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**Underwater acoustics – Hydrophones – Calibration of hydrophones –
Part 1: Procedures for free-field calibration of hydrophones**

**Acoustique sous-marine – Hydrophones – Étalonnage des hydrophones –
Partie 1: Procédures d'étalonnage en champ libre des hydrophones**



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IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**UNDERWATER ACOUSTICS – HYDROPHONES –
CALIBRATION OF HYDROPHONES –****Part 1: Procedures for free-field calibration of hydrophones****FOREWORD**

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This first edition of IEC 60565-1, together with IEC 60565-2, cancels and replaces the second edition of IEC 60565 published in 2006. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- 1) removal of all descriptions of methods for pressure calibrations of hydrophones – these are now included in Part 2;
- 2) removal of the derivations of formulae for free-field reciprocity calibration (both amplitude sensitivity and phase sensitivity) and placement of these into an informative annex;
- 3) inclusion within the scope of the calibration of the transmitting response of individual source **transducers** and hydrophones (but not sonar arrays);
- 4) re-ordering of the sections within the document such that the more general procedures for calibration such as guidance on obtaining conditions of acoustic free-field, far-field, and

steady-state, appear before the descriptions of procedures for absolute or relative calibrations;

- 5) revision of informative Annex A to include guidance on measurement of directional response of a hydrophone or projector;
- 6) addition of a new informative Annex B on measurement of electrical impedance of hydrophones and projectors;
- 7) revision of the previous informative annex on electrical loading corrections to include corrections to account for electrical loading by added cables (now Annex C);
- 8) addition of a new informative Annex D on acoustic far-field criteria in underwater acoustic calibration;
- 9) revision of the previous informative annex on pulsed techniques in free-field calibrations (now Annex E);
- 10) revision of the previous informative annex on assessment of uncertainty in the calibration of hydrophones (now Annex F);
- 11) deletion of the previous informative annex on equivalent circuit of the excitation system for calibration with a vibrating column;
- 12) addition of a new informative Annex G on derivation of the formulae for three-**transducer** spherical-wave reciprocity calibration;
- 13) addition of a new informative Annex H on calibration using travelling-wave tubes;
- 14) addition of a new informative Annex I on calibration of hydrophones using optical interferometry.
- 15) addition of a new informative Annex J on calibration in reverberant water tanks using continuous **signals**.

The text of this standard is based on the following documents:

CDV	Report on voting
87/708/CDV	87/736/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

NOTE Words that appear in **bold** in the text are terms explicitly defined in Clause 3.

A list of all parts in the IEC 60565 series, published under the general title *Underwater acoustics – Hydrophones – Calibration of hydrophones*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

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INTRODUCTION

Underwater acoustic measurements are made to provide validation and qualification in a wide range of ocean applications, including oceanography, defence, fisheries, geophysics and in developments in the off-shore energy industries. In addition, the increasing concern about the effect of anthropogenic sound on the marine environment has led to regulation which requires absolute acoustic measurement of the sound radiated by specific sources, and of the ambient sound field.

To be meaningful, it is important that measurements be performed in a technically sound manner, be related to common standards of measurement, and be made using calibrated sensors. **Hydrophones** are the most commonly-used sensor to measure sound in the ocean. It is important that the **hydrophones** used to measure sound pressure are calibrated using agreed standard methodologies, with valid uncertainties.

The purpose of this document is to establish procedures for calibration under free-field conditions of **hydrophones** used in underwater acoustics for ocean applications. Also covered are calibration procedures for individual underwater **electroacoustic transducers** which can be used as a **hydrophone** and/or source **transducer**. Principles, procedures, and sources of uncertainty are also provided in this document. The calibration methods described include absolute methods which do not require an acoustic reference **transducer**, and relative methods which make use of a calibrated acoustic reference **hydrophone** or **projector**. The methods described cover the frequency range from 200 Hz to 1 MHz.

UNDERWATER ACOUSTICS – HYDROPHONES – CALIBRATION OF HYDROPHONES –

Part 1: Procedures for free-field calibration of hydrophones

1 Scope

This part of IEC 60565 specifies methods and procedures for free-field calibration of **hydrophones**, as well as individual **electroacoustic transducers** that can be used as **hydrophones** (receivers) and/or **projectors** (source **transducers**). Two general types of calibration are covered within this document: absolute calibration using the method of three-**transducer** spherical-wave reciprocity, and relative calibration by comparison with a reference device which has already been the subject of an absolute calibration.

The maximum frequency range of the methods specified in this document is from 200 Hz to 1 MHz. The lowest acoustic frequency of application will depend on a number of factors, and will typically be in the range 200 Hz to 5 kHz depending mainly on the dimensions of the chosen test facility. The highest frequency of application for the methods described here is 1 MHz.

Procedures for pressure **hydrophone** calibration at low frequencies can be found in IEC 60565-2 [1]¹. Procedures for **hydrophone** calibration at acoustic frequencies greater than 1 MHz are covered by IEC 62127-2 [2].

Excluded from the scope of this document are low-frequency pressure calibrations of **hydrophones**, which are described in IEC 60565-2 [1]. Also excluded are calibrations of digital **hydrophones** and systems, calibration of marine autonomous acoustic recorders, calibration of acoustic vector sensors such as particle velocity sensors and pressure gradient **hydrophones**, calibration of passive sonar arrays consisting of multiple **hydrophones**, and calibration of active sonar arrays consisting of projectors and **hydrophones**.

This document presents a description of the requirements for free-field calibration in terms of test facility, equipment and instrumentation, **signal** processing, and frequency limitations. A description of achievable uncertainty and rules for the presentation of the calibration data are provided. Also included are informative annexes that provide additional guidance on

- measurement of directional response of a **hydrophone** or projector,
- measurement of electrical impedance of **hydrophones** and projectors,
- electrical loading corrections,
- **acoustic far-field** criteria in underwater acoustic calibration,
- pulsed techniques in free-field calibrations,
- assessment of uncertainty in the free-field calibration of **hydrophones** and projectors,
- derivation of the formulae for three-**transducer** spherical-wave reciprocity calibrations,
- calibration using travelling-wave tubes,
- calibration of **hydrophones** using optical interferometry, and
- calibrations in reverberant water tanks using continuous **signals**.

¹ Numbers in square brackets refer to the Bibliography.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-801, *International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics* (available at <http://www.electropedia.org/>)

IEC 60500:2017, *Underwater acoustics – Hydrophones – Properties of the hydrophone in the frequency range 1 Hz to 500 kHz*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-801, IEC 60500:2017 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

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- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

acoustic far-field

sound field at a sufficient distance from a sound source in a uniform medium where the sound pressure and sound particle velocity are substantially in phase and the direct-path sound pressure amplitude, compensated for absorption loss, varies inversely with distance

Note 1 to entry: The range (distance from the source) is taken along a direct path between the source and the receiver.

Note 2 to entry: The inverse dependence on range does not imply that the source radiates equally in all directions.

[SOURCE: IEC 60050-801:1994, 801-23-30, modified – In the definition, "and the direct-path sound pressure amplitude, compensated for absorption loss, varies inversely with distance" has been added, sourced from ISO 18405:2017, 3.3.1.1.]

3.2

electrical transfer impedance

Z_{PH}

<of a transducer pair> quotient of the Fourier transform of the **hydrophone** open-circuit output voltage $\mathcal{F}(U_H(t))$ to the Fourier transform of the electrical drive current through the **projector** $\mathcal{F}(I_P(t))$, for a **transducer** pair at a specified separation distance with one used as a **hydrophone** and one as a **projector**

$$Z_{PH} = \frac{\mathcal{F}(U_H(t))}{\mathcal{F}(I_P(t))} \quad (1)$$

Note 1 to entry: The **electrical transfer impedance** is a complex-valued parameter. The modulus of the **electrical transfer impedance** is expressed in units of ohm, Ω . The phase angle of the **electrical transfer impedance** is the argument of the **electrical transfer impedance** and represents the phase difference between the **hydrophone** voltage and the **projector** current [IEC 60050-351:2013, 351-45-45]. The unit of phase angle is the radian.

Note 2 to entry: Because the **electrical transfer impedance** depends on the field conditions, the hydrostatic pressure, water temperature and the length of the cable attached to the **transducer**, these parameters, as well as the frequency are specified.

Note 3 to entry: In a spherically-spreading sound field, the **electrical transfer impedance** of the **transducer** pair depends on the distance between the source and the receiver, with the modulus varying inversely with separation distance d and phase angle varying as $\exp(jkd)$ where j is the square root of -1 and k is the **wavenumber** (see 3.14).

3.3

underwater electroacoustic transducer

electroacoustic transducer

underwater transducer

transducer

device which transforms electrical **signals** into acoustic **signals** in water, or vice versa

Note 1 to entry: An **electroacoustic transducer** which is used as an acoustic receiver in water is called a **hydrophone**.

Note 2 to entry: An **electroacoustic transducer** which is used as an acoustic transmitter in water is called a **projector**.

3.4

free-field receive sensitivity

M_f

<of a **hydrophone**> quotient of the Fourier transform of the **hydrophone** open-circuit voltage **signal** $\mathcal{F}(U_H(t))$ to the Fourier transform of the acoustic pressure **signal** $\mathcal{F}(p(t))$, for specified frequency and specified direction of plane wave sound incident on the position of the reference centre of the **hydrophone** in the undisturbed free-field if the **hydrophone** was removed

$$\underline{M}_f = \frac{\mathcal{F}(U_H(t))}{\mathcal{F}(p(t))} \quad (2)$$

Note 1 to entry: The **hydrophone free-field receive sensitivity** is a complex-valued parameter. The modulus of the **free-field receive sensitivity** of a **hydrophone** is expressed in units of volt per pascal, $V \cdot Pa^{-1}$. The phase angle is the argument of the sensitivity, and represents the phase difference between the **hydrophone** electrical voltage and the sound pressure. The unit of phase angle is the radian.

