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TNO report

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Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing

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Summary

The Netherlands Ministry of Infrastructure and the Environment, Directorate-General for Water Affairs has asked TNO to identify and work with suitable European partners towards the development of standards for the measurement of underwater sound, with a primary focus on acoustic monitoring in relation to the environmental impact of off-shore wind farms. To date, the licensing requirements for offshore wind farms in the European nations are very diverse. Noise monitoring requirements are generally project specific, with a large influence of the national licensing authorities. The approach adopted in this report is to compare existing monitoring approaches and to identify common ground. The purpose of this report is to propose a minimum requirement for monitoring procedures that fulfils the common requirements. Additional national requirements and scientific needs can lead to extensions of the procedure. These can be defined in cooperation with the national licensing authorities.

Samenvatting

In opdracht van het Nederlandse Ministerie van Infrastructuur en Milieu, Directoraat-Generaal Rijkswaterstaat, heeft TNO, samen met een aantal Europese partners, gewerkt aan de totstandkoming van standaarden voor het meten en rapporteren van onderwatergeluid. De primaire focus hierbij was de onderwatergeluidmonitoring gerelateerd aan mogelijke effecten op het mariene milieu van windmolenparken op zee.

De vergunningseisen die de diverse Europese landen stellen bij de bouw van windmolenparken op zee zijn tot op heden zeer divers. De eisen die gesteld worden aan het monitoren van onderwatergeluid worden nu in het algemeen specifiek per project opgesteld door het bevoegde gezag. De aanpak die in dit rapport wordt gevolgd bestaat uit het vergelijken van bestaande monitoringprogramma's in de diverse landen en het vaststellen van een gemeenschappelijke basis daarin.

Het doel van dit rapport is om een minimale set van eisen aan procedures voor onderwatergeluidmonitoring voor te stellen, die voldoet aan de gemeenschappelijk basis. Aanvullende nationale eisen en wetenschappelijke behoeften kunnen leiden tot meer uitgebreide monitoring procedures. Deze kunnen worden vastgesteld in overleg met de nationale vergunningverleners.

Contents

1 Introduction

In Europe, initiatives like the Marine Strategy Framework Directive and the OSPAR Convention are aimed at protection of the marine environment. At the same time there is an increased anthropogenic activity in the marine environment.
For example: in March 2009, at the European Wind Energy Conference 2009 (EWEC 2009), the European Wind Energy Association (EWEA) increased its 2020 target to 230 GW wind power capacity, including 40 GW offshore Wind [Fichaud & Wilkes 2009].

The Netherlands Ministry of Infrastructure and the Environment, Directorate-General for Water Affairs has asked TNO to identify and work with suitable European partners (in particular the North Sea countries Belgium, Denmark, Germany and United Kingdom) towards the development of standards for the measurement and reporting of underwater sound[1], with a primary focus on acoustic monitoring in relation to the environmental impact of off-shore wind farms.

This report concerns the development of standardized measurement and reporting procedures, specifically aimed at acquiring the relevant acoustic data for assessing the impact of the construction, operation and decommissioning of offshore wind farms on marine life.

Building further on the 2009 project on the development of such a standards (TNO report TNO DV-2009-C613 [de Jong et al. 2010]), criteria have been developed for measurement locations, measuring periods, averaging time, frequency range, etc. These criteria are described in the present report.

This report is connected to the report of a parallel study (part I) towards standards and definitions of quantities and units related to underwater sound [anon. 2011]. That report concentrates on a clear and unambiguous definition of the metrics that are relevant to underwater noise in relation to its impact on marine life.
Those unambiguous definitions are used here.

1.1 Background

The European Marine Strategy Framework Directive (MSFD) took effect in 2008 and, within the planning period, will also set preconditions for the offshore wind farms. Standards developed under the MSFD are in principle generic for the North Sea, not area specific, and can have an influence on the development of the farms. Underwater noise due to piling for the construction of wind farms is one of the most significant negative effects mentioned at this time, and the secondary effect this might have on fish larvae, fish and marine mammals is considered as very significant [Boon et al. 2010, Prins et al. 2008].

As explained in [de Jong et al. 2010], there are no standardized methods for measuring and reporting underwater sounds. There are still many gaps in the knowledge on underwater noise and its effects on marine life.

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[1] In the context of this report, the terms ‘underwater sound’ and ‘underwater noise’ are considered to be equivalent and interchangeable.

For the second round of wind farms in Dutch waters, regulations were drawn up for the farms that were granted a permit, including those for monitoring the ecological effects of the wind farm. These regulations require that a Monitoring and Evaluation Plan (MEP) be drawn up, including underwater noise recordings, with the aim to collect data to model the pile driving noise and operational noise [Boon et al. 2010].

Underwater noise and fish
Insight into threshold values and the duration of noise levels at which disturbance of the behaviour or damage is caused is not available. Provisional results from research in MEP-OWEZ during the operational phase show that tagged individuals of the cod and sole species are present in the farm during several consecutive months, which suggests that the noise may not have a repelling effect (E. Winter, IMARES, pers. com.). The noise could still have a masking effect, thus having a negative effect on reproduction, for example. Many fish species, including commercially important species such as sole and plaice have no swim bladder and they are thus predominantly sensitive to the particle motion component of sound, rather than the pressure component. There is a large gap in knowledge on a) magnitude and extent of the particle motion fields connected both to pile driving and to operational wind turbines, and b) the effects of intense particle motion (as from pile driving) on fish. There is a very poor understanding of how fish use sound in communication and even poorer understanding of how masking could affect reproductive success.

Underwater noise and marine mammals
In a general sense, relatively little is known concerning the effect of underwater noise (vibrations) on the behaviour of marine mammals. No data are known as yet about any direct harmful effects on the hearing organs of marine mammals of the North Sea. Furthermore, it is not known what type of noise and levels cause changes in behaviour, under different conditions (rest, foraging, pregnancy, migration, size of habitat, etc.). It is unknown how marine mammals respond to these noises over in the short term as well as when chronically exposed to underwater noise. The effects of underwater noise in the operational phase of the wind farm are important with respect to masking of communication between members of the same species, and between predators and their prey. This applies even more during large-scale construction and the presence of wind farms. Changes in behaviour may lead to decreased population fitness.

Text copied from [Boon et al. 2010]

1.2 Objective

The aim of the study that is described in this report is to develop measurement, analysis and reporting procedures for underwater noise in connection with offshore wind farm licensing, based on the definitions developed in the parallel study and on the available knowledge of and practical experience with existing procedures and equipment. International collaboration (in particular with the North Sea countries) is a crucial aspect in the scope of this project. The work on standards is therefore carried out in coordination with similar activities in UK, Germany, Denmark and Belgium.

1.3 Approach

The following activities were foreseen at the start of this project:
1. Definition of the relevant metrics (‘noise indicators’) for assessment of the impact of wind farm related underwater noise on marine life, based on literature

survey and discussions with international (e.g. from the North Sea countries) and national (e.g. within the team of the ‘Masterplan Ecologische Monitoring Wind’ for the biological and ecological implications) experts, and in coordination with the national regulators (‘bevoegd gezag’) and the requirements imposed by them.
2. Description of the associated measurement and analysis procedures.
3. Description of the data (acoustic parameters and environmental, geometrical and meteorological data) to be reported and stored including advice on how to organise the storage of such (meta) data.
4. Development of practical examples, based on available data (simulated or measured, if permission can be obtained to use those data).

1.4 Short review of findings

There are still large gaps in the practical knowledge of the underwater sound distribution the North Sea and of the impact of anthropogenic sound on marine life. The main goal behind acoustical monitoring programmes is to provide the data that are needed to improve on the environmental impact assessments for future projects. But these assessments cannot be made on the basis of data only.
The data are needed to validate (or calibrate) models which can be used to estimate the sound produced by future offshore activities and the resulting sound distribution in the environment. In order to gain confidence in these model predictions, sufficient data of different activities in different environments is needed. Such a database can only be obtained in international cooperation, using standardized procedures for measurement, reporting and data storage.
The objective of this study is to contribute to the development of standardized procedures.

The monitoring projects in which the data are gathered are to be carried out by the industry as part of licensing procedures. The licensing requirements for offshore wind farms in the European nations are, however, very diverse. Noise monitoring requirements are generally still project specific, with a large influence of the national licensing authorities. For example, the German licensing authority has defined threshold values for acoustic levels that should not be exceeded beyond a distance of 750 m from offshore piling projects. This provides a clear guidance for the acoustic monitoring. To date, no other EU nation has adopted threshold values. Hence, the monitoring requirement in the other nations is more generally focussed on acquiring data for future studies and in some cases to check the initial assumptions for the environmental impact assessment study of the project.

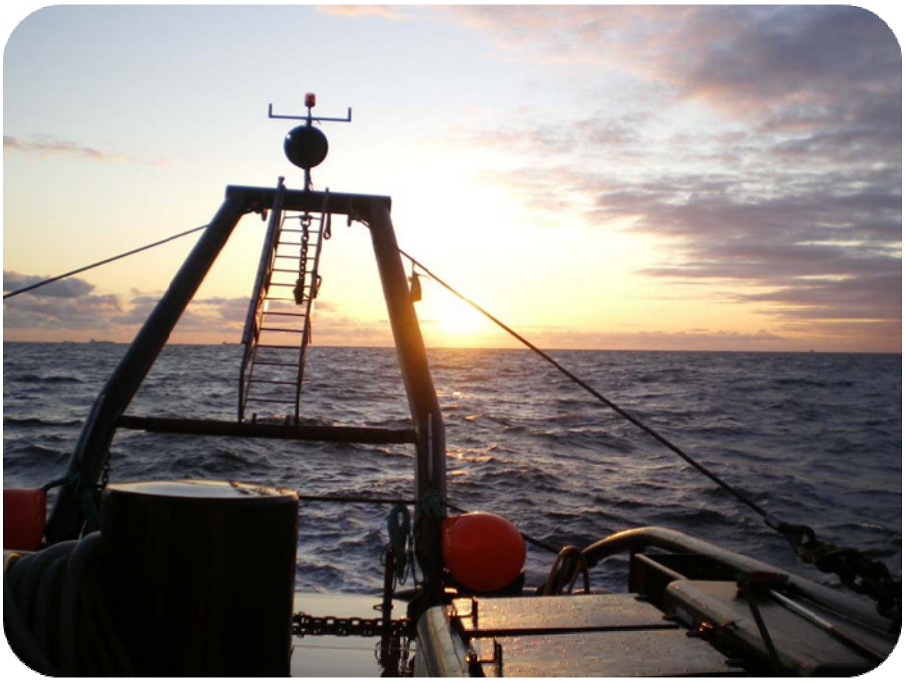
The development of standard procedures for noise monitoring would be much simpler after international harmonization of the licensing process. To date, Germany and The Netherlands have running projects for the development of measurement standards for offshore wind farms, based on different monitoring requirements.

To solve the dilemma of the differences in monitoring requirements, the approach adopted here is to compare existing monitoring approaches, to identify common ground and to define a minimum requirement for monitoring procedures that fulfil the common requirements. Additional national requirements and scientific needs can lead to extensions of the procedure. These can be defined in cooperation with the national licensing authorities.

Due to the diverse requirements, it appeared to be much more difficult to obtain consensus in tasks 1 to 3 than originally foreseen. Consequently, the development of practical examples (task 4) has not been addressed.

1.5 Contents of this report

In this report we first discuss the development of relevant metrics for underwater noise in connection with offshore wind farm licensing (Chapter 2). Next a review is given of the various monitoring approaches that are currently adopted and the considerations on which common standards could be based (Chapter 3).
In Chapter 4, a proposal is given for standardized measurement, analysis and reporting procedures.



2 Noise indicators

The first task in the development of measurement standards is the definition of the relevant metrics (‘noise indicators’) for assessment of the impact of wind farm related underwater noise on marine life. The development is based on a literature survey and discussions with international experts, from the UK, Germany, Denmark, Norway, Sweden, Spain and the US, and with the national regulating authority (‘bevoegd gezag’).

As argued in [de Jong et al. 2010], it is a task of the legislating authorities to decide which marine species and which effects of underwater sound are to be considered in an impact assessment . That means that the development of noise indicators and measurement procedures is kept sufficiently general to be able to apply these to the various species and various effects, both physiological and behavioural. The noise indicators will also depend on the type of sound and on the specific assessment procedure. After describing the types of sound (section 2.1), a review is given of the noise metrics as they are currently reported by various organizations. Based on this review, a proposal is presented for the most relevant noise metrics to be reported (Section 2.9).

2.1 Types of sound

The effects of underwater sound on the marine fauna greatly depend on the character of the sound. A useful distinction can be made between *continuous* (long duration), *transient* (short duration) and *repeated transient* sounds.

According to [Southall et al. 2007] “*the current state of scientific knowledge regarding mammalian hearing and various noise impacts supports three distinct types as relevant for marine mammal noise exposure criteria: (1) single pulse, (2) multiple pulses, and (3) nonpulses*”. In the definition of [Southall et al. 2007], ‘pulses’ are brief, broadband, atonal transients; quote: “*Examples of pulses (at least at the source) are explosions, gunshots, sonic booms, seismic airgun pulses, and pile driving strikes*”. These are all impulsive transient sounds that are characterized by a relatively rapid rise from ambient pressure to the maximal pressure value. Southall et al. acknowledge the lack of an explicit definition that distinguishes pulses from non-pulses. They suggest that the distinction could be made based on signal duration relative to the hearing integration time, as done in airborne noise. However, it would require further studies to adapt this for the relevant marine species. This would require further research. Without attempting at this stage to define these terms unambiguously[2], here we extend Southall’s approach by distinguishing between “transient sounds”, which have a clear start and end, and “continuous sounds”, which do not. Southall’s “pulse” is then a sub-set of our “transient”. In addition it might be important to distinguish between narrow-band (*tone*), incoherent broad-band and multi-tone or coherent broad-band sounds. Again, while recognizing the need to do so, we make no attempt here to make these definitions unambiguous, but provide an indication in Table 1 in the form of examples of sources likely to fall in each of the categories.

