Joint Monitoring Programme for Ambient Noise North Sea
2018 – 2020

Acoustic metric specification

WP 6

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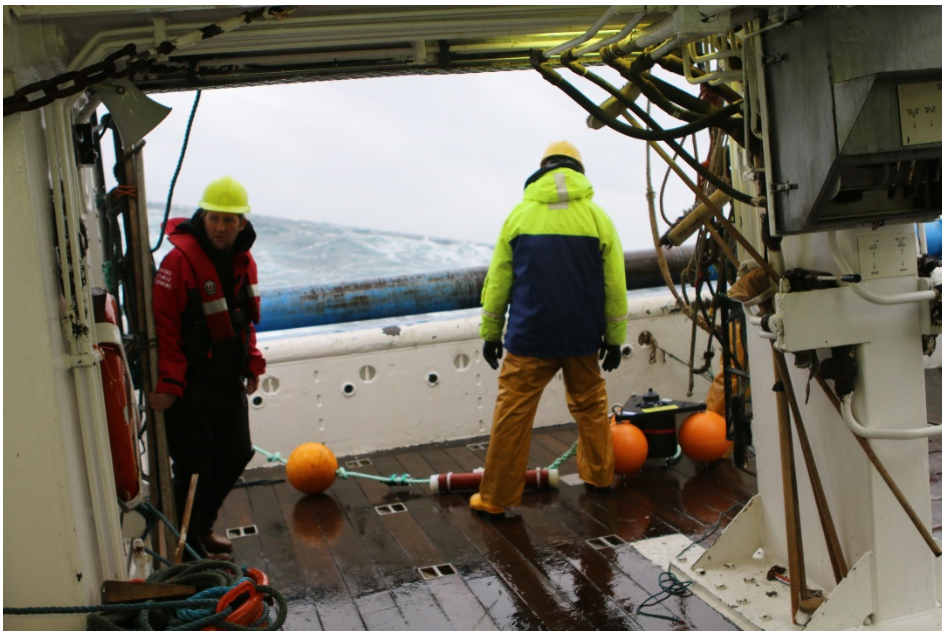

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Summary

This report specifies the acoustic metrics which will be used in the field measurements and acoustic modelling for the JOMOPANS project. These acoustic metrics will form the basis of acoustic indicators of anthropogenic pressure from continuous noise in the North Sea, and will inform the development of risk indicators when combined with species and/or habitat data (under work package 7).

The report sets out the context and rationale for the acoustic metric specification. The objective of the JOMOPANS project is to inform management of continuous underwater noise levels in the North Sea and to assess the risk of impact on marine life: the criteria for specifying the acoustic metrics have been defined accordingly. The first criterion for the metrics is ecological relevance, i.e. that the metrics used to measure and model underwater sound are reflective of the way that marine species are affected by sound. Secondly, the metrics must be realistic in terms of the practical constraints on monitoring, both for the field measurements and the modelling. Finally, the metrics should be tailored (where possible) to the requirements of environmental indicators for management, such as being easily understood by non-specialists.

The metrics are specified in each of four physical dimensions: physical quantity, time, frequency, and space.

- **Physical quantity**: sound pressure level (SPL), measured in decibels relative to 1 micropascal (dB re 1 μPa).
- **Temporal unit**: percentiles of the SPL distribution, based on individual SPL measurements of 1 second (snapshot duration). The period over which the percentiles will be computed is one month. Suggested percentiles are 5th, 10th, 25th, 50th, 75th, 90th, and 95th.
- **Frequency**: one-third octave bands, with centre frequencies between 10 Hz and 20 kHz, defined using the base-ten convention (ANSI 2009; IEC 2014).
- **Space**: Depth-averaged value of the metric either at the centroid of each grid cell, or as a spatial average of the levels within the grid cell. Geospatial grid referenced using the standardised C-square notation (Rees 2003).

This acoustic metric specification is consistent with the definition of MSFD Descriptor 11 Criterion D11C2, as stipulated in the 2017 European Commission decision (European Commission 2017). A detailed rationale for the selection of these parameters is provided herein. The report is structured in bulleted paragraphs for readability.

1 Introduction

- In the North Sea region, marine environmental policy on underwater noise pollution is coordinated through the OSPAR Convention, and most Contracting Parties to the OSPAR Convention in the North Sea region are also Member States of the European Union (presently, the only exception is Norway), which manages underwater noise pollution through the Marine Strategy Framework Directive (MSFD).
- The MSFD categorises noise pollution as either continuous or impulsive. Broadly speaking, impulsive noise is characterised by brief duration and fast rise time (the length of time taken to reach the peak sound level), and may be repetitive in nature (e.g. percussive pile driving) or not (e.g. detonation of unexploded ordnance). Continuous noise pollution, by contrast, is less variable and longer duration: examples include shipping, drilling, and dredging. This report, and the JOMOPANS project, address continuous noise pollution.
- We take as a starting point the MSFD indicator for continuous underwater noise pollution (D11C2), with the objective to define the metrics within the MSFD definition unless there are clear reasons to deviate from or augment this definition.
- Thus far, the MSFD D11C2 specification leaves open several aspects (temporal, spatial, and frequency) of the metrics to be used (text in square brackets added by authors):

> ***Annual average, or other suitable metric*** [temporal dimension] *agreed at regional or subregional level, of the squared sound pressure in each of two '1/3-octave bands', one centred at 63 Hz and the other at 125 Hz, expressed as a level in decibels in units of dB re 1 µPa, at* ***a suitable spatial resolution in relation to the pressure*** [spatial dimension]. *This may be measured directly, or inferred from a model used to interpolate between, or extrapolated from, measurements.* ***Member States may also decide at regional or subregional level to monitor for additional frequency bands*** [frequency dimension]. (European Commission 2017)

- Further to these MSFD-specific considerations, the acoustic metric needs to be relevant to assessing the risk of ecological impact, and to be feasible to measure, model, and map. These issues are addressed in the **Ecological relevance**, and **Monitoring considerations** sections below.
- Finally, the metric needs to meet generic **criteria for management indicators**, such as were discussed at the Hamburg TG Noise workshop in 2016, and outlined in Table 1, below.

