
- The measurements were taken using a drifting vessel on specific days and long term in situ measurements were not made. In some cases wind speeds were very low.

Measurements made from a drifting vessel



Utgrunden Measurements
Ingemassen Report (2003)

- This study used bottom mounted hydrophones that were fixed at three different ranges (83m,160m and 483m) from one turbine in the Utgrunden wind farm



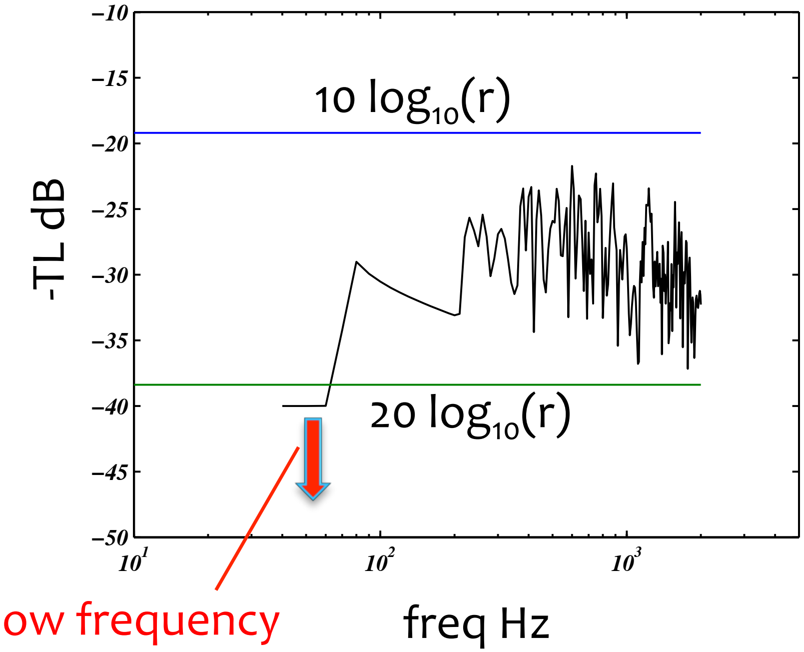
Utgrunden Measurements Ingemassen Report (2003)

- The water depth of the turbine was 10 m. Details of the turbine and its operational characteristics were provided, and simultaneous measurements were made of the tower vibration

- The far field sound levels showed clearly defined tones with the maximum peaking at 170 Hz. These tones were correlated to the gearbox vibration by comparing the acoustic spectra with the vibration spectra. The peak tone spectral level was 124 dB re 1e-6 Pa at 83 m.

- The data scaled with range as $13\log_{10}(r)$

Shallow Water Sound Propagation



low frequency cut off at 60 Hz

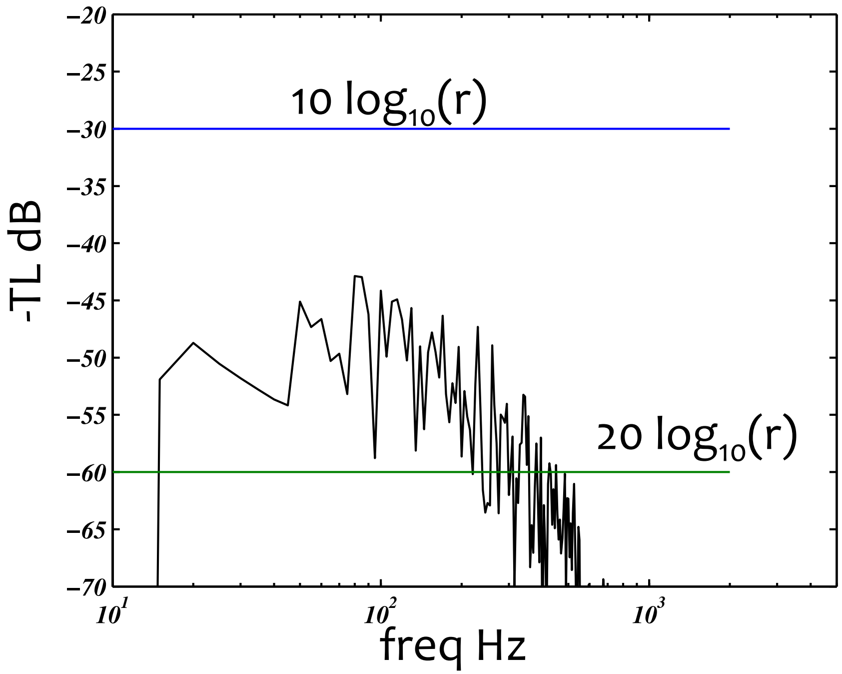
Transmission loss vs frequency for the measurement at Utgruden with a hydrophone 1m above bottom based on adiabatic mode theory