[2] An additional consideration is whether a source of sound is categorized by the sound field close to that source or at some as yet unspecified receiver location.

Table 1 Classification of sound in time and frequency.

	continuous	*transient*	*repeated transient*
incoherent broadband	Mid to high frequency ship noise (due to propeller cavitation)	explosion	pile driving/air-guns
narrow-band (tone)	e.g. wind turbine gear box tonal	continuous wave (CW) sonar (single pulse)	continuous wave (CW) pinger or echo sounder
multi-tone or coherent broadband	low-frequency ship noise (e.g. engine tonals)	frequency modulated (FM) sonar (single pulse)	frequency modulated (FM) pinger or echo sounder

2.2 Noise indicators in relation to impact on marine life

Leading papers by US researchers propose different metrics in connection with the effects of noise on marine mammals [Southall et al. 2007] and fish [Popper and Hastings 2009]. In terms of the definitions from [anon. 2011], these metrics are:
1. 'M-weighted' sound exposure level (SEL_w) of transient sounds, in connection with impact on marine mammals.
2. Unweighted sound exposure level (SEL) of transient sounds, in connection with impact on fish.
3. Unweighted zero to peak sound pressure level (L_{z-p}) of transient sound.
4. Unweighted sound pressure level (SPL) of continuous sound.

[Southall et al. 2007] and [Popper and Hastings 2009] propose that the SEL metrics for transient sounds can be accumulated over multiple transient sounds during a period of 24 hours to determine the dose of exposure in relation to physiological impact on marine mammals and fish. However, recent findings indicate that the cumulative SEL metric does not uniquely relate to the onset of a temporary threshold shift (TTS) in marine mammals. Studies in which bottlenose dolphins [Mooney et al. 2009] and harbour porpoises and harbour seals [Kastelein et al. 2011] were exposed to sounds at the same SEL but with varying duration have shown that SEL alone is an insufficient metric for predicting TTS. Hence, it is advised not to rely on the cumulative SEL metrics only and to include information about the duration of the exposure (including the total number and the repeat rate of transient sounds) when reporting the results of underwater noise monitoring.

Several other acoustic metrics may be relevant for physiological or behavioural impact on marine life. Examples are all metrics associated with acoustical particle motion, to which several marine organisms are sensitive [Popper & Hastings 2009, Tasker et al 2010], peak to peak sound pressure, Kurtosis [Southall et al 2007] (a statistical metric which describes the shape of the pressure wave form of transient sounds) and acoustic impulse, which seems to correlate with the effects of underwater blast on fishes [Popper & Hastings 2009]. However, at present very little information is available on the dose-response relationships for these metrics.
It is encouraged to report any metric that is considered relevant in addition to the basic metrics SEL, L_{z-p} and SPL.

It is acknowledged that the current knowledge is too limited to make a definitive choice of the appropriate metrics for impact assessment. The limits in knowledge are clearly illustrated by the following quote from [Popper and Hasting 2009]: "*it is clear that the available literature is equivocal in what it teaches and leaves great gaps that need to be filled before meaningful noise exposure metrics or reliable noise exposure criteria can be developed. Indeed, there is some indication that some sounds, under some conditions, with some species, may cause some kind(s) of effects. But, extrapolation to the same sounds under other conditions, or to other fish species, or to other effects, is not possible.*"

2.3 Weighting

In the event that underwater sound is measured with the aim of determining the risk to underwater sea life, there might be a need to consider the hearing characteristics of the species under consideration, when expressing the processed recorded signals in a single level.

If such a number is meant for assessing the impact on sea mammals, the 'M-weighting' may be used [Southall et al. 2007] prior to integrating over the frequency bands. M-weighting is a frequency weighting function defined by

$$W_{\mathrm{M}}(f) = \frac{S(f)}{\max S(f)}$$

where

$$S(f) = \frac{f^4}{(f^2 + f_{\mathrm{high}}^2)^2 (f^2 + f_{\mathrm{low}}^2)^2}$$

NOTE: The function $W_{\mathrm{M}}(f)$ is defined here as a linear quantity. It is related to the logarithmic weighting $M(f)$ defined by Southall via the equation $M(f) = 10\log_{10}W_{\mathrm{M}}(f)$ [Ainslie et al. 2011]

f_{low} and f_{high} are the lower and upper 'functional' hearing limits respectively. They are different for various species; see Table on functional hearing limits for species relevant to the North Sea situation.

Table 2 Functional hearing limits for some North Sea species, from [Southall et al 2007].

	f_{low}	f_{high}
pinnipeds in air	75 Hz	30 kHz
pinnipeds in water	75 Hz	75 kHz
harbour porpoise in water ('high frequency cetacean')	200 Hz	180 kHz

Alternatives to M-weighting that might be relevant to behavioural effects include weighting schemes based on the audiogram or 'equal loudness contours' [Schlundt and Finneran 2011], similar to A-weighting in air. The authors of the present report are aware of proposals by Nedwell and Verboom to incorporate the effect of animal audiograms [Nedwell et al. 2007, Verboom & Kastelein 2005], but to date these proposals have not gained widespread international acceptance.

There are still many uncertainties associated with the relevance of these weighting functions for dose-response relationships. Therefore it is not yet possible to rely on reporting of weighted metrics only. We advise to always report the unweighted spectra. If weighted metrics are reported in addition, the weighting should be clearly specified, either implicitly by use of standard terminology (and citing the standard in which an explicit statement of the weighting can be found), or by stating the weighting function explicitly.

2.4 EU Noise indicators

The European Marine Strategy Framework Directive (MSFD) is an important driver for this study. On the basis of the report that was produced by the JRC Task Group 11 (TG11, [Tasker et al. 2010]), the European Commission decided to adopt two indicators for good environmental state in relation to underwater noise (‘Good Environmental State descriptor 11’). The following text box copies the relevant text from the EU commission decision [EU 2010].

Descriptor 11: ***Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.***

Together with underwater noise, which is highlighted throughout Directive 2008/56/EC, other forms of energy input have the potential to impact on components of marine ecosystems, such as thermal energy, electromagnetic fields and light. Additional scientific and technical progress is still required to support the further development of criteria related to this descriptor, including in relation to impacts of introduction of energy on marine life, relevant noise and frequency levels (which may need to be adapted, where appropriate, subject to the requirement of regional cooperation). At the current stage, the main orientations for the measurement of underwater noise have been identified as a first priority in relation to assessment and monitoring, subject to further development, including in relation to mapping. Anthropogenic sounds may be of short duration (e.g. impulsive such as from seismic surveys and piling for wind farms and platforms, as well as explosions) or be long lasting (e.g. continuous such as dredging, shipping and energy installations) affecting organisms in different ways. Most commercial activities entailing high level noise levels affecting relatively broad areas are executed under regulated conditions subject to a license. This creates the opportunity for coordinating coherent requirements for measuring such loud impulsive sounds.

11.1. *Distribution in time and place of loud, low and mid frequency impulsive sounds*
— Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1μPa^2 s) or as peak sound pressure level (in dB re 1μPa$_{peak}$) at one metre, measured over the frequency band 10 Hz to 10 kHz (11.1.1)

11.2. *Continuous low frequency sound*
— Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate (11.2.1).

Text copied from [EU 2010]

The implementation of the proposed indicators is currently under discussion in the EU Technical Subgroup Noise (TSG).This group aims at providing the EU member states who need to implement the indicators with clarifications on the terminology used.

The TG11 report [Tasker et al. 2010] explains that "*loud, low and mid-frequency impulsive sounds are those that have caused the most public concern, particularly in relation to perceived effects on marine mammals and fish. These sounds include those from pile driving, seismic surveys and some sonar systems.*" Hence, these will occur in connection with offshore wind farm licensing when turbine foundations are installed by means of pile driving or when they are removed by means of explosives. Continuous low frequency sound may be generated by operating wind turbines, but also wind farm construction and maintenance activities may contribute to the ambient underwater noise.

The EU indicators 11 refer to three different acoustic metrics:
1. Sound Exposure Level of impulsive sounds.
2. peak pressure level of impulsive sounds.
3. RMS noise level of continuous sound.

This choice is clearly based on papers on the effects of noise on marine mammals [Southall et al. 2007] and fish [Popper and Hastings 2009].

In terms of the definitions from [Ainslie 2011], these can be interpreted as:
1. Unweighted sound exposure level (SEL) of transient sounds.
2. Unweighted zero to peak sound pressure level ($L_{z\text{-}p}$) of transient sound.
3. Unweighted sound pressure level (SPL) of continuous sound.

NOTE: In box 1 (page 9) of [Tasker et al. 2010], the SEL is defined as 'ten times the logarithm to the base ten of the ratio of a given time integral of squared instantaneous frequency-weighted sound pressure over a stated time interval or event'. However, since the report provides no specification of the frequency-weighting function, we propose to ignore the frequency-weighting.

2.5 Noise indicators for offshore wind farm licensing in The Netherlands

The licensing decision for the second round of offshore wind farms in The Netherlands, e.g. [Ministerie van Verkeer & Waterstaat 2009a&b], specify a requirement for monitoring the underwater noise.

The licensing decision requires reporting the following three noise metrics, referring to the Deltares report on 'appropriate assessments' [Prins et al. 2008]:
1. The broadband sound level, L_p; the sound pressure level, summed over the analysis bandwidth.
2. The sound exposure level, SEL; the broadband sound level normalised to a 1-s period.
3. The equivalent continuous sound level, L_{eq}; the steady dB-level which would produce the same sound energy over a stated period of time as a specified time-varying sound. This parameter is only relevant for multiple strokes.

A precise and unambiguous definition of these metrics is lacking. We propose the following interpretation in terms of the definitions from [anon. 2011]:

1 Because reported zero to peak sound pressure levels from [de Jong & Ainslie 2008a] are referred to as 'broadband sound level' (L_p) in [Prins et al. 2008], we assume that this term is to be interpreted as the *zero to peak sound pressure level (L_{z-p}).*
2 We assume that this concerns a weighted sound exposure level (SEL_w). However, apart from the imprecise description that 'weighting is filtering by the process of the listening animal species', a clear specification of the weighting function is lacking. The remark 'broadband sound level normalised to a 1-s period' is confusing and deviates from the definition of sound exposure as the integral of the square of the acoustic pressure.
3 'equivalent continuous sound level' is equivalent to weighted sound pressure level (SPL_w). Apart from the imprecise description that 'weighting is filtering by the process of the listening animal species', a clear specification of the weighting function is lacking.

2.6 Noise indicators for offshore wind farm licensing in Germany

The German Bundesamt für Schiffahrt und Hydrographie (BSH) has issued a standard for the investigation of the impacts of offshore wind turbines on the environment (StUK 3) [BSH 2007]. This standard contains a Technical Instruction (Table 4.3 of the standard) that describes the requirements for 'surveys of waterborne sound emissions and immissions'. Currently, Müller-BBM is developing an updated 'measurement instruction for waterborne sound measurements' [Müller & Zerbs 2011]. This new instruction will be the basis for future licensing.

The current version (5D) of the [Müller & Zerbs 2011] instruction mentions the following three noise metrics:

1 Equivalent continuous sound level L_{eq} for continuous signals.
2 Sound exposure L_E for impulsive signals.
3 Peak level L_{peak} for impulsive signals.

Based on the definitions given for these terms in [Müller & Zerbs 2011], we conclude that these refer to the following metrics from [anon. 2011]

1 unweighted sound pressure level (SPL) for continuous sound.
2 unweighted sound exposure level (SEL) for transient sounds.
3 unweighted zero to peak sound pressure level (L_{z-p}) for transient sounds.

2.7 Noise indicators for offshore wind farm licensing in the UK

Previous piling noise monitoring studies in the UK [Nedwell at al. 2007, Bayley et al. 2010] reported unweighted and 'hearing threshold' weighted (dB_{ht}) peak-to-peak sound pressure levels of transient signals. However, the UK Joint Nature Conservation Committee currently recommends the use of the [Sourthall et al. 2007] criteria for impact assessment. Consequently, underwater noise monitoring projects report the metrics described in section 2.2., see e.g. [Robinson et al. 2007, Lepper et al. 2009].

2.8 Noise indicators for in-water pile driving projects in the USA

In 2009, a ‘Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish’ was issued for the California Department of Transportation [Oestman et al. 2009]. This guidance refers to three metrics that are commonly used in evaluating hydroacoustic impacts on fish:

1. Peak sound pressure level (L_{PEAK}): The maximum absolute value of the instantaneous sound pressure that occurs during a specified time interval, measured in dB re 1μPa,
2. Effective Root Mean Square Sound Pressure Level: A decibel measure of the square root of mean square (RMS) pressure. For pulses, the average of the squared pressures over the time that comprises that portion of the wave form containing 90 percent of the sound energy of the impulse in dB re 1 μPa
3. Sound exposure level (SEL): The integral over time of the squared pressure of a transient waveform in dB re 1μPa^{2}s. This is an approximation of sound energy in the pulse.

All metrics are for transient sounds. In terms of the definitions from [anon. 2011], these can be interpreted as:

1. Unweighted zero to peak sound pressure level ($L_{z\text{-}p}$).
2. Unweighted sound pressure level (SPL), averaged over the time during which 90% of the unweighted sound exposure of a single transient occurs.
3. Unweighted sound exposure level (SEL).

2.9 Conclusion about noise metrics

The above review reveals that there is a trend towards consensus about the noise metrics to be reported. The selection is based on a very limited knowledge of dose-response relationships. Because the increased public interest in understanding the environmental impact of human offshore activities has triggered several research programmes, new findings and increased knowledge may lead to a future update of the metrics. Hence it is advised to store raw measurement data (with all necessary information about the measurements) as well as reporting the proposed noise metrics. The stored data could then be reanalysed to the new metrics and be used in future studies of environmental impact.

It is proposed here to report at least the following three basic noise metrics when measuring underwater noise in relation to the impact on marine life.