Table 1. Criteria for the specification of indicators (Ferreira et al. 2016).

Criterion	Specification
Sensitivity	Does the indicator allow detection of any type of change against background variation or noise?
Accuracy	Is the indicator measured with a low error rate?
Specificity	Does the indicator respond primarily to a particular human pressure, with low responsiveness to other causes of change?
Simplicity	Is the indicator easily measured?
Responsiveness	Is the indicator able to act as an early warning signal?
Spatial applicability	Is the indicator measurable over a large proportion of the geographical to which it is to apply e.g. if the indicator is used at a UK level, is it possible to measure the required parameter(s) across this entire range or is it localised to one small scale area?
Management link	Is the indicator tightly linked to an activity which can be managed to reduce its negative effects on the indicator i.e. are the quantitative trends in cause and effect of change well known?
Validity	Is the indicator based on an existing body or time series of data (either continuous or interrupted) to allow a realistic setting of objectives?
Communication	Is the indicator relatively easy to understand by non-scientists and those who will decide on their use?

- **Strategy to define the acoustic metric.** The approach we have taken is to consider each of the physical dimensions of the acoustic metric in turn (physical quantity, time, frequency, space), and to optimise the acoustic metric definition such that it is as relevant as possible to the risk of ecological impact without compromising the generic nature of the acoustic metric. The feasibility to measure, model and map the metric are also key considerations, as are the generic criteria for indicators in Table 1.

2 Ecological relevance

- This section considers which effects are relevant to assessing the impact of continuous underwater noise pollution.

Masking

- Masking occurs when a listener is unable to detect, recognise, or interpret an acoustic signal due to the presence of some other confounding sound source (Clark et al. 2009).
- Rising levels of continuous noise pollution may reduce *communication space* - the range over which animals can communicate – due to masking (Clark et al. 2009; Hatch et al. 2012; Putland et al. 2018).
- Masking may result in missed opportunities to communicate, navigate, and forage, which could have significant effects at the population level.
- The risk of masking can be quantified in terms of the extent of communication space reduction and the percentage of time such a reduction occurs (Hatch et al. 2012; Putland et al. 2018), and in the form of a *range reduction factor* (Møhl 1981; Jensen et al. 2009), which expresses the ratio by which communication range is reduced under increased noise conditions.

Physiological stress

- Continuous anthropogenic noise has been shown to elicit physiological stress responses in marine mammals (Rolland et al. 2012), fish (Anderson et al. 2011), and invertebrates (Filiciotto et al. 2014).
- Chronically elevated levels of physiological stress are known to be detrimental to individual fitness, and may have consequences at the population level (Wright et al. 2007).

Behavioural responses

- Exposure to sources of continuous noise pollution can induce changes in behaviour, including displacement from habitat (Pirotta et al. 2013; Rako et al. 2013), disruption to foraging (Wale et al. 2013; Blair et al. 2016; Wisniewska et al. 2018), and impaired antipredator behaviour (Simpson et al. 2015, 2016). These effects may be interlinked with the effects of stress and masking.

Permanent or temporary auditory impairment

- TTS from continuous sources is possible but perhaps unlikely (Gervaise et al. 2013) – sustained exposure to high levels of continuous noise would be necessary. There is also the potential for long-term noise-induced hearing loss in marine mammals, which is known to occur in humans but is poorly understood in marine mammals.

Mortality

- Mortality due to physical trauma (barotrauma) from noise exposure is perhaps unlikely from continuous noise sources. Nevertheless, mortality is possible as a consequence of behavioural response to noise, e.g. stranding/decompression sickness in beaked whales.

3 Monitoring Considerations

- The total distribution of underwater sound levels is composed of natural and anthropogenic sounds, as illustrated in Fig. 1(a-c).
- The objective of monitoring is not to measure the total distribution of sound levels (Fig. 1c), but to measure levels of anthropogenic noise pollution (Fig. 1b). To understand the potential impact of underwater noise pollution, it also necessary to understand the extent to which noise pollution exceeds natural levels (Fig. 1c).
- However, in practice, only the total distribution of sound levels can be measured [Fig. 1(d)].
- Acoustic models can be used to estimate levels of natural and anthropogenic sound separately, and then combine them to predict what total distribution may be measured in a field recording [Fig. 1(e-g)]. However, to have any confidence in such predictions, they must be compared to field measurements and the error in the predictions quantified, a process we here term *validation* [Fig. 1(h)].
- While the acoustic metrics will summarise the measured and modelled sound level distributions (e.g. in the form of percentiles), the validation process will involve comparing the entire distribution of measured and modelled sound levels, to assist in identifying sources of disagreement between measurements and models.
- Ideally, the acoustic metric will be defined such that it can be robustly measured and modelled, and be directly relevant to ecological impacts and the management of human activities as described above.
- These considerations are revisited in more detail when we consider each physical dimension of the acoustic metric in the next section.

