TO WHAT DEGREE IS AQUATIC LIFE EXPOSED TO UNDERWATER SOUND?

Christ de Jong
CONTENTS

› standardization of underwater sound terminology and metrics
› standardization of underwater sound measurements and analysis
› dredger sound measurement and mapping
› quantifying exposure of marine animals to sound
Every science requires a special language because every science has its own ideas. It seems that one ought to begin by composing this language, but people begin by speaking and writing and the language remains to be composed.

Étienne Bonnot de Condillac (1715-1780)
STANDARDIZATION
DIFFICULT BUT ESSENTIAL

3.1.1.1
sound
sound wave
disturbance in pressure that propagates through a compressible medium, or a superposition of such disturbances

3.1.2.1
sound pressure
$p(t)$
difference between instantaneous total pressure and pressure that would exist in the absence of sound waves

Note 1 to entry: Sound pressure is expressed in pascals (Pa).

Note 2 to entry: The term “sound pressure” is sometimes used as a synonym of root-mean-square sound pressure. This use is deprecated.

ETC, ETC, ETC, .....
Sound Pressure Level (SPL)
- Time average squared sound pressure, expressed in dB re 1µPa²

Sound Exposure Level (SEL)
- Time integrated squared sound pressure, in dB re 1µPa²s
- = ‘dose’ of sound over a defined period (e.g. 24 h)

WARNING: there are many different decibel (dB) scales
‘LEVELS’ IN DECIBELS: RULES

#1 The nature of the physical parameter must always be stated clearly
    Sound exposure level = 200 dB re 1 μPa² s, and not
    Received level = 200 dB re 1 μPa² s

#2 The reference value must always be stated explicitly
    Spectral density level = 160 dB re 1 μPa²/Hz, and not
    Spectral density level = 160 dB

#3 The reference value must always be expressed in coherent SI units
    Source spectral density level = 180 dB re 1 μPa² m²/Hz, and not
    Source spectral density level = 180 dB re 1 μPa²/Hz @ 1 m

0 dB + 0 dB = 3 dB
3 dB + 3 dB = 6 dB
100 dB + 100 dB = 103 dB
100 dB + 110 dB ≈ 110 dB

\[
L_p = 10 \log \left( 10 \left( \frac{L_{p1}}{10} \right) + 10 \left( \frac{L_{p2}}{10} \right) \right)
\]
FREQUENCY ANALYSIS
NARROWBAND (FFT) & PROPORTIONAL BANDS

To what degree is aquatic life exposed to underwater sound?

SPL dB re 1μPa²

Frequency (Hz)
To what degree is aquatic life exposed to underwater sound?

**Single number SPL:**
weighted sum or average in space, time and frequency
RECEIVED SOUND VS RADIATED SOUND

- SPL and SEL are measures of received sound
- depend on source radiation and on propagation in the environment
To what degree is aquatic life exposed to underwater sound?

SOUND PROPAGATION MODELS

- Various models
- Different applications & requirements
- No standard approach

http://oalib.hlsresearch.com/

Propagation models / software
- Rays
- Normal Modes
- Parabolic Equation
- Wavenumber integration
- Energy flux
- Other …
UNDERWATER SOUND MEASUREMENT

- Hydrophones
- Sound recording

To what degree is aquatic life exposed to underwater sound?
To what degree is aquatic life exposed to underwater sound?

Based on ANSI/ASA S12.64-2009/Part 1

Acoustics — Quantities and procedures for description and measurement of underwater sound from ships — Part 1: General requirements for measurements in deep water