1. **unweighted sound pressure level (SPL) for continuous sound.**
2. **unweighted sound exposure level (SEL) for transient sounds.**
3. **unweighted zero to peak sound pressure level ($L_{z\text{-}p}$) for transient sounds.**

This is as a minimum requirement. It is encouraged to report additional metrics whenever that is considered useful, e.g. peak-to-peak or peak rarefactional sound pressure level, or metrics weighted according to the sensitivity of specific species. In any case, all metrics should be reported according to the principles outlined in [anon. 2011]:

- State the physical parameter clearly.
- State the bandwidth clearly.
- State the averaging time clearly.
- State the weighting clearly.

For noise of offshore pile driving (and other activities that generate repeated transient sounds), the SEL and L_{z-p} metrics should be determined for each individual transient. It is essential to report information on the total number of transients, the repeat rate and the total duration of the piling activity. Results can be reported in terms of the statistical distribution of the measured values (maximum, minimum, arithmetic averages, energy average, standard deviation, *N* percent exceedance level, etc.). The total (cumulative) sound exposure can then be determined from the individual contributions.

3 Noise monitoring for offshore wind farms

In the report TNO DV-2009-C613 [de Jong et al. 2010] of the initial study towards underwater noise measurement standards and noise descriptors, a first step was taken towards the development of acoustic monitoring plans for offshore wind farms. It was recognised that more work was required to develop criteria for measurement locations, measuring periods, averaging time, frequency range, etc. Since then, information has been exchanged and procedures discussed with international partners. After reviewing the different reasons for sound monitoring, this chapter presents a review of the various measurement procedures that are currently in use for monitoring wind farm related underwater sound in The Netherlands, Germany the UK and the USA.

Based on this review, a proposal is developed for a measurement procedure in connection with offshore wind farm licensing in The Netherlands, which could function as a basis for international standardization (Chapter 4).

3.1 Different procedures for underwater noise assessment

There may be multiple reasons for carrying out noise assessment in the marine environment. The following types of assessments are considered of relevance for standardization.

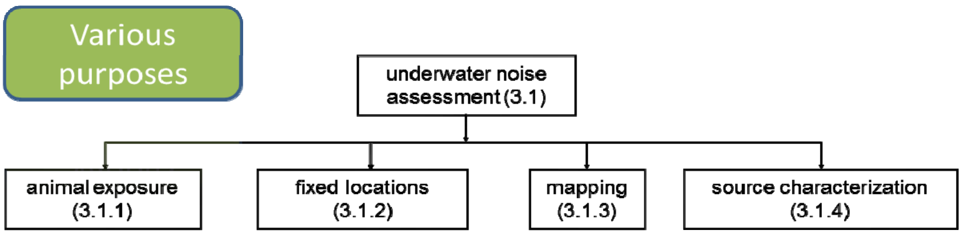


Figure 1 Overview of the various purposes for underwater noise assessment.

3.1.1 *Monitoring of the exposure of individual animals to underwater sound*

Existing criteria for humans in air (e.g. EU Directive 2003/10/EC) and recently proposed criteria for animals underwater [Hastings & Popper 2005, Southall et al. 2007] are of dual nature, providing limits to the peak sound pressure (the maximum instantaneous amplitude of the sound pressure) and to the sound exposure level. They have been based on information about the animal behaviour, i.e. its location as a function of the exposure time. A direct way of assessing the exposure is using an acoustic ‘tag’ (see e.g. [Johnson & Tyack 2003]), which monitors position and received sound simultaneously. An indirect way is via calculations that combine an estimated position in space and time of the animal with calculated data of the spatial and temporal distribution of the underwater sound (§3.1.3).

3.1.2 *Monitoring of the underwater sound at one or more fixed locations*

Criteria for environmental noise in air (see EU Directive 2002/49/EC) are based on noise indicators that express a long-term averaged and weighted sound pressure level at fixed locations. Similarly, in the case of monitoring underwater environmental noise, data can be obtained via measurements from fixed monitoring stations which sample the sound at regular intervals. Fixed location measurements are easily compared against criteria for environmental noise. Also sound sources can be monitored at a fixed location. An example is the measurement procedure for underwater noise due to impact pile driving as proposed in [Müller and Zerbs 2011], which aims at checking whether the 'dual criterion' thresholds of the German Federal Environmental Agency[3] are met.

3.1.3 Noise mapping

One of the applications mentioned in EU Directive 2002/49/EC is generating *strategic noise maps*, which are useful for spatial planning in relation to sound exposure. Similar sound maps for underwater sound are proposed in [Ainslie et al. 2009]. A sound map gives a two-dimensional representation of a sound distribution in five dimensions: the three spatial dimensions as well as time and frequency. This requires a reduction of dimensions, for example by selection of a noise metric that is integrated or averaged over three of the five dimensions.
Here the differences between the air and underwater domains become clear.
In air, the frequency content of the sound is 'removed' by use of an A-weighted sound level, which represents the sound as perceived by a human observer.
In the underwater domain, with its wide variety of marine species, which all have different hearing sensitivities, a similar approach would require separate maps for each (group of) species. Another difference is the fixed height that is representative for sound reception by human observers in air, whereas different species use different parts of the water column. In the development of two-dimensional sound maps for the three-dimensional underwater environment a choice has to be made whether to present noise indicators for a given depth or for a (possibly weighted) average or maximum over depth. The sound field can be strongly depth dependent, especially at low frequency and close to the sea surface. The third choice is for the temporal component of the noise indicator. Instead of long-term averaged noise indicators, it may be useful in some cases to present maps of the sound exposure due to a single event (e.g. an explosion) or a limited period of activities (e.g. piling of a single monopile). The long term may also be split into seasonal variations, day-night differences, etc. This means that different sound maps may present different noise indicators, dependent on the application. Hence it is very important to provide a clear description of what is presented in each map.

It is not possible to determine maps from measurements only, because it is not practicable to measure sound at all map locations in an appropriate time frame. Hence, sound mapping requires the use of models for the sound distribution. These models have to be fed with measurements that describe the sources of sound. Currently, the available sound propagation models are insufficiently validated to rely on modelling only. This means that additional measurements are required to validate the model predictions.

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[3] The German Federal Environment Agency (UBA) has defined `injury` as Temporal Threshold Shift (TTS) based on data provided by [Lucke et al. 2009]. A threshold consisting of a dual criterion of 160 dB re 1 $\mu Pa^2 s$ (Sound Exposure Level) and 190 dB re 1 μPa^2 (peak to peak sound pressure level) should not be exceeded at a distance of 750 meters around the piling site. The threshold is based on a TTS found in a harbour porpoise at 164 dB re 1 $\mu Pa^2 s$ (Sound Exposure Level) and 199 dB re 1 μPa^2 (peak to peak sound pressure level). Thus the chosen values include some safety adjustment. This threshold is part of the licence, and therefore legally binding.

3.1.4 *Sound source assessment*

Where the previous sections dealt with sound as received by the marine animals, this section deals with the emission by the sound sources themselves. In air, a variety of source-specific assessment standards and noise control legislation is in place for motor vehicles, aircraft, outdoor equipment and household appliances. Sound source levels are of relevance to be able to check the quality of products against requirements, but also as input for the models that are used for sound mapping (§3.1.3). These two applications do not necessarily require the same type of noise indicator. While it might be sufficient for a noise acceptance test to determine the sound of a product in a single direction for a single product setting, accurate sound mapping requires a complete description of the directivity of the source at the appropriate setting. A review of underwater sound sources [Ainslie et al. 2009] revealed that useful information of source characteristics is very scarce, due to the lack of standardization. Even the definition of acoustic source level in the underwater domain is subject to confusion [anon. 2011]. The acoustic 'source level' is not a directly measurable quantity, but must be derived from measurements of received sound at some distance away from the source, applying a propagation loss correction. Definitions and procedures for determining source level might be different for different sources.

3.2 Procedures for monitoring in connection with offshore wind farm licensing

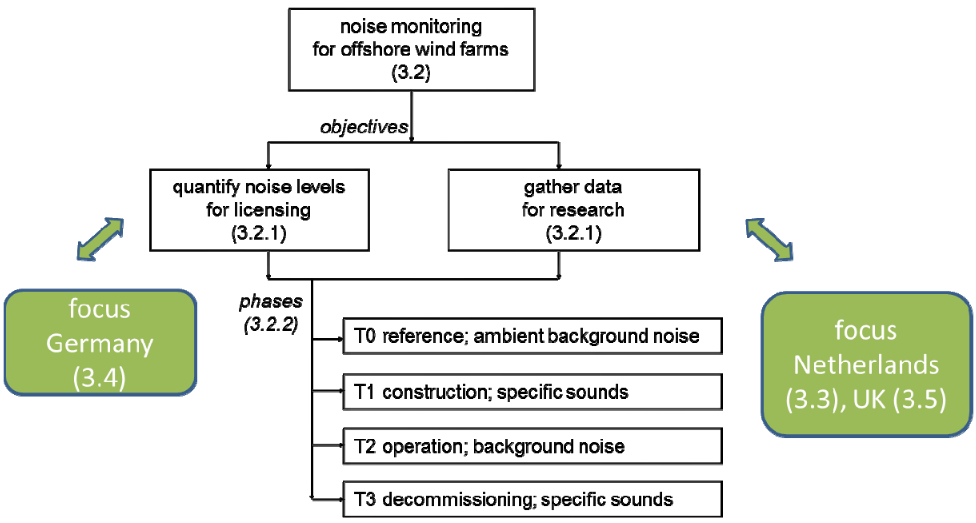

Figure 2 Overview of the objectives and phases for an underwater noise monitoring plan.

3.2.1 *Objective(s)*

The objective for underwater noise monitoring is to be specified by the licensing authority, which requires the noise to be monitored. Two different main objectives for monitoring can be identified:

1. To quantify the actually received noise level (average value and fluctuations) at one or more specific locations, for comparison with a normative threshold level or to check the assumptions on the underwater noise in the Environmental Impact Assessment on which the license for the offshore projects was granted (§3.1.2)

2. To gather data for further studies of underwater noise and its impact on the marine environment, for example to determine the spatial distribution of the produced noise ('noise mapping', §3.1.3), based on a combination of measurements to characterize the sound sources (§3.1.4) and sound propagation models

In general, monitoring plans attempt to fulfil both main objectives. Monitoring procedures to achieve objective 2 are more complex than procedures to achieve objective 1.

In two international workshops that were held in the context of this study (Delft, February 2011 and Hamburg, June 2011), it became clear that there is no general agreement on the choice between these objectives. Currently, only the German licensing authority has established normative threshold levels for underwater noise. Consequently, the focus of the German monitoring programmes is aimed at objective 1. Other nations (UK and Netherlands) currently seem to aim at gathering data for objective 2, but without specific requirements for application of the data for noise mapping or impact assessment.

3.2.2 Monitoring phases for offshore wind farm licensing

For monitoring underwater sound in connection with offshore wind farm licensing we distinguish the following four phases:

- T0: the period prior to construction of the wind farm
- T1: the construction phase
- T2: the period while the wind farm is in operation
- T3: the decommissioning phase

Each of these phases has its own requirements for monitoring underwater noise. Licensing authorities decide for which phases and which activities there is a requirement to monitor underwater noise. Currently, monitoring requirements in connection with offshore wind farm licensing are different in different nations. The following sections give an overview of the current requirements in The Netherlands, Germany, the UK and in the USA.

3.3 Licensing for the 'round two' offshore wind farms in The Netherlands

The licensing decision for the second round of offshore wind farms in The Netherlands, e.g. [V&W 2009a&b], specify a requirement for monitoring the underwater noise. These requirements concern monitoring of the underwater noise during two specific activities: impact pile driving in the construction phase (T1) and operational wind farms (T2).

3.3.1 Monitoring underwater noise due to impact pile driving

The aim of the monitoring requirement for pile driving noise is to gather data for future studies of the distribution of piling noise on the North Sea, which are needed for environmental impact assessment studies for the next 'rounds' of offshore wind farm development in the Dutch Economic Zone.

The licensing decision for 'round two' describes measurements with a 'permanent' noise measurement system, plus a ship based measurement system which

measures the underwater noise along transects, with hydrophones at various depths, to get a good overview of the spatial characteristics of the noise.
The measurements have to be carried out ‘during piling activities’ and have to include measurements of the ‘ambient noise between the piling activities’. Transects should extend to distances at which the piling noise can no longer be ‘distinguished from the ambient noise’. Special attention is required for transects in the direction of the Dutch coastal zone. The measurement plan has to be approved by the licensing authority, who will judge whether the measurements provide sufficient detail for modelling the spatial distribution of the underwater noise.

3.3.2 *Monitoring underwater noise during operation of the wind farm*

The aim of monitoring the noise during operation of the wind farm is ‘to determine the long-term averaged SPL and the $L_{z\text{-}p}$ of transients’.

This noise has to be monitored ‘continuously’, during the first year of operation of the wind farm, by ‘permanent’ measurement systems, in the wind farm and in an area around the wind farm up to a distance where the noise can no longer be ‘distinguished from the ambient noise’. The systems should operate during ‘all weather conditions’.

3.4 Offshore wind farm licensing in Germany

The German *Bundesamt für Schiffahrt und Hydrographie* (BSH) has issued a standard fort he Investigation of the impacts of offshore wind turbines on the environment (StUK 3) [BSH 2007]. This standard contains a Technical Instruction (Table 4.3 of the standard) which describes the requirements for ‘surveys of waterborne sound emissions and immissions’. This describes both a baseline survey consisting of predictions of underwater noise and ambient noise measurements before the construction of the wind farm and underwater noise monitoring during the construction and operation phases of the wind farm.

Currently, Müller-BBM is developing an updated ‘*measurement instruction for waterborne sound measurements*’ [Müller & Zerbs 2011]. This new instruction will be the basis for future licensing. The following descriptions summarize the requirements.

For each project part background noise measurements have to be carried out before construction starts. Measurements must be carried out for three wind classes, which correspond with sea state 1 (without rainfall) and, with regard to average and nominal capacity, also to the wind farm’s power range. - The exact measuring sites must be coordinated with the licensing authority 12 weeks in advance considering project-specific and site-specific needs. For evaluating the measurements $L_{eq,5s}$-values (in dB re 1 µPa) are generated frequency-resolved in 1/3-octave bandwidths with an averaging time of 5 seconds.