Note 2 to entry: The term "response" is sometimes used instead of "sensitivity".

[SOURCE: IEC 60500:2017, 3.15, modified – In the definition, "the root-mean-square" has been deleted, and "Fourier transform of the" has been added before "open-circuit output voltage" and "sound pressure".]

3.5

free-field receive sensitivity level

L_M

twenty times the logarithm to the base 10 of the ratio of the modulus of the free-field sensitivity M_f to a reference value of sensitivity, M_{ref} , in decibels

$$L_M = 20 \log_{10} \frac{|\underline{M}_f|}{M_{ref}} \text{ dB} \quad (3)$$

Note 1 to entry: The unit of **free-field receive sensitivity level** is the decibel, dB. The reference value of sensitivity, M_{ref} , is $1 V \cdot Pa^{-1}$ or any valid SI multiple or submultiple thereof. The most common reference value used for underwater acoustics is $1 V \cdot \mu Pa^{-1}$.

[SOURCE: IEC 60500:2017, 3.16, modified – In the definition, "modulus of the" has been added before "free-field sensitivity".]

3.6

omnidirectionality

feature of a **transducer** response such that it is invariant to direction to within a specified tolerance

Note 1 to entry: The tolerance is specified.

Note 2 to entry: **Omnidirectionality** can be specified in a two-dimensional space in one plane only, while in three dimensions a **transducer** can be omnidirectional in all planes through the reference centre.

Note 3 to entry: As a rule, a **transducer** directional response approaches **omnidirectionality** when the **transducer** dimensions are much smaller than the acoustic wavelength.

3.7

reciprocal transducer

linear, passive, and reversible **electroacoustic transducer** such that the coupling coefficients are equal for transduction regardless of whether transduction is electrical to mechanical or vice versa

[SOURCE: IEC 60050-801:1994, 801-25-08, modified – In the definition, "in either direction" has been replaced by "regardless ... vice versa".]

3.8

reversible transducer

transducer capable of acting as a **projector** as well as a **hydrophone**

3.9

projector

underwater sound projector

electro-acoustic **transducer** that converts electrical **signals** into sound that propagates in water

[SOURCE: IEC 60565:2006, 3.37, modified – The term "underwater sound **projector**" has been added.]

3.10

transmitting response to current

S_1

quotient of the product of the Fourier transform of the sound pressure $\mathcal{F}(p(t))$ at a position in the **acoustic far-field** of a **projector** (compensated for absorption loss) and the distance, d , from the reference centre of the **projector**, to the Fourier transform of the electrical current through the **projector** $\mathcal{F}(I(t))$, at a specific frequency and in a specified direction, under acoustic free-field conditions in a uniform medium

$$S_1 = \frac{\mathcal{F}(p(t)d)}{\mathcal{F}(I(t))} \exp[jk(d-d_0)] \quad (4)$$

where d_0 is the reference distance, chosen to be equal to 1 m

Note 1 to entry: The **transmitting response to current** of a **projector** is a complex-valued parameter. The modulus of the **transmitting response to current** is expressed in units of pascal metre per ampere, $\text{Pa} \cdot \text{m} \cdot \text{A}^{-1}$. The phase angle is the argument of the transmitting response and represents the phase difference between the sound pressure at a distance d from the **projector** and the electric current. The unit of phase angle is the radian.

Note 2 to entry: The term "sensitivity" is sometimes used instead of "response".

3.11

transmitting current response level

$L_{S,I}$

twenty times the logarithm to the base 10 of the ratio of the modulus of the **transmitting response to current**, S , to a reference value of the transmitting response, $S_{I,\text{ref}}$, in decibels

$$L_{S,I} = 20 \log_{10} \frac{|S_I|}{S_{I,ref}} \text{ dB} \quad (5)$$

Note 1 to entry: The unit of **transmitting current response level** is the decibel, dB. The reference value of the transmitting response, $S_{I,ref}$, is $1 \mu\text{Pa} \cdot \text{m} \cdot \text{A}^{-1}$.

Note 2 to entry: The **transmitting response to current** of a **projector** is sometimes shortened to "transmitting current response" or "TCR".

[SOURCE: IEC 60565:2006, 3.27, modified – In the definition, "modulus of the" has been added before "**transmitting response to current**", and "in decibels" has been added to the end. The formula has been added. Notes to entry have been combined.]

3.12 transmitting response to voltage

S_V

quotient of the product of the Fourier transform of the sound pressure $\mathcal{F}(p(t))$ at a position in the **acoustic far-field** of a **projector** (compensated for absorption loss) and the distance d from the reference centre of the **projector** to the Fourier transform of the electrical voltage across the terminals of the **projector** $\mathcal{F}(V(t))$, at a specific frequency and in a specified direction, under acoustic free-field conditions in a uniform medium

$$\underline{S}_V = \frac{\mathcal{F}(p(t))d}{\mathcal{F}(V(t))} \exp[jk(d-d_0)] \quad (6)$$

where d_0 is the reference distance chosen to be equal to 1 m

Note 1 to entry: The **transmitting response to voltage** of a **projector** is a complex-valued parameter. The modulus of the **transmitting response to voltage** is expressed in units of pascal metre per volt, $\text{Pa} \cdot \text{m} \cdot \text{V}^{-1}$. The phase angle is the argument of the transmitting response and represents the phase difference between the sound pressure at a distance d from the **projector** and the electrical current. The unit of phase angle is the radian.

Note 2 to entry: The term "sensitivity" is sometimes used instead of "response".

Note 3 to entry: The **transmitting response to voltage** of a **projector** is sometimes shortened to "transmitting voltage response" or "TVR".

3.13 transmitting voltage response level

$L_{S,V}$

twenty times the logarithm to the base 10 of the ratio of the modulus of the **transmitting response to voltage**, S_V , to a reference value of the transmitting response, S_{ref} , in decibels

$$L_{S,V} = 20 \log_{10} \frac{|S_V|}{S_{ref}} \text{ dB} \quad (7)$$

Note 1 to entry: The unit of **transmitting voltage response level** is the decibel, dB. The reference value of the transmitting response, S_{ref} , is $1 \mu\text{Pa} \cdot \text{m} \cdot \text{V}^{-1}$.

[SOURCE: IEC 60565:2006, 3.30, modified – In the definition, "modulus of the" has been added before "**transmitting response to voltage**", and "in decibels" has been added to the end. The formula has been added. Notes to entry have been combined.]

3.14 wavenumber

k

reciprocal of the acoustic wavelength, multiplied by 2π

$$k = 2\pi/\lambda \quad (8)$$

Note 1 to entry: **Wavenumber** is expressed in units of per m, m^{-1} .

Note 2 to entry: In different branches of physics, the term **wavenumber** can be considered equal to either $2\pi/\lambda$ or $1/\lambda$, but in the technical field of acoustics, $2\pi/\lambda$ is preferred. This term is named as "angular **wavenumber**" in IEC 60050-103:2009, 103-10-12.

[SOURCE: IEC 60050-726:1982, 726-05-02, modified – In the definition, "of the waveguide wavelength or the reciprocal of the wavelength for a plane wave" has been replaced by "acoustic wavelength" and "multiplied by 2π " has been added. Notes to entry have been added.]

3.15

hydrophone

electroacoustic transducer that produces electrical voltages in response to water borne pressure **signals**

Note 1 to entry: A **hydrophone** is designed to respond principally to underwater sound pressure.

Note 2 to entry: In general, a **hydrophone** may also produce a **signal** in response to non-acoustic pressure fluctuations (for example, those existing in a turbulent boundary layer during conditions of high water flow).

Note 3 to entry: **Hydrophone** types include reference **hydrophones** and measuring **hydrophones**. Measuring **hydrophones** are used in general measurements of sound fields, and reference **hydrophones** are principally used for calibration purposes (for example in comparison calibrations with measuring **hydrophones**).

Note 4 to entry: **Hydrophones** are principally used as listening devices, but in reciprocity calibration, a **hydrophone** is used as reciprocal **transducer**, not only acting as a **hydrophone**, but also as a projector (sound source).

Note 5 to entry: A **hydrophone** which is integrated with a digital acquisition system is sometimes termed a "digital **hydrophone**", but the combination is best considered as a measuring system, not a **hydrophone** alone.

Note 6 to entry: If a **hydrophone** is connected to a charge amplifier, the sensitivity of the **hydrophone** is sometimes described in terms of charge sensitivity, which is related to the voltage sensitivity of the **hydrophone** by its electrical capacitance.

[SOURCE: IEC 60500:2017, 3.17, modified – In the definition, "signals" has been replaced by "voltages".]

3.16

signal

specified time-varying field quantity of interest, such as electric current, voltage, sound pressure, sound particle velocity, or other quantity

[SOURCE: ISO 18405:2017, 3.1.5.8]

3.17

directional response

directivity

directivity pattern

normalized variation in **transducer** sensitivity with angle, applying to both receive and transmit sensitivity of an **electroacoustic transducer**

Note 1 to entry: The sensitivity value used for normalization is the sensitivity in a specified reference direction, most commonly the sensitivity in the direction of the principal axis of the **transducer** (as defined in IEC 60500:2017).