Table 1 – Summary of measurement grades

<table>
<thead>
<tr>
<th>Grade</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade name</td>
<td>Precision method</td>
<td>Engineering method</td>
<td>Survey method</td>
</tr>
<tr>
<td>Achievable</td>
<td>1.5 dB</td>
<td>3.0 dB</td>
<td>4.0 dB</td>
</tr>
<tr>
<td>measurement uncertainty</td>
<td>± 1.0 dB</td>
<td>± 2.0 dB</td>
<td>± 3.0 dB</td>
</tr>
<tr>
<td>Measurement</td>
<td>One-third-octave band</td>
<td>One-third-octave band</td>
<td>One-third-octave band</td>
</tr>
<tr>
<td>repeatability</td>
<td>10 Hz to 50 000 Hz</td>
<td>20 to 25 000 Hz</td>
<td>50 Hz to 10 000 Hz</td>
</tr>
<tr>
<td>Narrowband</td>
<td>Required</td>
<td>Required</td>
<td>As needed</td>
</tr>
<tr>
<td>measurements</td>
<td>Three</td>
<td>Three</td>
<td>One</td>
</tr>
<tr>
<td>Number of</td>
<td>Three</td>
<td>Three</td>
<td>One</td>
</tr>
<tr>
<td>hydrophones</td>
<td>Figure 1</td>
<td>Figure 1</td>
<td>Figure 2</td>
</tr>
<tr>
<td>Hydrophone geometry</td>
<td>15°, 30°, 45° angle</td>
<td>15°, 30°, 45° angle</td>
<td>20° ± 5° angle (see 5.4)</td>
</tr>
<tr>
<td>Minimum hydrophone</td>
<td>Greater of 300 m or</td>
<td>Greater of 150 m or</td>
<td>Greater of 75 m or</td>
</tr>
<tr>
<td>depth(s)</td>
<td>3x overall ship length</td>
<td>1,5x overall ship length</td>
<td>1x overall ship length</td>
</tr>
<tr>
<td>Minimum water depth</td>
<td>Greater of 300 m or</td>
<td>Greater of 150 m or</td>
<td>Greater of 75 m or</td>
</tr>
<tr>
<td></td>
<td>3x overall ship length</td>
<td>1,5x overall ship length</td>
<td>1x overall ship length</td>
</tr>
<tr>
<td>Minimum distance</td>
<td>Greater of 100 m or</td>
<td>Greater of 100 m or</td>
<td>Greater of 100 m or</td>
</tr>
<tr>
<td>at closest point of</td>
<td>1x overall ship length</td>
<td>1x overall ship length</td>
<td>1x overall ship length</td>
</tr>
</tbody>
</table>

DEEP WATER STANDARDS (under development):
- ISO DIS/16554-3 (‘survey method’)
- ISO CD/18702-1 (‘precision method’)

To what degree is aquatic life exposed to underwater sound?
SHIP RADIATED NOISE DEPENDS ON OPERATIONAL CONDITION

To what degree is aquatic life exposed to underwater sound?

M/V OVERSEAS HARRIETTE

P Arveson & D Vendittis 2000
J Acoust Soc Am

1/3 octave band RNL [dB re 1 μPa²m²]

frequency [Hz]

120 130 140 150 160 170 180 190 200

Overseas Harriette 8 kn
Overseas Harriette 10 kn
Overseas Harriette 12 kn
Overseas Harriette 14 kn
Overseas Harriette 16 kn

propeller cavitation

generator
SHIP RADIATED NOISE METRICS:

- SPL measured when ship passes a hydrophone at distance > ship length

- **Radiated Noise Level:**
  \[ RNL(f, R, \theta, \phi) = SPL(f, R, \theta, \phi) + 20\log_{10}(R/1m) \]

- **Monopole Source Level:**
  \[ MSL(f) = SPL(f, R, \theta, \phi) + PL(f, R, \theta, \phi) \]
PROCEDURE FOR DETERMINING ‘SOURCE LEVEL’

› No standard available for measurements or analysis of dredger radiated noise in shallow water

→ **New procedure developed to estimate dredger source levels from measurements in shallow water** (TNO & NPL, 2009)

› Consistent with what would be measured according to the standards for radiated sound of ships in deep water

→ **Results can be compared!**
SOURCE LEVEL ESTIMATION METHOD

\[ \text{SL}(\text{freq.}) = \text{SPL}(\text{distance, freq.}) + \text{PL}(\text{distance, freq.}) \]

- Measured SPL at the hydrophones in dB re 1 μPa²
  (1/3-octave band, 1 s average)
- Calculated Propagation Loss (PL) in dB re 1 m²
- Estimated Ship Source Level (SL) in dB re 1 μPa²m²
- Average of multiple estimations per run:

![Diagram of non-stationary and stationary dredgers with monitoring stations and vessels.](image)
EXAMPLE: MAASVLAKTE 2
http://www.maasvlakte2.com/en/index/

- Extension Port of Rotterdam
- Major civil engineering project
  - Land reclamation
  - Dredging
- Underwater sound measurements
- Environmental impact assessment

Monitoring Programme for the Maasvlakte 2, Part III - The Effects of Underwater Sound
FLOOR HEINIS, CHRIST DE JONG, MICHAEL AINSLIE, WIL BORST AND TIEDO VELLINGA

October 2009

Terra et Aqua | Number 132 | September 2013
DREDGER SOURCE LEVEL MEASUREMENTS (2009)

- 7 different trailing suction hopper dredgers (hopper volume 300 – 20000 m³)
  - transiting (31 runs)
  - dredging (23 runs)
  - sand laying (2 runs)
  - rainbowing (10 runs)
  - pumping ashore (2 runs)

- Maximum levels (envelope)
- Mainly cavitation (propellers & thrusters)

To what degree is aquatic life exposed to underwater sound?