In the construction phase monitoring measurements must be executed during high-noise activities (e.g. deterrent measures, use of vibrators, pile driving). For each type of foundation and each installation method used in a wind farm a complete registration of the noise pollution caused by the foundation work must be performed at least once. Principally, the measurements are to be carried out during the installation of the first foundation. All measures for sound protection (e.g. deterrent measures, soft-start, pile-drive vibrations, quenching water, hydro sound absorbers, coffer dam) must be supervised by sound measurements. The measuring sites are to be determined in a distance of 750 m and 5 000 m to the foundation structure and in the closest nature reserve, provided that it is more than 5 km away from the project site. Typical sequences of the sound pressure history shall be represented with the equivalent continuous sound level L_{eq} at the beginning, at half time and at the completion of the relevant building project. Furthermore, the single event sound exposure level L_E and the peak sound pressure level L_{peak} shall be given for impulsive installation methods (piling).

In accordance with the licensing authority, control measurements have to be carried out after the start-up of the plant, when all construction work is completed in the area surrounding the wind farm. The three power ranges “low”, “medium” and “nominal power” are to be recorded. Data are to be collected on a random basis at positions inside the wind farm, whereas the sound measurements need to be carried out at a short distance of approx. 100 m from the sound source. Additionally, measurements must be performed in the nearest nature reserve, provided that it is not more than 4 km away from the project site. Should there be no neighboured nature reserves, a sound measurement in 4 km distance to the wind farm must be carried out alternatively. $L_{eq,5s}$ (in dB re 1 µPa) shall be determined frequency-resolved with an averaging time of 5 s in 1/3-octave bands.

3.5 Offshore wind farm licensing in the UK

Licensing in the UK requires an application under the Food and Environmental Protection Act 1985 (FEPA) and Section 34 of the Coast Protection Act 1949 (CPA). Both Acts require assessment of a proposed project within the marine environment with regards to its potential for environmental impact. Typical FEPA Licence clauses for round 2 wind farms (as provided in a presentation by Stephen Robinson during the February meeting in Delft) are:

Construction *(T1)*
The Licence Holder must undertake measurements of the noise generated by the installation of foundation pieces. Measurements will need to be taken at various distances for the first few foundation pieces (minimum of four) including during the ‘soft start’ procedure. The specification for these measurements should be agreed with the Licensing Authority, consultation with Cefas and Natural England at least four months before the construction work commences. The results of these initial measurements should be processed and the report submitted to the Licensing Authority within six weeks of the installation of the first foundation piece. Assessment of this report by the Licensing Authority will determine whether or not any further noise monitoring is required. Should noise levels be significantly in access of those predicted during the Environmental Impact Assessment process then further pile installation will not occur without the consent of the Licensing Authority.

Operation *(T2)*
The Licence Holder must develop plans for subsea noise and vibration from the turbines to be assessed and monitored during the operational phase of the wind farm. Before completion of the construction phase the Licence Holder must supply specification to the Licensing Authority of how it proposes to measure subsea noise and vibration. These measurements must be taken various frequencies across the

sound spectrum at a selection of locations immediately adjacent to, and between turbines, within the array and outside the array at varying distances.

A typical measurement plan for monitoring piling noise (T1), as presented during the June 2011 international workshop on standardization in Hamburg by the team of the National Physical Laboratory and Loughborough University, employs two fixed noise monitoring buoys to measure the entire piling sequence, including soft start. typically, these buoys are deployed at about 1.5 and 3 km from the pile, with two hydrophones each at about 2.5 and 7.5 m from the sea bed. Additional measurements are taken from a vessel at various ranges from the pile, ideally at increasing range along a predetermined transect with a relatively flat bathymetry. Typical distances chosen are 250 m, 500 m, 750 m, 1 km, 1.5 km, 2 km, 3 km, 5 km, 7.5 km, etc., depending on time. Two hydrophones are deployed, one below mid water column and one close to mid water column. These range dependent measurements are taken to estimate source characteristics.

3.6 Licensing for in-water pile driving projects in the USA

In 2009, a '*Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*' was issued for the California Department of Transportation [Oestman et al. 2009].

This guidance describes measurements during piling activities to be carried out with a hydrophone sensor which is normally placed in a water column at least 1 metre deep, with the sensor located at a depth of 0.5 metre above bottom of the water column. It is noted that 'Monitoring plans typically specify the minimum water column depth and the depth of the hydrophone sensor'. 'Reference sound levels from pile driving normally are reported at a fixed distance of 10 meters'.

Annex II to the technical guidance [Oestman et al. 2009] provides a detailed description of the methodology for the underwater sound measurements and for data analysis and quality control.

3.7 Considerations for standardization of noise monitoring

Two categories of monitoring can be distinguished:
1. Monitoring of *background noise ('soundscape')*. This applies to project phases T0 and T2, which involve a long period during which the background noise will vary as a function of environmental conditions.
2. Monitoring of *specific sounds*. This applies more to project phases T1 and T3, in which noise sources are present during a limited period of time. Specific sounds may be monitored at a specific receiver location. Measurements of specific sounds may also be aimed at characterizing the sound sources, or at determining the distance at which the source can have some kind of impact on marine life (e.g. injury, behavioural or ecological). Also the characterization of operating individual wind turbines, or complete offshore wind farms, as sound source (phase T2) fits in this category.

3.7.1 When to measure?
Background noise ('soundscape') monitoring requires gathering data during conditions that are statistically representative of the noise environment under

consideration. To obtain a reliable estimate of the equivalent continuous sound pressure level as well as the maximum sound pressure level, the measurement time interval shall encompass a minimum number natural variations in the background noise. Hence the background noise measurements should include various wind speeds (at least in the range of wind speeds in which the wind turbines will be operational), but also possible temporal variation patterns (day-night, week-weekend, summer-winter, etc.). Practicality will limit the possibilities to encompass all variations. For some variations, incidental measurements may be combined with known trends and statistics to predict long term behaviour (e.g. wind related noise).

Monitoring of *specific sounds* requires gathering data during conditions that are statistically representative of the sound sources under consideration. For construction or demolition noise, the measurement time interval shall encompass the complete process for at least one representative turbine. For operational noise of turbines, measurements should include the range of wind speeds in which the wind turbines will be operational.

3.7.2 Where to measure?

The selection of measurement locations for monitoring underwater sound depends on the aim and the type of monitoring and on specific details of project and environment. Because the knowledge on underwater noise and its effects on marine life is too limited to provide general guidelines on where to measure, expert judgement plays an important role. The Environmental Impact Assessment studies for the project under consideration may provide guidance, if ranges are predicted at which noise may have significant effect for the relevant marine species at or around the project site. In that case, noise monitoring can be aimed at checking the assumed source characteristics of the noise sources and at checking the predicted impact ranges.

3.7.2.1 Hydrophone depth?

Underwater sound is depth dependent. A strong depth dependence is present in the upper quarter of a wavelength in the water column, in part because of the constructive and destructive interference between the direct and surface reflected sound, which is known as the Lloyd mirror effect [Urick 1983]. Also measurements close to the bottom can be influenced by interference effects. Moreover, pile driving may generate surface waves (Rayleigh or Stonely-Scholte waves) on the sea floor around the pile. The sound pressure and particle velocity associated with these waves decreases exponentially away from the sea floor. Measurements closer to the bottom can be required to assess the impact of sound on benthic species. Unless only benthic species are considered, additional measurements in the water column away from the bottom are required to determine whether surface wave contributions are relevant.

For monitoring sound in relatively shallow water (North Sea), we advise to measure at two depths in the lower half of the water column: e.g. at 3/4 and at 1/2 of the total depth (measured from the sea surface). In some cases, there may be a need to select other hydrophone depths, for example if there is a specific interest in the impact of noise on species that reside closer to the sea bottom or near the sea surface.

When deploying hydrophones from the surface, one has to take into account that the actual hydrophone position may be influenced by displacement of the cable under influence of water currents. This effect may be mitigated by applying a weight at the end of the cable, but if it is required to know the hydrophone position with a great accuracy bottom mounted or anchored hydrophones have a preference.

Generally, applying more than one hydrophone per measurement location has several advantages:
- Redundancy, in case one hydrophone or measurement chain fails.
- The possibility to select hydrophones of different sensitivity, when there is the suspicion that a larger dynamic range is required for the measurements than can be covered by a single measurement channel.

3.7.3 *Frequency range and bandwidth?*

Sound spectra describe the distribution of sound pressure as a function of frequency. Which minimum and maximum frequencies are chosen depends on the purpose of the measurements and on the expected properties of the sources and the sound propagation. Apart from the spectral properties of the source, the following considerations should be taken into account:

1. Marine animals will only react to sound that they can sense. The hearing sensitivity varies with frequency. Audiograms (i.e. graphs of the hearing threshold versus frequencies) are typically U-shaped, showing a poor sensitivity at the lowest and highest frequencies. The intermediate frequency range of optimal sensitivity varies from one species to another. Available audiograms of marine mammals and fish (see e.g. [Popper & Hastings 2009, Richardson et al. 1995]) indicate that the upper frequency limit of the hearing range is generally below 200 kHz. The low frequency limit is less clear. Some animals might be sensitive to very low-frequency sound (order 1 Hz or less) but it is extremely difficult to measure the hearing sensitivity at such low frequencies. A global indication of the hearing frequency range of marine mammals can be obtained from the definition of the ‘M-filters’ for groups of cetaceans and pinnipeds, as defined in [Southall et al. 2007].
2. Propagation losses will influence the frequency range of received sound. Absorption losses in sea water increase with increasing frequency and range. As a consequence the effective upper limit of the frequency content of the received sound decreases. In shallow water, low frequency sound (at wavelengths smaller than the water depth) cannot propagate. This limits the lower frequency of received sound at a horizontal distance to the source that is greater than the water depth.
3. All components of the equipment that is used to record and analyse the sound will have their own frequency limitations. These limitations should be taken into account in the analysis.

Experience with measurements of piling noise and operational offshore wind farms [de Jong & Ainslie 2008a&b, Robinson et al. 2007, Betke et al. 2010, Thomson et al. 2006, OSPAR 2009] shows that the main acoustic energy measured at a distance at 1 km or more from these activities occurs in the frequency range below 10 kHz. This is illustrated by the example from the measurements during the piling for the Q7 wind farm in the North Sea shown in Figure 3. Even when weighted with the audiogram of the harbour porpoise, that has its highest sensitivity at frequencies above 100 kHz, the main energy in the spectrum is found at frequencies below 20 kHz. Pile driving generates transient noise with energy up to much higher frequencies at closer distances to the pile, but propagation loss increases with frequency and distance, due to absorption in water and sediment.

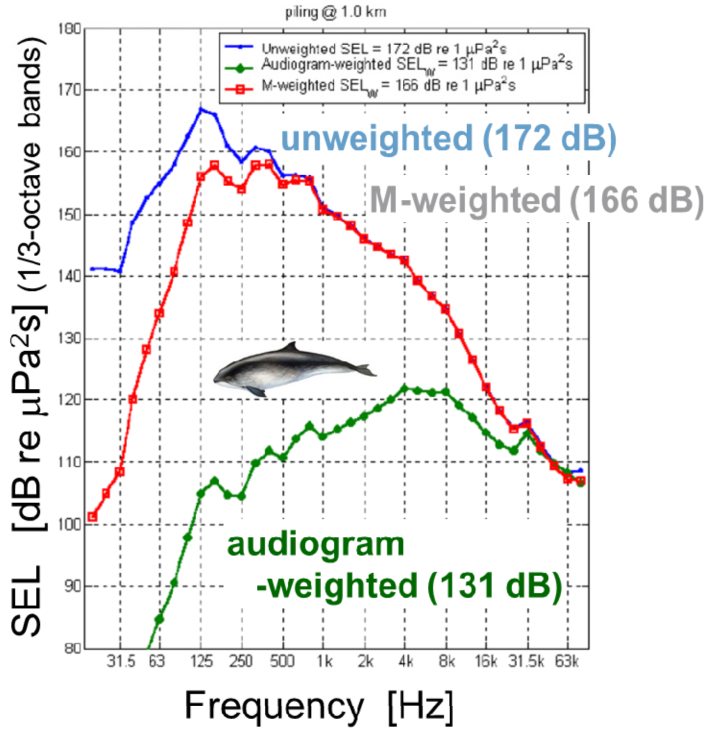

Figure 3 1/3-octave spectra of the measured SEL of a single transient sound during piling for the Q7 wind farm, unweighted, with 'M-weighting' [Southall et al. 2007] and weighted with the porpoise audiogram [de Jong & Ainlsie 2008a&b].

Hence, it is in many cases sufficient to measure underwater noise in the frequency band up to about 16 kHz[4].

Sound spectra can be presented in various ways. They present a measure for the amplitude of the sound in frequency intervals (bands) that are either *constant* or proportional to the centre frequency of the band. Spectral densities represent the sound per unit frequency, determined by a correction for the measurement frequency bandwidth. A relevant type of proportional bandwidth is the *one-third octave band*, as defined in the ISO 266:1997 and IEC 61260 standards (see also ANSI/ASA S1.11-2004 and ANSI S1.6-1984). Two options exist for determining an octave-band or fractional-octave-band, using a 'base-ten' or a 'base-two' frequency ratio. The base-ten[5] system is preferred.

We propose to calculate 1/3-octave band spectra of the SEL for each transient sound and 1/3-octave band spectra of the SPL for continuous sound with an averaging time of about 5 seconds. Variations in the spectra over a representative

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[4] This has the practical advantage that it makes it possible to use digital audio recording equipment (at 44.1 kHz or 48 kHz sample frequency), provided that this is properly calibrated.
[5] In the base-ten system, '1/10-decade' would be a more accurate name for the bandwidth than '1/3-octave', but we adhere to the conventional name.

recording period (hour, day, etc.) can be summarized in terms of minimum and maximum spectra in combination with the 5%, 50% and 95% percentile spectra (see e.g. [Richardson et al. 1995]).

