DEMASK | Interreg North Sea | Co-funded by the European Union

Saturn – Developing Solutions for Underwater Radiated Noise

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DEMASK-SATURN acoustic metrics workshop report

On 27 May 2025 DEMASK organized in close co-operation with SATURN a workshop on **acoustic metrics for underwater noise**. This report summarizes the workshop and input provided by participants after the workshop.

Christ de Jong, TNO, 7 November 2025

1. Introduction

Over the last 15 years various projects have made their own choices for the acoustic metrics that are presented in underwater sound maps for assessing the pressure on the environment and the impact on aquatic life. The Interreg North Sea Region project DEMASK is in the process of making these choices and took the opportunity of the final event of the EU Horizon 2020 project SATURN to organize a joint workshop to discuss the advantages (pros) and disadvantages (cons) of different choices.

2. Objectives

Both projects acknowledge that there is not one answer for the 'best' metric to be used. The objectives of the workshop were:

- to share information on the choices made by various projects
- to share information on the rationale behind these choices
- to discuss the pros and cons of various selected metrics

3. Agenda

The program of the workshop was:

11.15 Introduction by Niels Kinneging.
11.30 Collecting information on metrics and rationale for different projects, led by Christ de Jong.
12.50 Summary of morning session by Niels Kinneging
13.00 Lunch break.
14.00 Relation of metrics and biological effects by Katharina Grunert
14.15 Discussion on pros and cons, led by Jeff Schnitzler and Christ de Jong.
15.45 Wrap-up and close by Gerry Sutton and Niels Kinneging.

4. DEMASK and SATURN

DEMASK

Niels Kinneging provided a short summary of the Interreg North Sea Region project DEMASK[1]. The project is developing an approach for defining policy scenarios for underwater noise management and a method to quantify the effectiveness of those scenarios to mitigate noise pollution and its effects on marine life. DEMASK envisions assessing the impact of the various policy scenarios on aquatic species by combining sound maps with species distribution maps, incorporating available information on species sensitivities to sound exposure. DEMASK builds on the North Sea sound maps produced by the Interreg North Sea Region project JOMOPANS[2].

SATURN

The workshop was organised in collaboration with the EU Horizon 2020 project SATURN (Solutions AT Underwater Radiated Noise)[3] at the occasion of the SATURN final event in Brussels on 26-27 May 2025. SATURN has investigated solutions to the problem of underwater radiated noise (URN) caused by shipping and other vessels. This included studies of the sensitivity of some marine mammal, fish and marine invertebrate species to URN exposure as well as studies of technical and operational measures to reduce URN exposure. In the context of the discussion on sound maps and acoustic metrics, SATURN developed an acoustical terminology standard[4], guidelines for sound particle motion mapping[5], and tools to include URN in marine spatial planning[6].

5. Underwater sound mapping in European projects

Various European projects have produced underwater sound maps in response to the EU Marine Strategy Framework Directive, that requires addressing the potential negative impact of underwater noise on marine life. Several of the institutes and companies that created these sound maps were represented in the workshop (in arbitrary order):

- JASCO (Özkan Sertlek): Sound maps for all European seas for the EMSA project NAVISON[7]
- Quiet Oceans (Thomas Folegot): Sound maps for Baltic sea (BIAS[8]/HOLAS-3[9]), Atlantic (JONAS[10]), Irish Sea (STRIVE[11]), North-Adriatic Sea (SOUNDSCAPE[12]/ SATURN[3]), Mediterranean (PIAQUO[13]) and Kattegat (TANGO[14]).
- SHOM (Laura Ceyrac, online): Sound maps for Atlantic (JONAS[10]) and Mediterranean Sea (QUIETSEAS[15])
- CEFAS (Adrian Farcas): Sound maps for UK seas
- TNO (Christ de Jong): North Sea sound maps for DEMASK[1], JOMOPANS[2]

The sound map metrics selected for these projects were discussed in the workshop, see below.

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[1] https://www.interregnorthsea.eu/demask
[2] https://northsearegion.eu/jomopans/
[3] https://www.saturnh2020.eu/
[4] SATURN deliverable D2.3
[5] SATURN deliverable D2.2
[6] https://doi.org/10.1016/j.marpol.2023.105725
[7] https://www.emsa.europa.eu/navison.html
[8] https://biasproject.wordpress.com/
[9] https://stateofthebalticsea.helcom.fi/
[10] https://www.marei.ie/project/jonas/
[11] (Sutton, Jessopp, Folegot, & Clorennec, 2014)
[12] https://programming14-20.italy-croatia.eu/web/soundscape
[13] http://lifepiaquo-urn.eu/en/home/
[14] (Tougaard, et al., 2023)
[15] https://quietseas.eu/

6. International context

Michael Ainslie (JASCO, online) drew attention to the international initiatives to harmonize underwater sound monitoring, such as the IQOE monitoring guidelines[16] and ISO 7605[17] ('Underwater acoustics — Measurement of underwater ambient sound', now in the final draft stage). These specify metrics that are relevant for the comparison of sound maps with local measurements.

