BUNDESAMT FÜR
SEESCHIFFFAHRT
UND
HYDROGRAPHIE

Offshore wind farms

Measuring instruction for underwater sound monitoring

Current approach with annotations

Application instructions

Client:
Bundesamt für Seeschifffahrt und Hydrographie /
Federal Maritime and Hydrographic Agency
Bernhard-Nocht-Straße 78
20359 Hamburg

Acoustic consultants:
MÜLLER-BBM

Müller-BBM GmbH
Niederlassung Hamburg

Dr. Andreas Müller
Dr. Carsten Zerbs

Bramfelder Str. 110b
22305 Hamburg

Total number of pages:
31 pages, thereof
19 pages text,
12 pages Appendix

As of:
October 2011

The present measuring instruction was drawn up within the scope of the research project „Ecological research at the *alpha ventus* offshore test field to evaluate the BSH Standard for the Environmental Impact Assessment” (StUKplus).

The StUKplus project is funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety with the project number 0327689A. The authors are responsible for the contents of this paper.

Gefördert durch:

Bundesministerium
für Umwelt, Naturschutz
und Reaktorsicherheit

aufgrund eines Beschlusses
des Deutschen Bundestages

Table of contents

1 Preliminary remarks

According to the Marine Facilities Ordinance (SeeAnlV), the Federal Maritime and Hydrographic Agency (BSH) is responsible for the licensing of offshore wind farms in the German exclusive economic zone (EEZ). Within the scope of licensing procedures for offshore installations it is necessary to analyse to what extent noise caused by the construction, operation and decommissioning of wind turbines has an impact on the marine environment.

According to the Environmental Impact Assessment Act (UVPG), it is obligatory to carry out an environmental impact assessment (UVP) for offshore wind farms. During the application process, the applicant performs an environmental impact study (UVS) where, among others, the possible effects of noise emission on the marine environment are described and assessed.

Condition 14 of a BSH license prescribes regular measures to determine and minimize waterborne sound. Measurements of waterborne sound during noisy work phases (e.g. impact pile driving) have to be carried out at defined distances and have to be documented. Protective and noise mitigating measures have to be verified during implementation for their efficiency by means of sound measurements. The results have to be documented and reported to the licensing authority.

However, worldwide validated empirical values concerning underwater noise caused by the construction and operation of offshore wind farms are missing, as there are no standardized measuring methods and no validated sound propagation models.

The temporal and spatial scope of the acoustic investigations is described in the Standard for the Environmental Impact Assessment (StUK3 2007, [1]). For this purpose, underwater sound measurements have to be carried out prior to construction, during construction and during operation. First results from acoustic investigations at the *alpha ventus* test field (itap 2011, [20]), from offshore research platforms and measuring masts have provided the basic information to revise the present measuring procedure according to StUK and to summarize the results in a detailed measuring instruction. The measuring instruction is part of the StUK and specified in the appendix.

The following specification describes the general procedure for underwater sound measurements connected with the construction and operation of offshore wind farms. It covers the four phases of licensing and enforcement procedures of offshore installations in the German EEZ:

a) Baseline study - preliminary investigations

b) Construction phase

c) Operation phase

d) Decommissioning phase.

Deviations from the procedure described in the following, which are justified by project-specific or site-specific needs, might be agreed upon with the licensing authority.

The institutions in charge of the sound measurements must hold appropriate qualifications for the execution of sound and vibration measurements, which can be obtained by an accreditation according to DIN EN ISO/IEC 17025 or a comparable qualification. The required certifications must be provided by the respective institutions.

2 Definitions and symbols

2.1 Terms

The physical quantities used in this measuring instruction, their symbol and the SI unit are stated in Table 1.

Table 1: Applied quantities and symbols.

Quantity	Symbol	SI unit	Remark
Sound pressure	p	Pa	
Sound velocity	c	m/s	
Sound power	P	W	
Sound intensity	I	W/m^2	
Sound pressure level	L_p		in dB
Sound power level	L_P, L_W		in dB

Further level quantities and their definitions are given in section 2.2.

2.1.1 Single sound events

A sound event is a physical process determined by acoustic parameters (sound field quantities). The term defines the physical part of sound generation. The perceived sound is usually marked by the term “hearing event”.

During the construction of offshore wind farms, single sound events are of special interest, in particular during impact pile driving.

2.2 Level parameters

For this measuring instruction, the following level parameters apply:

- equivalent continuous sound level L_{eq} for continuous sound signals
- single sound event level L_E for impulsive sound signals
- peak level L_{peak} for impulsive sound signals.

The applied level quantities are based on the definitions in ISO 1996-1 (2003), but not identical with these. For example, the definition of L_{eq} is made without frequency weighting. According to ISO 1996-1, the peak sound pressure level is determined with a detector according to IEC 61 672. However, the definition in the present document is based on the signal amplitude.

The application of these level parameters was investigated in a study by Elmer, Betke, Neumann (2007).

At present, no frequency and time weighting for the evaluation of stationary and impulsive signals is described.

The **equivalent continuous sound level L_{eq} (or average level)** is defined by

$$L_{\mathrm{eq}} = 10\log_{10}\frac{\frac{1}{T}\int_0^T p(t)^2 dt}{p_0^2}.$$

Here, p(t) stands for the sound pressure, p_0 for the reference sound pressure in 1 µPa and T for the averaging time[1].

Single sound event level (or sound exposure level, SEL)

The single sound event level[2] L_{E} characterizes impulsive noise:

$$L_{\mathrm{E}} = 10\log_{10}\frac{E}{E_0}$$

with the sound exposure E

$$E = \int_0^T p(t)^2 dt$$

and the reference quantity

$$E_0 = p_0^2 \cdot T_o.$$

Here, p_0 is the reference sound pressure in 1 μPa, T_0 the reference time in 1 s and T the averaging time. For the evaluation of single sound events, the averaging time corresponds to the duration T_{E} of the event.

Peak level L_{peak}

This parameter is used as a measure for maximum sound pressure peaks without time or frequency weighting and without averaging

$$L_{\mathrm{peak}} = 20 \cdot \log_{10}\frac{p_{\mathrm{peak}}}{p_0}.$$

Here, p_0 is the reference sound pressure in 1 µPa and p_{peak} the maximum positive or negative sound pressure p_{peak}

$$p_{\mathrm{peak}} = \max(|p(t)|).$$

2.3 Other measuring quantities and related parameters

The sea state has to be noted down according to the sea state scale of Petersen.