Although narrow-band spectra are useful to reveal information about source mechanisms, e.g. those related to rotating machinery, this level of detail is often unnecessary when considering underwater sound in relation to the effects on marine life. An argument for the use of 1/3-octave band spectra is that the *critical bands*, in which additional noise causes masking of a pure tone, for marine mammals are roughly 1/3-octave wide (ranging from $1/12^{th}$ to $2/3^{th}$), but the main reason to choose for 1/3-octave bands is the agreement with common practice. [Madsen et al. 2006, Richardson et al. 1995]. *Whatever spectral representation is chosen, it is essential to provide a clear description of what is presented, including the bandwidth over which the sound was measured.*

3.7.4 Measurements to support noise mapping

To answer the question 'what measurements are required in order to feed sound propagation models such that reliable information on the full area (*x*, *y*, *z*, *t*) is obtained', given the current state-of-the-art propagation models, we propose the following approach:

1. Carry out measurements to characterize the sources.
2. Carry out spot check measurements at larger distance from these sources to validate the results of the predictions based on the source characterization and propagation modelling.

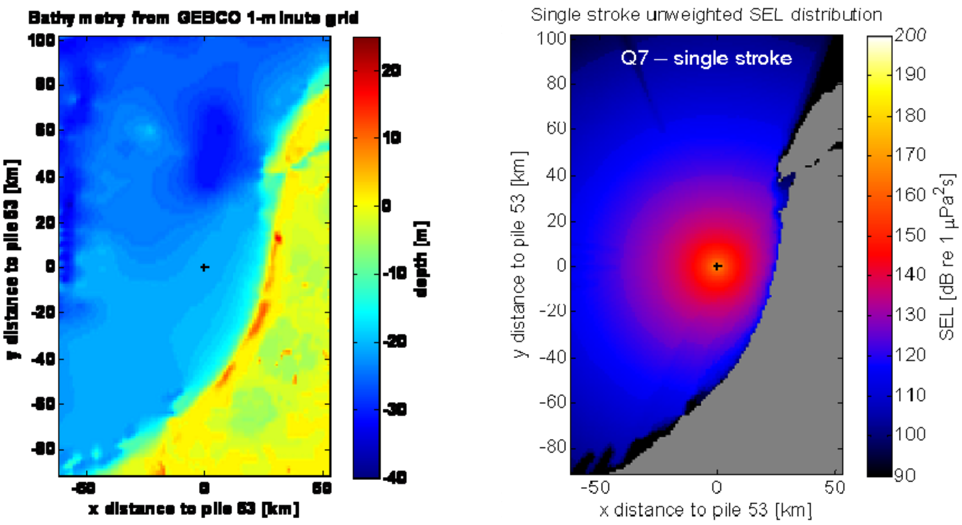

Figure 4 Example of a noise map. The image to the left shows the bathymetry of the North Sea. The image to the right shows an estimation of the spatial distribution of the unweighted SEL for a single transient sound due to pile driving at the location of the Q7 wind farm. This map is based on an energy source level based on measurements [Ainslie & de Jong 2010], using the mapping tool that is described in [Ainslie et al. 2009].

Source characterization (see also §3.7.5) requires measurements at not too great distance from the source, to avoid large errors in the estimation of the propagation loss. On the other hand, the measurements should not be so close to the source that local effects in the sound field obscure the view on the total radiated noise. The terms 'near-field' and 'far-field' are often used to identify the difference between the region far from the source, where the angular field distribution is essentially independent of distance, with the region close to the source, where the distribution depends on distance. However, this distinction can only be clearly made in free field conditions and the ‘near-field’ is not defined for sources like monopiles and dredgers which may span the complete water depth in shallow water. Typically, in shallow water ‘not too close too the source’ can be interpreted as ‘at a distance larger than the maximum of the largest source dimension and the water depth’. The shortest measurement distance might also be limited by the upper limit to the sound level for the measurement chain (hydrophone and amplifiers). In order to get confidence in the propagation correction, it is wise to carry out measurements at more than one distance. When these are not carried out simultaneously, an extra fixed measurement position is required to monitor the stability of the source during the subsequent measurements.

To measure at a particular distance from a source, means to measure somewhere at a circle around the source. In some cases, depending on the symmetry of the activity and of the environment, it may be required to measure in different directions. Alternatively, a model prediction could be used to determine the direction with the smallest attenuation and measure in that direction only. However, in many cases, the assumption of cylindrical symmetry may be acceptable so that a single, convenient, measurement direction is sufficient. Unlike in the situation in air, where wind speed is an important environmental parameter that determines where to measure, the current and its direction are parameters that are not relevant in the case of relatively short-range underwater sound measurements. In the underwater context, the bathymetry (bottom slope) has an important influence on propagation. It is often the case that the conditions that most favour propagation to long distances are associated with increasing water depth, especially at low frequency.

3.7.5 Source characterization

The terms “source level” and “propagation loss” are used in the sonar equation [Urick 1983, Ainslie 2010] to characterise, respectively, the sound radiated by an underwater sound source (such as a sonar transmitter), and the transfer function from source to receiver. Both are expressed in decibels and together they provide a quantitative description of the sound field at a receiver in the far field of the sound source [anon. 2011]. Sources are often characterized using the term ‘source level’, but it is not always clear how the term is defined [de Jong et al. 2010, Ainslie et al 2011].

The term “source level”, though not straightforward to define generally, under certain idealised conditions (in an infinite lossless uniform medium, and in the far field of the source) can be related in a simple way to source radiant intensity (power per unit solid angle). However, for sources close to the water surface or in shallow water, the sound reflected from boundaries complicates the definition. Consequently, there is no international consensus to date for a general definition of “source level” in the context of underwater sound [de Jong et al. 2010, anon. 2011].

Without consensus for a general definition of ‘source level’, it is not possible to develop general measurement and analysis procedures for characterizing sources. Different definitions and procedures may be required for different sources. In [de Jong et al. 2010], initial suggestions are presented for characterizing sources that were identified in [Ainslie et al. 2009] as being of potential concern in the North Sea area (explosives, shipping, air guns and pile driving). Some of these are addressed in the following sections.

3.7.5.1 *Ships*

Some progress is made in the development of procedures for characterizing ships as source of underwater sound. Working Group WG47 of the Acoustical Society of America (ASA) S12 Committee on Noise Standards has recently produced the American National Standard ANSI/ASA S12.64-2009 "Quantities and Procedures for the Description and Measurement of Underwater Sound from Ships - Part 1: General Requirements”. This provides a commercial standard describing the general measurement systems, procedures and methodologies used for the measurement of underwater sound pressure levels from ships. Working groups[6] in the International Standard Organization (ISO) are currently developing this further into international standards. Challenges faced by these groups are the definition of the metrics (radiated noise level or source level?) and the development of measurement and analysis procedures that can be used in deep and shallow water.

3.7.5.2 *Pile driving*

It is not clear how to provide a proper definition of the source level for impact pile driving. This is a source of large complexity, because it penetrates both the water surface and the sea bed. Two different approaches are investigated by TNO:

1. Estimation of an ‘energy source level’ [Ainslie et al, 2010], assuming that the pile can be represented by a monopole sound source in the water column.
2. Characterizing pile driving noise by means of a numerical model[7] of the pile construction and environment (water and sea bed), driven by a force which represents the hammer strike (energy and wave form) [Zampolli et al. 2011].

The first approach is based on underwater noise measurements in the far field of the pile. An acoustic ‘far field’ is hard to define in the shallow water environment where piling takes place, but it is assumed that measurements at a range of ten times the water depth or further from the pile are sufficiently far away to be relatively independent of the local details of the sound radiation mechanisms from the pile.

The second approach requires measurements for validation of the numerical models and for characterizing the hammer strikes This requires measurements at close distance to the pile. Preferably, these are combined with measurements of the dynamic behaviour of the pile construction, using strain gauges and accelerometers, according to standard ‘Pile Dynamic Analysis’ (PDA), see [ASTM D 4945-08].

As long as different approaches are under development, little consensus is likely to emerge for the standardization of procedures for measurement and analysis of the source characteristics of pile driving noise. In the meantime, measurements of the received sound in terms of the sound exposure level and zero to peak sound pressure at a fixed distance to the pile, e.g. 500 or 750 m enable a direct comparison with available data for wind farms in the North Sea and Baltic Sea [Ainslie et al. 2009, Müller and Zerbs 2011].

[6] Working groups started under ISO Technical Committee TC8 ‘Ships and marine technology’ (SC2WG6) and under TC43 ‘Acoustics’ (SC1WG55).
[7] Numerical modelling is the topic of a parallel research project at TNO under the shortlist

NOTE: In the ‘development of a framework for appropriate assessments of Dutch offshore wind farms’ [Prins et al. 2008], it was concluded that ‘*for marine mammals the sounds produced during monopile driving will be audible several tens of kilometres from the driving location, maybe even 100 km or more. The Harbour Seal may show avoidance behaviour to pile driving noise within a radius of approximately 80 km, the Harbour Porpoise within a radius of approximately 12 km*’. The radii mentioned in his conclusion were estimated by extrapolation of piling noise, which was measured up to a maximum range of 5.8 km from a pile driving project in the North Sea [de Jong & Ainslie 2008]. The radius of 80 km is also mentioned in [Thomsen et al. 2006] as the minimum range of audibility of piling noise to harbour seals and harbour porpoises. No data are available to validate this extrapolation. Hence, it would be valuable for future impact assessment studies if future piling noise monitoring studies were to include measurement positions at 15 to 80 km distance from the pile driving site.

4 Proposal for a measurement procedure

Based on the review of noise monitoring procedures (Chapter 3), this Chapter provides a proposal for a measurement and reporting procedure for underwater sound in connection with offshore wind farm licensing in The Netherlands, which could serve as a basis for international standardization. The structure of the ISO standard 1996-2 for environmental noise measurements in air is followed in this proposal. A similar structure is chosen for the German ‘Measurement instruction for waterborne sound measurements’ [Müller & Zerbs 2011], from which some parts are copied.

4.1 Scope

This is a proposal for a procedure for measuring and reporting underwater sound in connection with offshore wind farm licensing. The main objective of the measurements is to gather data for risk assessment associated with the impact of underwater noise on the marine environment.

For monitoring underwater sound in connection with offshore wind farm licensing we distinguish the following four phases:

- T0: the period prior to construction of the wind farm
- T1: the construction phase
- T2: the period while the wind farm is in operation
- T3: the decommissioning phase

Each of these phases has its own requirements for monitoring underwater noise. The licensing authority decides for which phases and which activities there is a requirement to monitor underwater noise. A detailed measurement and analysis plan has to be agreed with the licensing authority prior to the measurements.

This proposal describes measurement and analysis procedures for

1. the monitoring of *background noise* at specific locations during all project phases
2. the monitoring of *specific sounds*, limited to the noise generated due to the installation and removal of wind turbine foundations (phases T1 and T3) and due to the operation of the turbines (phase T2)

This proposal concerns a minimum requirement for measurement, analysis and reporting. Additional requirements may be specified by the licensing authority, depending on specific conditions for the project activities and environment.

4.2 Normative references

The following referenced documents are referred to in this document:

- Ainslie, M.A. (ed.) 2011 The Hague: TNO. report TNO-DV 2011 C235 'Standards for measurement of underwater sound, Part I: physical quantities and their units' [anon 2011]
- Guide to the expression of uncertainty in measurement (GUM), BIPM/IEC/IFCC/ISO/IUPAC/IUPAP/OIML, 1993 (corrected and reprinted, 1995)
- ISO 80000-8: Quantities and units. Part 8: Acoustics.

- ISO 1996: Acoustics – Description, measurement and assessment of environmental noise. Part 1: Basic quantities and assessment procedure.
- ISO 1996: Acoustics – Description, measurement and assessment of environmental noise. Part 2: Determination of environmental noise levels.
- IEC 60050-801: International Electro technical Vocabulary – Chapter 801: Acoustics and electroacoustics.
- IEC 60565: Underwater acoustics – Hydrophones. Calibration in the frequency ranges 0,01 Hz to 1 MHz
- IEC 61260:1995, Electroacoustics — Octave-band and fractional-octave band filters
- IEC 60263: Scales and sizes for plotting frequency characteristics and polar diagrams.

4.3 Terms and definitions

For the purposes of this document, the following terms and definitions apply:

NOTE: When reporting noise levels in decibels, the following principles are applied [anon. 2011]:

- State the physical parameter clearly
- State the averaging time clearly
- State the frequency bandwidth clearly
- State the frequency weighting clearly

4.3.1 Unweighted Sound Pressure Level (SPL) for continuous sound

Ten times the logarithm to the base 10 of the square of the ratio of a given root-mean-square sound pressure to the reference sound pressure

$$\mathrm{SPL} = 10\log_{10}\frac{1}{T}\int_0^T \frac{p(t)^2}{p_{ref}^2}\,dt \qquad \text{in dB re 1 µPa}^2$$

in which $p(\mathrm{t})$ stands for the instantaneous sound pressure, p_{ref} for the reference sound pressure 1 µPa and T for the averaging time.[8]

4.3.2 Unweighted zero to peak acoustic pressure (p_{peak}) for transient sounds

The maximum absolute value of the unweighted instantaneous sound pressure during a stated time interval.

$$p_{\mathrm{peak}} = \max\left(\left|p(t)\right|\right) \qquad \text{in Pa}$$

4.3.3 Unweighted zero to peak sound pressure level ($L_{z\text{-}p}$) for transient sounds

Ten times the logarithm to the base 10 of the ratio of the square of the *unweighted zero to peak acoustic pressure* (p_{peak}) to the square of the reference sound pressure.

$$L_{z\text{-}p} = 10\log_{10}\frac{p_{peak}^2}{p_{ref}^2} \qquad \text{in dB re 1 µPa}^2$$

in which p_{ref} is the reference sound pressure 1 µPa

4.3.4 Unweighted sound exposure level (SEL) for transient sounds

Ten times the logarithm to the base 10 of the ratio of the unweighted sound exposure (E) to the reference sound exposure (E_{ref}) the sound exposure being the

[8] The SPL is also referred to as the equivalent continuous sound (pressure) level (L_{eqT})

time integral of the time-varying square of the unweighted instantaneous sound pressure over a transient sound event.[9]:

$$\mathrm{SEL} = 10\log_{10}\frac{E}{E_{ref}} \qquad \text{in dB re 1 µPa}^2\text{s}$$

with the unweighted sound exposure $E = \int_{-\infty}^{\infty} p(t)^2\,\mathrm{d}t$

and the reference exposure $E_{ref} = p_{ref}^2 \cdot T_{ref}$ in which p_{ref} is the reference sound pressure 1 μPa and T_{ref} the reference duration 1 s.