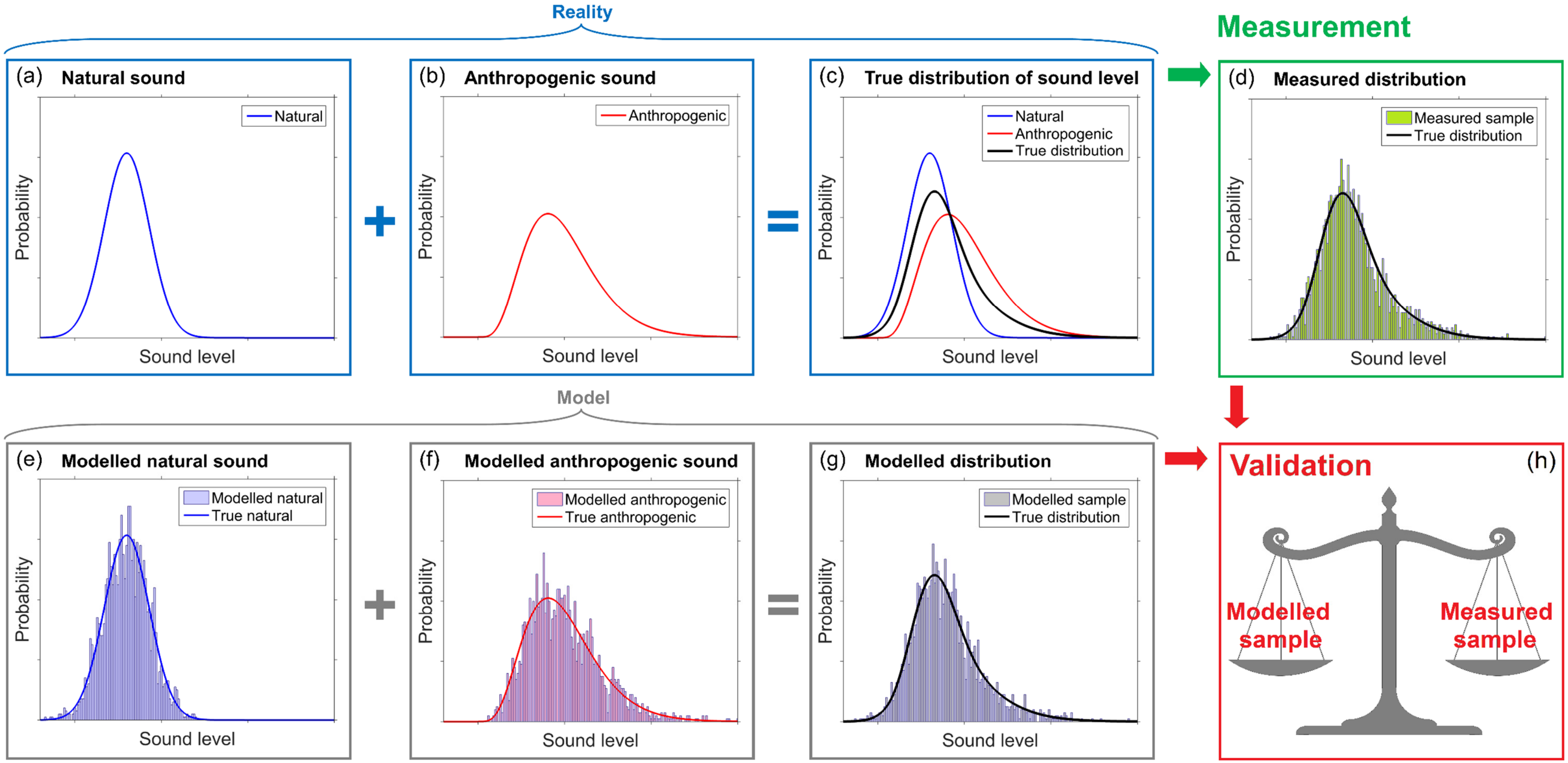

Figure 1. Schematic illustrating the constituent components of the underwater sound field [natural (a) and anthropogenic (b)] which combine to form the true distribution of sound levels (c), which can be measured (d), and modelled (g) based on models of the natural (e) and anthropogenic (f) components. The accuracy of the models is assessed by the process of validation (h), whereby model predictions at certain locations (g) are compared to measured sound levels (d) at the same site.

4 Physical dimensions of the acoustic metric

- The physical dimensions of the acoustic metric are (i) the physical quantity of sound, (ii) time, (iii) frequency, (iv) space. We consider each of these in turn below.

Physical quantity of sound

Context

- Sound can be understood to consist of two components: sound pressure and particle motion.
- It is necessary to define whether one or both of these components will be included in the metric.

Ecological relevance

- Most acoustically-sensitive marine organisms primarily sense particle motion (fish and acoustically sensitive marine invertebrates), while marine mammals sense sound pressure and some fish species can sense sound pressure indirectly via the swim bladder or gas-filled cavities near the ear.
- Evidence of impact from exposure to particle motion is not as clear or as substantial as for sound pressure (Popper et al. 2014).

Monitoring considerations

- Methodologies to measure (Nedelec et al. 2016) and model (Farcas et al. 2016) particle motion in the marine environment are far less developed than for sound pressure. However, sound pressure is proportional to particle motion in areas far from the sound source and away from boundaries (sea surface and seabed), and sound pressure may arguably be a suitable proxy for particle motion at the large scales considered in regional monitoring programmes such as JOMOPANS.

MSFD-specific considerations

- MSFD D11C2 is defined in terms of sound pressure (and particle motion is not mentioned in current MSFD monitoring guidance; Dekeling et al. 2014).

Conclusion: to adopt sound pressure as the physical quantity to be measured

Rationale: although particle motion is clearly the more relevant component of anthropogenic noise for non-mammals (i.e. the majority of acoustically sensitive marine organisms), the technology and methods to measure and model particle motion are underdeveloped, and evidence of impact in terms of particle motion is scarce. The opposite is true for sound pressure. Particle motion is also not explicitly considered in the MSFD or OSPAR indicator specifications, although this should not preclude the inclusion of particle motion if this is feasible.

Time

- The temporal dimension of the metric needs to be considered at two levels:

(i) **Summary metric**: the type of average or other temporal metric (e.g. percentiles) used to aggregate and summarise individual measurements of sound for target setting purposes. This includes the period over which the summary metric will be calculated (e.g. daily, monthly, yearly).
(ii) **Snapshot duration**: the period of time over which individual measurements or predictions of sound pressure are made.

Summary metric

Context

- A range of possible summary metrics are described in Table 2, below, and their position on an illustrative sound level distribution is shown in Fig. 2.

Table 2. Summary metrics considered (see Fig. 2 for comparison of typical relative values).

Metric	Description
Mode	The sound level with greatest probability to occur, i.e. the peak of the sound level probability distribution (see illustrative probability distribution in Fig. 2)
Median	50th percentile, i.e. the centroid value in the distribution of measurements
Geometric mean	Mean level computed after conversion to decibels
Arithmetic mean (a.k.a. RMS level, linear mean)	Mean level computed before conversion to decibels
Xth percentile	The sound level below which X% of the measurements occur.