Information on the wind speed refers to the Beaufort scale. It is also allowed to state the wind speed in m/s or kn.

---

[1] According to ISO 1996-1 the equivalent continuous sound level can also be marked with the index T $L_{\mathrm{eqT.}}$

[2] The single sound event level L_{E} is also referred to as “SEL” (sound exposure level).

3 Measuring devices

The hydrophone measuring chain for the hydro-acoustic measurements consists of the following components:

- Hydrophone (with preamplifier) with a sensitivity deviation of less than 2 dB up to a frequency of 40 kHz, omnidirectional
- Analogue high-pass filter (which can be integrated in the measuring amplifier) to limit the low-frequency dynamics of the measuring data
- Measuring front-end consisting of low-pass filter (anti-aliasing filters), amplifiers, D/A converters and the possibility of raw time data storage
- Cables, connectors, etc.

For post-processing, analysis software is required comprising the following methods:

- Third-octave band analysis
- Narrow-band analysis
- Time weighting, averaging.

If possible, the software should also enable frequency weightings.

The post-processing might already be integrated in the measuring front-end.

If frequency weightings are included in the measuring instruction, they can be implemented both in the amplifier or the measuring front-end and digitally in the evaluation software. This is also valid for the whole subsequent analysis like band pass filters (e.g. third-octave band filters).

The following testing instruments, devices and recording equipment are needed:

- Pistonphone for the calibration of the hydrophone measuring chain before and after each measurement
- Distance meter (laser, GPS)
- CTD sensors for recording the data required to determine the sound velocity profile
- AIS data (in particular to assess the background noise before construction and during operation).

4 Calibration

The institution in charge of the measurements has to make sure that the instruments of the acoustic measuring chain are calibrated according to the manufacturer’s instruction. The calibration interval is maximal 24 months.

The required calibration certificates have to be available at any time.

5 Measurements in the project phases

The measurements cover all project phases:

- Baseline study prior to construction
- Construction phase

- Operation phase
- Decommissioning phase.

Background noise measurements have to be carried out before construction start for each project area.

During the construction phase, monitoring measurements have to be done during high-noise work activities (e.g. vibratory piling, impact pile driving).

Besides, all measures serving to protect the marine environment (e.g. use of deterrent devices, soft start, vibratory piling, noise mitigation methods) have to be documented by hydro-acoustic measurements.

In accordance with the licensing authority, control measurements in the area surrounding the wind farm have to be carried when the construction is completed and the wind farm is in operation.

5.1 General remarks

The installation of stationary acoustic measurement instruments is subject to approval according to § 2 of the Marine Facilities Ordinance (SeeAnlV) of 23rd January 1997 (BGBl I. page 57), last amended by its article 26 of 29th July 2009 (BGBl. I page 2542). Approval is mandatory during the baseline study as well as during the construction and operation phase outside the safety zone and the buoying of the construction site. Besides, installations of stationary acoustic measurement instruments inside the safety zone need the agreement of the wind farm operator and the information of the licensing authority.

5.1.1 Measuring sites

- The hydrophones have to be placed 2 to 3 m above sea ground by the use of remote systems. It has to be guaranteed that the selected measurement depth is kept during the different project phases.
- When positioning the hydrophones, it has to be ensured that interfering structure-borne noise transmission is avoided as far as possible.
- Alternative measurement set-ups need to be discussed with the licensing authority, e.g. installation of hydrophones halfway down the water depth or the use of several hydrophones in different depths over the entire water column.

To avoid misinterpretations of the measuring results, alternative installation concepts might become necessary (e.g. due to strong stratification of the water body and consequently varying sound velocity profiles).

5.1.2 Measuring quantities and related parameters

Acoustic measuring quantities:

- Linear (unweighted) sound pressure (raw time data). The measurement and recording of the sound pressure need to be carried out in a frequency range of at least 10 Hz to 20 kHz.

Documentation and related parameters:

- GPS coordinates
- Soil condition

- Water depth
- During construction work: pile driving record with the number of hammer strokes, pile driving frequency, pile diameter, pile penetration depth and piling energy, deterrent report (use of pinger and seal scarer), noise mitigation record
- During operation: performance data, engine speed, number and distance of the turbines in accordance with the operator.

The related parameters need project- and site-specific agreement of the licensing authority.

If the licensing agency agrees, the following related parameters might be taken from close-by measuring stations:

- Wind velocity and wind direction (see section 5.2.1)
- Water depth
- Sea state
- Sound velocity profile
- Flow velocity and direction.

All factors which might have an influence on the sound measurements have to be documented and evaluated in the monitoring report, if necessary. For example:

- Shipping traffic
- Precipitation noise (especially rainfall)
- Thunderstorms
- Fish (schools of fish, in particular with acoustically active swim bladder)
- Acoustically active mammals
- Other sound sources.

5.1.3 Analyses

The following analyses of the measured course of the sound pressure level are required:

- Linear (unweighted) sound pressure level
- Frequency analysis in third-octave bands of 10 Hz to 20 Hz. A reduction of the evaluated frequency range is in accordance possible
- Narrow-band frequency analysis, bandwidth (frequency resolution) $\Delta f \leq 2$ Hz.

5.1.4 Measured values and measuring conditions

- The function of the hydrophone measuring chain has to be tested before and after the measurements with a suitable pistonphone. The test needs to be documented comprehensibly.
- The measured quantities have to be determined for the test scopes as described in section 5.2.1, 5.3.1 and 5.4.1 and for the measuring sites as described in section 5.2.2, 5.3.2, 5.4.2.
- Insofar as noisy work takes place in parallel to the measurements, which are not related to the project at hand (e.g. construction work at another wind farm), the interfering background noise must be recorded and documented.

- Background noise, e.g. clinking of chain noise (anchor chains, sea marks and buoys), has to be avoided in the close vicinity to the measuring set-up. It has to be assured that the measurements are not distorted by ambient noise (e.g. caused by pitching of ships, ship machinery, movements of crew).

5.2 Baseline study (preliminary investigations in the pre-construction phase)

5.2.1 Test scope

The measurements have to be carried out for three classes of wind (on the Beaufort scale), corresponding to sea state 1 (without rainfall) and to the wind farm's power output range "medium" and "nominal capacity", and have to provide a sufficient statistical basis for the results. At least three hours of evaluable measuring time are required for every wind class. Seasonal and diurnal peculiarities have to be documented.

Start and duration of the preliminary investigations will be determined prior to construction in accordance with the licensing authority.