Note 2 to entry: If the **transducer** is reciprocal, the normalized **directional response** is the same in both transmit and receive modes.

Note 3 to entry: The response is sometimes expressed as normalized **directional response** level in decibels.

Note 4 to entry: **Directional response** can be specified in a two-dimensional space in one plane only. Conventionally, the two-dimensional **directional response** is specified in the three planes defined for the **transducer** coordinate system defined in IEC 60500:2017 (XY, XZ, YZ). In three dimensions, a **transducer directional response** can be specified in all planes through the reference centre.

3.18

angular deviation loss

sensitivity level of the **transducer** on the principal axis minus the sensitivity level of the **transducer** in a specified direction

Note 1 to entry: The loss is expressed as a (relative) level in decibels.

Note 2 to entry: The **angular deviation loss** is the same as the level of the normalized **directional response**.

[SOURCE: IEC 60050-801:1994, 801-25-69]

3.19

quality factor

Q-factor

Q

measure of sharpness of resonance of a **transducer**, equal to 2π times the ratio of the maximum stored energy to the energy dissipated during one cycle

Note 1 to entry: The quality factor is typically measured as the reciprocal of fractional bandwidth at resonance (see Annex B).

[SOURCE: IEC 60050-801:1994, 801-24-12, modified – In the definition, "system" has been replaced by "transducer". Note 1 to entry has been added.]

4 Symbols and abbreviated terms

D	largest linear dimension of transducer
C	electrical capacitance
c	speed of sound in water
D_i	directivity index
d	distance between projector and hydrophone
dS	differential area on a sphere
f	acoustic frequency
f_R	resonance frequency (of a transducer)
I	electrical current
I_P	electrical current through projector
I_T	electrical current through transducer
j	square root of minus one
K_f	far-field correction factor
l	width of tank
L_M	free-field receive sensitivity level
$L_{S,I}$	transmitting current response level
$L_{S,V}$	transmitting voltage response level
$\underline{M}_f$	free-field receive sensitivity
$\underline{M}_H$	free-field receive sensitivity of hydrophone
$\underline{M}_T$	free-field receive sensitivity of transducer
$\underline{M}_P$	free-field receive sensitivity of projector (when used as a hydrophone)
$\underline{M}_R$	free-field receive sensitivity of reference hydrophone
p	sound pressure
p_a	sound pressure in the reference direction for R_θ during directional response measurements

P	projector
Q	quality factor of transducer (or measuring system)
r	range from source (distance from source to point in acoustic field)
R	resistance
R_θ	directivity factor
S_I	transmitting response to current
$S_{I,H}$	transmitting response to current of a hydrophone (when used as a projector)
$S_{I,P}$	transmitting response to current of a projector
$S_{I,T}$	transmitting response to current of a transducer
S_V	transmitting response to voltage of a projector
U	electrical voltage
U_H	open circuit voltage at hydrophone
U_R	open circuit voltage at a calibrated reference hydrophone
U_{PH}	open circuit voltage at hydrophone , from a projector as sound source
U_{PH}	open circuit voltage at hydrophone , from a transducer as sound source
U_{PT}	open circuit voltage at transducer , from a projector as sound source
V_P	transmitting electrical drive voltage at projector
V_T	transmitting electrical voltage at transducer
W	bandwidth
Z	electrical impedance
Z_{PH}	electrical transfer impedance of projector and hydrophone
Z_{TH}	electrical transfer impedance of transducer and hydrophone
Z_{PT}	electrical transfer impedance of transducer and projector
θ	vertical angle (elevation angle)
λ	wavelength of sound in water
ρ	density of water
τ	pulse duration
φ	azimuth angle (horizontal plane)
ω	angular frequency

5 General procedures for calibration

5.1 General calibration requirements

5.1.1 Types of calibration

Two general types of calibration are covered within the scope of this document:

- Absolute calibration without the need for an acoustic reference **transducer**

In this case, the calibration is typically based upon the principle of acoustic reciprocity, with the method requiring three **electroacoustic transducers**, at least one of which is required to be a **reciprocal transducer**. This is a primary calibration method, mainly traceable to primary electrical standards, and is capable of achieving high accuracy.

- Relative calibration using a calibrated acoustic reference **transducer**

Here, the calibration is performed by comparison to another acoustic **transducer** which has already been calibrated. The reference **transducer** may be either a calibrated **hydrophone** or a calibrated **projector**. The accuracy is typically degraded compared to a reciprocity calibration, mainly due to the added uncertainty contributed by the acoustic reference device.

5.1.2 Acoustic field requirements

For the calibrations to be valid, the following general requirements shall be satisfied [3] [4] [5]:

- acoustic free-field conditions, requiring minimal influence from acoustic reflections from medium boundaries (see 5.2);
- **acoustic far-field** conditions, requiring a sufficient separation distance between source and receiver (see 5.3);
- acoustic steady-state conditions, requiring any transient behaviour displayed by resonant **transducers** to have died down (see 5.4).

5.2 Acoustic free-field requirements

5.2.1 Continuous signals

With continuous **signals**, to limit the fluctuations in **signal** amplitude due to interference from boundary reflections, the minimum distance from the **transducers** to nearest medium boundary shall be such that the amplitude of the reflected **signals** is no more than 3 % of the amplitude of the direct **signal**.

NOTE 1 For a given measurement configuration, the minimum distance to the boundaries to satisfy the above requirement depends on the **directivity** of the **transducers**, the reflection coefficient of the boundary surfaces and on the **signal** frequency (at high acoustic frequencies, absorption in the water will increase the propagation loss, and reduce the minimum distance needed). An individual assessment of these factors can be undertaken before deciding on the minimum distance to the boundaries to meet the requirement for continuous **signals**. Often the water surface is the nearest boundary. As an example, for two omnidirectional **transducers** positioned at 5 m separation, for the amplitude of reflections to be within the above requirement, the **transducers** are positioned at a depth of approximately 16 m (assuming total sound reflection occurs at the water surface, and that the acoustic frequency is sufficiently low that absorption is not significant) [4] [5].

NOTE 2 An alternative means of achieving acoustic free-field conditions for continuous **signals** is by use of an anechoic acoustic lining deployed on the inner surface of a test tank. In this case, the performance of the anechoic material (in terms of reflection loss as a function of angle) needs to be sufficient to achieve the above requirement for reflected **signal** amplitude at the **hydrophone** over the frequency range of interest. Note that the water surface is a strong reflector of sound, and a fully anechoic test tank will require the anechoic material to be suspended just below the water surface, in addition to lining the walls and floor of the tank [4].

NOTE 3 Some calibration methods using reverberant water tanks make use of continuous **signals** (or at least **signals** that are significantly longer than the echo-free time of the tank). In such methods, pseudo-free-field conditions can be achieved by use of **signal** processing techniques which compensate for the effect of reflections from the tank boundaries. See Annex J for examples of such methods.

5.2.2 Time-limited signals

When time-limited **signals** are employed, such as pulses or bursts of single frequency (tone-burst **signals**), reflections shall be eliminated by choosing the minimum distance from the **transducers** to each boundary surface (water surface, tank bottom and side walls) such that the time delay of the reflected **signals** with respect to the direct **signal** is greater than the duration of the direct **signal**.

NOTE Burst or pulsed **signals** can be used in finite-sized test tanks to eliminate reflections by use of **signals** of finite time duration and suitable time-windowing. In this way, the reflected **signals** arrive sufficiently later than the direct **signals** that there is sufficient echo-free **signal** to undertake the required analysis. In such cases, there is a lower limiting frequency below which it is not possible to make measurements of the steady-state **signal** by conventional means. See Annex E for a detailed description of the use of pulsed and burst **signals** in calibration [4] [5] [6].

5.3 Acoustic far-field requirements

The distance d between the **projector** and the **hydrophone** shall be sufficiently large that the **acoustic far-field** conditions are met and errors due to the finite size of the **transducers** are minimized. To this end, the **projector-hydrophone** separation shall be larger than the size of the largest **transducer**, and the **hydrophone** shall be positioned in the **acoustic far-field** of the source.

For the two **transducers** with maximum dimensions of the sensitive areas of D_1 and D_2 respectively, the minimum separation distance, d , shall be chosen according to the relations:

$$d > K_f \left(\frac{D_1^2}{\lambda} + \frac{D_2^2}{\lambda} \right) \quad (9)$$

and simultaneously:

$$d > 5D_1 \quad \text{and} \quad d > 5D_2 \quad (10)$$

where K_f is the far-field correction factor chosen to ensure that the acoustic field approximates to spherical spreading to within a specified tolerance.

To obtain a separation that reduces the error due to lack of spherical divergence to less than 0,2 dB, the value of K_f in Formula (9) shall be chosen to be greater than 1,3.

See Annex D for more details on the above criteria.

NOTE When measuring the **directional response** of a **transducer**, the distance between the **projector** and the **hydrophone** is chosen to be larger than that given by Formulae (9) and (10). The distance is less than twice that given by Formula (9) or Formula (10), whichever is larger. See Annex D and references [3] to [9].

5.4 Requirements for steady-state conditions

When tone-burst **signals** are used in calibration, the time-window employed to select the **signal** for analysis shall be positioned such that the start of the window is at a time delay which is at least Q cycles of the **projector** resonance frequency after the arrival of the direct **signal**, where Q represents the quality factor (Q-factor) of the **projector**'s main resonance.