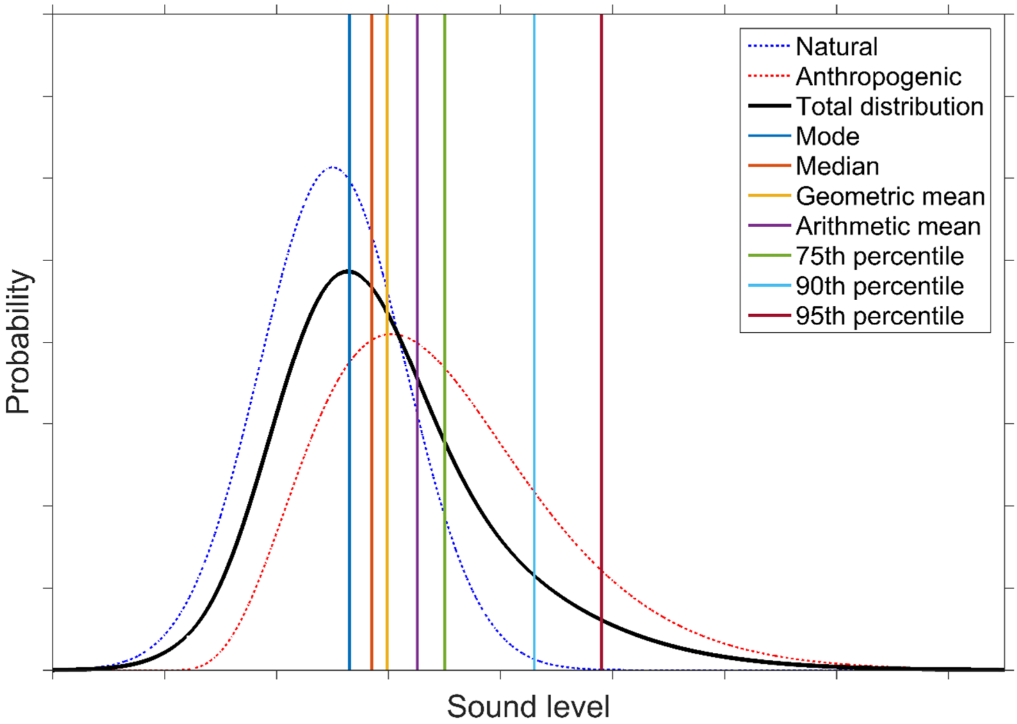

Figure 2. Schematic illustrating the position of each metric on a hypothetical sound level distribution (Total distribution). Note that the position of the arithmetic mean is highly variable depending on the spread of the right tail of the distribution. Also plotted are illustrative natural and anthropogenic components (red and blue dotted lines).

- **Exceedance levels vs. percentiles**: percentile means X% of the measurements are **below** this level (see Fig. 3 below), while exceedance level means X% of the measurements are **above** this level. For example, the 95th percentile is the level which is exceeded 5% of the time, while L_{10} (the notation used to specify the 10% exceedance level) is the level which is exceeded 10% of the time.

Ecological relevance

- The effects of primary concern for continuous noise are auditory masking and physiological stress. The risk of these effects can be understood in terms of the percentage of time in which sound levels exceed levels which are likely to induce such effects (Hatch et al. 2012; Putland et al. 2018).
- Since the abundance and distribution of animals (and their vulnerability to noise exposure) may vary seasonally, it will be more informative to managers to have indicators at more frequent intervals than annually.