5.2.2 Measuring sites

- The hydro-acoustic background noise exposure has to be measured at not less than three hydrophone positions simultaneously with at least one measuring station in the project area. One measuring station hast to be placed in the nearest nature conservation reserve. A third measuring station has to be located at a distance of 5,000 m.
- The exact measuring positions have to be coordinated with the licensing authority at least 12 weeks in advance, considering project-specific and site-specific features.
- It has to be checked whether the installation of measuring equipment is subject to licensing or notification. If licensing is required, an appropriate application has to be handed in to the BSH at least eight weeks before the scheduled installation date.

5.2.3 Evaluation and presentation of the results

To evaluate the measurements, $L_{eq,5s}$ values (in dB re 1 µPa) are generated frequency-resolved in third-octave bands with an averaging time of 5 seconds. The documentation should contain the following information (parameters) for each wind class:

a) L_{eq} = energetic average value over the total measuring period of the respective wind class

b) $L_{90,5s}$ = 5 seconds percentile level, which is exceeded in 90 % of the measurements over the total measuring period of the respective wind class (90 % limit exceedance level)

c) $L_{50,5s}$ = 5 seconds percentile level, which is exceeded in 50 % of the measurements over the total measuring period of the respective wind class (50 % limit exceedance level)

d) $L_{5,5s}$ = 5 seconds percentile level, which is exceeded for 5 % of the measurements over the total measuring period of the respective wind class (5 % limit exceedance level).

Time records of the broad band $L_{eq,5s}$ have to be given for the total measuring period. The respective wind class has to be indicated in the diagrams.

For each wind class, a spectral presentation of the parameters a) to d) in third-octave bands is required.

The parameters a) are to be determined according to DIN 45 641, the parameters b) to d) according to the method described in VDI 3723, sheet 1.

5.2.4 Assessment

The assessment of the background noise measurements is not done separately. The results are used for assessing the measurement results of construction and operation phase as well as for the evaluation of the immission forecast data. Here, especially cumulative effects must be considered (e.g. simultaneous construction projects, shipping traffic, other noisy activities).

5.3 Construction phase

The monitoring measurements during the construction phase (pile driving), especially in the closer surroundings of the site, have to be included in the project planning at an early stage to take care of work safety aspects.

5.3.1 Test scope

- During all noisy construction works underwater sound measurements have to be carried out in the vicinity of the wind farm site. The monitoring of noise emissions is obligation of a BSH license (condition 14) and an integral part of the standard monitoring concept (StUK). For each foundation type installed and each installation method applied at a wind farm, at least one complete registration of noise emission of a foundation installation (pile driving) has to be carried out. Principally, the measurements have to be carried out during the installation of the first foundation.
- Additional measurements have to be carried out if the construction work is not running homogeneously (e.g. due to strongly varying soil conditions at the turbine sites or if a modified installation method is used).
- All measures implemented to meet condition 14 and to protect the marine environment (e.g. deterrent methods, soft start, vibratory piling) have to be accompanied by sound measurements. The efficiency of noise mitigation measures (e.g. coffer dam, silencers, bubble curtain) has to be documented by sound measurements as well. Here, measurements with and without noise mitigation have to be carried out. The efficiency control of deterrent and noise mitigating measures are condition of the approval and demanded by the licensing authority.

5.3.2 Measuring sites

- The measuring sites have to be determined at a distance of 750 m and 5,000 m from the foundation structure and in the closest nature conservation area, provided that it is more than 5 km away from the project site.
- The exact positions have to be coordinated with the licensing authority taking into account project-specific and site-specific features.

5.3.3 Evaluation and presentation of the results

Typical sequences of the sound pressure history have to be presented by the equivalent continuous sound pressure level L_{eq} at the beginning, in the middle and at the end of the construction activities. Furthermore, the single-event sound pressure level L_{E} and the peak sound pressure level L_{peak} have to be given for impulsive installation methods (impact pile driving).

It is allowed to determine the single-event sound pressure level L_{E} with

$$L_{\mathrm{E}} \approx L_{\mathrm{eqT}} - 10\log\frac{nT_0}{T}.$$

Here, n is the number of impulses per period T. This evaluation is only valid if the background noise is significantly lower than the impulse noise and for impulses of similar character. For measurements at a far distance this method remains to be checked. The time period T is 30 s.

L_{eq30s} is composed of the background noise $L_{\mathrm{eq,bgn}}$ (equivalent continuous sound level of the background noise, “background”) and the measuring signal $L_{\mathrm{eq,impulse}}$ (equivalent continuous sound level during construction work). To determine the single-event sound pressure level, the requirement $L_{\mathrm{eq,impulse}} - L_{\mathrm{eq,bgn}} > 10$ dB must be fulfilled.

For the presentation of the results, time records of the level parameters $L_{\mathrm{eq,30s}}$, L_{E} and L_{peak} in diagrams over the entire measuring period are required.

The unweighted sound pressure $p(t)$ over the entire measuring period has to be presented.

According to the following statistics, the broad band levels (L_{eq}, L_{E}, L_{peak}) have to be determined:

- $L_{90,30\mathrm{s}}$ = 30 seconds percentile level, which is exceeded in 90 % of the measurements over the total measuring period
- $L_{50,30\mathrm{s}}$ = 30 seconds percentile level, which is exceeded in 50 % of the measurements over the total measuring period
- $L_{5,30\mathrm{s}}$ = 30 seconds percentile level, which is exceeded in 5 % of the measurements over the total measuring period.

If the broad band levels L_{E} and L_{peak} are calculated for single events (pile strokes), the calculation of the percentile levels is valid for the entire single-event sound pressure levels during pile driving.

The evaluation has to be done for pile driving works with and without noise mitigation measures. By means of noise mitigation with the open bubble curtain, the influence of flow velocity and flow direction on the bubble curtain has to be proofed and documented by additional measurements.

The equivalent continuous sound pressure level and the single-event sound pressure level shall be displayed for typical sequences spectrally in third-octave bands depending on e.g. the pile driving energy.

5.3.4 Evaluation

In the BSH approvals for offshore wind farms, reference values were introduced in 2003 and threshold values in 2008 for pile driving noise emissions.

The threshold values are stated in condition 14 of a BSH license:

„During the foundation and installation of offshore wind turbines, the method has to be applied which is according to the state-of-the-art as noise-reduced as possible with regard to the respective circumstances. By means of a suitable noise-mitigation concept, the sound exposure level (SEL) must not exceed 160 dB (re 1 μPa) outside of a circle of 750 m radius."