The requirement of 5.4 applies only for time-limited signals. When continuous signals are used, the transducers are regarded as having reached steady-state conditions.

NOTE 1 In the conventional arrangement for tone-burst **signals** used for calibrations in test tanks, measurements are made on the steady-state portion of the received **signal**, with time-gating techniques used to isolate the direct-path **signal** from reflections from the tank boundaries and the water surface. In such measurements, the steady-state **signal** available for analysis is limited in time both by the arrival of boundary reflections, and by start-up transients caused by the resonant behaviour of the **transducers** under test. For a simple measuring **hydrophone**, the Q-factor is typically of the order of only 3 or 4 with a relatively high resonance frequency, leading to short start-up transients which place little restriction on the **signal** duration available for measurement. However, **transducers** used as **projectors** can possess a higher Q-factor, which reduces the available **signal** (particularly if the resonance frequency is low) [4] [5] [6] [10].

NOTE 2 If the voltage **signal** generated by the **hydrophone** does not reach steady-state conditions during the available echo-free time, it is not possible to observe the steady-state directly. This means that for a given tank size and **transducer** Q-factor, there will be a lower limiting frequency below which it is not possible to perform calibrations by using tone-burst **signals** by conventional means. See Annex E for more guidance on ensuring steady-state conditions.

NOTE 3 If narrow-band filtering is applied to the **signals** (perhaps to increase the **signal**-to-noise ratio in the presence of broadband noise), this will modify the transient build-up at the start of the tone-burst. Although such filtering can eliminate the transients due to higher frequency **transducer** resonances, it can also delay the onset of steady-state and reduce the **signal** duration available for analysis. For this reason, filter bandwidths narrower than one-octave are rarely used in calibration with tone-burst signals.

NOTE 4 The required **signal** parameters can also be determined using more advanced **signal** processing techniques. These make it possible to estimate the amplitude and phase of the steady-state **signal** without the need to observe a full steady-state period. These include the use of advanced **signal**-modelling and **signal** prediction methods which utilise the transient part of the **signal** to predict the steady-state amplitude and phase, and also the use of quadrature-supplemented tone bursts (see Annex E and Annex J for more details).

5.5 Equipment requirements

5.5.1 Calibration facility

The calibration facility used shall be capable of realizing the acoustic requirements described in 5.2, 5.3 and 5.4 over the desired range of acoustic frequencies and for the **hydrophone** and **transducer** types under test.

The calibration facility shall enable a minimum of at least two **transducers** at a time to be positioned reproducibly at a known separation distance and aligned for calibration in conformance with the requirements of 5.6.

NOTE 1 The most common type of calibration facility is based around a water-filled test tank constructed from concrete, steel or wood (leading to the tank being reverberant due to the reflective boundaries). Time-limited **signals** (such as tone-bursts) are used with time-gating to eliminate the reflections. Such a facility allows for convenient access, precise positioning of devices (by use of a rigid support framework or positioning system), and control over the environmental conditions. However, the finite size places limitations on the frequency range and type of **transducer** to be calibrated. Testing of a large aperture **projector** at high frequencies (a 'high ka value' **transducer**) can be difficult in a small test tank because it is not always possible to achieve **acoustic far-field** conditions (see 5.3). A small test tank will also limit the echo-free time such that it is not always possible to observe the steady-state **signal** for high Q-factor **transducers** (see 5.4). See Annex E for more guidance and references [3] to [6], [10].

NOTE 2 If the test tank is lined with an anechoic material, it is possible to achieve free-field conditions required by 5.2 in a smaller test tank, depending on the validated performance of the anechoic material (see 5.2.1). However, deploying the **transducers** into the tank can present more practical difficulty if the water surface is covered with the anechoic material [4].

NOTE 3 For open-water facilities, the deployment of the **transducers** is typically achieved from the surface using a floating structure such as a raft or pontoon. The **transducers** are typically deployed at greater depth than for tanks, but the precision of the positioning and alignment can be degraded compared to test tanks. The lack of control over the environmental conditions can present additional problems from: (i) variations in water temperature (both diurnal and seasonal) causing changes in **transducer** performance and introducing thermoclines; (ii) weather (wind and wave action) causing relative motion of the **transducers**; and (iii) acoustic noise from natural sources and other human activities in the vicinity [4].

5.5.2 Instrumentation

5.5.2.1 General

The following measuring instrumentation is required in order to perform a calibration of an underwater **electroacoustic transducer**. All are required to have a performance that covers the desired acoustic frequency range for calibrations (this is a maximum of 200 Hz to 1 MHz, but can be a narrower range depending on the application) [4], [6], [10].

5.5.2.2 Signal source

This shall be used to provide the electrical **signal** to drive **projectors**. It can also be used to provide the trigger used for synchronizing the **signal** acquisition by the digitizer.

NOTE Typically, the **signal** source will provide a maximum output of only a few volts, but will provide a range of **signal** types, including gated-bursts of single frequency.

5.5.2.3 Power amplifier

This is required to drive the **transducer** used as a **projector** with sufficient electrical power to generate sound pressures at the **hydrophone** which are at least 6 dB higher than the ambient noise in the facility.

NOTE 1 Typically, a power amplifier capable of 100 W output power is sufficient for most **hydrophone** and **transducer** calibration purposes, but higher power performance can sometimes be required for specialized applications.

NOTE 2 Typically, the power amplifier will have a low electrical output impedance (but alternatively can have the output electrical impedance matched to the **transducer** for maximum power delivery).

5.5.2.4 Hydrophone preamplifier

This shall be required to amplify the electrical voltage developed by the **hydrophone**, and shall ideally have electrical input impedance greater than the **hydrophone** by at least a factor of 100 (since the electrical impedance of a piezoelectric **hydrophone** is mostly capacitive, the input capacitance of the preamplifier shall have a sufficiently low value).

NOTE 1 Typically, the preamplifier will have selectable voltage gain and has selectable electronic filtering (alternatively, filtering can be accomplished by use of a separate dedicated unit, or can be achieved digitally in post-processing).

NOTE 2 A separate **hydrophone** preamplifier is not needed when using a **hydrophone** with a built-in integral preamplifier.

5.5.2.5 Current measuring instrument

This is required if the electrical drive current through the **projector** is measured (for example, during a free-field reciprocity calibration). Preferably, this should consist of a calibrated current transformer which provides an output voltage proportional to electrical current (with the voltage then measured by the digitizer along with the **hydrophone** voltage).

NOTE As an alternative, a calibrated resistor and voltmeter can be used.

5.5.2.6 Drive voltage measurement instrument

This is required if the electrical drive voltage to the **projector** is measured, for example, when determining the **transmitting response to voltage** (TVR).

NOTE This typically will consist of a high impedance voltage probe, or a calibrated attenuator to reduce the drive voltage down by up to 40 dB so that it can be measured by the digitizer.

5.5.2.7 Digitizer

The digitizer used shall be an analogue-to-digital converter (ADC) or digitizing oscilloscope, which captures a digital waveform as a record of the electrical **signals** during calibration (**hydrophone** voltage, voltage from the current transformer, etc.).

The sampling rate of the digitizer shall be at least two and a half times the maximum frequency of interest, and the resolution shall be sufficient for accurate recording of the **signal** without quantization errors, with a recommended minimum resolution of 8 bit. It is recommended that the digitizer be capable of being externally triggered (typically by the **signal** source or computer). When making absolute electrical measurements, the digitizer shall be calibrated over the range of operation.

The requirement for unambiguous representation of the signals within the desired frequency range requires the sampling rate of the ADC to be greater than the Nyquist rate of the signal which is input to the ADC.

NOTE 1 Digitizers and digitizing oscilloscopes of the required sampling rates are readily available with resolutions of between 8 bit and 16 bit. The higher the resolution, the better for measurement of the signals, with less likelihood of errors due to quantization noise.

NOTE 2 To provide an anti-aliasing function, a low pass filter can be used which is designed to restrict the frequency content of the signal before digitization to below the Nyquist frequency of the acquisition system.

5.5.2.8 Computer controller

It is recommended that the calibration be controlled by a computer running appropriate acquisition software which controls the digitizer and **signal** acquisition (and can also provide the trigger for the **signal** source).

NOTE 1 The software will typically be used to undertake the required **signal** analysis, including the time-windowing and calculation of the amplitude of the recorded **signals**. However, some of these functions can be undertaken using the on-board processing features available on a digitizing oscilloscope.

NOTE 2 Although some of the above measurement tasks are capable of being performed manually (for example using an analogue oscilloscope), this practice is now discouraged.

5.5.2.9 Electroacoustic transducers

A number of **transducers** is required for use as **projectors** and **hydrophones** during calibrations. For example, calibration by three-**transducer** free-field reciprocity requires at least two **transducers** in addition to the device under test (see Clause 8), and relative calibration by use of a calibrated **hydrophone** or **projector** requires calibrated reference **transducers** and potentially auxiliary **projectors** for use in generating a suitable acoustic field (see Clause 9).

NOTE It is possible that a number of different **transducers** will be required to cover a wide frequency range (this is especially true for **projectors** which can have a limited frequency range due to their inherently resonant behaviour).

5.6 Positioning and alignment

5.6.1 Coordinate system

The angular coordinate system chosen shall be that specified by IEC 60500:2017.