4.3.5 *Unweighted cumulative sound exposure level (SEL_{cum}) for multiple transient sounds*

Ten times the logarithm to the base 10 of the ratio of the unweighted cumulative sound exposure (E_{cum}) to the reference sound exposure (E_{ref}) the cumulative sound exposure being the sum of the time integrals of the time-varying square of the unweighted instantaneous sound pressure over multiple transient sound events.

$$\mathrm{SEL}_{\mathrm{cum}} = 10\log_{10}\frac{E_{cum}}{E_{ref}} \qquad \text{in dB re 1 µPa}^2\text{s}$$

with cumulative sound exposure E_{cum} for N transient sound events with unweighted sound exposure E_n

$$E_{cum} = \sum_{n=1}^{N} E_n$$

and the reference exposure $E_{ref} = p_{ref}^2 \cdot T_{ref}$ in which p_{ref} is the reference sound pressure 1 μPa and T_{ref} the reference duration 1 s.

4.3.6 *Unweighted mean square pressure (MSP) spectral density level*

Ten times the logarithm to the base 10 of the square of the ratio of a given unweighted root-mean-square sound pressure density $Q(f)$ to the reference sound pressure

$$10\log_{10}\frac{Q(f)}{p_{\mathrm{ref}}{}^2 / f_{\mathrm{ref}}} \quad \text{in dB re 1 µPa}^2\text{/Hz}$$

where $Q(f)$ stands for the contribution of the mean square pressure per unit of frequency bandwidth, p_{ref} for the reference sound pressure 1 µPa and f_{ref} for the reference frequency 1 Hz.

4.3.7 *N percent exceedance level*

The *unweighted sound pressure level* (in dB re 1 µPa^2) or *sound exposure level* (in dB re 1 µPa^{2}s) for continuous sound that is exceeded for N % of the time interval considered.

4.3.8 *Time intervals*

4.3.8.1 *Signal duration (τ_x) for transient sounds*

The time during which a specified percentage x of *unweighted sound exposure* occurs (e.g., τ_{90} is the time window during which 90 % of the energy arrives), expressed in milliseconds (ms).

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[9] The sound exposure level SEL is also referred to as L_E, or L_{ET} when the exposure is defined over a specified time interval T

NOTE: made unambiguous by starting at 50-x/2 % and ending at 50+x/2 % of total energy. (e.g., for τ_{90} this is 5 to 95 %)

4.3.8.2 Total duration (T) for multiple transient sounds

The time during which a specified number of transient sounds occurs, expressed in seconds (s)

4.3.8.3 Repetition rate for repeated transient sounds

The number of transient sound events per unit of time., expressed per second (s^{-1})

4.3.8.4 measurement time interval

time interval during which a single measurement is conducted

4.3.8.5 observation time interval

time interval during which a series of measurements is conducted

4.3.9 Sound designations

4.3.9.1 total noise

total noise observed with a non-directional hydrophone in a given situation at a given time

4.3.9.2 background noise

total noise without contributions of *self noise*, usually composed of sound from many sources near and far

4.3.9.3 specific sound

component of the background noise that can be specifically identified and which is associated with a specific source

4.3.9.4 ambient noise

background noise remaining at a given position in a given situation when the specific sounds under consideration are suppressed

4.3.9.5 initial ambient noise

ambient noise (mean value and fluctuations) present in an initial situation before any change to the existing situation occurs

4.3.9.6 self noise

noise due to the hydrophone and its manner of mounting (including noise generated on the measurement platform) and to electronic components of the measurements chain

4.4 Measurement uncertainty

The uncertainty of the reported noise metrics, as determined according to the proposed procedures, depends on the uncertainties associated with the sound sources, withthe measurement and observation time intervals, with the propagation conditions, with the distance between the source and the hydrophones and with the measurement method and instrumentation. The measurement uncertainty shall be determined in accordance with the '*GUM*'[10]?

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[10] Guide to the expression of uncertainty in measurement (GUM), BIPM/IEC/IFCC/ISO/IUPAC/IUPAP/OIML, 1993 (corrected and reprinted, 1995)

4.5 Instrumentation

Instruments used for measuring, recording, and analysing underwater sound are available from a wide variety of manufacturers, and different types of systems can be used to accomplish the task. A typical single channel measurement system consists of a hydrophone (an underwater electro-acoustic transducer), signal conditioning electronics (either within or exterior to the hydrophone), amplifiers and filters and a recording unit or real-time measurement system. Depending on the type of measurement, multiple channels may be required.

4.5.1 Hydrophones

It is important to select an appropriate hydrophone, depending on the objective of the measurements. Typical specifications are frequency range (bandwidth), linearity, sensitivity, directivity pattern, maximum operating depth (or pressure), self noise, maximum and minimum acoustic pressure (dynamic range), operating temperature range and impedance. Measurements at short ranges from offshore pile driving signals require hydrophones and signal conditioners which can deal with the high peak pressures and larger frequency bandwidth without overload. Measuring ambient noise requires much more sensitive hydrophones, with a low noise floor. The hydrophone response characteristics (sensitivity as a function of frequency and direction) should be known (either from recent calibration by the manufacturer or from own measurements) and be taken into account in the design of the measurement set-up and in the subsequent data analysis.

4.5.2 *Hydrophone deployment*

Hydrophones have to be submerged to the appropriate depth. The deployment depth depends on the specific objective of the measurements.

For measurements of ambient noise or other relatively weak sounds, it is important to minimize ‘self-noise’ due to the measurement platform, the suspension of the hydrophones and due to water flowing along the hydrophone, at least for that part of the frequency range where it overlaps with the sounds to be measured.
There are several ways of deploying hydrophones, each with its particular pros and cons. In the case of deployment from a ship, one should consider switching off the ship’s engines, generators, etc., as far as possible, to prevent the ship’s own noise to interfere with the underwater sound measurements. This does not remove other sounds like wave slap against the ship’s hull and noise due to motion of the anchoring cable. By suspension of the hydrophones from a buoy, one may increase the distance to the ship, which helps to reduce the contribution of ship noise.
If a subsurface buoy is used, the hydrophones are less sensitive to wave motion. To secure the position of the hydrophones, the hydrophones may be mounted on a mooring line anchored to the seafloor and kept vertical by a buoy.
Turbulence in the flow along the cable and hydrophones can cause cable strumming and ‘flow noise’ at the hydrophones. Cable strumming can be reduced by ‘fairing’ the cable. Flow noise is reduced when the hydrophone is allowed to drift with the flow, at the cost of losing control of the measurement location. This could in some cases be compensated by monitoring the position of the hydrophone, for example by means of a GPS receiver.

4.5.3 Amplification

Most hydrophones require a pre-amplification of their output to better drive the cable and to reduce electronic noise. For this reason some hydrophones are provided with built-in preamplifiers. Also, before digitizing the signal, amplification may be required. After amplification, the signal dynamic range should match the digitizer dynamic range. The amplifier specifications should match the signal properties (frequency range, maximum voltage).

Because underwater sound spectra generally show a decrease towards higher frequencies, the required dynamic range for recording could be decreased by application of a so-called ‘pre-whitening’, in which the higher frequencies are amplified more than the lower frequencies, such that after pre-whitening all frequencies have a similar dynamic range. The amplifier characteristics (gain as a function of frequency) should be known (either from recent calibration by the manufacturer or from own measurements) and be taken into account in the data analysis.

4.5.4 Filtering

Before the signal can be fed into an analogue-to-digital (A/D) converter, its frequency range should be limited to the bandwidth that can be handled by the A/D converter. At the high-end this is to avoid temporal aliasing (low-pass filtering); at the low-end this is to avoid large pressure variations, not related to underwater sound (high-pass filtering).
The filter characteristics (gain as a function of frequency) should be known (either from recent calibration by the manufacturer or from own measurements) and be taken into account in the data analysis.

4.5.5 A/D conversion and recording

The dynamic range of the A/D converter should be sufficiently large, so that the dynamic range of the signal, that is the ratio of the maximum measured value to the minimum measured value of the sound pressure, is preserved sufficiently well.
The number of bits per sample, i.e., the word length, is an important parameter: it determines the quantization error. This can be understood as follows: in the digitization process, the actual acoustic pressure value is rounded to the nearest available value of the digitizer. The quantization error is linearly distributed between plus and minus half the value of the least significant bit. Therefore, this quantization error ‘adds’ quantization noise the recorded signal. The quantization noise should preferably be lower than the lowest noise that one would like to analyse.
The required word length is determined by the ratio of the expected maximum and minimum sound pressure to be recorded. Currently, a word length of 24 bits, or 3 bytes, is considered to be the largest that is commercially attractive. In this case the maximum ratio is thus 2^{24}= 16777216 and expressed in dB, the dynamic range is at maximum $20\log10(2^{24})\approx144$ dB.

The sample frequency should be at least twice as high as the maximum frequency that is present in the analogue signal that goes into the A/D converter, i.e. the highest frequency present in the signal after low-pass filtering. A higher sample frequency (‘oversampling’) is always allowed, but a lower sample frequency (‘undersampling’) is not: it causes temporal aliasing.

Note that the sample frequency and the number of bits per sample are related as far as quantization noise is concerned: every factor of four oversampling corresponds to one additional bit per sample.

Finally, the digitized signal is to be stored on a storage medium of choice, e.g. hard disk, solid state memory, tape. A widely used acoustic encoding format is WAV. However, one has to make sure that the absolute calibration of the amplitude is not lost, because some WAV formats scale the data to the maximum amplitude in the file. Note that a format using lossy data compression, such as MP3, is preferably not used in order to preserve all information contained in the data. In some cases, limitations in storage capacity might be solved by applying lossy compression techniques. These limit the possibilities to analyse the data, but can be accepted as long as the specific analysis to be applied to the data does not lead to significant errors. This has to be demonstrated by comparison of the analysis results for a full and compressed version of the same representative recording example.

4.5.6 Auxiliary measurements

In addition to the underwater sound measurement equipment, the following equipment may be needed, where considered to be relevant:

- CTD probe, to measure the profile of conductivity, temperature and hydrostatic pressure as a function of depth in the water column. From this information the salinity, density and sound velocity profiles can be calculated. Alternatively, the sound velocity profile can be measured directly, using a velocimeter.
- pH meter, to determine the pH of the seawater. An estimate of pH could be required for calculation of the absorption coefficient [anon. 2010].
- Anemometer, to determine wind speed and direction at a standard height of 10 m above the water surface,
- Air-thermometer, to determine the air-water temperature difference,
- Echo sounder, to measure the local water depth
- GPS (Global Positioning System) receiver, to measure the position of sound sources and measurement equipment
- AIS (Automatic Identification System) receiver, to monitor the presence of vessels in the environment of the measurements.

4.5.7 *Calibration of equipment*

The complete measurement chain (hydrophone-amplifiers-filters-A/D conversion) should be tested before deployment to check whether it functions within its specifications.

It is advised to make use of a hydrophone-calibrator (‘pistonphone’), which provides the hydrophone with a single-frequency tonal of well-defined amplitude.
This enables a quick calibration of the measurement chain at that frequency.

A calibration across the full frequency range of the measurement chain can be based on the specifications of the individual components as provided by the manufacturers, or measured in a laboratory according to standardized procedures, e.g. IEC 60565 or ANSI S1.20-1988 (R2003).

Calibration charts of measurement equipment must be available, and dated at maximum 24 months before the measurements.

4.6 Measurements in different stages of offshore wind farm projects

For monitoring underwater sound in connection with offshore wind farm licensing we distinguish the following four project phases:

- T0: the period prior to construction of the wind farm
- T1: the construction phase
- T2: the period while the wind farm is in operation
- T3: the decommissioning phase

Each of these phases has its own requirements for monitoring underwater noise. The licensing authority decides for which phases and which activities there is a requirement to monitor underwater noise. A detailed measurement and analysis plan has to be agreed with the licensing authority prior to the measurements.

4.6.1 General

A measurement plan must be approved by the licensing authority prior to the measurements, considering project-specific and site-specific needs.

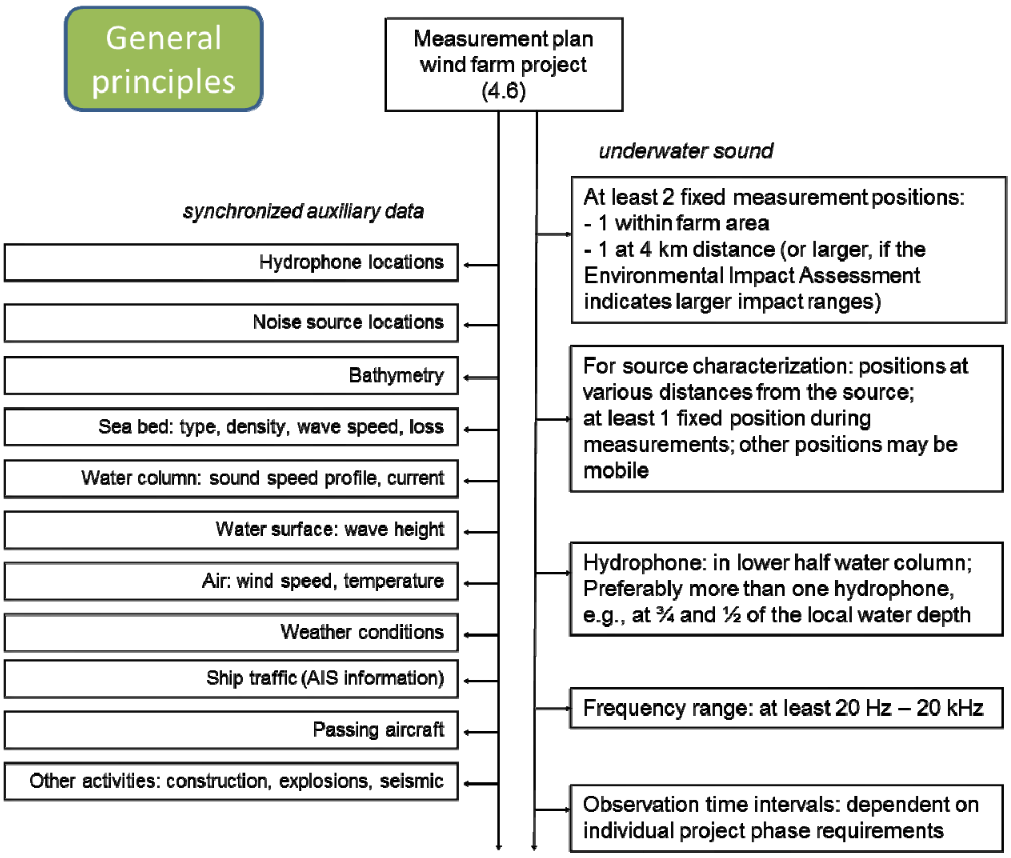

Figure 5 Overview of the general principles for an underwater noise monitoring plan.