- The IQOE guidelines require reporting SPL statistics (arithmetic mean and 10th, 25th, 50th, 75th and 90th percentiles), over a month (TAW), with TOW = 60 s, for the decidecade bands from 10 Hz to 1 kHz.
- ISO 7605 (to be published in 2025) requires reporting SPL statistics (arithmetic mean and 10th, 25th, 50th, 75th and 90th percentiles), for each measured UTC day (TAW), with TOW = 60 s, in decidecade bands.

7. Sound map metric considerations

There are no standards for creating underwater sound maps. Sound maps for assessing the pressure on the environment and the impact on aquatic life ideally show metrics that are

- suitable for policy advice on the effectiveness of mitigation measures,
- relevant in context of MSFD thresholds,
- related to characteristics of sound sources,
- related to potential effects on aquatic animals,
- useful for quantifying potential effects on animal populations,
- comparable between projects.

Potential effects of underwater sound on marine animals include:

- masking of relevant sounds,
- behavioural responses, distracting animals from foraging, mating, predator avoidance and other essential activities,
- physiological effects (stress), including effects on growth and early-life development,
- possible injury or even mortality by (cumulative) exposure to very loud sounds.

Different effects may be caused by different sound characteristics.

Underwater sound varies in time, space and frequency. Sound characteristics can be summarized in various acoustic metrics, depending on the specification of:

- quantity (sound pressure, sound particle acceleration, sound exposure, sound energy, etc.)
- frequency bandwidth and/or frequency weighting,
- averaging or integration time for individual observations (temporal observation window; TOW),
- averaging or integration volume for individual observations (spatial observation window; SOW),
- temporal and spatial analysis windows (TAW and SAW),
- temporal, spatial and frequency resolution.

frequency

To cause masking or behavioural disturbance the sound exposure needs to occur within the animal hearing range. Sound mapping projects account for this by selecting representative frequency bands within the hearing range of the relevant species. Projects that have calculated sound metrics over a broad range of frequencies could also calculate frequency-weighted sound pressure levels, as suggested by different authors (Tougaard, Wright, & Madsen, 2015; Southall, et al., 2019; Lucke, et al., 2024). Auditory frequency weighted metrics are specific for one species (group), requiring multiple sound maps for assessing the impact on multiple species.

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[16] https://scor-int.org/IQOE/IQOE_2019_Standards_Workshop_Report.pdf
[17] https://www.iso.org/standard/82844.html

temporal aspects
Exposure to sound is never stationary in time. Sound sources change their operation over time and the distance between sources and receivers generally varies as well. Moreover, temporal sound characteristics can be very different (e.g. impulsive versus continuous, but also absence or presence of amplitude modulation, tonal versus broadband and other aspects that affect the 'roughness' of the sound). The considered acoustic metrics for 'continuous' sound involve averaging over a temporal observation window (TOW). Temporal aspects that occur on a time scale shorter than the duration of the TOW are not explicitly captured. Animals may be more sensitive to disturbance during specific times (day, night, dusk, dawn, season). Also, the activities of some sound sources vary over time (e.g. recreational vessels are more active during day time and weekends). Representing multiple time periods requires multiple sound maps.

spatial aspects
Sound exposure varies with location. Sound maps present the geospatial distribution of selected sound metrics for a specified depth or range of depths. Different depth ranges are relevant for different aquatic animal species. The plotted metrics are calculated at grid points or averaged over specified spatial observation windows.

sound map calculations
Calculating sound maps requires models for sound sources and sound propagation, and all relevant input data for these models, including locations and characteristics of sound sources and environmental characteristics such as water depth, sound speed profile and acoustic properties of the seabed.

sound map metrics
The SATURN D2-3[18] 'Bioacoustics and ship acoustics terminology standard' provides definitions relevant for sound map calculations. Frequency-domain sound map calculations calculate the 'steady state sound pressure level' (SSSPL, see Table 1) for a specified static distribution of source and receiver points (and a specified TOW, TAW and frequency), sometimes referred to as 'snapshot'. Resulting sound map metrics can be selected statistic of calculated SSSPL maps for multiple time steps within the TAW, but some projects use selected time statistics of the source distribution and the corresponding 'areic source level' as input for the sound map calculation. Table 1 provides a definition for areic source level. Calculation of areic source level for shipping sound maps is not standardized.
The excess level definition from SATURN D2-3 applies to the instantaneous difference between 'all ambient sound' and 'natural ambient sound'. Some projects use the same term for the difference between the instantaneous SPL of 'all ambient sound' and the mean or a specified temporal percentile of 'natural ambient sound'.