The prediction is consistent with the TL=13 $\log_{10}(r)$ of the measured data

Estimating Source levels in shallow water environments is difficult

Deep Water Sound Propagation

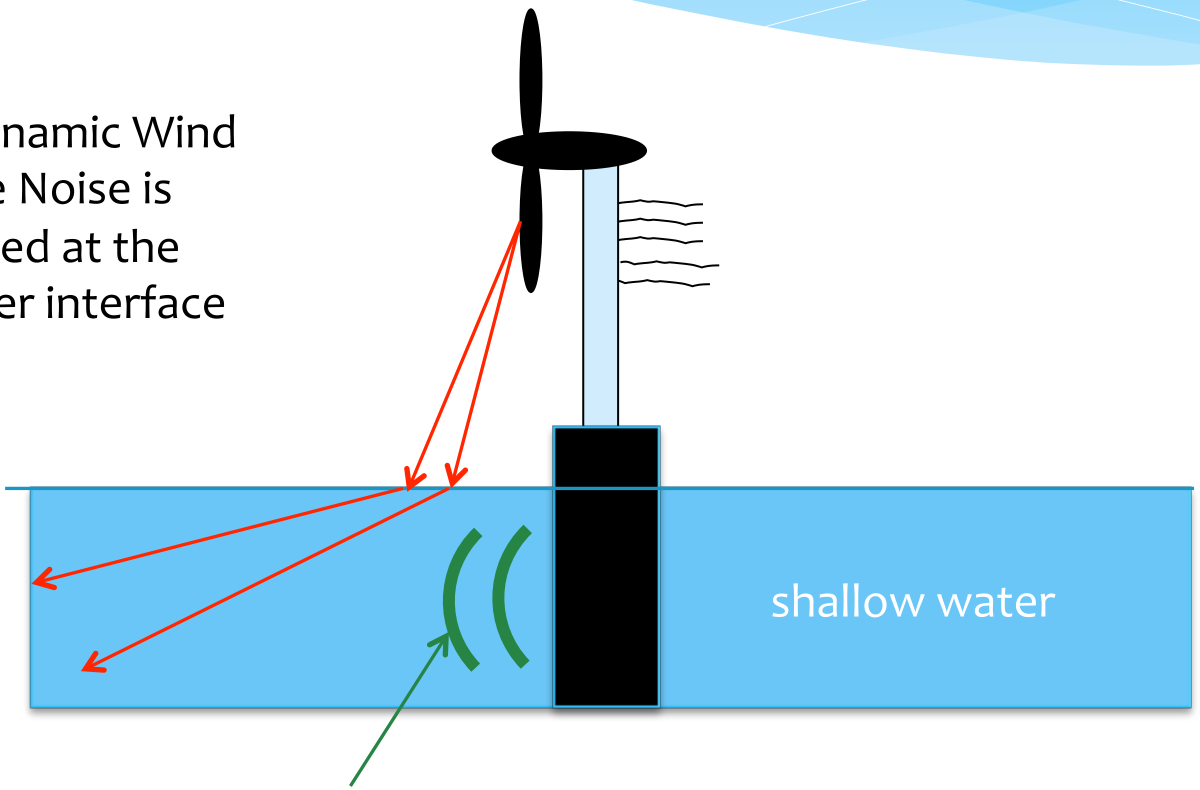
- In deep water and larger ranges (1km shown below) the low frequencies are no longer cut off but the high frequencies are suppressed



- **It is not clear that shallow water levels can be scaled to deep water without detailed analysis**

How Should We Scale Offshore Wind Turbine Noise?

Offshore Wind Farms



Aerodynamic Wind Turbine Noise is diffracted at the air water interface

shallow water

Structureborne Noise

Calculating WT Blade Noise

- It is assumed that the blade noise is dominated by trailing edge scattering of boundary layer pressure fluctuations
- The basic TE noise source is coupled to a rotating blade and the propagation to the observer is calculated
- Amplitude modulation is caused by blade motion relative to the observer

Basic Formulation

$$p(\mathbf{x},t)=\int_{-T}^{T}\int_{S} p(\mathbf{y},\tau)\frac{\partial}{\partial y_i}G(\mathbf{x},t\,|\,\mathbf{y},\tau)n_i dS(\mathbf{y})d\tau$$

Fundamental Equation

$$p(\mathbf{x},t)=$$

$$\int_{-T}^{T}\int_{\Sigma}\left\{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\hat{P}(\omega,k_1,k_3)e^{-i\omega\tau-ik_1z_1-ik_3z_3}d\omega dk_1dk_3\right\}\frac{\partial}{\partial y_i}G(\mathbf{x},t\,|\,\mathbf{y},\tau)e_i^{(2)}dz_1dz_3d\tau$$

Wavenumber Spectrum of Surface Pressure

$$G(\mathbf{x},t\,|\,\mathbf{y},\tau)=\int_{-\infty}^{\infty}\frac{e^{ik_aR-ik_a(x_1y_1+x_2y_2+x_2y_2)/R}}{4\pi R}e^{-i\omega_o(t-\tau)}d\omega_o$$

Free field Greens function for rotating source

Prediction Methodology (Air)

$\Omega T << 1$ **Slow speed of rotation**

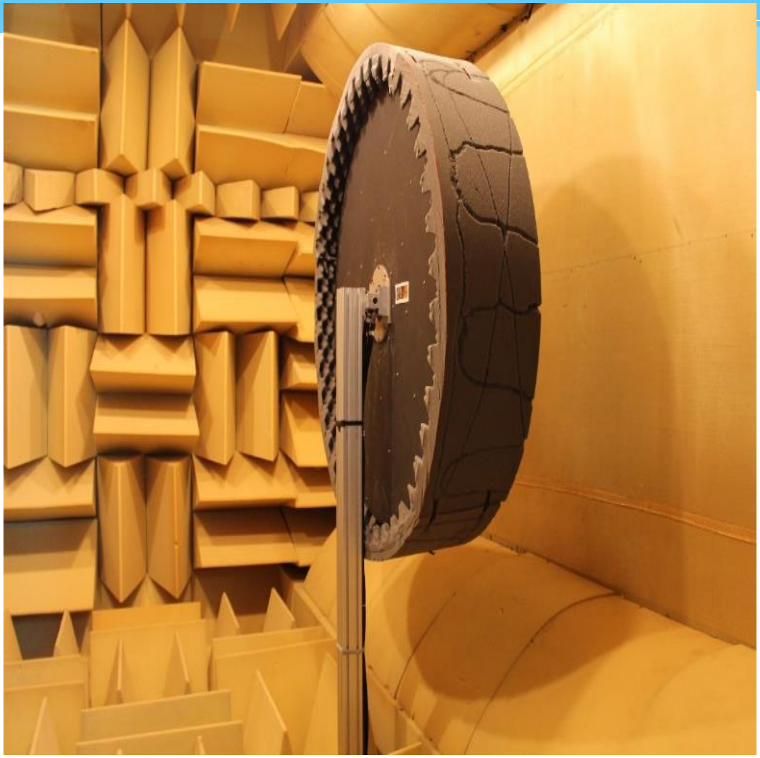
$$p(\mathbf{x},\omega_o,t_s)=D_a(\mathbf{x},t_s)\left\{\frac{\hat{P}(\omega_o,k_1^{(a)},k_3^{(a)})e^{ik_aR}}{4\pi R}\right\}$$