If it is not possible to meet the above mentioned measuring distance of 750 m, the assessment levels have to be corrected. The maximum measuring distance R is 1,100 m. A measuring distance shorter than 750 m is not preferred. The correction factor is calculated with the following correction formula

$$L = L_{750\mathrm{m}} - X \cdot \log_{10}(R / 750\ \mathrm{m})$$

with $X = 15$.

The percentile levels $L_{5,30\mathrm{s}}$ have to be compared with the basis for the assessment. The number and amount of the limit exceedings have to be documented in a suitable way.

The exceeding of the rating level is not allowed.

5.4 Operation phase

Control measurements of the underwater noise have to be carried out in accordance with the licensing authority not later than 12 months after commissioning of a wind farm.

5.4.1 Test scope

- The three power output ranges "low", "medium" and "nominal power" have to be recorded. Per power range, at least three hours of measurements must be suitable for evaluation, taking into account seasonal and diurnal peculiarities.
- Measurements have to be carried out with the wind turbines switched off or at calm, respectively.
- The exact determination of the power output ranges is done in accordance with the licensing authority.
- The exact test scope and the selection of the investigated turbines are determined in accordance with the licensing authority taking account of project-specific and site-specific features.

5.4.2 Measuring sites

- Data has to be collected on a random basis at individual turbines of the wind farm. The sound measurements have to be carried out at about 100 m from the sound source and in the middle of the wind farm.
- Additionally, measurements have to be done outside the wind farm at a distance of 1,000 m and in the nearest nature conservation area, provided that it is not more than 5 km away from the project site. Is no nature conservation area in the vicinity, a sound measurement must be carried out at 5 km distance to the wind farm.
- The exact measuring sites have to be determined in accordance with the licensing authority taking account of project-specific and site-specific features.

5.4.3 Evaluation and presentation of the results

A frequency-resolved analysis has to be carried out in third-octave bands and in narrowband spectra with a resolution of < 2 Hz.

L_{eq5s} (in dB re 1 µPa) has to be determined frequency-resolved with an averaging time of 5 s in third-octave bands. The

- $L_{5,5s}$ = 5 seconds percentile level, which is exceeded in 5 % of the measurements over the total measuring period for the respective wind class

has to be determined and compared with the results from the preload investigation of the relevant wind class.

Representative equivalent continuous sound levels L_{eq5s} have to be presented frequency-resolved in third-octave bands and in narrow-band spectra for each wind class.

5.4.4 Presentation of the results

The measuring results have to be compared with the background noise level.

5.5 Decommissioning phase

No experience has yet been made concerning the course of this project phase and the associated noisy work activities.

The applied measuring concept will comply with the noise emission forecast and the noise mitigation concept for decommissioning works and will be submitted to the licensing authority twelve months before the planned decommissioning start. The licensing authority will define the measuring concept on the basis of the achieved state of knowledge.

6 Data storage

All measuring data (raw time data) as well as the processed and evaluated data has to be kept available for further assessments for a period of ten years and has to be forwarded to the licensing authority on request. The data format is selected in accordance with the licensing authority.

The data transferred to the licensing authority including the related parameters has to be in Windows PCM WAV with a 24-bit resolution.

7 Reporting

7.1 Formal report details

7.1.1 Front page

The front page must contain at least the following information:

- Title (mentioning the project)
- Report number
- Company name
- Report date, if necessary with revision status

- Name and address of the client
- Date of the measurements
- Place of the measurements
- Names of the persons involved
- Information on the total number of pages, including appendices
- If the appendix is numbered separately, the respective number of pages of the appendix needs to be listed on the front sheet.

7.1.2 Constant information on the following pages

All pages following the front page must contain the following information:

- Company name
- Report number
- Date
- Page numbering.

The total number of pages must not necessarily be printed on the consecutive pages.

7.1.3 Signatures

In general, the reports are signed by their respective authors.

7.2 Contents of the reports

7.2.1 Structure

The report should have the following structure:

- Information on the execution of the investigations
- Information on the results
- Evaluation.

7.2.2 Requirements for the description of the measurements

If investigations were carried out following defined procedures, the text must contain *at least* the following information:

- Designation and description of the measuring set-up
- Descriptions of the measuring subject, e.g. type of foundation, pile driving method and piling times
- Description of the test specification or description of the applied test method
- If measurements are carried out "following" a standard, it must be indicated how the applied method deviates from the standard
- Any information relevant for the measurement or for its repeatability
- Information on the measurements and investigations carried out as well as on the results obtained. Usually, this information will be completed by tables, diagrams, sketch-

es and photos. It should be especially documented to what extent the sound velocity profile might have an impact on the measuring results

- Details on the test used equipment (description, manufacturer, type, serial number) and the applied software (description, manufacturer, type, revision/modification status)
- To be able to retrace the impact of such testing devices, which are subsequently found to be faulty, the serial numbers of all measuring devices must be given as well as the revision state of respective calculation programmes
- The use of calibrated measuring devices has to be noted down. There also have to be records on the function test of the hydrophone chain before and after each measurement
- Information on the measurement uncertainty.

7.2.3 Requirements for the presentation of the results

The following information has to be given in the diagrams:

- Measuring object, measuring position
- Reference values
- Information on the analysis, third-octave band or narrowband spectra indicating the bandwidth. If appropriate, details of the conversion of bandwidths, etc.
- Averaging period
- Sea conditions, flow characteristics, wind velocity
- For measurements during the construction phase: time and duration of pile driving as well as piling energy from the piling records, time and duration of the soft start, time and duration of the deterrent measures as well as the kind of deterrence, taken from the deterrence records, time, duration and type of noise mitigation measures
- Measurements during the operation phase in accordance with the operator: speed level, power
- Reference quantities (level representation)
- For frequency presentations, a standardised format has to be used: 10 dB = 20 mm; 1 octave = 15 mm.

8 Documents and normative references

[1] BSH, Standard „Untersuchung der Auswirkungen von Offshore-Windenergieanlagen auf die Meeresumwelt (StUK 3), Stand Februar 2007.

[2] DIN 1304-1:1994-03, Formelzeichen – allgemeine Formelzeichen.

[3] DIN EN ISO/IEC 17025 – Allgemeine Anforderungen an die Kompetenz von Prüf- und Kalibrierlaboratorien.

[4] DIN EN ISO 14001:2009-11 – Umweltmanagementsysteme – Anforderungen mit Anleitung zur Anwendung.

[5] ISO 80000-8: Quantities and units. Part 8: Acoustics.