Table 1 definitions of 'steady-state sound pressure level', 'excess level' and 'steady-state source level', from the SATURN D2-3 bioacoustics and ship acoustics terminology standard, and of 'areic source factor spectral density' and 'areic source factor spectral density level' from the ADEON terminology standard[19].

Term	Definition
steady state sound pressure level abbreviation: SSSPL unit: dB	for specified sources, sound pressure level that would arise (at position x) if the specified sources were stationary at their actual positions, but with the same steady state source level that the sources would have had if they had remained moving at their actual speed **remarks**: SSSPL is a hypothetical construct. It is not physically realisable. The term SSSPL applies to various anthropogenic and natural sources, including ships and wind.

18 https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e50e045acb&appId=PPGMS
19 (Ainslie, et al., 2020)

	The steady state sound pressure level can be spatially averaged. The spatial observation window shall be specified.
excess level unit: dB	SSSPL (for all ambient sound) minus SSSPL (for natural ambient sound) at the same position and time **remark**: Sometimes a statistic of excess level, such as the median in space and time, is represented on a map.
steady state source level abbreviation: SSSL unit: dB reference value: 1 μPa^2 m^2	source level measured over a temporal observation window that is long enough for the source level to be independent of the duration of the window
areic source factor spectral density symbol: $\boldsymbol{F}_{S,f,A}$ unit Pa^{2}m^{2}Hz^{-1}/m^2	Quotient of source factor spectral density from a specified region of the surface and the area of that specified region
areic source spectral density level synonym: areic source spectrum level abbreviation: ASSL symbol: $\boldsymbol{L}_{S,f,A}$	Level of the areic source factor spectral density. In equation form: $L_{S,f,A} = 10\lg\frac{F_{S,f,A}}{F_{S,f,A,0}}$ dB Reference value: $F_{S,f,A,0} = 1\ \mu\text{Pa}^2\text{m}^2/(\text{m}^2\text{Hz})$

8. Sound maps metrics selected by various projects

Details of the metrics that were collected in a table during and after the workshop, see Annex A, are here described per partner.

JASCO - NAVISON

The European Maritime Safety Agency funded the NAVIs SONus (NAVISON) project[7] in which JASCO calculated shipping sound maps for all European seas from 2016 to 2050.

NAVISON sound map metric specifications are:

- sound pressure level (level of arithmetic mean-square pressure),
- 63 Hz and 125 Hz decidecade bands,
- TOW = 3 months,
- TAW = 3 months or 1 year,
- Depth average (up to a maximum depth of 200 m), with SOW defined per regional sea (North Sea: 0.08° lat × 0.04° lon; ~22.3 km^2),
- SAW: regional sea,
- Temporal resolution: AIS track data converted to areic SL per TOW and SOW,
- Spatial resolution: SOW.

For the NAVISON maps, JASCO applied its ARTEMIA soundscape mapping model, including a propagation loss model using the parabolic equation (PE) method. The PIANO ship source level model, developed in NAVISON, was used to calculate source levels for the following five vessel categories:

- Cargo vessels and bulk carriers (CAR),
- Container ships (CON),
- Cruise and passenger vessels (except Roll-on Roll-off (Ro-Ro)) (PAS),
- Tankers and gas carriers (TGC), and
- Ro-Ro vessels (cargo and passenger) (RRO).

NAVISON calculates **sound energy density** (expressed in joules per cubic metre) from each sound map to analyse temporal trends, the effectiveness of mitigation measures and the contributions of different vessel categories to underwater sound.

To apply the spatial threshold value suggested by TG Noise (DL3), the SPL map can be used to quantify the percentage of the map area in which the SPL exceeds a specified threshold value.

Quiet Oceans – BIAS/HOLAS-3, JONAS, SOUNDSCAPE/SATURN, PIAQUO, BLUES, STRIVE, TANGO

The QUONOPS underwater sound mapping service, developed by Quiet Oceans, has been applied in various European projects.