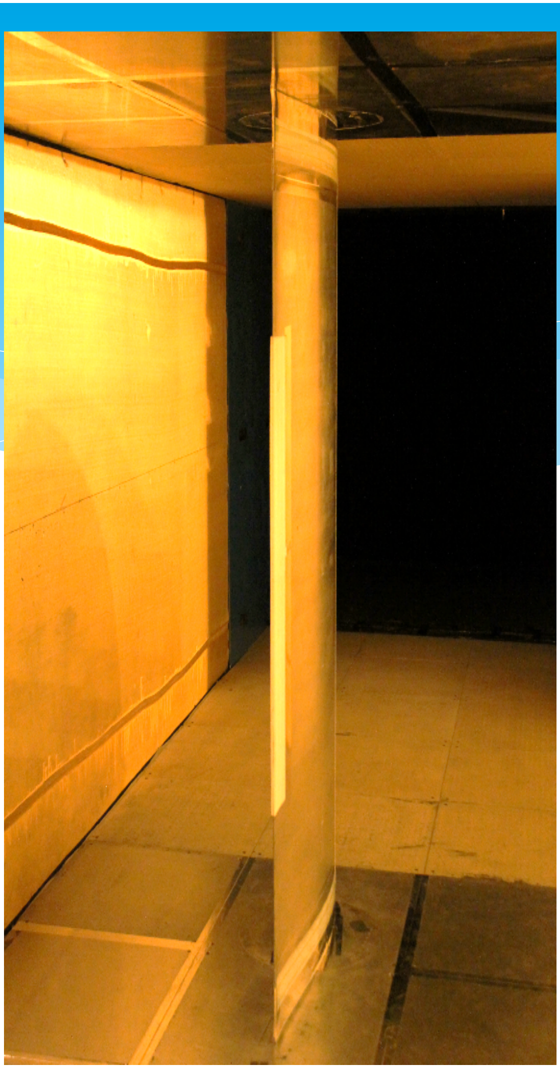
← **Far field Sound**

$$D_a(\mathbf{x},t_s)=-k_a(x_1\cos\mu-x_2\sin\mu\cos\Omega t_s+x_3\sin\mu\sin\Omega t_s)/R$$

Directionality Factor (time dependent)

VT Wind Tunnel



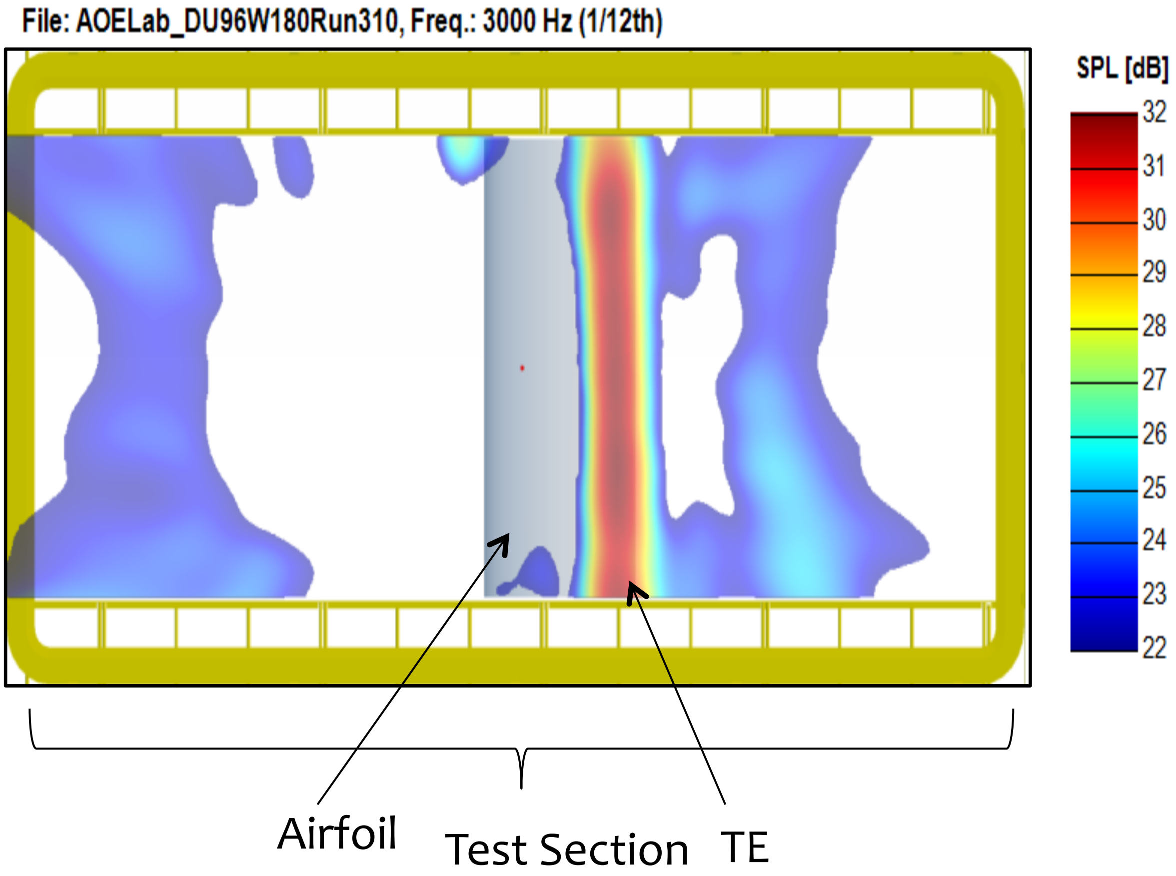


- 117 microphone array for far field acoustics
- Surface pressure taps for C_p and lift
- Wake rake and drag measurements