5.6.2 Reference direction

Before calibration, a reference direction shall be defined for each **hydrophone** and **projector**. Unless there is good reason, the reference direction shall be chosen to be coincident with the principal axis of the **hydrophone** or **projector** [as defined in IEC 60500:2017].

For omnidirectional **hydrophones** with a symmetric construction, the reference direction shall be in a plane orthogonal to the axis of the **hydrophone** body and shall be indicated by a mark on the body of the **hydrophone** [10].

NOTE 1 The reference direction is the direction for which the free-field calibration will be valid. For directional **transducers**, the reference direction will in general be chosen to coincide with the principal axis of the **transducer**.

NOTE 2 The direction can also be chosen by determining the angle of maximum response of the **transducer** at a stated frequency by undertaking a **directional response** measurement (see Annex A for a description).

5.6.3 Transducer mounting and support

Each **projector** and **hydrophone** shall be firmly attached to a mount and support which enables the devices to be positioned accurately and reproducibly at fixed points in the water.

The supporting mount for a **hydrophone** shall be chosen to cause minimal influence on the measured sensitivity, as far as is commensurate with the above requirement for precise positioning of the **transducers**.

If a rotational stage is incorporated into the support framework or positioning system, the mount shall enable a **transducer** to be positioned with its reference centre located along the axis of rotation.

If the mount is considered to influence the measured sensitivity, the **transducer** shall be calibrated in the same mount that will be used when the device is deployed for measurements made in the field. Where the device is thought to be sensitive to the type of support or mount, a description of the mounting arrangement shall be stated with the results.

Some **transducers** are more susceptible than others to the influence of the method of mounting. To avoid the influence from the mount, it is recommended to avoid air-filled supports or poles. Where possible, it is recommended to use free-flooding supports such as hollow poles, constructed from carbon-fibre or plastic. However, note that a certain degree of rigidity is required of any mount for precise positioning and alignment [10].

For some directional **transducers**, a right-angled bracket is required to position the **transducer** at the correct orientation in the water to align the principal axis with that of the other **transducer**.

If the **transducer** is heavy, a counterweight is required to prevent the support tilting and causing the principal axis to deviate from the desired horizontal orientation. Note that if such a right-angled bracket is used, the **transducer** reference centre shall still be located along the axis of rotation of any rotational stage incorporated into the support framework or positioning system [4], [10].

Take care to minimize the amount of structure borne noise which can be picked up by the mount and supporting framework and communicated to the **transducers**.

5.6.4 Alignment

Before each acoustic measurement during the calibration, the relevant **transducer** pair (for example, a **projector** and **hydrophone**) shall be positioned at the same water depth and oriented such that the reference directions of the **transducers** are aligned. [4], [10]

NOTE 1 This alignment can be performed either mechanically using special mounting poles or rigging, or by use of an automated positioning system (for example, consisting of stepper motors and controllers). When the **transducers** are both small omnidirectional **hydrophones** which show little change in sensitivity with angle, mechanical alignment is more commonly used than acoustic alignment. Note that the lengths of the mounting poles to the **hydrophone** active elements are carefully measured so that they can be immersed precisely to the same depth.

NOTE 2 For **transducers** that show appreciable **directivity** about their principal axis, the **transducers** can be aligned acoustically by looking for the maximum received **signal** at a specific frequency. Sometimes the reference direction is chosen at an angle of the **directional response** pattern where the response does not change significantly with the directional angle, for a specific frequency. Note that if a reference direction is chosen this way, the same direction is then chosen for all frequencies.

NOTE 3 For acoustic alignment between two **transducers** (by searching for the maximum received **signal** at a specific frequency), a minimum of two degrees of freedom are required for each **transducer** mount: vertical displacement in the water to enable the **transducer** depths to be modified; and rotation about a vertical axis which goes through the **transducer** reference centre by use of a rotational stage incorporated into the support framework or positioning system.

5.6.5 Separation distance

The mounting and support framework shall enable the **projector** and **hydrophone** to be deployed in the water at a known separation distance, with uncertainty of better than 2 %.

When a **hydrophone** has a body which is large compared to the active element, it is recommended that the **hydrophone** be calibrated at the largest separation feasible in the facility (so that the incident field provides as close an approximation to a plane-wave as possible). In addition, it is recommended that the separation be reported with the calibration results.

NOTE 1 The separation distance can be measured mechanically in a number of ways. A rigid support framework can be calibrated such that the **transducer** mounting poles are suspended from fixed positions on the framework above the tank, with known separations between the pre-set positions (assuming that the **transducers** hang vertically). If an automated positioning system is employed which has been calibrated, the **transducer** separation can be taken from the displays of the controllers. Note that adjustments sometimes need to be made to account for any slight off-sets introduced when mounting the **transducers**.

NOTE 2 The separation distance can be calculated from the acoustic propagation delay between the **signal** trigger and the direct **signal** arrival at the **hydrophone**. This assumes a knowledge of the speed of sound which can be calculated using formulae from the scientific literature and knowledge of the water temperature, depth and salinity [11] to [14]. Note that a **transducer** begins to respond to the sound wave as soon as it impinges on the active element, and so for a large spherical or cylindrical device, a small correction sometimes has to be made to the acoustically derived separation distance to obtain the separation of the **transducer** reference centres (for example, to account for the radius of each device).

NOTE 3 When a **hydrophone** has a body which is large compared to the active element, the scattered sound incident on the body can interfere with the sound wave arriving directly at the element and cause small fluctuations in the frequency response. For modest separation distances, these fluctuations can vary with **projector-hydrophone** separation due to small changes to the acoustic path differences as the separation distance is varied [15], [16].

5.7 Representation of the frequency response

A sufficient number of acoustic frequencies shall be chosen for calibration to ensure that the **transducer** performance is well characterized over the desired frequency range.

For **hydrophones**, over the low-frequency range where the sensitivity is relatively invariant with frequency, the minimum recommended resolution for the acoustic frequencies is one-third octave spacing.

For **projectors**, and for **hydrophones** close to the resonance frequency, the sensitivity varies more dramatically with frequency and the minimum recommended resolution for the acoustic frequencies is one-twelfth octave spacing.

5.8 Frequency limitations

5.8.1 High-frequency limit

The calibration methods described herein can be used for frequencies up to 1 MHz, but the uncertainties can be greater at frequencies of hundreds of kilohertz. Due consideration shall be given to the limitations of the method at high frequencies, and the influence of any limitations shall be reflected in the evaluation of overall uncertainty (see Annex E).

NOTE 1 The minimum separation distance required to allow suitable **acoustic far-field** conditions to exist for a specific **transducer** pair increases with frequency (see 5.3). At sufficiently high frequencies, the distance required to achieve **acoustic far-field** conditions can exceed the tank dimensions. Also, when using tone-burst **signals**, increasing the **transducer** separation distance will tend to reduce the echo-free time available because the **transducers** are closer to the tank boundaries, making measurements more difficult.

NOTE 2 The attenuation of sound due to absorption in the water increases rapidly with frequency, reaching approximately 0,25 dB/m at 1 MHz for fresh water (at 16 °C) and approximately 0,4 dB/m for sea water (at 8 °C, 5 m depth, pH of 8 and salinity of 35 parts per thousand). This will increase the propagation loss at very high frequencies causing the **signal**-to-noise ratio available for large separation distances to become poor. If very high acoustic frequencies are used in calibration, corrections will need to be made for propagation loss due to sound absorption by water. The attenuation of sound due to absorption in the water over the separation distances typically used in calibration is relatively small. The correction is less than 0,05 dB and can be neglected for separation distances of the order of a few metres and acoustic frequencies less than 500 kHz in fresh water, and for frequencies less than 300 kHz in sea water. Information on the absorption of sound in water, and its dependence on temperature, depth, pH and salinity, is available in the scientific literature (see Annex E and references [17] to [22]).

NOTE 3 The high-frequency limit is governed by a number of factors. These are described in detail in Annex E.

NOTE 4 At frequencies greater than 0,5 MHz, the alternative primary calibration methods described in IEC 62127-2 [2] and in Annex I can be used.

5.8.2 Low-frequency limit

Due consideration shall be given to the limitations of the calibration method at low frequencies, and the influence of any limitations shall be reflected in the evaluation of overall uncertainty.

NOTE 1 One of the main limitations when using tone-burst **signals** in finite-sized test tanks is that the small number of cycles of steady-state **signal** available for measurement depends on the quality factor of the **transducers** and the echo-free time of the test tank (which in turn depends upon tank size and **transducer** separation). As the frequency is lowered, the number of cycles in the available time-window is reduced until eventually the steady-state **signal** amplitude can no longer be determined by conventional means. This provides a lower limiting frequency on measurements made using tone-burst **signals**. For most large test tank facilities of minimum dimension 5 m or greater, the practical low-frequency limit for calibration of **hydrophones** will be of the order of 1 kHz depending on the Q-factor of the source **transducer** which governs the slope and sharpness of resonance of the transmitting response. The factors governing the lowest frequency for calibrations are described in detail in Annex E.

NOTE 2 In addition, the sound pressure level produced by the **projector** will be reduced as the frequency is lowered, eventually falling to where it is less than 6 dB above the ambient noise level, thereby limiting the minimum frequency for calibrations.

NOTE 3 For continuous **signals** in anechoic tanks, the performance of the anechoic lining can degrade at low frequencies, limiting the ability to achieve free-field conditions.

NOTE 4 The lower frequency limit for free-field calibration in reverberant tanks can be extended by use of more sophisticated **signal**-processing techniques. With some of these techniques, it is not necessary to have a complete **signal** period for amplitude and phase estimation. See Annex E and Annex J for more details.