QUONOPS sound map metric specifications are (Folegot, Clorennec, Chavanne, & Gallou, 2016; Gallou & Folegot, 2022):

- Seven spatio-temporal percentiles (5, 10, 15, 25, 50, 75, 90, 95) of sound pressure level and of excess level,
- BIAS/HOLAS-3: 63 Hz, 125 Hz, and 2 kHz decidecade bands; JONAS: 63 Hz, 125 Hz; SOUNDSCAPE/SATURN: 63 Hz, 125 Hz, 250 Hz, and 4 kHz decidecade bands,
- TOW: "snapshot" or "steady state" maritime and environmental properties are used to model the propagation. The transmission loss is then applied to a Source Level term. Therefore, the TOW is inherited from the Source Level used. We currently use the ECHO/JOMOPANS model.
- TAW = Steady state every 15 minutes (TANGO), 1 week, 1 month, 1 quarter or 1 year,
- SOW: Time-depth percentiles at lat-lon grid points, for three depth layers: full depth, 0 to -15 m, and -30 m to seabed.
- SAW: BIAS/HOLAS-3: Baltic Sea and HELCOM Sub-Basins; JONAS: Atlantic; SOUNDSCAPE/SATURN: North-Adriatic Sea; STRIVE: Irish Sea; TANGO: Kattegat, PIAQUO: Pelagos Sanctuary (Mediterranean)
- Temporal resolution: BIAS/HOLAS-3: 1 hour; JONAS: 1 hour; SOUNDSCAPE/SATURN: 1 hour, STRIVE: 1hour; TANGO: 15 minutes. The shorter the TAW, smaller the temporal resolution.
- Spatial resolution: BIAS/HOLAS-3: ~500m; JONAS: ~300m; SOUNDSCAPE/SATURN: 181 × 179 m.

The QUONOPS model calculates propagation loss using the parabolic equation for lower frequencies and Gaussian energy distribution ray modelling for the higher frequency range. Natural (wind and waves) noise levels are estimated from wind models (Wenz, Ainslie, Hildebrand) and measurements when available. For the BIAS/HOLAS-3 and JONAS projects the ship SL was calculated using the RANDI-3 model (depending on frequency, ship length and ship speed only). For the SOUNDSCAPE/SATURN sound maps the JOMOPANS-ECHO (MacGillivray & de Jong, 2021) model was used with addition of an estimated SL for fishing trawlers (with and without trawl), based on measurement data.

QUONOPS uses the statistics of the SPL from measurement stations in the SAW to 'adjust' the model, by adapting source levels and sediment properties to match the percentiles of model results to the measurements. All available measurement stations in the study area are used to calibrate the mapping. The quality of the adjustment is quantified by the root mean square of the difference between the modelled and measured CFD at the hydrophones positions for each decidecade over the entire period of the measurement time series.

In SATURN, Quiet Oceans and The National Research Council of Italy (CNR) propose calculating an **Acoustic Noise Pressure Index (ANPIndex)**. This is calculated as the relative area under the **Acoustic Noise Pressure Curve**, that is calculated from the **Temporal Exceedance Curve (TEC)**, which plots the temporal percentiles of a calculated excess level, using an assumed relationship that quantifies the severeness of disturbance (on a scale from 0 to 1) as a function of excess level. To apply the spatial threshold value suggested by TG Noise (DL3), the ANPIndex map can be used to quantify the percentage of the map area in which the ANPIndex exceeds a specified threshold value.

SHOM – JONAS, QUIETSEAS

In the QUIETSEAS project, SHOM calculated sound maps for parts of the Mediterranean and Baltic seas with the following sound map metric specifications:

- Monthly average sound pressure level,
- 63 Hz decidecade band,
- TOW = 1 month, based on monthly average AIS shipping density.
- TAW = 1 month,
- SOW: maximum over depth, at lat-lon grid points.
- SAW: part of Mediterranean or Black Sea,
- Spatial resolution: 1 arc minute × 1 arc minute.

In the JONAS project, SHOM calculated sound maps for parts of the Atlantic and Irish Sea with the following sound map metric specifications (Dellong & Le Courtois, 2021):

- Monthly sound pressure level percentiles,
- 63 Hz decidecade band,
- TOW = 1 day, based on daily average AIS shipping density.
- TAW = 1 month,
- SOW: maximum over depth, at lat-lon grid points.
- SAW: part of Atlantic or Irish Sea,
- Spatial resolution: 10 arc minutes by 10 arc minutes.

In the JONAS project, SHOM studied various options for using measurement data for 'data fitting or field calibration' (Dellong & Le Courtois, 2023).