[6] ISO 1996: Acoustics – Description, measurement and assessment of environmental noise. Part 1: Basic quantities and assessment procedure.

[7] ISO 1996: Acoustics – Description, measurement and assessment of environmental noise. Part 2: Determination of environmental noise levels.

[8] ISO 18431-2: Mechanical vibration and shock – Signal processing. Part 2: Time domain windows for Fourier Transform analysis.

[9] IEC 60050-801: International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics.

[10] IEC 60565: Underwater acoustics – Hydrophones. Calibration in the frequency range 0,01 Hz to 1 MHz.

[11] IEC 61672-1: Electroacoustics – Sound level meters. Part 1: Specifications.

[12] DIN 45 641: Mittelung von Schallpegeln. Juni 1990.

[13] VDI 3723, Blatt 1: Anwendung statistischer Methoden bei der Kennzeichnung schwankender Geräuschimmissionen. 1993.

[14] DIN 13320: Spektren und Übertragungskurve, Begriffe, Darstellung.

[15] IEC 60263: Scales and sizes for plotting frequency characteristics and polar diagrams.

[16] ISO/WD 16554: „Measurement and reporting of underwater sound radiated from merchant ships".

[17] EG-MSRL 2008/56/EG – Meeresstrategie-Rahmenrichtlinie.

[18] IEC 61400-11: Wind turbine generator systems –Part 11:Acoustic noise measurement techniques.

[19] Elmer, Betke, Neumann (2007): Standardverfahren zur Ermittlung und Bewertung der Belastung der Meeresumwelt durch die Schallimmissionen von Offshore-Windenergieanlagen, Mitteilungen des Instituts für Statik und Dynamik der Leibniz Universität Hannover 08/2007

[20] Betke, Matuschek (2011): Messungen von Unterwasserschall beim Bau der Windenergieanlagen im Offshore-Testfelt „alpha ventus“. itap, 2011.

9 Contributors

This measuring instruction was produced with the assistance of:

- Mr. Ainslie (TNO)
- Dr. Betke (ITAP)
- Mr. Benesch (FH Flensburg)
- Ms. Blasche (BSH)
- Mr. Brensing (WDCS)
- Dr. Boethling (BSH)
- Ms. Eickmeier (BSH)
- Mr. Fischer (BSH)
- Mr. Fricke (ISD)
- Mr. Gabriel (DEWI)
- Ms. Grießmann (ISD)
- Mr. Herklotz (BSH)
- Mr. de Jong (TNO)
- Mr. Kock (GL Garrad Hassan)
- Mr. Matuschek (ITAP)
- Dr. Nejedl (FWG)
- Dr. Nissen (FWG)
- Mr. van Radecke (FH Flensburg)
- Mr. Verfuß (PtJ)
- et al.

10 Update

This measuring instruction is part of the “Standards for the Environmental Impact Assessment” (StUK3) and will be adjusted or updated on the basis of the experience and knowledge gained during its application, as required – but after two years at the latest.

Appendix

Glossary

11 Glossary

In the form of a glossary, this document describes the most important terms from the field of sound emission and offshore sound measurements related to the construction and operation of offshore wind farms. The basic terms concerning acoustics, level quantities, underwater sound measurements and predictions as well as noise impact are defined.

11.1 Physical terms and quantities

Sound field quantities

German	English
Schall	*sound*
Schallwelle	*sound wave*
Schallfeld	*sound field*
Luftschall	*airborne sound*
Unterwasserschall	*waterborne sound*
Druckschwankungen	*pressure fluctuations*
Dichteschwankungen	*density fluctuations*
Fluidschall	*fluid borne sound*
Körperschall	*structure-borne sound*
Schalldruck	*sound pressure*
Schallschnelle	*sound particle velocity*
Schallbeschleunigung	*sound particle acceleration*
Schallgeschwindigkeit	*sound velocity*
Schallausschlag	*sound particle displacement*
Wechseldichte	*fluctuating densitiy*
Schallereignis	*sound event*
Hörereignis	*auditory event*

Sound is the propagation of *pressure fluctuations* and *density fluctuations* in an elastic medium. Sound is a mechanical wave in a medium. The area where sound waves propagate is called *sound field*.

For the description of the acoustic conditions of a field, sound field quantities (and the accompanying levels) are used. These are (with typically applied symbol):

Sound pressure p, *Sound velocity* v, *sound deflection* ξ (also: x, s), *alternating density* ρ (describing density fluctuations). The applied units of the sound field quantities are summarized in Table 2 in the following section.

The pressure in the water is the sum of the static pressure and the acoustic alternating pressure (sound pressure):

$$p_{\text{total}}(t) = p_{\text{static}} + p(t)$$

Structure-borne sound is the term for sound in solid objects. It is obtained from surface movements usually in the form of the *(sound) acceleration*, rarely in the form of the *particle velocity* or *deflection* by means of suitable sensors. In connection with a fluid, structure-borne sound can also be radiated from a structure in the form of underwater sound.

The *sound velocity* is the velocity of sound waves propagating in the medium to be considered. The *sound particle velocity* is the speed of change by which the particles in the fluid, where the sound wave propagates, oscillate around their neutral position (instantaneous speed).

The sound field quantities are dependent on time and location. A sound field is completely described if all quantities are known at each location and at each time. By means of measurements, sound field quantities are recorded locally at a measuring position.

The most important quantities with regard to measuring technology are the sound pressure for sound propagation in a fluid and the acceleration for structure-borne sound.

Remark: Perception and sound

Physical processes causing sound are called *sound event*. For human beings, the acoustic perception is called *hearing event*.

Sound power quantities

German	English
Schallenergie	*sound energy*
Schallintensität	*sound intensity*
Schallleistung	*sound power*

Sound propagation also implies a transport of energy. This phenomenon can be characterised by sound energy or sound power quantities:

Sound energy, sound energy density (energy per volume), *sound power* (sound energy radiated by a sound source for a certain unit of time), *sound intensity* (energy per unit of time and area). Sound power quantities are normally not recorded directly, but calculated from other measuring quantities (sound pressure, sound particle velocity).

For example, the sound intensity is the sound pressure multiplied by the sound particle velocity

$$I = \overline{p(t) \cdot v(t)}\,.$$

Here, the overline stands for temporal averaging.

In Table 2, the symbols and units of the most important sound field quantities are summarized.