5.9 Checks for acoustic interference

With tone-burst **signals**, a tone-burst repetition rate shall be chosen that is low enough for all reverberation in the tank to die away before transmission of the next pulse.

The interference level from reflected acoustic **signals** shall be at least 30 dB lower than the **signal** level.

NOTE 1 Further details on the influence of reflections are given in Annex E.

NOTE 2 Where smooth periodic ripples can be observed in a plot of **electrical transfer impedance** (or sensitivity) against frequency, this is an indication that there is likely to be acoustic reflections present leading to constructive and destructive interference effects. If the frequency interval between successive peaks in the plot is Δf and c is the speed of sound in the medium, the path difference Δd between the direct and reflected **signals** arriving at the **hydrophone** can be calculated from $\Delta d = c/\Delta f$ [1].

NOTE 3 The oscillations caused by a reflected acoustic **signal** with a path difference Δd can be eliminated by a complex moving averaging of the frequency dependence of the transfer impedance in the frequency interval Δf . The methods for free-field calibration in the reverberation sound fields of **signals** with a power distributed in the frequency band are based on this approach. See Annex J for more details.

6 Electrical measurements

6.1 Signal type

The default electrical **signal** used for the calibration is either continuous wave (sinusoidal) or tone burst (gated sine wave).

Whatever **signal** type is chosen, the requirements of 5.2, 5.3 and 5.4 still apply. Note that requirements for achieving an acoustic free-field will vary depending on the **signal** type used (see 5.2).

NOTE Other **signal** types are possible, such as short broadband pulses or frequency modulated chirps. The **signal** analysis techniques for such **signals** will require spectral analysis to determine the **signal** amplitude (and phase) as a function of frequency. Where **signal** analysis is undertaken by Fourier transform, the frequency resolution (specified in 5.7) will depend on the **signal** record length.

6.2 Electrical earthing

In order to avoid earth loops, the electrical terminals of the **transducers** shall be kept free from contact with the water. Exposed metal parts of one **hydrophone** shall be the only earth connection for the cable screen of the **hydrophone** and for the **hydrophone** amplifier. All other earth contacts shall be excluded.

6.3 Measurement of hydrophone output voltage

6.3.1 General

The open-circuit voltage of the **hydrophone** shall be measured at the end of the **hydrophone** cable. The electrical terminals selected shall be specified (see IEC 60500:2017, 3.7).

For tone-burst **signals**, the **hydrophone** voltage waveform shall be digitized, for example using a digitizing oscilloscope or a computer-based analogue-to-digital converter.

For a continuous wave **signal**, the measurement shall be done using a voltmeter of high electrical input impedance, or by a digitizing oscilloscope or a computer-based analogue-to-digital converter.

Where an amplifier, attenuator or filter is used in combination with the voltmeter or digitizer to form an absolute measuring channel, these elements shall be calibrated. However, a calibration is unnecessary if the same measuring channel is used only for the measurement of voltage ratios, though in this case, the linearity of this channel shall still be determined. When measuring voltage ratios, both voltages shall be expressed in the same metric (for example, both as peak voltages, or both as root-mean-square voltages).

6.3.2 Signal analysis

For tone-burst **signals**, the **signal** amplitude (and if required, **signal** phase) shall be determined from the time-windowed **hydrophone** voltage waveform, with the time window positioned on the steady-state portion of the echo-free **signal**. The start of time window shall be positioned on the waveform after any **projector** start-up transients have died down, and the end of the window shall be positioned before the arrival of the first reflected **signal** or before the end of the direct **signal** (whichever occurs first). See Annex E for more guidance on measuring amplitude and phase of time-windowed steady-state **signals**.

6.3.3 Electrical loading by measuring instruments

During the measurements, the **hydrophone** shall be connected to a high electrical input-impedance measuring instrument (preamplifier, voltmeter, oscilloscope or digitizer) such that the electrical input impedance is much larger than the electrical impedance of the **hydrophone** (ideally, more than 100 times larger).

When measuring the phase angle of the **hydrophone** output voltage, the electrical input impedance of the measuring instrument should ideally be more than 1 000 times the electrical impedance of the **hydrophone**.

Where the electrical impedance of the **hydrophone** is high (for example, for a small piezoelectric **hydrophone** of low capacitance), consideration shall be given to the electrical loading of the **hydrophone** by the measuring instrument. In such cases, electrical loading corrections shall be applied to the measured voltage to obtain the open-circuit voltage. The corrections may be calculated using the procedure given in Annex C [2].

NOTE If the same electrical load is used throughout the calibration for a particular **hydrophone**, the corrections can be applied to the sensitivity rather than to the individual measured voltages.

6.3.4 Electrical loading by extension cables

If an extension cable of significant length is attached to the **hydrophone**, this cable will electrically load the **hydrophone** reducing the measured end-of-cable voltage (and therefore, the sensitivity). In this case, corrections shall be applied to obtain the open-circuit end-of-cable **hydrophone** voltage. Guidance on calculating the electrical loading correction is given in Annex C.

NOTE 1 Where the cable and **hydrophone** appear electrically to be purely capacitances (this is generally true for a cable and is true for a **hydrophone** in the frequency range well below resonance), a correction can be derived from the capacitances of the **hydrophone** and cable. See Annex C for further details [23].

NOTE 2 Where the electrical impedance of the **hydrophone** is not purely capacitance, for example, at frequencies close to resonance, the complex electrical impedance of the **hydrophone** and extension is used to calculate the loading correction. See Annex C for further details [23].

NOTE 3 If the same extension cable is used throughout the calibration for a particular **hydrophone**, the corrections can be applied to the sensitivity rather than to the individual measured voltages.

6.3.5 Electrical noise

The **signal**-to-noise ratio shall be sufficient that the measurements can be made without significant loss of accuracy. The measured sound pressure should be at least 6 dB greater than the equivalent bandwidth noise pressure (see IEC 60500:2017).

The level of broad-band interfering noise can be reduced by the use of a band-pass filter. However, the bandwidth shall be sufficiently wide to allow the **signal** to pass through without distortion.

NOTE 1 The level of electrical noise can degrade the accuracy when making electrical measurements [3], [4]. The **signal**-to-noise ratio is likely to be lower when using **projectors** at frequencies well below resonance.

NOTE 2 In the presence of electrical noise, the **signal** to noise ratio can be improved by coherent averaging of repeated **signals**. For random noise, averaging N **signals** will improve the **signal** to noise ratio by a factor of $\sqrt{N}$ (square root of N).

6.3.6 Cross-talk

In the presence of coherent interference from electrical cross-talk, **signal** averaging and narrow-band filtering will not in general lead to an improvement in accuracy. Therefore, in such cases, efforts shall be made to determine the cause of the problem and steps taken to minimize the effects by suitable electrical grounding, for example of the **projector** drive cables.

In the case of a continuous wave **signal**, the electrical cross-talk level shall be at least 40 dB lower than the **signal** level.

Where cross-talk is present with tone-burst **signals**, this will only cause interference if the length of the burst is greater than the acoustic propagation delay. If the cross-talk cannot be eliminated by suitable electrical grounding, the length of the burst shall be reduced so that there is no overlap in time with the acoustic **signal**.

NOTE For burst **signals**, the effect of the interference can also be significantly reduced by signal subtraction. This is done by fitting an approximation to the cross-talk **signal** at the frequency of the drive **signal** in the region before the acoustic **signal** arrival, continuing the approximation for the duration of the overlap of the transmitted **signal** with the acoustic **signal**, and then subtracting it from the total **signal** in the region of overlap. The effect of cross-talk can also be determined by observing the **signal** change when the distance between the **projector** and receiver is modified by a predetermined amount (for example, by half of the acoustic wavelength).

6.3.7 Integral preamplifiers

Where a **hydrophone** has an integral preamplifier, the sensitivity shall be expressed as end-of-cable sensitivity (by including the performance of the preamplifier as part of the device).

NOTE Where a **hydrophone** has an integral preamplifier, corrections for electrical loading by extension cables or measuring instruments are unnecessary [23].

6.4 Measurement of projector drive current

6.4.1 Instrumentation

The current through the **projector** should be determined by a calibrated current transformer (producing a voltage proportional to the drive current).

For tone-burst **signals**, the voltage waveform from the current transformer shall be digitized, for example using a digitizing oscilloscope or a computer-based analogue-to-digital converter.

For a continuous wave **signal**, the voltage from the current transformer shall be measured using a voltmeter of high electrical input impedance, or by a digitizing oscilloscope or a computer-based analogue-to-digital converter.

Where an amplifier, attenuator or filter is used in combination with the voltmeter or digitizer to form an absolute measuring channel, these elements shall be calibrated, unless the same measuring channel is also used only for the measurement of voltage ratios.

NOTE Although the current transformer is the preferred instrument, an alternative method is to measure the voltage drop across a small-valued calibrated resistor (value of only a few ohms) connected in series with the **projector**.

6.4.2 Signal analysis

For tone-burst **signals**, the **signal** amplitude (and if required, **signal** phase) shall be determined from the time-windowed voltage waveform from the current transformer, with the time window positioned on the steady-state portion of the echo-free **signal**.

The start and end of the time window shall be positioned on the waveform at the same positions chosen for the **hydrophone** voltage (see 6.3.2).