CEFAS – UK projects, **including UK Marine Strategy assessment (2018-2023)**

CEFAS published shipping noise maps of the Northeast Atlantic (Farcas, Powell, Brookes, & Merchant, 2020) with the following sound map metric specifications:

- sound pressure level temporal percentiles, excess level temporal percentiles, dominance
- 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, and 4 kHz decidecade bands,
- TOW = 'snapshot'
- TAW = 1 month and 1 year,
- SOW: average over depth, at lat-lon grid points.
- SAW: For the purposes of the UK Marine Strategy (UKMS) assessment - corresponding to the EU MSFD - the SAW was done over the entire UK EEZ and its subregions ("Celtic Seas" and "Greater North Sea"),
- Temporal resolution: 10 minutes intervals,
- Spatial resolution: lower resolution grid with latitude-longitude spacing of 3' x 5' (approximately 5 × 5 km) for coverage of the entire domain, as well as a high-resolution grid of 0.75' × 1.25' (approximately 1.3 × 1.3 km) for selective coverage of smaller areas near the coast and in areas of high shipping density.

Ship source levels were estimated using an ensemble ship source model (Wales & Heitmeyer, 2002). In more recent calculations CEFAS has used the JOMOPANS_ECHO model. Sound propagation was modelled using the energy-flux method (Weston, 1971). Sound pressure levels of wind-generated noise were modelled based on (Reeder, Sheffield, & Mach, 2011). The model was 'calibrated' by adapting the seabed attenuation in a second model iteration after comparing the monthly statistics of calculated noise levels with measurements at two monitoring sites in the Southern North Sea and one in the Irish Sea, taken in 2018-2019.

To apply the spatial threshold value suggested by TG Noise (DL3), CEFAS analyses the temporal statistics (e.g., annual average) of the percentage of the assessment area (SAW) in which a specified SPL threshold value (e.g., 120 dB) is exceeded for each time step.

TNO – JOMOPANS, SATURN, DEMASK

InterReg North Sea Region funded the Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS)[2] in which TNO calculated shipping and wind sound maps for the North Sea in 2019 and 2020.

JOMOPANS sound map metric specifications are:

- sound pressure level temporal percentiles, excess level temporal percentiles, dominance
- Calculations for the 10 Hz to 20 kHz decidecade bands; map outputs for the 63 Hz and 125 Hz decidecade bands, the three decade bands covered by the 20 Hz to 160 Hz, 200 Hz to 1.6 kHz and 2 kHz to 16 kHz decidecade bands respectively and the full bandwidth (covering the 10 Hz to 20 kHz decidecade bands).
- TOW = 'snapshot'. Quoting the TG Noise DL3 report[20]: "The precise TOW duration of a 'snapshot' is not clearly defined, but is considered to be between 10 s (the estimated minimum averaging duration for the source level of a fast ship) and 60 s (the estimated time for a ship distribution to change sufficiently to affect the sound map).",
- TAW = 1 month and 1 year,
- SOW: Depth average at lat-lon grid points,
- SAW: North Sea,
- Temporal resolution: 10 minute intervals,
- Spatial resolution: North Sea: 0.025° lat × 0.08° lon; ~9 km^2.

For the JOMOPANS maps, TNO applied its AQUARIUS 3 sound mapping model, including a propagation loss model using the hybrid normal mode energy flux method. The JOMOPANS-ECHO ship source level model, developed in JOMOPANS, was used to calculate source levels for the following vessel categories:

- Fishing vessel
- Tug
- Naval vessel
- Recreational vessel
- Government/Research
- Cruise vessel
- Passenger vessel
- Bulker
- Container Ship
- Vehicle Carrier
- Tanker
- Other

The source level of dredgers was calculated from data obtained during the construction of the Rotterdam Port extension (Tweede Maasvlakte)[21]. Wind noise was calculated with wind noise source and propagation models based on the semi-empirical expressions described in (Ainslie, Principles of Sonar Performance Modeling, 2010).
AIS data, recorded at different temporal intervals per ship track, and wind data, at 1-hour intervals, were interpolated to a regular 10-minute grid and to a source location grid with approximately the same spatial resolution as the map grid.

In addition to the temporal percentiles of SPL (from ship classes, wind and ships plus wind), JOMOPANS calculated relative metrics:

- **Excess level**
  (i) Instantaneous excess of "ambient noise" from all ships and wind over "natural" wind noise
  (ii) Instantaneous excess of "ambient noise" from all ships and wind over median values of "natural" wind noise over the TAW.
- **Dominance**

[20] https://publications.jrc.ec.europa.eu/repository/handle/JRC133476
[21] https://dredging.org/media/ceda/org/documents/resources/othersonline/uwn-tno-dv2010c335.pdf

The percentage of the TAW over which excess level or SPL exceeds a specified cut-off value.