Table 2: Symbols and units of the sound field quantities applied in acoustics.

quantity	Symbol	Unit	Remark
Sound pressure	p	Pa	
Sound particle velocity	v	m/s	
Acceleration	a	m/s²	
Sound deflection	s, x, ξ	m, mm	
Sound energy		J	No common symbol
Sound energy density	E	J/m³	
Sound intensity	I	W/m²	
Sound power	P	W	

Level

German	English
Pegel	*level*
Schalldruckpegel	*sound pressure level*
Schallintensitätspegel	*sound intensity level*
Schallleistungspegel	*sound power level*

The logarithm of the ratio of a quantity proportional to power or energy and a defined reference quantity is called *level*. For example: *sound power level*.

Level quantities resulting from the common logarithm of the quotient of two quantities proportional to power are stated in the pseudo unit Bel (unit symbol B). It is common practice to state the tenfold value in decibel (unit symbol dB).

$$L_\mathrm{P} = \log_{10} \frac{P}{P_0}\,\mathrm{B} = 10 \cdot \log_{10} \frac{P}{P_0}\,\mathrm{dB}\,.$$

For levels, the reference quantity must always be stated. For example:

$$L_\mathrm{P} = 118\,\mathrm{dB} \quad \mathrm{re}\,10^{-12}\,\mathrm{W}\,.$$

As quantities proportional to power can in general (at least approximately) be presented as proportional to the square of a linear (sound) field quantity, the statement in the form of levels is also common practice for these sound field quantities. For example, the sound power is proportional to the square of the sound pressure $P \sim p^2$. Here, the *sound pressure level* is normally used:

$$L_\mathrm{p} = 10 \cdot \log_{10} \frac{p^2}{p_0{}^2}\,\mathrm{dB} = 20 \cdot \log_{10} \frac{p}{p_0}\,\mathrm{dB}\,. \tag{1}$$

The sound pressure level is usually calculated by substituting p in equation (1) by the effective value of the sound pressure level history:

$$p^2 = p_\mathrm{eff}^2 = \frac{1}{T}\int_0^T p^2(t)\,dt\,.$$

The level calculated from p^2_eff is also called equivalent continuous sound level (see following section).

The quantities *sound particle velocity* v, *intensity* I and *power* P, which describe the sound field, can also be stated in the form of levels.

The most important internationally standardized reference values are listed in the following Table 3.

Table 3: Reference values for level quantities.

Measuring quantity	Symbol	dB reference factor	Other reference values
Sound pressure	p_0	$1\mu\text{Pa} = 10^{-6}\ \text{Pa}$	$20\mu\text{Pa} = 2 \cdot 10^{-5}\ \text{Pa}$ (in air)
Sound particle velocity	v_0	$5 \cdot 10^{-8}\ \text{m/s}$	
Acceleration	a_0	$\pi \cdot 10^{-4}\ \text{m/s}^2$ (acoustics)	$10^{-6}\ \text{m/s}^2$ (ISO)
Sound deflection	s_0, x_0, ξ_0	$10^{-6}\ \text{m}$	
Sound intensity	I_0	$10^{-12}\ \text{W/m}^2$	
Sound power	P_0	$10^{-12}\ \text{W}$	

Usually, levels referring to a restricted bandwidth are used. The bandwidth can result from a filter arranged in front of the measuring device. The spectral analysis is common practice where the sound pressure level history is calculated for a bank of filters (example: octave band filters, third-octave band filters), so that a series of level values can be stated for each band (each filter).

According to the standards of DIN, IEC and ISO, the described physical level quantities have to be marked by a corresponding index. Besides, information on the weighting and other supplements (like time and frequency weightings) have to be added to the evaluated quantity and not to the pseudo unit dB. Examples:

- The non-standard notation dB(A) can still be found in textbooks or legislative texts.
- The correct notation would be, for example,
    - $L_{\text{pAS}} = 75\,\text{dB}$ (spectral A-weighted sound pressure level, temporally weighted with the time constant „slow“, i.e. 1 s) or
    - $L_{\text{pME,T0}} = 110\,\text{dB}$ (spectral M-weighted sound exposure level with the reference period T_0, see below).

Remark: The use of levels compared with signal amplitudes is advantageous for the following reasons:

- Better readability due to the reduced range of values
- More transparent presentation, especially concerning spectral presentation
- Simplified calculation, if transfer quantities are applied to the levels.

Remark: Definition of **measures**

The logarithm of the ratio of two quantities proportional to energy or power is called *measure* (example: sound reduction index, transmission loss). Unlike the measure, the level has a specified reference quantity.

Assessment of sound (sound immission)

German	English
Beurteilung	*assessment*
Einzelereignispegel	*sound exposure level, SEL*
Spitzenpegel	*peak level (zero-to-peak level)*
Spitzenschalldruckpegel	*(zero to peak) sound pressure level*

The aim of an *assessment* of sound immission is to assess the impact of sound on an object of protection by means of suitable methods and to state whether the aimed protection objectives have been achieved.

There are measurement and assessment methods to predict the impact of noise. It is stipulated within the scope of standards or by the legislator and the licensing authorities, respectively, which methods have to be applied in the specific case.

For the assessment of sound it has to be considered that the effects on protective goods depend on the characteristics of the assessed sound events. Rough classifications can be made according to temporal features, for example according to periodic, stochastic and transient (temporary) sounds [31]. Spectral features are narrowband or broadband spectra, tonal or harmonic sound events.

For the assessment of underwater sound, at present the following assessment quantities are taken into account (as at July 2011):

Single-event level L_E**,** (also called *sound exposure level SEL*):

$$L_{\mathrm{E}} = 10\log_{10}\frac{E}{E_0}.$$

Here, E is the sound exposure $E = \int_0^T p(t)^2 dt$ during the measuring period T and $E_0 = p_0^2 \cdot T_0$ the reference quantity (dB reference factor) (reference sound pressure level p_0 = 1 µPa, reference period T_0 = 1 s). The single-event level is stated in decibels with the reference value 1 µPa^2·s. As an abbreviation, the notation $L_{\mathrm{pE,T0}}$ is also common practice.

The single-event level of a sound event corresponds to the level of a square pulse with a duration of 1 second, which has the same sound exposure as the sound event.

Within the scope of offshore sound measurements, the single-event level is only used to assess single sound events. In principle, it can also be applied for the assessment of a cumulative influence.

Peak level L_{peak}:

The quantity is a measure for sound pressure peaks (without time or frequency weighting and without averaging):

$$L_{\mathrm{peak}} = 20 \cdot \log_{10}\frac{p_{\mathrm{peak}}}{p_0}.$$

Here, p_0 is the reference sound pressure 1 µPa and p_{peak} the maximum positive or negative sound pressure amplitude:

$$p_{\text{peak}} = \max(|p(t)|).$$

The peak level is used for the assessment of transient noise.