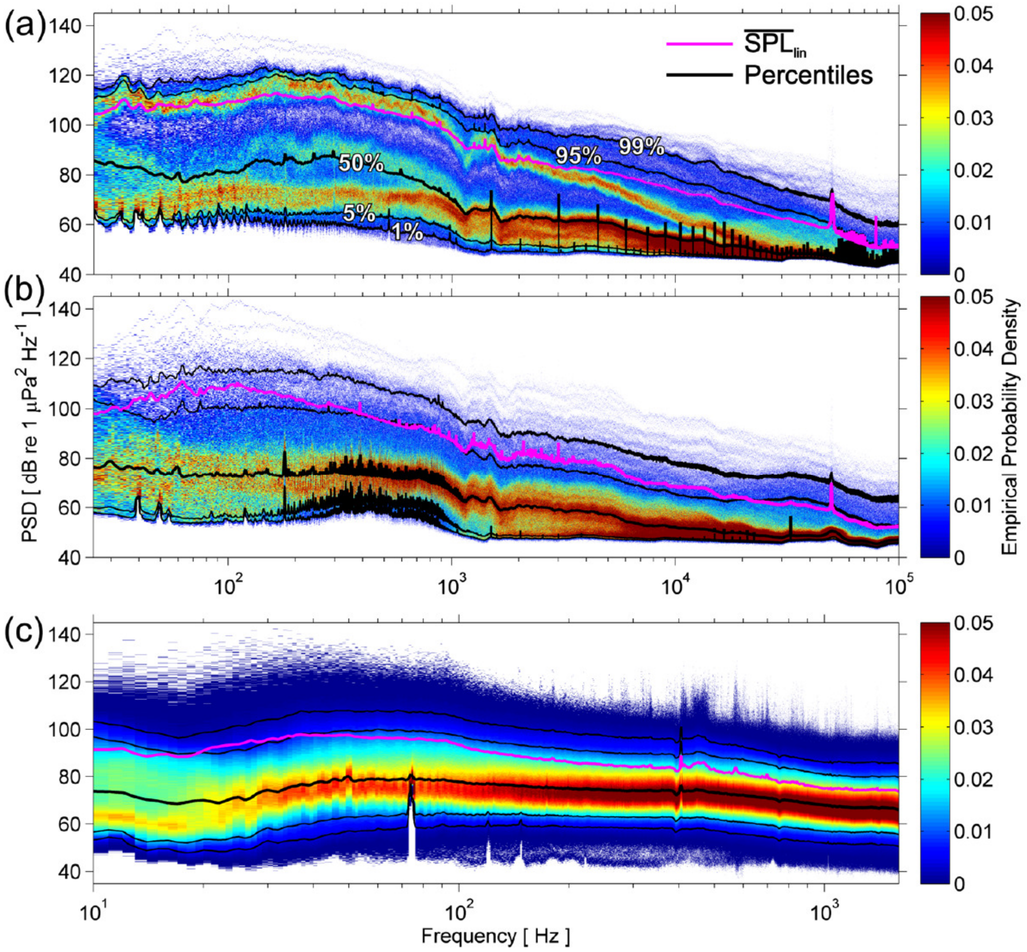

Fig. 3. Spectra from Merchant et al. (2013) illustrating the percentile metrics and the arithmetic mean (here termed $\overline{SPL}_{lin}$), together with the underlying noise level distribution (spectral probability density). (a) and (b) are from the Moray Firth in Scotland, (c) is from a shipping lane, the Strait of Georgia in British Columbia.

Monitoring considerations

- The purpose of monitoring is to measure levels of anthropogenic noise and the extent to which anthropogenic noise exceeds natural levels, not to measure the total distribution of sound levels (see Section 3). As illustrated in Fig. 1(c), noise levels from anthropogenic noise are prevalent at higher sound levels, while the natural background sound is prevalent at lower sound levels. For this reason, centroid metrics such as the mode, median and (geometric) mean are unlikely to be appropriate for monitoring, since they may be dominated by the natural background sound, which is not the target of monitoring (or management). Referring to the generic indicator requirements in Table 1, the mode, median and geometric mean would not meet the criteria of **sensitivity** and **specificity**.

- Measurements: ideally, field recordings will be closely screened for extraneous sources of noise, such as noise from the mooring. However, for long-term monitoring this is unlikely to be practicable. It is therefore important that the metric used is robust to outliers in the sound level distribution, since the objective is to monitor overall levels of noise pollution and how these may be changing. While metrics based on percentiles of the distribution are robust to statistical outliers, mean levels are not, particularly the arithmetic mean, which can be highly skewed by unrepresentative high noise levels (Merchant et al. 2012). This is evident in Fig. 3(c), from measurements made in a shipping lane outside the Port of Vancouver, in which at low frequencies the arithmetic mean exceeds the 95th percentile, yet approaches the median at higher frequencies. The fact that this metric is decoupled from the temporal distribution of decibel levels presents problems for the relevance to effects such as masking and physiological stress, where it is relevant to consider how much time sound levels may exceed a particular level. Furthermore, the counterintuitive scaling of this metric also presents challenges for communication to non-specialists, since interpreting the metric requires in-depth knowledge of acoustical metrology, whereas percentiles can be easily communicated in the form ‘X% of the time the sound is below this level’. Referring to the generic indicator requirements in Table 1, the arithmetic mean does not meet the criteria of **communication**, and there would be concerns regarding **sensitivity** and **accuracy** for the reasons above.
- Of the metrics in Table 2, this leaves percentiles remaining. Percentiles are statistically robust, temporally representative, and (if a suitable percentile is chosen) sensitive to changes in anthropogenic noise. The question then is: which percentile is most appropriate for the acoustic metric?
- **Picking a percentile: responsive vs. representative.** The trade-off in selecting a percentile for noise monitoring is between having a representative metric (closer to the median, 50%) and having a metric which is highly responsive to changes in anthropogenic noise levels (closer to 99%). For the reasons given above, it is preferable to avoid centroid metrics, as these may be more reflective of natural sound levels than anthropogenic noise. Conversely, going too high in the distribution (e.g. 99%) risks basing the metric on unrepresentative outliers. For this reason, we suggest that using a percentile higher than the 95th percentile is not advisable.
- Previous studies have advocated using the 95th percentile (Merchant et al. 2016; Heise et al. 2017) or 90th percentile (Merchant et al. 2016). It is worth noting that L_{10}, equal to the 90th percentile, is used in terrestrial acoustics for noise assessment of transient anthropogenic events (e.g. aircraft passing), since it “is largely determined by transient events and is less sensitive to background sound levels” (Mennitt et al. 2014).
- Since the oceanographic conditions and the level and distribution of human activities will vary seasonally, it will be more informative to managers to have indicators at more frequent intervals than annually.

MSFD-specific considerations

- D11C2 specifies “Annual average, or other suitable metric,” which leaves the definition of summary metric open to interpretation.

Conclusion: to use a range of percentiles of the sound level distribution, e.g. 5, 10, 25, 50, 75, 90, 95; and to retain the underlying sound level distribution for validation purposes. It is suggested to compute the percentiles on a monthly basis.

Rationale: considering the alternative summary metrics, the mode, median and geometric mean lack sensitivity to the anthropogenic component of the sound level distribution, while the arithmetic mean is not robust to outliers, is not representative of the temporal distribution of sound levels, and has a counterintuitive scaling which is challenging to communicate. By contrast, percentiles in the upper quartile of the sound level distribution (and below ~95%) do not have these drawbacks. Including percentiles in the lower quartile (5%, 10%, 25%) will allow understanding of whether there are ‘noise-free’ periods or if noise is persistent most of the time. By specifying a range of percentiles which broadly covers the sound level distribution, the agreement between measurements and modelling can be more fully understood. Similarly, by computing the metrics on a monthly basis, managers will be able to identify seasonal periods of greater risk, and respond accordingly.

Snapshot duration

Context

- Individual measurements of sound level need to be made over some specified and standardised duration.

Ecological relevance

- The sound level perceived by marine animals is related to the temporal period over which the auditory system integrates the sound it receives, known as the *auditory integration time*.
- To ensure that the level and variability in sound levels received by marine fauna are accurately reflected in acoustic monitoring, the snapshot duration should ideally be comparable to the auditory integration time.
- The auditory integration time for marine mammals is similar to that of humans, at ~0.1 s (Johnson 1968; Kastelein et al. 2009, 2010; Tougaard et al. 2015); for fish and invertebrates this is unclear.