JOMOPANS proposed calculating a **Pressure Index** from the dominance map. This is calculated as the relative area under the **Pressure Curve** that plots the spatial percentiles of the dominance metric.

To apply the spatial threshold value suggested by TG Noise (DL3)[20], the Dominance map can be used to quantify the percentage of the map area in which the Dominance exceeds a specified threshold value.

For DEMASK, TNO has so far also calculated monthly and annual arithmetic mean SPL maps for the North Sea in 2020.

In SATURN, TNO showed[22] how shallow-water depth-average SPL maps can be converted to depth average sound particle acceleration level (PAL) and sound particle velocity level (PVL) maps, see also (Oppeneer, de Jong, Binnerts, Wood, & Ainslie, 2023).

DEMASK

The numerical model by TNO outputs SPL time series for a range of frequencies. Within DEMASK different metrics will be calculated from that, considering the aspects discussed in the workshop.
A parametric study has tested the influence of different frequency weightings.
TOW and SOW are chosen based on the resolution of the available input data (AIS) and computational load. Different resolutions will likely be chosen for the large-scale and small-scale scenario. SAW and TAW will also be chosen depending on the scenario scale and biological relevance, as discussed during the workshop.

Özkan Sertlek (JASCO) presented comparative analysis of North Sea sound maps produced by the JOMOPANS and NAVISON projects. Originally, both project produced maps of different metrics. To facilitate the comparisons, TNO reprocessed the JOMOPANS sound maps to calculate the broadband arithmetic mean SPL, the same metric as calculated by NAVISON. Harmonization of the metrics is an essential preliminary step to allow comparison of project results. In this case, the maps still showed significant differences, due to many differences in the approach (e.g. a different ship SL model) and input data (e.g. a different AIS data source).

9. Discussion and evaluation

The overview of sound map specifications (Annex A) confirms that the sound maps generated by the various projects are not compatible. Projects make their own choices in relation to the project objectives. However, the main motivation behind the sound mapping projects considered here is the European Marine Strategy Framework Directive. Hence some argue that harmonization (or standardization) of underwater sound maps is needed. Others argue that there is still insufficient knowledge to be able to summarize the impact of underwater sound on aquatic life in a few harmonized maps.
The workshop discussion provided insight into the pros and cons of the various choices.

There are various possible effects of underwater sound on marine animals (see section 7). The main two effects so far considered relevant for continuous underwater sound are masking and behavioural disturbance, mainly based on effects studied in mammals. However, physiological stress responses and effects on early-life development are known from studies on invertebrate and fish species. There is no consensus on the selection of acoustic exposure metrics that predict the probability of causing such effects, because many sound characteristics could play a role. Evaluating different effects may require analysing different metrics. Therefore, there was a consensus in the discussions to keep options open and to encourage calculating multiple metrics. Lessons learned from evaluating various maps may provide guidance for future projects.

Choices concerning the frequency content of impact metrics are strongly species dependent and therefore not ready for harmonization. Many projects follow the initial specification of the MSFD indicator

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[22] https://www.saturnh2020.eu/_files/ugd/a39dff_3b494535d7b64742a2715c1a1092e011.pdf

by selecting the 63 Hz and 125 Hz decidecade bands. However, it may be relevant to add more bands or evaluate wider frequency ranges and auditory frequency weighting to evaluate the impact of sound exposure on different species.

Spatial aspects are also species dependent. Maps represent the geospatial distribution of a specified statistic of the SPL distribution over depth. Many projects calculate SPL on a receiver grid without explicit spatial averaging, some (e.g. NAVISON) present an areic (SOW) average.

To cover temporal aspects, multiple temporal statistics of SPL are being considered:

- The monthly, seasonal or annual arithmetic mean (AM) SPL was recommended by TG Noise[20] for use as pressure indicator. The main reason for this recommendation was the robustness of AM to choice of TOW and SOW.
- The AM SPL is compatible between projects and can be directly converted to sound energy density, which is a linear quantity that facilitates ranking of source types and mitigation scenarios. It is sensitive to occasional large errors in measurement or model prediction. This can be an advantage as well, because it can help detecting errors.
- TG Noise[20] was not yet able to provide recommendations on the choice of metric for an impact indicator, hence recommended retaining the full time series of SPL.
- Comparing SPL percentile maps requires a compatible choice of TOW and temporal resolution.
- Validation of percentile maps against data also requires a compatible choice of TOW and temporal resolution. There are no international standards for sound maps, but measurement of underwater sound for the purpose of ambient sound monitoring is (nearly) standardized in ISO 7605. ISO 7605 requires a TOW duration of 60 s (1 minute).
- The TOW duration of SPL calculated for a single temporal 'snapshot' of the ships represented in AIS is not clearly defined. It can be considered to be between 10 s (the estimated minimum averaging duration for the source level of a fast ship) and 60 s (the estimated time for a ship distribution to change sufficiently to affect the sound map). We are not aware of tests of the compatibility with the TOW required by ISO 7605.

Temporal and spatial averaging reduces the amount of information to be interpreted. This facilitates assessment of maps by regulators, but reduces the possibility to study specific impacts on specific aquatic species. Metrics that include more information about the temporal and spatial distribution, such as 'Dominance' and 'ANPindex', provide an interesting alternative, but rely on several choices (TOW, threshold values) that cannot yet be harmonized.

Threshold values for impact of underwater sound on aquatic animals were kept outside the scope of the workshop. Setting thresholds can only be done after selection of the appropriate metrics.

Although the focus was on modelled maps, ambient noise measurements were added because these are essential for model validation and used by some parties to tune their modelling parameters. Hence, compatibility of modelled metrics with the metrics calculated from ambient noise measurements, such as specified in the upcoming ISO 7605 standard[23], is considered important.

Gerry Sutton promoted performing detailed/highest possible resolution calculations at the modelling stage and the storage/documentation of the maximum possible volume of output data to be able to create various derivative products in postprocessing. That would suggest that harmonizing or standardizing the underlying mechanisms of carrying out the key calculations might be useful. This could perhaps be done while impact metrics are being further developed.

10. Conclusion

Chairs Niels Kinneging and Gerry Sutton concluded that this has been a very interesting and productive workshop, greatly benefiting from teaming up between SATURN and DEMASK.

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[23] https://www.iso.org/standard/82844.html

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Annex A: Sound map specifications

Abbreviations

AM	**arithmetic mean**
EL	excess level[24]
J-E	Jomopans-ECHO (MacGillivray & de Jong, 2021)
n/a	not applicable
SAW	spatial analysis window
SL	source level
SOW	spatial observation window
SPL	sound pressure level
TAW	temporal analysis window
TOW	temporal observation window

Empty cells indicate that the information was lacking at the time of reporting.

	metric	frequency	TOW	TAW	temporal resolution	SOW	SAW	spatial resolution	measurements	source level model
JOMOPANS - TNO	SPL/EL percentiles Dominance	10 Hz – 20 kHz ddec	'snapshot'*	1 month / 1 year	10 min	depth average	North Sea	~9 km²	comparison	J-E ship SL & Ainslie wind SL model
BIAS - QO	SPL percentiles (5, 10, 25, 50, 75, 90, 95)	63 Hz 125 Hz 2 kHz ddec	'snapshot'*	1 month 1 year	1 hour	time-depth percentiles for depth layers	Baltic Sea	~500m	Ground truthing	RANDI ship SL model
JONAS - QO	SPL/EL percentiles (5, 10, 25, 50, 75, 90, 95)	63 Hz 125 Hz 4 kHz ddec	'snapshot'*	1 month 1 quarter 1 year		time-depth percentiles for depth layers	Azores Irish sea Atlantic English channel Srtait of Gibraltar Bay of Biscay	~300m	Calibration	RANDI III ship SL model

[24] It was proposed to use the abbreviation 'EXL' for excess level, instead of 'EL', to make it more explicit and to use three letters, similar to SPL.