Besides, the ***equivalent continuous sound level*** L_{eq} is used (also in the form of an average level with the symbols L_{T} oder L_{eqT}):

$$L_{\text{eq}} = 10\log_{10}\left(\frac{\frac{1}{T}\cdot\int_0^T p(t)^2\,dt}{p_0^2}\right)$$

(see also DIN EN 61672-1). The L_{eq} includes all shares of sound according to their intensity, duration and frequency.

Apart from these quantities, a number of other assessment quantities are used. The following selection is not complete:

L_{peak}, the peak/peak level ($L_{\text{pk-pk}}$, $L_{\text{peak-peak}}$) is a measure for sound pressure peaks. It is defined by the difference of the largest and smallest sound pressure amplitude (i.e. highest or lowest pressure peak, $p_{\text{max+}}$ or $p_{\text{min-}}$):

$$L_{\text{pk-pk}} = 20\cdot\log_{10}\left(\frac{p_{max+} - p_{\text{min-}}}{p_0}\right).$$

The peak/peak level is maximal 6 dB higher than the peak level.

The single-event level is sometimes defined via the signal energy:

$$L_{\text{E90}} = 10\cdot\log_{10}\frac{E_{90}}{E_0} \text{ with } E_{90} = \int_{t_5}^{t_{95}} p^2(t)\,dt\ ,$$

E_0 like stated above. The integration limits t_5 and t_{95} describe those points in time when 5 % or 95 % of the signal energy are reached. This definition is at first only suitable for single sound events.

Weighted levels (see section “Levels”) are used to demonstrate time or frequency-dependent properties of the hearing of different species. Concerning the assessment of underwater sound, there are no standardized time or frequency weightings (yet).

11.2 Measuring technology, analysis methods

Measurements

German	English
Hydrofon	*hydrophone*
Elektroakustische (Schall-)wandler	*electroacoustic transducers*
Aufnehmer (Sensor)	*sensor*
Messsystem	*measurement system (measuring system)*
Messkette	*measurement chain (measuring chain)*
Messabweichung	*observational error*

Concerning underwater sound measurements, *sound pressures* p are recorded almost exclusively with *hydrophones*. Hydrophones are special *electroacoustic transducers*, i.e. systems suitable to convert mechanical vibrations into electric energy.

With a hydrophone, the underwater sound (pressure) is converted into a voltage which is proportional to the (local) sound pressure. The voltage signals can be recorded and analysed with *measuring and analysing systems* (see section 11.2).

For the recording and assessment of the sound pressure, the complete *measuring chain* or measuring facility (all measuring devices and additional systems to obtain a measuring result) have to be taken into account. The measuring chain consists of all devices on the path of the measuring signal, typically of a *sensor*, a preamplifier, a measuring transducer, an analysis device with display, storage of data or measuring values.

Correct measurement descriptions include statements on the always existing tolerances and *measurement errors*.

Further sound field quantities (*sound particle velocity*, *sound intensity*, *sound power*, see section “Sound power quantities”) can be recorded indirectly (as calculated values resulting from sound pressure level measurements). Such procedures are rather unusual concerning underwater sound.

In some special cases, vibrations of the sea bed are recorded with geophones. Geophones are electromechanical transducers, which provide an output voltage proportional to the ground movement.

Signal processing and signal analysis

German	English
periodisches Signal	*periodic signal*
stochastisches Signal	*stochastic signal*
transientes Signal	*transient signal*
Signalverarbeitung	*signal processing*
Signalanalyse	*signal analysis*
A/D-Wandler	*A/D converter*
Spektralanalyse	*spectral analysis*
Filterung	*filtering*
Terz	*3^{rd} octave band*
Oktave	*octave*
Oktavspektrum	*octave spectrum*
Fouriertransformation	*Fourier transformation*

Bandpassfilter	*band pass filter*
Frequenzbewertung	*frequency weighting*
Zeitbewertung	*temporal weighting*

A signal is a quantity variable in time[3]. As for the classification of sound, there is a rough differentiation in periodic, stochastic and transient signal types.

Signal processing comprises processing steps with the aim to extract information from a measuring signal. Acoustic measuring signals are the sound pressure levels recorded in a certain period of time. Relevant information is, for example, levels of certain sound events or the frequency of existing tones.

The *signal analysis* investigates the properties of signals with mathematic tools such as *spectral analysis*, *filtering*, *smoothing*. The terms “signal processing” and “signal analysis” are often used synonymously.

Usually, digital measuring signals are the basis for modern analysis systems, i.e. the signal was converted from an analog to a digital measuring signal before data storage or processing. Software-assisted analysis systems offer the possibility to calculate suitable analyses and to present the results graphically.

The most important element of signal analysis is the spectral or frequency analysis. Each (time) signal can be decomposed in its spectral components (spectrum).

A distinction is made between band pass spectra (e.g. *third-octave spectra*, *octave spectra*) and narrowband spectra.

A third-octave filter (also called 1/3 octave filter) is a special form of a *band pass filter*. To characterize band pass filters, their pass band is used (frequency range where spectral shares can pass the filter). It is usually described by the centre frequency and the bandwidth (further filter properties are e.g. limiting frequencies, centre frequency and quality). If a series of filters consecutive in the spectral range is used for the signal analysis, it is called a filter series. For octave filters, the centre frequency of adjacent filters $f_{m,2} = 2 \cdot f_{m,1}$ is valid. For third-octave filters, $f_{m,2} = \sqrt[3]{2} \cdot f_{m,1}$ is valid, i.e. three third-octave filters comprise the frequency range of an octave. Third-octave filters are standardized according to DIN 45652.

The mathematical basis for narrowband analyses is the *Fourier transformation*.

The hearing sensitivity which depends on the frequency can be presented by the *frequency weighting*. The measuring quantity sound pressure level is weighted by a weighting filter. The frequency weighting can thus be presented as a frequency-dependent level deduction for each spectral band.

Concerning the *time weighting*, a time constant is added to the measured sound pressure levels. Thus, the adjusted time constant has an influence on the “inertia” of the level course. The applied time constants represent the properties of the temporal processing of the ear.

Combinations of time and frequency weighting are possible and common practice.

---

[3] Sometimes (in sonar technology, the signal detection theory or information theory) a signal is only named a signal if it contains useful information. The opposite (variable quantity without information) is then called *disturbance* or *background noise*.