The following general principles apply:

- Select at least two fixed reference measurement position(s) for measuring background noise in all phases of the wind farm project. One position can be chosen within the borders of the (planned) wind farm, another at either a distance for which the Environmental Impact Assessment of the project

indicates that the sound generated during construction or operation can have a significant effect on marine species, or a fixed distance of 4 km from the site (when the predicted impact ranges are smaller than 4 km).[11]
- Select positions at various distances from the source for determining source characteristics (of pile driving, operational wind turbines, etc.). Some of these positions may be mobile, but a least one measurement position has to remain fixed during a complete cycle of source activities, to monitor temporal variations in the source mechanism.
- Use hydrophone(s) in the lower half of the water column. Preferably use more than one hydrophone per location: e.g. at 3/4 and at 1/2 of the local water depth.
- The measurements shall at least provide reliable data in the frequency range between 20 Hz and 20 kHz.
- Select observation time intervals according to the requirements for the individual project phase.

With all measurements auxiliary data are to be gathered of:
- Locations of hydrophones (GPS position, depth)
- Locations of noise sources (GPS position, depth)
- Bathymetry (water depth, including tidal variations)
- Sea bed: type, (layered) sediment density, wave speed, loss, …
- Water column: temperature, salinity (sound speed profile), current
- Water surface: RMS wave height, averaging time
- Air: wind speed (+ averaging time), temperature (+ measurement height)

Where possible, a log should be kept of acoustic events, synchronized with the time of the acoustic measurements:
- Weather: precipitation (rain, snow, hail), thunder and lightning, …
- Shipping traffic (+ distance to hydrophones, e.g. from AIS)
- Passing aircraft
- Other activities (+ distance to hydrophones):
  - construction, explosions, seismic exploration, …

[11] [Müller & Zerbs 2011] specify a fixed distance of 5 km for piling noise and 4 km for operational noise, or a position in the nearest ‘nature reserve’, if that is closer than this fixed distance. We propose to deviate from these fixed distances when the EIA suggests that the impact ranges of wind farm related noise may be much larger.

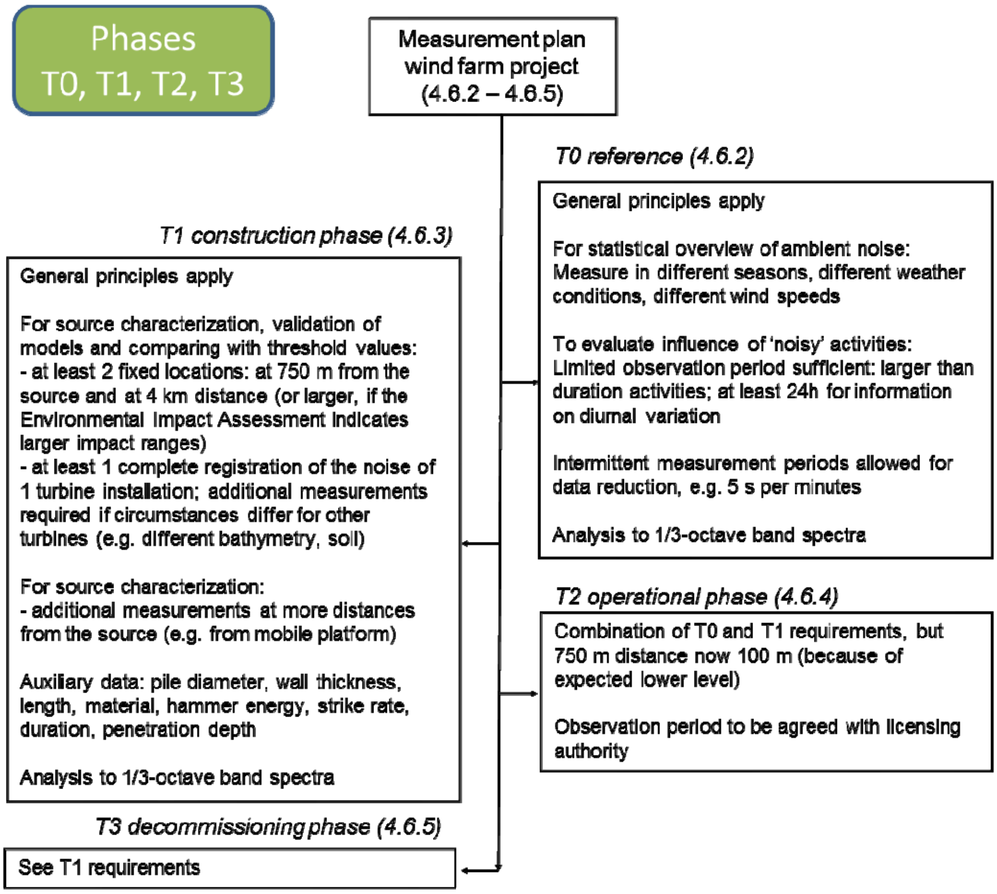

Figure 6 Overview of the principles for underwater noise monitoring in the four phases.

4.6.2 *T0-phase: measuring initial ambient noise prior to construction phase*

The main purpose of measuring the initial ambient noise prior to the construction of the wind farm is to acquire a reference for determining the relative impact of construction and operation noise of the wind turbines in later phases.

Measurements must be carried out at (at least) two fixed locations, one within the borders of the (planned) wind farm, another at either a distance for which the Environmental Impact Assessment of the project indicates that the sound generated during construction or operation can have a significant effect on marine species, or a fixed distance of 4 km from the site (when the predicted impact ranges are smaller than 4 km), preferably in the direction of sensitive areas for environmental impact (e.g. Natura 2000 area). The remote measurements position should be selected where the possible contribution of the noise generated by wind farm related activities will be the largest. Criteria for this are the lowest propagation loss, which could be for example in a direction where the water depth gradually increases, and the lowest ambient noise, which could be at the largest distance to shipping lanes, harbours and offshore installations.

The observation periods for the measurements must be selected in coordination with the licensing authorities. Much depends on the intended use of the initial ambient noise data:

- A good statistical overview of the initial ambient noise in and around the project site requires several observation periods in different seasons and at different

weather conditions, including the range of wind speeds in which the wind turbines will be operational.
- For obtaining reference ambient noise data for the evaluation of the effects of 'noisy activities', like impact pile driving, a limited observation period prior to the activities may be sufficient. The duration of this observation period should be greater than the expected duration of the activities and at least span a continuous period of 24 hours, to get a first impression of diurnal variations in the noise.

In order to reduce the amount of data to be stored, observation periods may be divided into intermittent measurement periods of e.g. 5 s per minute[12].

The measured background noise at each hydrophone position shall be analysed to 1/3-octave band spectra of the 5 second average unweighted sound pressure level (SPL_{5s}). The resulting spectra are to be reported in a spectrogram (1/3-octave band levels on a colour scale versus frequency –vertical axis- and time –horizontal axis) of the total observation period. Additionally, a plot shall be provided of the broadband SPL_{5s} versus time for the total observation period.
SPL_{5s} spectra that contain contributions of specific sources (passing ships or aircraft, distant explosions, etc.) are to be separately described and discarded from the following statistical analysis. For the residual ambient noise, to be reported are 1/3-octave band spectra of:
- the maximum SPL_{5s}
- the median (50% exceedance) SPL_{5s}
- the mean and the standard deviation of the SPL_{5s}
- the minimum SPL_{5s}

4.6.3 the average value of the mean square pressure, expressed as a levelT1-phase: measuring underwater noise during the construction phase

The objective of noise monitoring during the construction phase is to be determined in coordination with the licensing authorities and can be:
1. To monitor noise at fixed locations, for validating the results of predictions in the environmental impact assessment, or for comparing the measured levels with threshold values, if these are set by the licensing authority
2. To carry out measurements, for characterizing the sources (here limited to the installation of turbine foundations) and for validating source and propagation models

Acoustic monitoring shall be carried out during operation of all noise sources which are considered relevant in the environmental impact assessment for the construction phase. For both objectives, measurements must be carried out at (at least) two fixed locations, one at a distance of about 750 m from the source location[13], another at either a distance for which the Environmental Impact Assessment of the project indicates that the sound generated during construction or operation can have a significant effect on marine species[14], or a fixed distance of

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[12] The 5 s measurement period is chosen in agreement with [Müller and Zerbs 2011].
[13] NOTE: the 750 m is specific for the installation of turbine foundations and is selected in agreement with the German requirement [Müller & Zerbs 2011].
[14] For the next round of pile driving projects in The Netherlands' part of the North Sea, the initial appropriate assessment study [Prins et al 2008], based on estimations from [Thomsen et al 2006], indicates that impact ranges can extend to 15 and 80 km from the pile driving location for marine mammals (harbor porpoises and harbor seals).

4 km from the site (when the predicted impact ranges are smaller than 4 km), at or close to the position where the initial ambient noise measurements were taken.

A complete registration of the noise produced during the installation of a turbine foundation must be performed at least once for each type of foundation and for each installation method used in the wind farm, including the effects of mitigation measures like soft-start procedures, bubble screens and cofferdams. Preferably, the measurements are to be carried out during the installation of the first foundation. Additional measurements must be carried out if the environmental properties (bathymetry, soil layers) vary significantly between foundation locations.

For the characterization of the noise produced during the installation of turbine foundations (objective 2), it is advised to carry out additional measurements at various distances from the source. These measurements can be used to validate numerical models that describe the source mechanisms and propagation loss models for the project site and its environment. Measurement distances are to be selected according to the specifics of the project site and the source activity. Ideally, a series of measurement positions is selected along a straight transect away from the source, along which the bathymetry is relatively flat. Hydrophones can be deployed from static buoys or from one or more measurement vessels which move along the transect between measurement periods. For pile driving activities, each measurement period at a position along the transect should contain a recording of at least 10 transient pile driving sounds. Ideally, measurement positions start at close distance from the pile (e.g. one water depth or less) and extend to distances at which the piling noise can no longer be detected. Intermediate measurement position along the transect can be, for example selected, by exponential increase of the distance to the source. Observations positions along transects are to be described in the project plan, considering the properties of the environment around the project site (bathymetry, sediment), safety regulations (exclusion zones) and taking into account the time required for transiting and deploying and recovering of vessel based measurement systems, in relation to the total duration of the installation activity.

The measured continuous background noise at each hydrophone position (in the absence of transient noises) shall be analysed in 1/3-octave band spectra (minimum range 20 Hz to 20 kHz) of the 5 second average unweighted sound pressure level (SPL_{5s}). The resulting spectra are to be reported in a spectrogram (1/3-octave band levels on a colour scale versus frequency –vertical axis- and time –horizontal axis) of the total observation period. Additionally, a plot shall be provided of the broadband SPL_{5s} versus time for the total observation period.
For the residual ambient noise, to be reported are 1/3-octave band spectra (minimum range 20 Hz to 20 kHz) of:

- the maximum $SPL_{5s.}$
- the median (50% exceedance) $SPL_{5s.}$
- the mean and the standard deviation of the $SPL_{5s.}$
- the minimum $SPL_{5s.}$
- the average value of the mean square pressure, expressed as a level.

Transient sounds shall be analysed to 1/3-octave band spectra (minimum range 20 Hz to 20 kHz) of the unweighted sound exposure level (SEL) and single values of the unweighted peak acoustic pressure (p_{peak}) [15] and the duration (τ_{90}) for each individual transient in the recording for each hydrophone. For the measurements that monitor the complete foundation installation at a fixed location, plots shall be provided of the broadband SEL and of the peak acoustic pressure versus time for the total observation period. Values shall be reported of the maximum peak acoustic pressure and the cumulative broadband SEL at each fixed location over the total observation period.

For each measurement position and measurement period with a fixed hammer setting, to be reported are 1/3-octave band spectra (for individual transients, minimum range 20 Hz to 20 kHz) of:

- the maximum SEL.
- the median (50% exceedance) SEL.
- the mean and the standard deviation of the SEL.
- the minimum SEL.
- the average value of the sound exposure, expressed as a level.

Additionally, plots can be provided of the median broadband SEL and the median peak acoustic pressure as function of distance to the foundation - for a fixed hammer setting - or as function of hammer setting (strike energy) – at a fixed measurement position.

For measurements of pile driving noise, additional auxiliary data are to be gathered of:

- Foundation geometry (e.g. pile diameter, wall thickness, length) and material properties.
- Details of construction method (hammer energy per strike, strike rate, total duration, penetration depth of the pile per strike, etc.).

4.6.4 *T2-phase: measuring underwater noise during the operational phase*

The objective of noise monitoring during the operational phase is to be determined in coordination with the licensing authorities and can be:

1. To monitor noise at fixed locations, for validating the results of predictions in the environmental impact assessment, or for comparing the measured levels with threshold values, if these are set by the licensing authority.
2. To carry out measurements, for characterizing the sources (here limited to individual operational wind turbines).