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SATURN/QO Pelagos	SPL/EL percentiles (5, 10, 25, 50, 75, 90, 95)	11 Hz – 4 kHz decade	‘snapshot’*	1 quarter		time-depth percentiles for depth layers	Pelagos Sanctuary (Mediterranen sea)	~400m	Calibration	J-E ship SL model
PIAQUO	SPL/EL percentiles (5, 10, 25, 50, 75, 90, 95)	63 Hz 125 Hz ddec	snapshot’	1 month		time-depth percentiles for depth layers	Mediterranen sea, Irish sea, North sea	~300m	No	J-E ship SL model
BLUES	SPL/EL percentiles (5, 10, 25, 50, 75, 90, 95)	63 Hz 125 Hz 500 Hz ddec	snapshot’*	1 month 1 quarter 1 year		time-depth percentiles for depth layers	Baltic sea	~500m	Calibration	RANDI III ship SL model
STRIVE	SPL percentiles (5, 10, 25, 50, 75, 90, 95)	63 Hz 125 Hz ddec	snapshot’	1 quarter		time-depth percentiles for depth layers	Irish sea	~1km	Partial calibration	Hildebrandt SL model
TANGO	SPL/EL percentiles (5, 10, 25, 50, 75, 90, 95)	63 Hz 125 Hz 2 kHz ddec	snapshot’	1day 1week 1 month 1 quarter 1 year	15 min	time-depth percentiles for depth layers	Kattegat	~100m	No	RANDI III ship SL model
SOUNDSCAPE / SATURN- QO	SPL / EL percentiles (5, 10, 25, 50, 75, 90, 95)	63 Hz, 125 Hz, 250 Hz, 4 kHz ddec	20 s, 60 s	1 month / 1 year		surface to 15 m, 30 m to the bottom and average water column	Adriatic Sea	181×179 m^2	Calibration	J-E ship SL model
JONAS - SHOM	SPL AM	63 Hz / 125 Hz ddec	daily	monthly	AIS density	max over depth	Atlantic	10 arc min	comparison	
QUIETSEAS - SHOM	SPL AM	63 Hz ddec	1 month	1 month	AIS density	max over depth	Mediterranean and Black Sea	10 arc min	No	
NAVISON - JASCO	SPL AM Volume average energy density	63 Hz / 125 Hz ddec	3 months	3 months / 1 year	AIS density	Per sea basin, e.g. North Sea 22.3 km^2 depth average	European seas	= SOW	No	PIANO model (tuned with ECHO data)

UK-CEFAS	SPL / EL percentiles	7 ddec centre frequencies	‘snapshot’*	1 month / 1 year	10 min	depth average	UK seas	3 min lat by 5 min lon	comparison and tuning	J-E ship SL & Reeder wind SL model
MEASUREMENTS:										
IQOE 2019	AM, median; SPL percentiles (10, 25, 75, 90)	decidecade bands (10 to 1000 Hz)	60 s	1 month	n/a	n/a	n/a	n/a	n/a	n/a
ISO 7605	AM, median; SPL percentiles (10, 25, 75, 90)	decidecade bands	60 s	24 h (0:00 to 24:00 UTC)	n/a	n/a	n/a	n/a	n/a	n/a

Annex B: Workshop participants

in person		in person		online	
Name	**Organisation**	**Name**	**Organisation**	**Name**	**Organisation**
Jakob Tougaard	AU	Dominik Nachtsheim	TiHo	Charlotte Findlay	AU
Katharina Grunert	BSH	Helena Eicher	TiHo	Michael Daehne	BfN
Eric Baudin	BV	Jeff Schnitzler	TiHo	Benedikt Niesterok	BSH
François Bruliard	BVS	Nina Maurer	TiHo	Carina Juretzek	BSH
Adrian Farcas	CEFAS	Robabe Ahmadi	TiHo	Sven Wieskotten	BSH
Gary Saggers	CEFAS	Christ de Jong	TNO	Giuseppa Buscaino	CNR
Emilio De Angeklis	CETENA	Santiago Molins	TSI	Stefano Menegon	CNR-ISMAR
Marta Picciulin	CNR-ISMAR	Gerry Sutton	UCC	Mohammad Ghasemi	DNV
Michol Ghezzo	CNR-ISMAR	Hans Slabbekoorn	ULEI	Aristides Prospathopoulos	HCMR
Øystein Solheim Pettersen	DNV	Kees te Velde	ULEI	Chris Waddington	ICS
Anna-Sara Krång	IVL Kristineberg Center	Arienne Calonge	VLIZ	Michael Bellman	itap
Roberto Yubero	Jasco	Bram Cuyx	VLIZ	Michael Ainslie	JASCO
Özkan Sertlek	Jasco	Elisabeth Debusschere	VLIZ	Thomas Lloyd	MARIN
Johan Bosschers	MARIN	Jo-Hannes Nowé	VLIZ	Aurelie Cosandey-Godin	Transport Canada
Valentin Meyer	Naval Group	Iulia Oprea	WARTSILA	Frank Wolkenfelt	Port of Rotterdam
José A. Díaz	PLOCAN			Lisa Fassola	RINA Consulting
Thomas Folegot	Quiet-Oceans			Laura CEYRAC	SHOM
Niels Kinneging	RWS			Maria Morell	TiHo
René Dekeling	SoundMarineNL			Emma Knowles	UCC
				Marta Solé	UPC