26 March 2015
GLOBAL AMBIENT SOUND: SOUND MAPS

› Ship locations from AIS
› Dredgers: source levels from measurements (2009)
› Regular ships: SL from Wales & Heitmeyer (2002)

› Energy flux & normal mode model AQUARIUS
  › Weston 1971/1976, Sertlek 2014
  › Bathymetry
  › Sediment properties; absorption
  › Shallow water ‘cut-off’

EXAMPLE: snapshot of North Sea shipping noise

To what degree is aquatic life exposed to underwater sound?

26 March 2015
To what degree is aquatic life exposed to underwater sound?
To what degree is aquatic life exposed to underwater sound?

<table>
<thead>
<tr>
<th>SEL_{24}</th>
<th>1 metre above seabed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FISH</strong> (unweighted)</td>
<td><img src="image1.png" alt="Image of FISH exposure" /></td>
</tr>
<tr>
<td><strong>Harbor Porpoise</strong> (‘high frequency cetaceans’ M-weighting)</td>
<td><img src="image2.png" alt="Image of Harbor Porpoise exposure" /></td>
</tr>
<tr>
<td><strong>Harbor Seal</strong> (‘pinnipeds in water’ M-weighting)</td>
<td><img src="image3.png" alt="Image of Harbor Seal exposure" /></td>
</tr>
</tbody>
</table>

Regular ships vs. ships + dredgers.
SWIMMING ANIMALS

- 15 straight lines
- South to North
- Starting at 15 minute intervals
- Total 1440 animal crossings in 24 hours
- Swim speed 1.7 m/s
  - 100 m in 1 minute
  - 15 km in 2.5 hours
- No behavioral response
To what degree is aquatic life exposed to underwater sound?

<table>
<thead>
<tr>
<th></th>
<th>Regular ships</th>
<th>ships + dredgers</th>
<th>cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FISH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(unweighted)</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
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<tr>
<td><strong>Harbor Seal</strong></td>
<td>(‘pinnipeds in water’ M-weighting)</td>
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</tr>
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</table>

Number of transits

Fraction of transits exceeding $SEL_{cum}$

SEL$_{cum}$ [dB] 150 200
To what degree is aquatic life exposed to underwater sound?

CUMULATIVE EXPOSURE

<table>
<thead>
<tr>
<th>SEL\text{\textsubscript{cum}} (unweighted) in dB re 1 (\mu\text{Pa}^2\text{s}) (± 16 dB)</th>
<th>without dredgers</th>
<th>with dredgers</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 hours stationary: area average</td>
<td>176 dB</td>
<td>180 dB</td>
</tr>
<tr>
<td>Swimming through the area once</td>
<td>171 dB</td>
<td>175 dB</td>
</tr>
<tr>
<td>Swimming through the area 8.9 times (24 hours)</td>
<td>181 dB</td>
<td>185 dB</td>
</tr>
</tbody>
</table>

Dredgers increase SEL\text{\textsubscript{cum}} by ~ 4 dB

- Behavioral response?
- TTS-onset in marine mammals:
  - Kastelein et al. 2012 (for continuous noise in 4 kHz octave band)
    - Harbour porpoise: SEL\text{\textsubscript{cum}} > 163 – 172 dB re 1 \(\mu\text{Pa}^2\text{s}\)
    - Harbour seal: SEL\text{\textsubscript{cum}} > 173 – 183 dB re 1 \(\mu\text{Pa}^2\text{s}\)
- Injury to fish? (data for impulsive sound only)
TO WHAT DEGREE IS AQUATIC LIFE EXPOSED TO UNDERWATER SOUND?

› Proper use of terminology: metrics & decibels
  › ISO standardization for underwater sound is under development

› Measurement of dredger sound
  › Procedure described in TNO & NPL reports.
  › Support for standard development?

› Sound mapping

› Exposure of moving marine animals to sound
THANK YOU FOR YOUR ATTENTION