For both objectives, measurements must be carried out at (at least) two fixed locations, one at either a distance for which the Environmental Impact Assessment of the project indicates that the sound generated during construction or operation can have a significant effect on marine species, or a fixed distance of 4 km from the site (when the predicted impact ranges are smaller than 4 km), at or close to the position where the initial ambient noise measurements were taken, and one at a distance of about 100 m from one (representative) turbine, in a direction with the maximum distance to the other turbines.

Acoustic monitoring for operational wind farms shall be carried out preferably during the first year after commissioning. The observation periods for the measurements

[15] To avoid ambiguity, we prefer to report the peak pressure in micropascals rather than its level (L_{peak}) in decibels. Reporting both is allowed.

must be selected in coordination with the licensing authorities. The observations should provide a good statistical overview of the operational noise in and around the project site. This requires multiple observation periods that cover the range of wind speeds in which the wind turbines are operational and (if deemed necessary) periods in which noisy activities (maintenance) take place. Each period should cover at least 24 hours. In order to reduce the amount of data to be stored, observation periods may be divided into intermittent measurement periods of 5 s per minute.

The measured background noise at each hydrophone position shall be analysed to 1/3-octave band spectra (minimum range 20 Hz to 20 kHz) of the 5 second average unweighted sound pressure level (SPL_{5s}). The resulting spectra are to be reported in a spectrogram (1/3-octave band levels on a colour scale versus frequency –vertical axis- and time –horizontal axis) of the total observation period. Additionally, a plot shall be provided of the broadband SPL_{5s} versus time for the total observation period.
SPL_{5s} spectra that contain contributions of specific sources (passing ships or aircraft, distant explosions, etc.) are to be separately described and discarded from the following statistical analysis. For the residual ambient noise, to be reported are 1/3-octave band spectra (minimum range 20 Hz to 20 kHz) of:
- the maximum $SPL_{5s.}$
- the median (50% exceedance) $SPL_{5s.}$
- the mean and the standard deviation of the $SPL_{5s.}$
- the minimum $SPL_{5s.}$
- the average value of the mean square pressure, expressed as a level.

For the characterization of the noise produced by an individual operating turbine (objective 2), the data recorded by the hydrophone at 100 m can be used. If possible, it is advised to repeat these measurements at positions near other turbines. In addition to the above mentioned analysis, the measured noise of the 100 m hydrophone shall be analysed to narrowband spectra (1 Hz resolution, minimum range 20 Hz to 1600 Hz) of the 5 second average unweighted sound pressure level (SPL_{5s}). This enables to identify tonal noises, which provide information on the relevant source mechanisms (e.g. gearbox frequencies).

For measurements of operational noise, additional auxiliary data are to be gathered of:
- Turbine foundation geometry (e.g. pile diameter, wall thickness, length) and material properties.
- Operational characteristics of the individual turbine(s), like rpm or power output as a function of time during the observation period.

4.6.5 *T3-phase: measuring underwater noise during the decommissioning phase*

The objective of noise monitoring during the decommissioning (demolition) phase is to be determined in coordination with the licensing authorities and can be:
1. To monitor noise at fixed locations, for validating the results of predictions in the environmental impact assessment, or for comparing the measured levels with threshold values, if these are set by the licensing authority.
2. To carry out measurements, for characterizing the sources (e.g. explosive techniques to remove turbine foundations).

The procedure for measurement and analysis of noise in this phase is similar to that for the construction phase (§4.6.3).

4.7 Data processing and analysis

In general, the following steps in the data processing and analysis procedure are followed:

1. Inspection of the digitized time signals of the hydrophone recordings: Do these exhibit the expected continuous or transient sounds? Are there unexpected disturbances? Do the signals show signs of overloading the maximum allowed amplitude of the measurement chain (‘clipping’)? Correct or discard erroneous recordings.
2. If required, apply digital low-, high- or band-pass filtering to the data, to limit the frequency content of the signal to the band of interest.
3. Select periods of the recordings for further analysis. If transient signals are to be characterized, these may be found automatically by checking where the signal exceeds a given threshold.
4. Convert the time signal amplitude to (micro)pascals, using a calibration factor that accounts for the sensitivity of the hydrophone and for the gain of amplifiers. If the response characteristics of the measurement chain are not uniform in the frequency range of interest, one has to correct for deviations by means of a digital filter before determining the broadband noise indicators in step 5.
5. Determine unweighted broadband noise indicators (e.g. sound pressure level, sound exposure level and peak acoustic pressure) from the selected periods of the time signal.
6. Convert the time signal in the selected periods to a 1/3-octave band frequency spectrum, either using an FFT analysis or via digital filtering with 1/3-octave band filters [IEC 61260:1995][16]. If the calibration corrections have not been applied in step 4, apply them here to the frequency spectra, using a frequency spectral representation of the calibration curves for the measurement system.
7. Analyse the statistics of the calculated noise indicators for the selected periods.

Note: depending on the purpose of the measurements one should consider the moment to apply the frequency corrections. Filtering the time signal might distort the phase information in the signal. Usually for purposes of measuring underwater sound this is no problem.

4.7.1 Analysis of continuous sound: SPL_{5s}

The unweighted broadband sound pressure level SPL_T, averaged over time T [s], can be obtained from the digitized time series of the sound pressure $p(t_n)$, recorded at a sample frequency f_s [Hz], using a computer implementation of the following formula:

$$\mathrm{SPL}_T = 10\log_{10}\frac{1}{Tf_s}\sum_{n=1}^{Tf_s}\frac{p(t_n)^2}{p_{ref}^2} \quad \text{in dB re 1 μPa}^2$$

A 1/3-octave band analysis of the unweighted sound pressure level $\mathrm{SPL}_T(f)$, averaged over time T [s], can be obtained by applying the same formula to the time

[16] Two options exist for determining an octave-band or fractional-octave-band, using a ‘base-ten’ or a ‘base-two’ frequency ratio. Here the base-ten system is preferred.

series after digital filtering with 1/3-octave band filters [IEC 61260:1995][16]. The broadband SPL_T should be equal to the power sum of the levels in the individual 1/3-octave bands. The 1/3-octave band spectrum can also be obtained via power summation of the narrowband levels within each 1/3-octave band.
A narrowband analysis of the unweighted sound pressure level $SPL_T(f)$, averaged over time T [s], can be obtained by power spectral analysis (FFT)[17].

4.7.2 *Analysis of transient sound: SEL, p_{peak} and τ_{90},*

Analysis of transient sounds starts with a manual or automated identification of the transient sounds in the recorded time series of the sound pressure. A section of the recording is then selected which contains the total of one single transient sound. The length of this section should not be longer than twice the duration of the transient sound.[18] The background noise is measured over a period of time before the transient occurs and then is subtracted from the cumulative sum-of-square pressures to determine the sum-of-square pressures from the impulsive sound alone. This is done by manually identifying a period of time (t_1,t_2) preceding the event, deemed to be representative of ambient noise. The mean-square ambient noise pressure (in µPa) is determined with the following relationship: $\overline{p_{amb}^2} = \frac{1}{t_2 - t_1} \sum_{n=t_1 f_s}^{t_2 f_s} p^2(t_n)/f_s$. The cumulative sound exposure $E_{cum}(t_n)$ of the selected period is then calculated as: $E_{cum}(t_n) = \frac{1}{f_s} \sum_n \left\{ p^2(t_n) - \overline{p_{amb}^2} \right\}$ [µPa²s].

Where the received pressure of the transient greatly exceeds the ambient noise, the correction for ambient noise may be omitted. Now, the 0% sound exposure point (t_0) is selected at the 'start' of the acoustic event, where the $E_{cum}(t_n)$ curve begins to rise, and the 100% sound exposure point (t_{100}) at the 'end of the event, where it levels off. Their selection can be difficult due to variation in ambient noise preceding (and overlapping) the acoustic event, as well as reverberation plus ambient noise following the event. Consequently, investigators identify these points subjectively. Next the cumulative exposure is recalculated for the duration of the event: $E_{cum}(t_n) = \frac{1}{f_s} \sum_{n=t_a f_s}^{t_b f_s} \left\{ p^2(t_n) - \overline{p_{amb}^2} \right\}$. Now $E_{100} = E_{cum}(t_{100})$ is 100% of the sound exposure. The 5% energy point is determined as $E_5 = E(t_5) = 0.05 \cdot E_{100}$ and the 95% energy point is determined as $E_{95} = E(t_{95}) = 0.95 \cdot E_{100}$. Thus, $E_{90} = E_{95} - E_5$ and duration $\tau_{90} = t_{95} - t_5$ [ms].

The unweighted broadband sound exposure level (SEL) is the decibel level of E_{100}:

$$\mathrm{SEL} = 10 \log_{10} \frac{E_{100}}{E_{ref}}$$ in dB re 1 µPa²s

A 1/3-octave band analysis of the unweighted sound exposure level SEL(*f*) can be obtained by applying the above formulae to the time series after digital filtering with 1/3-octave band filters [IEC 61260:1995].
A narrowband analysis of the unweighted sound exposure level SEL(*f*) can be obtained by power spectral analysis (FFT)[19] of the time signal over the 100%

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[17] We propose to apply the FFT to a block size of 1 second, so that the spectral resolution is equal to 1 Hz, with a 50% overlap and applying a Hann window.
[18] The analysis procedure for transient sounds is copied from [Southall et al 2007], Annex A
[19] For transient signal analysis, a flat top window should be applied.

energy duration τ_{100} ($=t_{100} - t_0$) and adding 10log(τ_{100}/t_{ref}) to the resulting level. Note that the spectral resolution will then depend on the duration of the transient, which makes it difficult to compare results of different transients. Where the received pressure of the transient greatly exceeds the ambient noise, the FFT can be applied to a time window of a fixed length (e.g. 1 s) that contains just one transient sound.

4.8 Data storage

All measured data (raw time data) and evaluated data must be kept available for further assessments for a period of ten years and must be handed over to the licensing authority on request. The data format has to be chosen in cooperation with the licensing authority.

In contrast with the large volumes of raw acoustic data, the volume of the processed broadband values and 1/3-octave spectra of the acoustic metrics, as described in §4.7, is of manageable size. It is recommended to investigate the possibilities for a central storage of the processed data and additional auxiliary (meta-)data. The maximum benefit of this central data storage would be achieve if a common format could be agreed on in an international context.

4.9 Information to be reported.

For all measurements carried out according to the proposed procedure, the following information, if relevant, shall be reported:

4.9.1 General description of the measurements

- Description of the purpose of the monitoring
  - background noise, specific sources, …
- Description of project and project phase
  - Number of turbines, type of foundation, planned activities, …
- Description of the site and its environment
  - Location, bathymetry, bottom type, distance to sensitive area’s, distance to shipping lanes, distance to other offshore activities, …
- Description and classification of sound sources
- Description of the measurements
  - Time and duration of measurements
  - Participants
  - General measurement conditions
    General quality of recorded data
  - Deviations from measurement plans and licensing requirements
  - Lessons learned

4.9.2 Experimental set-up

- Area map with measurement locations
- Description of equipment
  - Type, serial number, relevant specifications and calibration data of sensors
  - Mounting (including description of measurement platforms)
  - Hydrophone depth
  - Type of signal conditioning, recording system, power supply
  - Sample frequency, number of channels recorded

4.9.3 *Environmental conditions*

- Relevant bathymetry (including tidal variations)
- Bottom parameters (layers, type of sediment, density, compressional and shear wave speed, absorption, …)
- conductivity, temperature and hydrostatic pressure as a function of depth in the water column, sound velocity profile
- air-water temperature difference
- wind speed and direction (including measurement height above the sea surface) or ‘wind force’(Beaufort scale)
- wave height (‘sea state’, see §4.10)
- precipitation (rain, hail, snow), lightning, …
- AIS (Automatic Identification System) recordings
- Events (offshore activities, aircraft, distant explosions, etc.)

4.9.4 *Source properties*

- Relevant parameters describing the source activity.
- For pile driving:
  - Type of foundation (monopole, tripod, jacket, ...)
  - Pile geometry (diameter, length, wall thickness) and material properties
  - Mitigation measures (bubble screen, soft-start, …)
  - Hammer (type, nominal power, anvil geometry)
  - Total duration
  - Strike rate
  - Hammer energy per strike
  - Penetration into the sediment per strike
- For operating turbines:
  - Type of foundation and geometry and material properties
  - Type of turbine, details of generator and gearbox
  - Rpm and power versus time
  - Orientation of rotor versus time (adjustments)
  - …

4.9.5 *Results*

- Broadband and spectral representations of the various noise indicators and their statistical properties, as specified in §4.6.
- Information on the measurement uncertainty[20]
- Evaluation of the results

4.10 Remarks about units and presentation

- When reporting noise levels in decibels, the following principles should be applied [anon. 2011]:
  - State the physical parameter clearly
  - State the averaging time clearly
  - State the frequency bandwidth clearly
  - State the frequency weighting clearly

- Frequency spectra shall be preferably plotted according to the standard format
  - 10 dB = 20 mm, 1 octave = 15 mm (or at least with this aspect ratio)

[20] This proposal does not yet specify how to quantify mmeasurement uncertainty. This remains to be done.

- GPS longitude and latitude shall be reported with a definition of the reference system[21].

- ‘Sea state’ (Petersen’s scale) is an imprecise measure of wave height that is defined by different organisations in different ways. Thus it is open to misinterpretation and is unsuitable for scientific applications unless more precisely defined. Its use for scientific work is discouraged, but there may be occasions for which there is no good alternative

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[21] most GPS systems give latitude and longitude in the 1984 World Geodetic System -WGS84- but some outdated standards such as ED50 (European Datum 50) are still used in some systems

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- ISO 1996: Acoustics – Description, measurement and assessment of environmental noise. Part 1: Basic quantities and assessment procedure.
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- ISO 266:1997 'Acoustics – preferred frequencies'
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6 Signature

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