Monitoring considerations

- Measurements: To compute 1/3-octave bands at 63 and 125 Hz (as stipulated by MSFD D11C2) using the discrete Fourier transform (DFT) method, a longer snapshot duration than 0.1 s may be required. This is because frequency resolution varies inversely with snapshot duration, and there may be insufficient resolution at low frequencies to compute the 63 and 125 Hz bands within a 0.1 s snapshot.
- The BIAS joint monitoring project in the Baltic Sea used a 20-second average. This was not on the basis of a scientific rationale, but was the shortest snapshot duration which was permitted for data sharing by national defence restrictions.
- Note that although the snapshot duration will be identical for both field measurements and modelled predictions, the duty cycle may differ (i.e. the number of snapshots measured during a monitoring period). Since both field measurements and models will be designed to acquire sufficient data to provide representative samples of the noise level distribution, this should not affect the validity of the comparison between measurements and models.
- To test the effect of snapshot duration on the statistical distribution of measurements, a sample week of data was analysed from a UK monitoring location known as WARP, situated to the east of the Thames estuary (51°31’.907N, 001°02’.804E). Measurements were made using an Ocean Instruments New Zealand Soundtrap 300HF, on a duty cycle of 15 minutes on / 15 minutes off at a sampling rate of 48 kHz. A sample week of data (15-21 August 2017) was analysed using three different snapshot durations: 0.1 s, 1 s, and 60 s. Figure 4 shows the resulting statistical distributions, percentile values, and deviation from the values using the 0.1-s snapshot duration, for the 125-Hz 1/3-octave band. The results demonstrate that the 60-s snapshot duration deviates further from the most ecologically relevant value (0.1 s) than the 1-s snapshot duration. This result also applies at a range of other frequencies, for both the 50th percentile (median) and 90th percentile, as shown by the decibel differences and overall RMS errors in Table 3.

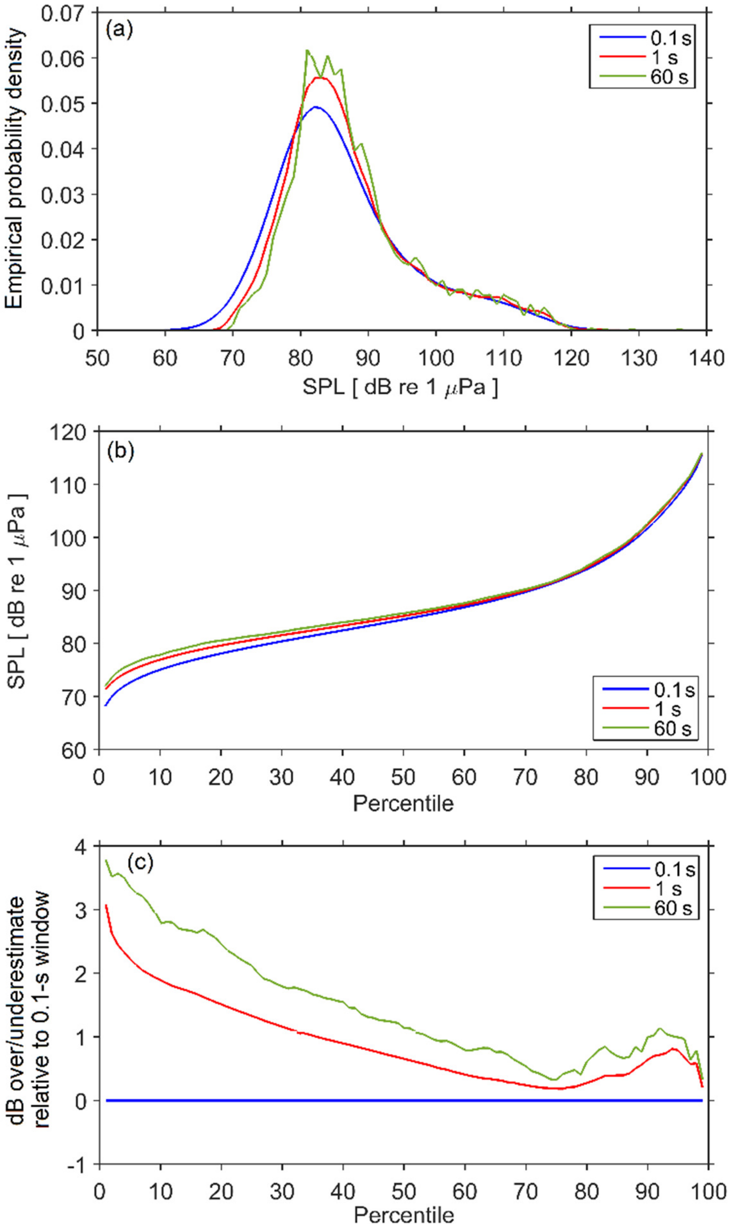

Fig. 4. Comparison of noise level statistics in the 1/3-octave band centred at 125 Hz measured over a one-week period using different snapshot windows: 0.1 s, 1 s, and 60 s. (a) Empirical probability densities; (b) Percentile values; (c) Deviation of each percentile from 0.1-s values.

Table 3. Measured values of the 50th percentile (median) and 90th percentile for a one-week sample period using different snapshot durations across a range of selected 1/3-octave frequency bands. All values are in dB re 1 μPa.

Snapshot duration (s)	**Metric**	**1/3-octave band centre frequency**						**RMS error**
		63	**125**	**250**	**500**	**1,000**	**10,000**	
0.1	50th %ile	87.87	84.52	90.22	91.22	86.76	80.92	-
1	50th %ile	90.77	84.67	89.17	92.19	89.02	81.26	-
	Difference to 0.1-s value	2.9	0.15	-1.05	0.97	2.26	0.34	**1.62**
60	50th %ile	92.72	85.43	89.49	92.33	89.15	81.49	-
	Difference to 0.1-s value	4.85	0.91	-0.73	1.11	2.4	0.57	**2.15**
0.1	90th %ile	104.76	101.6	102.35	101.28	94.85	85.57	-
1	90th %ile	105.66	101.54	102.25	102.49	97.91	85.94	-
	Difference to 0.1-s value	0.9	-0.07	-0.11	1.21	3.07	0.37	**1.3**
60	90th %ile	105.89	101.76	102.41	102.64	97.96	85.73	-
	Difference to 0.1-s value	1.13	0.15	0.05	1.36	3.12	0.16	**1.36**

MSFD-specific considerations

- The snapshot duration is not specified, although TSG Noise guidance from 2014 recommends a snapshot duration of not more than 1 minute (Dekeling et al. 2014).