6.5 Measurement of projector drive voltage

6.5.1 Instrumentation

The drive voltage across the **projector** shall be determined by a calibrated high impedance voltage probe (scope probe), or a calibrated attenuator to reduce the drive voltage down by approximately 40 dB so that it can be measured by the digitizer.

For tone-burst **signals**, the voltage waveform from the scope probe or a calibrated attenuator shall be digitized, for example using a digitizing oscilloscope or a computer-based analogue-to-digital converter.

For a continuous wave **signal**, the voltage from the scope probe or a calibrated attenuator shall be measured using a voltmeter of high electrical input impedance, or by a digitizing oscilloscope or a computer-based analogue-to-digital converter.

Where an amplifier, attenuator or filter is used in combination with the voltmeter or digitizer to form a measuring channel, these elements shall be calibrated, unless the same measuring channel is also used only for the measurement of voltage ratios.

6.5.2 Signal analysis

For tone-burst **signals**, the **signal** amplitude (and if required, **signal** phase) shall be determined from the time-windowed voltage waveform from the scope probe, or a calibrated attenuator, with the time window positioned on the steady-state portion of the echo-free **signal**.

The start and end of the time window shall be positioned on the waveform at the same positions chosen for the **hydrophone** voltage (see 6.3.2).

7 Preparation and conditioning of transducers

7.1 Soaking

Before calibration, the **transducers** shall be soaked for a short time sufficient to allow equalization of temperature with the water.

If the air temperature where the **transducer** is stored and prepared is close to that of the water (as would be the case for an indoor test tank), the length of soaking time need only be a few minutes. However, for cases where the water temperature is significantly lower than the air temperature in the laboratory (as might be the case for an open-water facility in winter conditions), soaking time of at least 30 minutes is recommended.

7.2 Wetting

A wetting agent such as a mild detergent shall be applied to the whole **transducer** surface before immersion in water. No dry patches shall be visible on the wetted **transducer** when it is immersed and then quickly removed from the water [24].

NOTE 1 The aim of wetting the **transducer** is to mitigate the effect of gas bubbles or trapped air clinging to its surface. Trapped air and bubbles cause significant scattering of sound waves and can behave in a strongly resonant manner, causing unpredictable errors in the calibration results. The application of a detergent as a wetting agent reduces the surface tension of the water and hinders the adhesion of bubbles to the surface.

NOTE 2 The presence of trapped air can sometimes manifest itself as a film of air which appears as a silvery sheen on the **transducer** surface. Any recesses on the **transducer** case (such as those adjacent to gaskets or screw fittings) can trap air bubbles. In cases where trapped air or bubbles are evident, the detergent can be applied several times.

NOTE 3 The process of air bubbles attaching to the **transducer** surface is more evident when immersing warm **transducers** into cold water because the warmer **transducers** have a slight heating effect on the colder water in contact with the **transducer** surface, causing dissolved gas to come out of solution (air is less soluble in warm water than cold).

7.3 Extending the hydrophone cable

If the cable to the **hydrophone** needs to be lengthened for the purposes of the calibration (for example in order to reach the instrumentation), then the guidance in 6.3.4 shall be followed.

NOTE A description of how to account for the influence of extension cable is given in Annex C [23].

7.4 Environmental conditions (temperature and depth)

Where the sensitivity of a **transducer** is required for specific conditions of water temperature and depth of immersion, the **transducer** shall either:

- a) be calibrated under the same conditions of temperature and depth for which it will be used in the field; or
- b) have corrections made to sensitivity values to account for the different environmental conditions, with corrections based on earlier calibrations as a function of temperature or depth, or by use of validated analytical models.

NOTE 1 The sensitivity of some **electroacoustic transducers** can vary with both ambient temperature and depth of immersion (the latter due to increased hydrostatic pressure) [25], [26]. The ability to conduct calibrations under a range of values of temperature and depth is relatively rare because specialized facilities are required [25], [26].

NOTE 2 The environmental conditions that exist in an indoor test tank facility are unlikely to replicate the conditions that exist in the ocean (for example, for water temperature or depth). Calibrations are strictly valid only for the conditions that pertain during the calibration. If an estimate is required of the performance under ocean conditions, the sensitivity obtained from the tank calibration can be corrected (with a suitable uncertainty component added to reflect the uncertainty in the correction) [25], [26].

NOTE 3 For measurements made in open-water facilities, the environmental conditions (water temperature or depth) are, in general, not the same as those for the intended end-user application. If an estimate is required of the performance under the conditions that pertain to the end-user application, the sensitivity obtained from the open-water facility can be corrected (with a suitable uncertainty component added to reflect the uncertainty in the correction) [27].

8 Free-field three-transducer spherical-wave reciprocity calibration

8.1 General principle

Three **transducers** (the **transducer** triad) shall be used for the calibration technique, of which at least one shall be reciprocal. For convenience, the three devices shall be labelled P (**projector**), H (**hydrophone**), and T (reciprocal **transducer**).

The devices shall be paired off in three measurement configurations, as shown in Figure 1. If the **projector**, P, is also a reciprocal **transducer**, then the fourth configuration also shown in Figure 1 shall also be employed.

For each measurement configuration, the **transducer** pair shall be deployed in water separated by a known distance, d , with their axes aligned towards each other (8.2.1, 8.2.2).

For all configurations, the requirements for acoustic free-field conditions (5.2), far-field conditions (5.3) and steady-state conditions (5.4) shall be met.

In each case, using one device as a **projector** and the other as a **hydrophone**, the **electrical transfer impedance** shall be determined at the desired number of frequencies throughout the frequency range of interest (8.2.4).

Using at least the first three configurations of **transducer** pairs, the **free-field receive sensitivity** and **transmitting response to current** of any of the three devices is calculated as

each frequency of calibration from the measurements of purely electrical quantities (transfer impedances), the separation distance, and the water density and acoustic frequency. (8.2.5, 8.2.6).

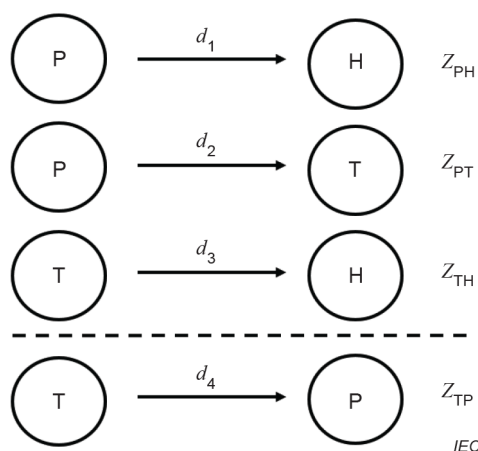


Figure 1 – Measurement configurations for three-transducer reciprocity

If the **projector**, P, is also a reciprocal **transducer**, then the measurement of the fourth **electrical transfer impedance** (see Figure 1) can be used to determine the validity of the assumption of reciprocal behaviour (8.2.8). Detailed derivations of all formulae for reciprocity calibrations can be found in Annex G.

NOTE 1 There are a number of calibration configurations which are based on the principle of acoustic reciprocity. [28] to [32]. The description here of the reciprocity calibration method is for three-**transducer** spherical-wave reciprocity only. The reciprocity calibration method can be applied to other configurations which use different acoustic field geometries such as acoustic plane-wave or cylindrical wave, and can be applied to pressure calibrations undertaken inside a closed coupler [1], [3], [33] to [36]. A self-reciprocity calibration can also be undertaken using a reflector which provides a specular acoustic reflection. [2], [37] to [39]. In each case, although the principle is similar, the different acoustic transfer impedance between source and receiver leads to a different formula for calculating the device sensitivities.

NOTE 2 This method is a primary calibration method and does not rely on the use of another acoustic reference **transducer**. The acoustic calibrations are traceable to primary standards of electrical measurement, length measurement, and frequency measurement.

NOTE 3 Each measurement configuration involves the deployment of a **transducer** pair in water. This is often accomplished using two positioning stages or mounts for alignment, with **transducers** paired off in the sequence shown in Figure 1. However, it is also possible to position all three in the test tank simultaneously. One arrangement is a co-linear configuration (see Figure 2). Alternatively, the **transducers** can be positioned in a triangular geometric configuration (typically in an equilateral triangle). In arrangements where all devices are immersed simultaneously, the **transducers** are configured to be capable of being turned to enable their reference directions to be aligned before each transfer impedance is measured. Note that if three devices are immersed simultaneously, there is a possibility of scattered sound from one device causing acoustic interference during the measurements made with the other two devices. In such cases, the device not being used is removed from the water during measurement of the electrical transfer impedances between the other two devices.

8.2 Calibration to determine sensitivity modulus (without phase)

8.2.1 Acoustic field requirements

For all measurements, the requirements for acoustic free-field conditions (5.2), far-field conditions (5.3) and steady-state conditions (5.4) shall be met.

8.2.2 Separation distance

The distance between the **projector** and the **hydrophone** shall be decided and measured according to the requirements of 5.6.5.

In choosing the separation distance the requirements of acoustic free-field conditions (5.2), and **acoustic far-field** conditions (5.3) shall be met.

It is recommended that each repeated calibration be conducted at a different separation distance (8.2.7).

NOTE For simplicity, the separation distances between the devices for each stage of the measurements shown in Figure 1 are sometimes chosen to be identical, but this is not necessary.

8.2.3 Transducer preparation, mounting and alignment

Before commencing the measurements, the requirements for soaking (7.1) and wetting (7.2) of the **transducers** shall be met.