- 0.8 m chord DU96-W-80 airfoil
- Tripped (0.5 mm tape) at 5% /10% chord
- Flow speeds 50 m/s and 60 m/s (M=0.18, Re=3
- AoA from -2.5° (zero lift) to 14.8°

Clean Airfoil

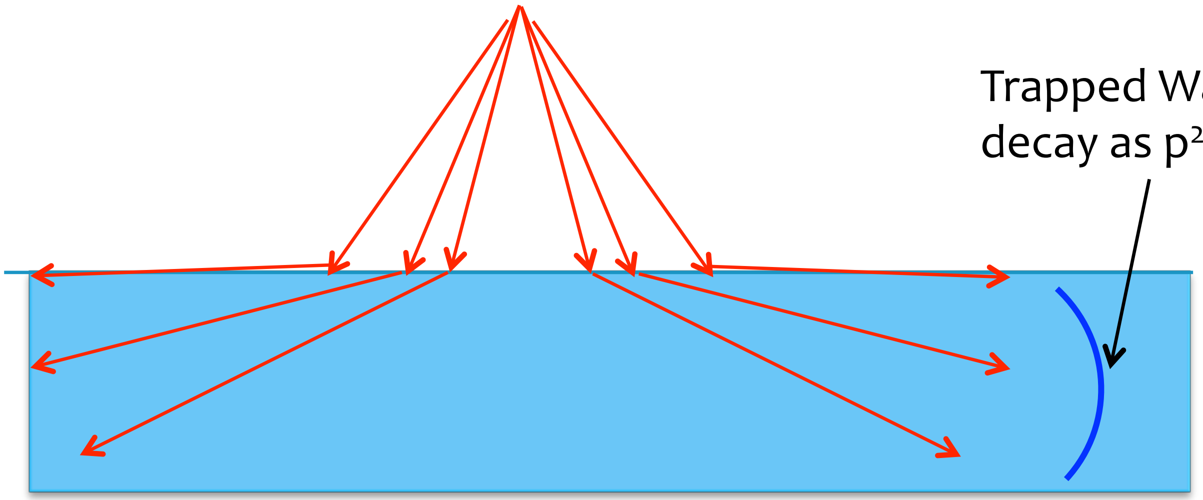
Clean



-2.5° Zero Lift

#0

Propagation Effects into water



Critical Angle of incidence 15 deg

Trapped Waves that decay as $p^2 \sim 1/R$

Modified Theory for UW sound

$$G(\mathbf{x},t\,|\,\mathbf{y},\tau) \approx \int_{-\infty}^{\infty} \frac{1}{2}\sum_{n} \frac{e^{i\gamma_n(y_3+h)-ik_n(x_1y_1+x_2y_2)/r_o+ik_nr_o}}{\gamma_n H\sqrt{\pi k_n r_o/2}} \nu_n \sin(\nu_n z) e^{-i\omega_o(t-\tau)} d\omega_o$$

Chapman and Ward Greens Function

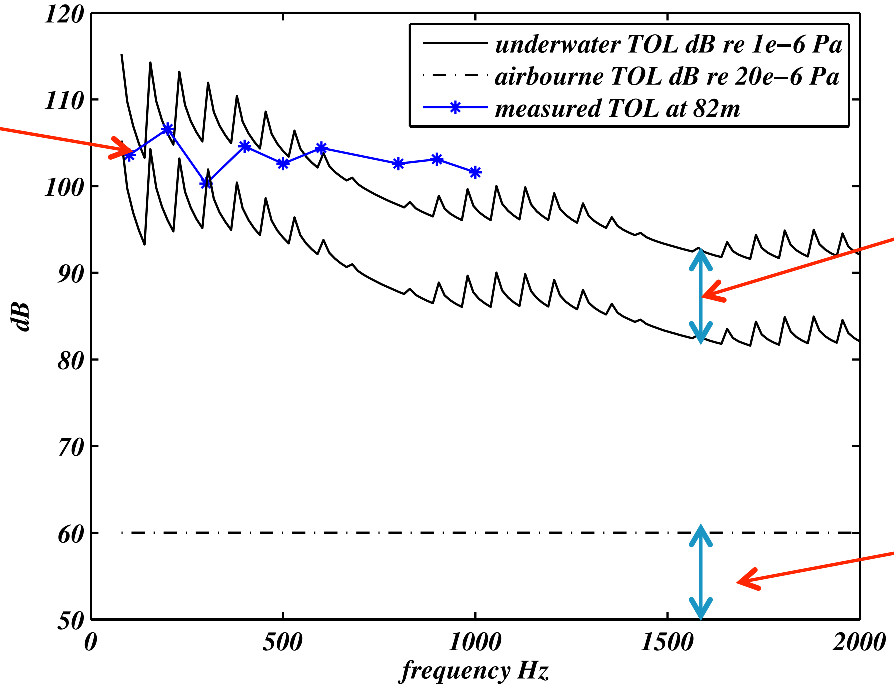
$$p(\mathbf{x},\omega_o,t_s) = \sum_{n} A_n(\omega_o,t_s)\sin(\nu_n z)\frac{e^{ik_nr_o}}{\sqrt{\pi k_n r_o/2}}$$

Modal Series for UW sound Field

$$A_n(\omega_{\mathrm{o}},t_s) = \int_{-T}^{T}\int_{\Sigma}\left\{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \hat{P}(\omega,k_1,k_3)e^{-i\omega\tau-ik_1z_1-ik_3z_3}d\omega dk_1 dk_3\right\}$$
$$\times\frac{\partial}{\partial y_i}\left(\frac{\nu_n e^{i\gamma_n(y_3+h)-ik_n(x_1y_1+x_2y_2)/r_o+i\omega_o(\tau+t_s)}}{2\gamma_n H}e_i^{(2)}\right)dz_1 dz_3 d\tau$$