Conclusion: snapshot duration of 1 second.

Rationale: while a snapshot duration of ~0.1 s would more closely reflect the mammalian auditory integration time, in practice this will be significantly more challenging to measure than a slightly longer duration of 1 s. If the snapshot duration is too long, it will smooth out variability in sound levels in a way which no longer reflects the risk of impact to the animal. Analysis of field measurements demonstrates how the 1-s snapshot window results in lower deviation from a 0.1-s snapshot duration than the 60-s window (Table 3). A snapshot duration of 1 s is therefore proposed as a pragmatic compromise between these factors. The BIAS programme, which monitored ambient noise for MSFD in the Baltic Sea, used a 20-second snapshot duration, but this was due to national defence restrictions and not considered optimal from a scientific perspective.

Frequency

Context

- Human activities emit noise at a range of frequencies, and marine species are sensitive to sound within specific frequency ranges. The risk of impact will therefore depend on how much noise pollution is present within relevant frequencies for a particular species. To manage underwater noise pollution effectively, it is therefore necessary to ensure that the metric covers frequencies that will be relevant for acoustically sensitive species in the North Sea.
- For the MSFD, the initial approach has been to adopt a proxy approach, whereby the default frequencies are currently the 1/3 octave bands centred at 63 and 125 Hz, intended as proxies for shipping noise. However, these bands may not be most representative of shipping noise in the North Sea (Merchant et al. 2014) or of risks to key North Sea species (e.g. harbour porpoise; Hermannsen et al. 2014). Following the 2017 Commission Decision, EU Member States now have the option to add further monitoring frequencies.

Ecological relevance

- Taxa which primarily sense particle motion are also generally most sensitive to sound below a few hundred Hz. For this reason, the existing low-frequency bands may be acceptable proxies for invertebrates and most fish.
- This is not the case for some marine mammal species. The marine mammals commonly occurring in the North Sea have been summarised by ICES:

> *Two species of seal occur commonly in the North Sea:* ***grey seal*** Halichoerus grypus *and* ***harbour seal*** Phoca vitulina*. Four cetacean species occur commonly or are resident****: minke whale*** Balaenoptera acutorostrata*,* ***harbour porpoise*** Phocoena phocoena*,* ***white-beaked dolphin*** Lagenorhynchus albirostris*, and* ***bottlenose dolphin*** Tursiops truncatus*. A further five species are considered regular but less common, short-beaked common dolphin* Delphinus delphis*, Atlantic white-sided dolphin* Lagenorhynchus acutus*, long-finned pilot whale* Globicephala melas*, killer whale* Orcinus orca*, and Risso's dolphin* Grampus griseus*.*[1]

- Taking the commonly occurring species, it may be argued that pressure on minke whale may be sufficiently represented by the existing 63 and 125 Hz bands, while the seals and small cetaceans species may require higher frequencies to be monitored, since their hearing is most sensitive at higher frequencies, from around 1-25 kHz for harbour seal (Kastelein et al. 2009), up to ~100 kHz for harbour porpoise (Kastelein et al. 2002).

Table 4. Species groups and the relevance of the default 63 and 125 Hz MSFD 1/3-octave bands.

Species/group	63/125 Hz appropriate proxy?
Fish and invertebrates	Yes, although possibly higher frequencies needed e.g. for herring
Minke	Possibly, although no data on hearing sensitivity, and vocalisations reported extend up to ~800 Hz (Winn & Perkins 1976; Risch et al. 2013)
Harbour seal and grey seal	Unlikely since this doesn't cover frequency range of greatest sensitivity
Harbour porpoise	Unlikely since this doesn't cover frequency range of greatest sensitivity
Various dolphin	Unlikely since this doesn't cover frequency range of greatest sensitivity

- To better address the risk of impact to harbour porpoises, seals, and herring, the BIAS joint ambient noise monitoring project in the Baltic Sea supplemented the 63 and 125 Hz bands with an additional 1/3 octave band centred at 2 kHz (Nikolopoulos et al. 2016).

Monitoring considerations

- Measurements: the sampling frequency at which recordings are made limits the upper frequency of recording. Higher sampling frequencies allow a higher upper frequency limit, but

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[1] http://www.ices.dk/explore-us/Action%20Areas/ESD/Pages/Greater-North-Sea-Key-State-Marine-mammals.aspx

also generate more data. Since the endurance of autonomous recording devices is limited in part by data storage capacity, this imposes an upper frequency limit on recording for a specific duty cycle and deployment duration.

- In areas with substantial tidal flow, flow noise caused by turbulence around the hydrophone may make the recordings unusable. Flow noise increases with decreasing frequency (Strasberg 1979), meaning the 63 and 125 Hz bands may be particularly affected, as acoustic monitoring in the North Sea has already demonstrated (Merchant et al. 2014).
- Although some marine mammal species have sensitive hearing up to many tens of kilohertz, the value of monitoring noise levels at such high frequencies is doubtful, since sound is attenuated much more quickly at high frequencies, and so any effects of noise at high frequencies are likely to be highly localised. As a result, in the case of shipping, for example, a map of risk from high-frequency shipping noise may look very similar to a simple map of shipping densities. Monitoring at higher frequencies therefore offers diminishing returns as frequency increases, and a balance needs to be reached between relevance to the species and the added value of the metric for monitoring anthropogenic pressures.
- Modelling: at higher frequencies, flux-based modelling methods can be applied which have fast computation times even at tens of kilohertz, so there is no constraint on frequency from the modelling perspective.