Sound propagation

German	English
Schallquelle	*sound source*
Quellpegel	*source level*
Schallemission	*sound emission*
Schallimmission	*sound immission*
Schallausbreitung	*sound propagation*
Salzgehalt (Salinität)	*salinity*
Schichtung	*stratification*
Brechung	*refraction*
Reflexion	*reflection*
Streuung	*scattering*
Ausbreitungsverlust	*transmission loss*
geometrische Abnahme	*geometrical spreading*
Anomalie der Schallausbreitung	*anomaly of sound propagation*
Flachwasser	*shallow water*

Sound emission describes the emission of sound from a *sound source*. A sound source is characterized by its *source level* (see also section “Levels”).

The term *sound immission* describes the effect of sound on a certain location. The sound immission depends on the sound emission and sound propagation.

The propagation of acoustic waves in the sea (*sound propagation*) depends on a number of external parameters and is thus a complex process.

- The sound velocity is not continuous, but changes with the depth. Furthermore, the salinity and temperature have an influence on the sound velocity. Especially the temperature itself varies depending on the water depth (*stratification*).
- As a consequence of the varying sound velocity, the sound is refracted towards the ground or the surface (*defraction*). Zones with high or low sound pressure are created.

  Thus, in case of complex propagation conditions there is often no monotonous sound pressure decrease with an increasing distance from the source.
- The quality of the surface and the ground leads to *reflection* and *dispersion* of sound.

An important quantity to describe sound propagation in the sea is the *propagation loss*. It depends on the location, distance and frequency. It is composed of the *geometric decrease* of the sound intensity and the frequency-dependent attenuation due to absorption. The term “anomaly” summarizes phenomena like refraction, inhomogeneity, reflection and dispersion.

In particular the sound propagation in shallow water (water depth below 200 m) or extremely shallow water (water depth below 50 m) is characterized by frequent reflections at the surface and on the ground. The propagation losses are decisively determined by the properties of the ground. The predictability of sound propagation is more difficult than for deep water. The losses due to reflection or dispersion at limiting surfaces are summarized by the term *anomaly of sound propagation*.

If the sound velocity profile has a minimum at a certain depth, a sound channel is created. In certain circumstances, sound is refracted towards the channel axis again and again and can propagate over long distances.

Impact of sound (on marine species)

German	English
Schallwirkung	*impact of sound*
Verhaltensreaktion	*behavioural reaction*
vorübergehende Hörschwellenverschiebung	*temporary threshold shift*
dauerhafte Hörschwellenverschiebung	*permanent threshold shift*

Sound emissions can be perceived by marine mammals over long distances. The impact of sound on marine mammals can lead to *behavioural reactions* (stress reactions, i.e. escape), but also to physiological reactions, i.e. influence on the hearing ability.

The first step of a physiological reaction is a *temporary hearing loss* or a temporary shift of the hearing threshold (TTS, temporary threshold shift). This decrease in the hearing ability can also have a negative effect on the sense of direction and the acoustic communication.

If no recovery from the TTS occurs within a certain period, it is called a *permanent hearing loss* or permanent threshold shift (PTS).

11.3 Prediction of underwater sound

German	English
Ausbreitungsmodell	*propagation model*
Prognose	*prediction*
Quellpegel	*source level (SL)*
entfernungsunabhängiges Modell	*range independent acoustic model*
entfernungsabhängiges Modell	*range dependent acoustic model (RAM)*
Nahfeld	*near field*
Fernfeld	*far field*

Acoustic *propagation models* are numerical methods to represent sound propagation in the sea. By changing the model parameters, different situations can be presented (e.g. seasonal changes of the sound velocity profile due to variation of temperature or salinity).

The model is called *range independent* if the specific oceanographic parameters of the medium do not change with the distance. Thus, the model is only horizontally stratified. A model is *range dependent* if the parameters are taken into account with regard to their spatial distribution.

There are a number of acoustic models to describe sound propagation in the sea, see for example [31].

During the approval process of offshore wind farms, numerical calculations and *predictions* aim to forecast the expected underwater sound emissions during construction and operation and to compare it with the requirements of the licensing authorities. It is important that the calculations are done in a way that a comparison between forecast and measurements is possible.

To model the sound field during the construction work at a wind farm, apart from knowing the propagation conditions a description of the sound source is required. In practice, the *source level* is normally used for this purpose. It is an idealized quantity (the sound pressure, which would be measured at a distance of 1 m from an isotropic source or acoustic monopole).

Using the source level and the modelled propagation conditions (sound velocity profile, water depth, sea state and ground characteristics), the predicted propagation loss and the calculated sound pressure level at the point-of-interest result from the model.

In comparison to the idealized source level, differences have to be taken into account when characterizing real sound sources, e.g. the extension of the sound source and directivity of the radiated sound.

In the *near field*, i.e. in areas near to the sound source, sound pressure and sound particle velocity are not in phase. Hence, an assessment of the sound power according to the assumption $P \sim p^2$ (in the distant *field*) is not allowed. The transition between near and distant field is not clear. For distant field conditions, the distance to the sound source should be clearly longer than the dimensions of the sound source and the largest wave length of interest.

12 Literature

[21]DEGA-Empfehlung 101, Akustische Wellen und Felder, März 2006.

[22]DIN 1304-1:1994-03, Formelzeichen – allgemeine Formelzeichen.

[23]DIN 1319-1:1995, Grundlagen der Messtechnik. Teil 1: Grundbegriffe.

[24]DIN 1319-2:1995, Grundlagen der Messtechnik. Teil 2: Begriffe für Messmittel.

[25]DIN 1320:2009-12, Akustik – Begriffe

[26]DIN EN ISO 80000-8:2007, berichtigt 2007-08-15, Größen und Einheiten – Teil 8: Akustik

[27]DIN 13320:1979-06, Akustik; Spektren und Übertragungskurven, Begriffe, Darstellung.

[28]DIN EN 61672-1, Elektroakustik; Schallpegelmesser. Teil 1: Anforderungen. 2003. (IEC 61672-1:2002).

[29]Hellbrück, J., Hören. Hogrefe, Göttingen, 1993.

[30]Müller, G., Möser, M. (Hrsg.), Taschenbuch der Technischen Akustik. 3. Auflage, Springer, Berlin, Heidelberg, 2004.

[31]Urban, Heinz. G., Handbuch der Wasserschalltechnik. STN Atlas Elektronik GmbH, Bremen, 2002.

[32]Urick, Robert J., Principles of Underwater Sound. 3rd edition. McGraw-Hill Book Company. New York, 1983.