Estimated Noise Levels at Utgrunden

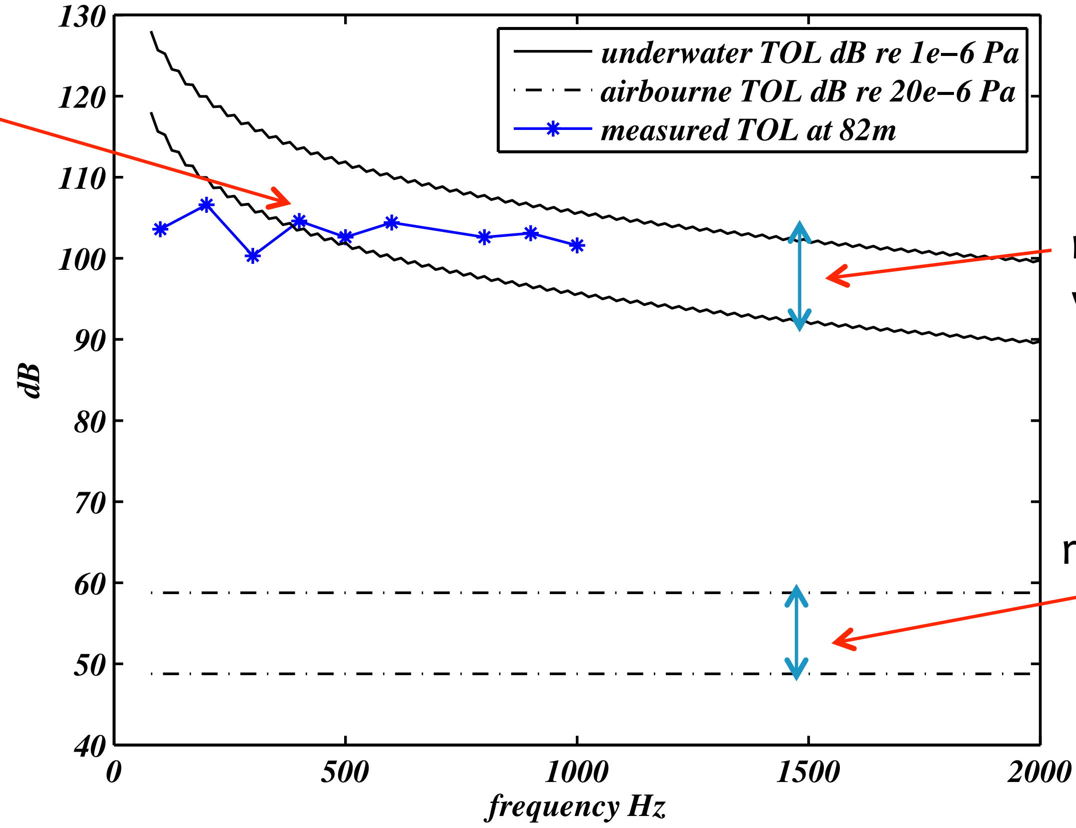
measured TOL without tones



range of levels in water

range of levels in air

Estimated Deep Water Noise Levels at 500m and 50m depth for 3MW WT

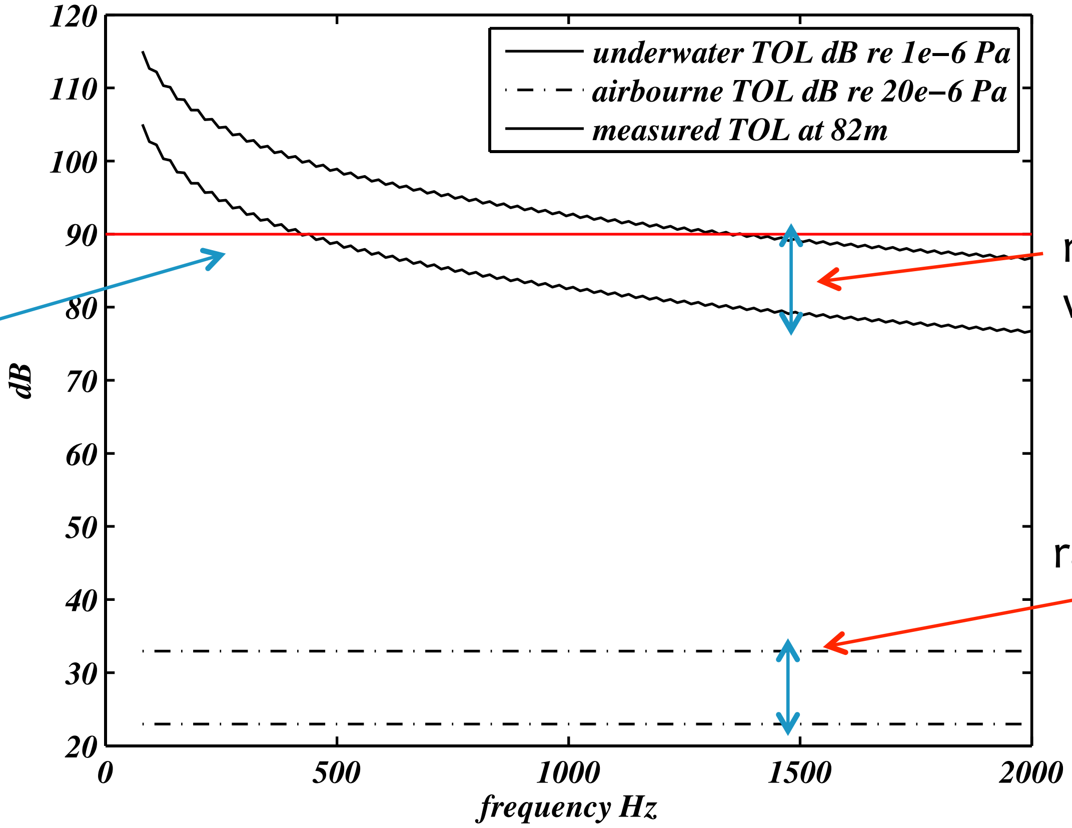


measured TOL without tones at 83 m

range of levels in water

range of levels in air