MSFD-specific considerations

- 1/3 octave bands centred at 63 Hz and 125 Hz are mandated, although there is scope to add further frequencies as appropriate. The 2014 TSG Noise monitoring guidance (Dekeling et al. 2014), which predates the 2017 Commission Decision, recommends monitoring in 1/3-octave bands centred between 10 Hz and 20 kHz.

Conclusion: to monitor within the 1/3 octave bands centred between 10 Hz and 20 kHz. The frequency range required to encompass to lower and upper bounds of these bands is 8.91 Hz to 22.44 kHz.

Rationale:

Ecological relevance: Monitoring at 1/3-octave bands within this wide frequency range provides coverage of the frequencies used by most marine species. It will also allow subsequent analysis and indicators based on these metrics to use approaches such as auditory weighting to better reflect the risk of impact based on the frequency composition of noise. The approach of adding a single 1/3 octave band at higher frequencies, such as the 2 kHz band added by the BIAS project (see above), would not support this kind of analysis.
Monitoring considerations: Although this frequency range covers most species, some high-frequency specialists such as echolocating harbour porpoises and dolphin species will not have the full extent of their acoustic range covered (up to ~150 kHz for harbour porpoise). However, due to the high sampling rates required to monitor at these high frequencies (which generate large volumes of data), monitoring at these frequencies is not practical since the autonomous recorders would need to be serviced frequently, substantially increasing costs. Since high-frequencies do not propagate as far underwater, any effects of noise at these frequencies are also likely to be highly localised, and may be correlated to noise levels at lower frequencies already covered by the monitoring. The upper limit of the 20 kHz 1/3-octave band suggests a sampling rate of ~48 kHz (giving a Nyquist frequency of 24 kHz, which allows for frequency roll-off and the fact that the upper frequency limit of the band is 22.4 kHz) is achievable for longer deployments on most autonomous systems.
Management relevance: monitoring across a range of frequencies will allow the specification of pressure and impact indicators which are more targeted for particular species or species groups (compared to using a small number of ‘proxy’ frequency bands, such as the 63 and 125 Hz bands). This should enable the resulting indicators to be more sensitive to relevant pressures and risks of impact.

Space

Context

- The acoustic metric needs to be mapped to inform management/MSP and to understand risk.
- Although indicators tend to be mapped in two dimensions, the marine environment is a three-dimensional space and noise levels may vary significantly in all three dimensions, including depth.
- It is therefore necessary to define not only the spatial resolution in latitude and longitude (or northings and eastings), but also the way in which depth will be considered, both in monitoring noise levels and when mapping the metric.

Ecological relevance

- Ideally, the spatial resolution adopted will be relevant to the scale of habitat use and distribution of species in the North Sea. However, the resolution of abundance and distribution data may not support fine-scale assessment of risk, and for pressure and risk maps at the North Sea scale, spatial resolution at finer scale than several km may add little to the assessment. If it is considered appropriate to focus on smaller areas for particular species (e.g. exposure around seal colonies; Jones et al. 2017), then finer resolution may become relevant.
- Since continuous noise pollution may vary significantly with depth (Chen et al. 2017), the exposure of animals will vary depending on behaviour (e.g. foraging dives) and habitat (benthic or pelagic). In some cases, there may be sufficient data to incorporate depth dependence into risk indicators, however for the generic acoustic metric it may be more relevant to average over depth.

Monitoring considerations

- Spatial averaging: depending on the underlying resolution of noise modelling, mapping the metric may require noise levels to be averaged in space to give a specified spatial resolution. In this case, it would be necessary to define how the average will be computed (i.e. using which metric and why, and the underlying spatial resolution to be averaged).
- Alternatively, it may be considered appropriate to model a point located at the centre of a gridded polygon (the centroid) as representing the value for the entire polygon. If the spatial resolution is sufficiently high, this may yield sufficient accuracy for the noise maps.
- Whichever approach is used, it will be necessary to have a standardised method of defining the spatial grid. A grid-referencing system known as "C-Squares" has been developed for this purpose (Rees 2003), and is used by ICES and others.

MSFD-specific considerations

- D11C2 suggests percentage area or units of km^2: "per unit area and its spatial distribution within the assessment area, and the extent (%, km^2) of the assessment area over which the threshold values set have been achieved." (European Commission 2017)

Conclusion: for indicator maps to represent the depth-averaged value of either the centroid of each grid cell, or the spatially averaged value of the metric for each grid cell.

Rationale: depth-averaging is the most pragmatic and straightforward way of addressing the depth dimension, although this may not be desirable in very deep waters (e.g. the Norwegian trench) where there is more stratification in the use of habitat by acoustically sensitive species, with harbour porpoises, dolphins, baleen whales and seals present in waters shallower than ~200 m, and only demersal fish and deep diving odontocetes at greater depths. The Norwegian trench will therefore be considered a special case. To quantify the uncertainty that depth averaging introduces compared to a depth-dependent approach, representative sites will be modelled at a range of depths. This will provide information on the variability of noise levels with depth, and the implications for risk assessment of particular species/taxa which inhabit certain depth layers (e.g. benthic or pelagic species). Mapping the centroid value avoids the issue of spatial averaging, while spatial averaging will require a method of averaging to be agreed which may affect the resulting values significantly. This specification is consistent with MSFD units of % area or km^2.

5 Acoustic metric specification

- The acoustic metric specification is summarised in Table 5, below.
- As intended, this definition is compatible with the existing definition of the MSFD Indicator (European Commission 2017).

Table 5. Acoustic metric specification.

Attribute	Specification
Physical quantity	Sound pressure level, dB re 1 μPa
Snapshot duration	1 second
Summary metric	Percentiles of the sound pressure level distribution measured over one-month periods. Suggested percentiles: 5, 10, 25, 50, 75, 90, 95
Frequency	1/3 octave bands, with centre frequencies ranging from 10 Hz to 20 kHz, defined according to the base-ten convention (ANSI 2009; IEC 2014)
Geospatial	Depth-averaged value either at the centroid of each grid cell, or as a spatial average of the levels within the grid cell. Grid referenced using the standardised C-square notation (Rees 2003).
Depth	Depth averaged (energy-wise)

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