Estimated Deepwater Noise Levels at 10 km and 50m depth for 3MW WT



Background Noise Limit

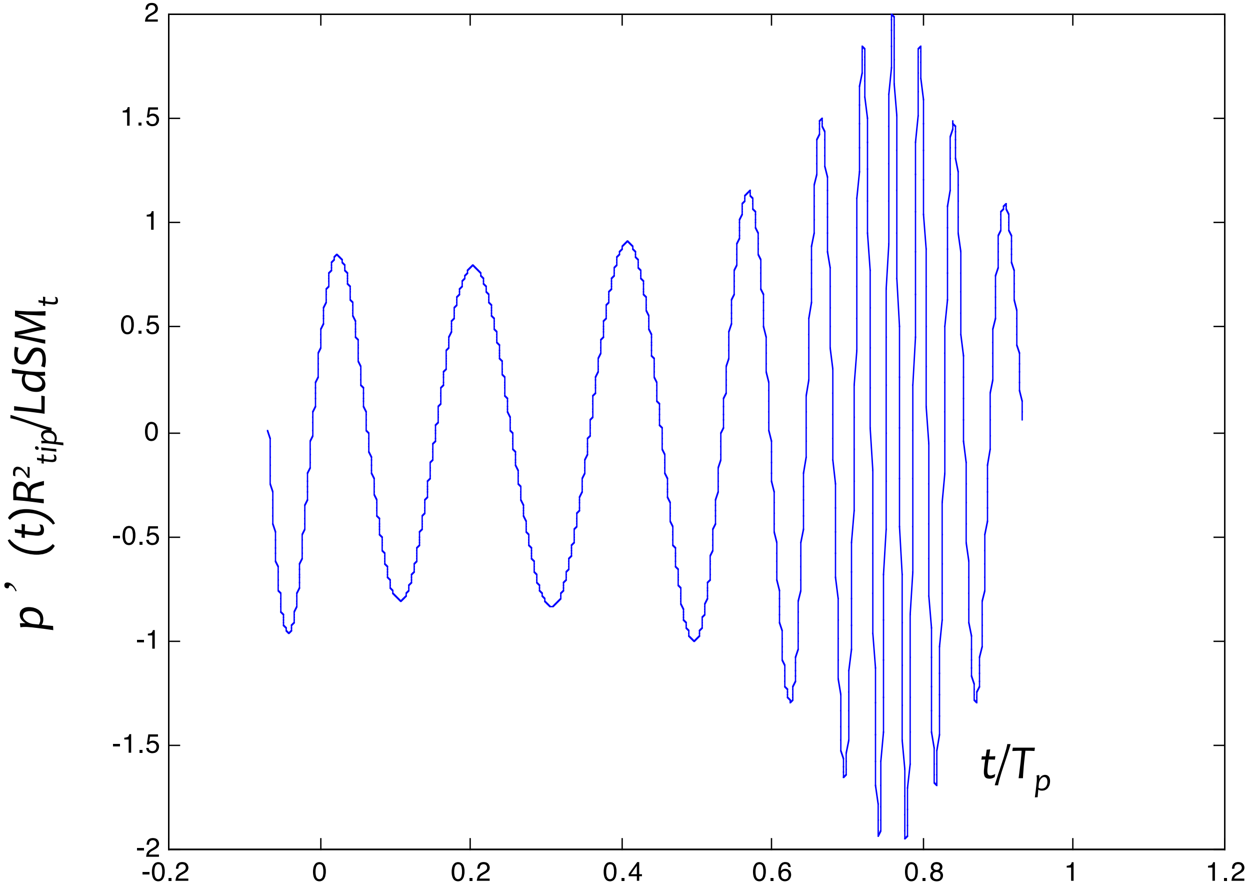
range of levels in water

range of levels in air

Amplitude Modulation

Acoustic Signature for Harmonic Rotating Source

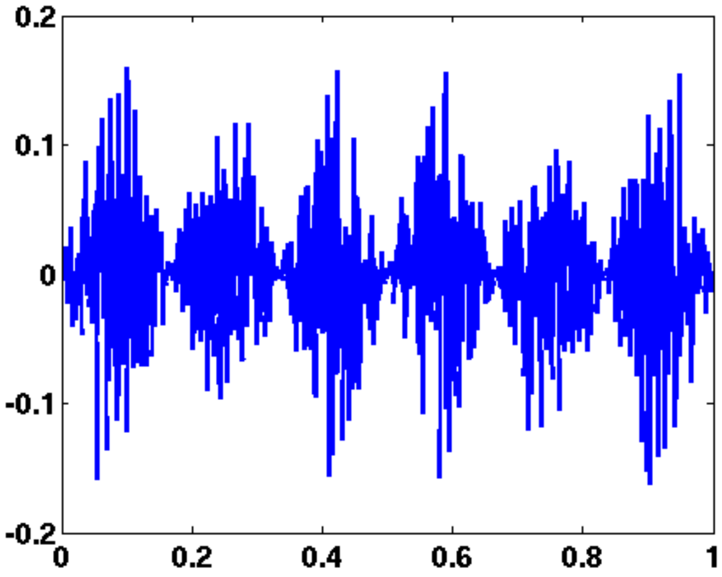
Doppler Amplification



Traditional Sources of Amplitude Modulation

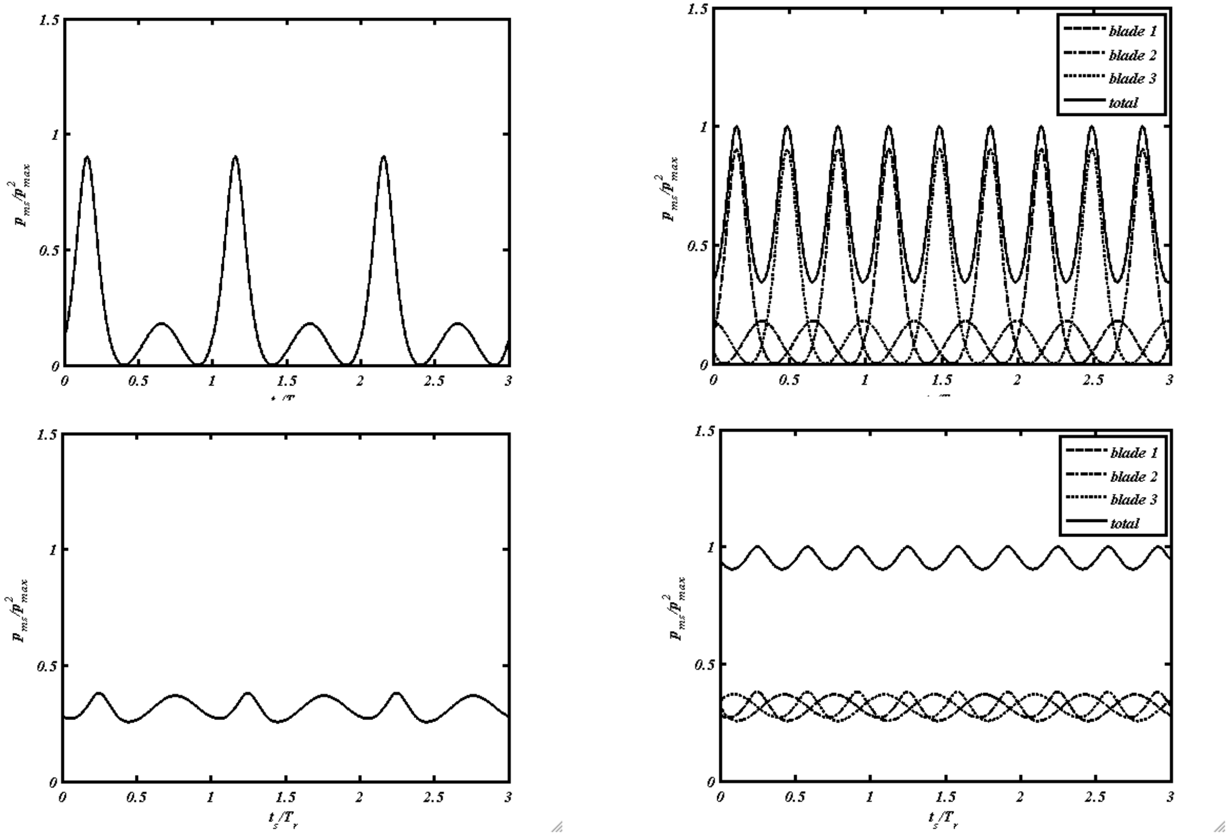
The engineering task is to understand and predict the sources of amplitude modulation. These have been characterized into two types:

1) Traditional AM caused by trailing edge noise and blade rotation
2) Other Sources of AM (or EAM) which are intermittent and not well understood



Predicted Directionality and the Effect of Multiple Blades

Predicted Near Field Levels



Single Blade

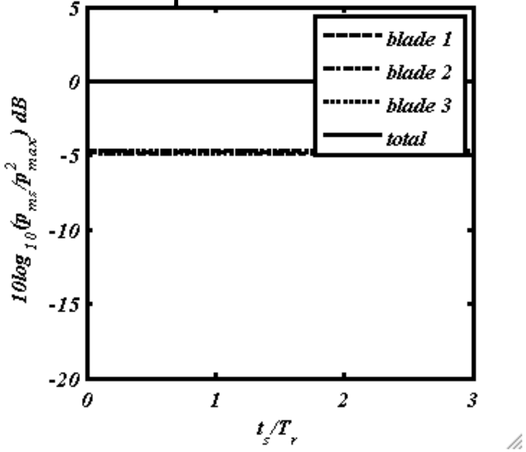
Three Blades

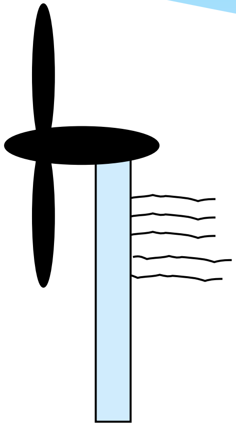
in plane of the rotor at 40m

upstream of the rotor at 40m

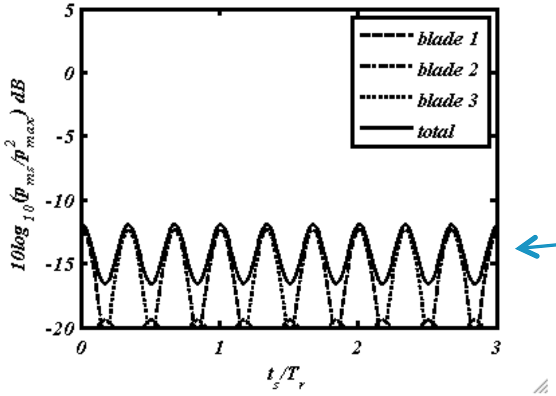
Predicted Levels of AM

Upwind Level





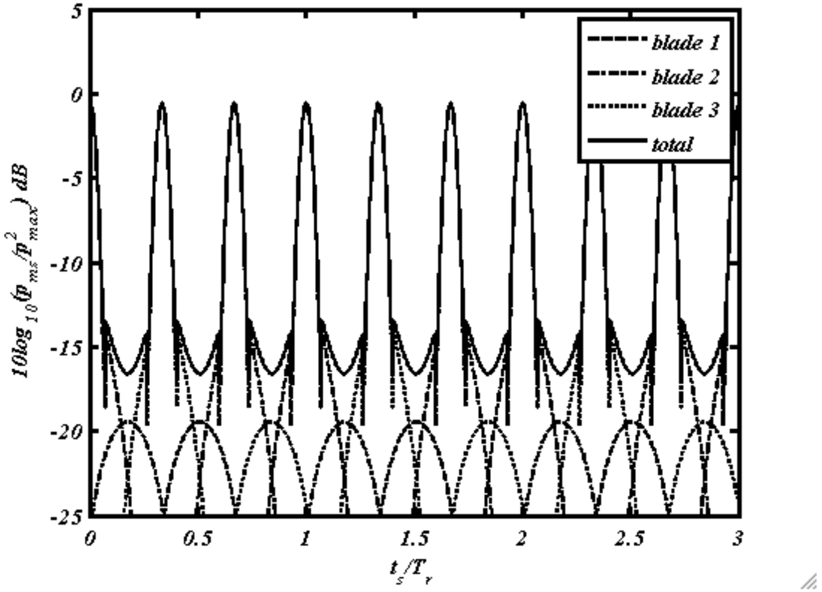
Cross wind Level



3 MW wind turbine
60m hub height
blade radius 41.2 m
observer at 1 km

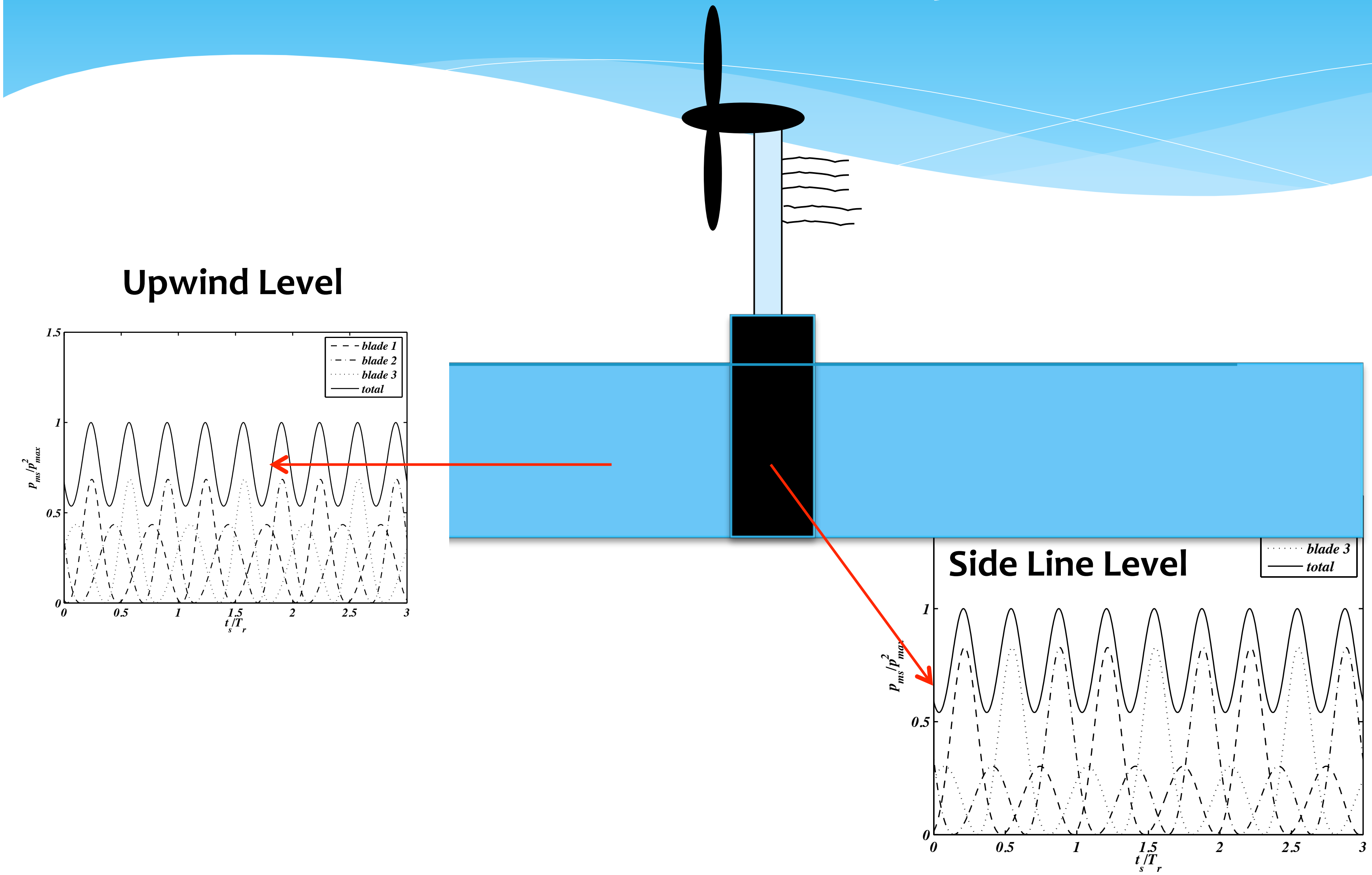
3-4 dB of AM in cross wind direction

Predicted EAM from Blade Stall



- Blade stall implemented over 50 deg arc
- Assumed level increase 12 dB

Offshore Wind Farms Noise Directionality



Upwind Level

Side Line Level

Conclusions

1. We have reviewed the currently available information on offshore wind turbine noise as it affects marine mammals and it is clear that offshore wind farms in shallow water do not cause a significant increase in ambient noise levels
2. We have developed a model to scale existing measurements of wind turbine noise to deep water installations. The input being the noise spectrum of the same turbine operating in air
3. Results indicate that offshore wind turbines in deep water will couple acoustically to the water column more efficiently than in shallow water, and that signals may be observable for distances of 10 km.

Ambient Noise Levels