For each measurement of electrical transfer impedance, the requirements for **transducer** mounting (5.6.3) and **transducer** alignment (5.6.4) shall be met.

8.2.4 Signal type

The **signal** type shall be chosen in accordance with 6.1.

8.2.5 Measurement of electrical transfer impedance

For each measurement configuration illustrated in Figure 1, at each acoustic frequency the **electrical transfer impedance** shall be determined by measuring the **hydrophone** voltage in accordance with 6.3 and the **projector** drive current in accordance with 6.4. Both the voltage and current shall be expressed in the same metric (for example, both as peak quantities, or both as root-mean-square quantities).

NOTE 1 For highest accuracy, the **projector** drive current can be measured through the same measuring channel as the **hydrophone** voltage (the measuring channel consists of an amplifier, filter, and digitizer). In this case, the instruments used in the measuring channel will not require absolute calibration since only ratios of electrical quantities are required.

NOTE 2 If required, a calibrated attenuator can be used to equalize the voltage representing the **projector** current with the **hydrophone** voltage. This will minimize errors due to non-linearity in the measuring channel.

NOTE 3 If very high acoustic frequencies are used, each **electrical transfer impedance** is corrected for loss due to sound absorption by water. Further details are given in 5.8.1 and in Annex E.

8.2.6 Calculation of the receive sensitivities

At each acoustic frequency, the modulus of the **free-field receive sensitivity** $\underline{M}_H$ of the **hydrophone** shall be calculated from Formula (11):

$$|\underline{M}_H| = \sqrt{\frac{2d_1d_3}{\rho f d_2} \frac{|\underline{Z}_{PH}||\underline{Z}_{TH}|}{|\underline{Z}_{PT}|}} \quad (11)$$

At each acoustic frequency, the modulus of the **free-field receive sensitivity** $\underline{M}_T$ of the **reciprocal transducer** shall be calculated from Formula (12):

$$|\underline{M}_T| = \sqrt{\frac{2d_2d_3}{\rho f d_1} \frac{|\underline{Z}_{PT}||\underline{Z}_{TH}|}{|\underline{Z}_{PH}|}} \quad (12)$$

If the **projector** is reciprocal, its modulus of free-field sensitivity shall be calculated from the relationship given by Formula (12) with the subscript PT replaced by TP, and distance d_2 replaced by d_4 .

NOTE If the **projector** is not reciprocal, then its calculated receive sensitivity has no physical meaning.

8.2.7 Calculation of the transmit sensitivities

At each acoustic frequency, the modulus of the **transmitting response to current** $\underline{S}_{I,P}$ of the **projector** (P) shall be calculated from Formula (13):

$$|\underline{S}_{I,P}| = \sqrt{\frac{\rho f d_1 d_2}{2 d_3} \frac{|\underline{Z}_{PH}| |\underline{Z}_{TT}|}{|\underline{Z}_{TH}|}} \quad (13)$$

The **transmitting response to current** $\underline{S}_{I,T}$ of the **transducer** (T) shall be calculated from Formula (14):

$$|\underline{S}_{I,T}| = \sqrt{\frac{\rho f d_2 d_3}{2 d_1} \frac{|\underline{Z}_{PT}| |\underline{Z}_{TH}|}{|\underline{Z}_{PH}|}} \quad (14)$$

If required, the **projector** or **transducer** transmitting voltage response ($\underline{S}_V$) shall be calculated from Formula (15):

$$\underline{S}_V = \frac{\underline{S}_I}{\underline{Z}_P} \quad (15)$$

where $\underline{Z}_P$ is the measured device electrical impedance (see Annex B).

If the **hydrophone** H is reciprocal, the modulus of its **transmitting response to current** $|\underline{S}_H|$ shall be calculated by use of Formula (14) with the $|\underline{Z}_{PH}|$ replaced by $|\underline{Z}_{PT}|$, $|\underline{Z}_{PT}|$ replaced by $|\underline{Z}_{PH}|$, and distance d_2 replaced by d_4 .

NOTE The transmitting response has no physical meaning where the **transducer** cannot be used as a sound source. An example is a **hydrophone** with an integral preamplifier, which precludes its use as a **projector**.

8.2.8 Repeatability

The calibration shall be repeated several times and the mean of the results at each frequency shall be used as the final value of sensitivity. The repeated calibrations shall be fully independent, with the **transducers** removed from the water and remounted between each calibration.

The standard deviation shall be determined and used in the calculation of uncertainties, see Annex F.

It is recommended that at least four repeated measurements are made.

NOTE 1 If a different separation distance is used for some of the repeated calibrations, this will be of assistance in assessing some of the assumptions in the method (free-field conditions, spherical-wave field, etc.) since the sensitivity is invariant with separation distance for spherically-spreading wave in free-field conditions (with corrections made for absorption by water at high frequencies).

NOTE 2 Lack of good repeatability indicates a problem with the calibration. Causes can include poor **signal-to-noise** ratio, the presence of acoustic reflections, poor precision with positioning and alignment, poor temporal stability in the performance of the acoustic **transducers** or instrumentation. With care, it is possible to achieve standard deviations as low as 1 % for **hydrophones** over their operating range.

8.2.9 Verification and checks

8.2.9.1 Reciprocity verification

The assumption that at least one **transducer** is reciprocal shall be verified.

The reciprocity of a pair of reciprocal **transducers** shall be verified by comparison of the **electrical transfer impedance** magnitudes when the functions of the transmitter and receiver are interchanged without altering the **transducer** positions (i.e., by comparing $|Z|_{PT}$ and $|Z|_{TP}$ where both P and T are reciprocal) [3], [4], [40].

If large discrepancies between $|Z|_{PT}$ and $|Z|_{TP}$ occur, this can be because one (or both) **transducers** is driven too hard resulting in non-linear behaviour. In this case, the amplitude of the drive **signal** to the **transducers** shall be reduced and the transfer impedance check repeated. However, if such a reduction in drive **signal** results in unacceptably low **signal**-to-noise ratio, consideration shall be given to the use of alternative **transducers**.

For the lowest uncertainty in reciprocity calibrations, the reciprocal **transducers** should be used within their normal operating band (typically up to 0,7 times the frequency of the first resonance for a piezoelectric **transducer**).

Use of a **transducer** at frequencies outside its linear dynamic range or operating frequency range (for example, at frequencies much greater than the resonance frequency) can result in non-reciprocal behaviour and degradation in the accuracy of the calibration. Calibration of a **hydrophone** over a broad frequency range can require the use of several different reciprocal **transducers** to cover the complete range with sufficiently small uncertainty.

NOTE 1 It is not possible to determine whether a **transducer** is reciprocal without using it in combination with another **transducer**. The check described above provides a good indication that a pair of **transducers** are reciprocal.

NOTE 2 For well-behaved **transducers** used within their operating frequency range, it is possible to obtain agreement between the electrical transfer impedances of better than 3 %.

NOTE 3 Disagreement of greater than 10 % indicates that at least one of the **transducers** might not be behaving in a reciprocal manner. The use of a third **reversible transducer** in the reciprocity verification can reveal which of the **transducers** is non-reciprocal. In a reciprocity calibration, non-reciprocal **transducers** can only be used as a **projector** or **hydrophone** (as appropriate), but not as the **transducer**, T.

NOTE 4 If the **transducers** in the reciprocity verification check are identical in construction, they can be nonlinear to the same extent and still appear reciprocal. Therefore, the reciprocity verification is ideally performed using **transducers** of different model, dimensions or construction.

NOTE 5 A better statistical accuracy is obtained from the calibration if more than one **transducer** is reciprocal. If the **projector** can also be used as a **hydrophone**, the **hydrophone** sensitivity M_H can be determined in two ways: with either $|Z|_{PT}$ or $|Z|_{TP}$ on the denominator of Formula (11). The uncertainty of the mean of the two values of sensitivity will be lower than that of either value alone.

NOTE 6 If the calibration is performed with more than three **transducers** and if two or more are reciprocal, the uncertainty is reduced because the sensitivity can be calculated several times, using independent results from different combinations of **transducers**. The mean value of all results at the same frequency possesses a lower statistical uncertainty than each value alone.

8.2.9.2 Spherical-wave verification

Consideration shall be given to the deviation from the assumed spherical-wave field, and the influence of any deviation shall be reflected in the evaluation of overall uncertainty.

In ideal conditions, it is possible to obtain deviation of less than ± 2 %. Variation of greater than ± 5 % indicates additional problems (e.g. from boundary reflections). In such cases, investigate further to ascertain the cause.

When operating at frequencies of high hundreds of kilohertz, corrections will be required to the **electrical transfer impedance** to account for absorption of sound by water (see 5.8.1 and Annex E).

NOTE 1 The existence of a spherically-spreading acoustic field can be verified by comparison of the **electrical transfer impedance** magnitudes when the distance between **projector** and **hydrophone** is varied. See Annex E. If the **hydrophone** is placed in the far-field of the **projector**, the transfer impedance is inversely proportional to the distance d between the reference centres of the **projector** and the **hydrophone**:

$$|Z_{PH}| d = \text{constant} \quad (16)$$

8.2.9.3 Linearity verification

The measured **signals** shall be checked for distortion during the calibrations. If there is any doubt regarding the linearity of the **transducers**, the linearity of each pair of **transducers** shall be verified by comparing the magnitudes of the **electrical transfer impedance** at different values of the **projector** current within the dynamic range of the system, at a specific frequency. Starting at a level of 6 dB higher than the background noise level up to the highest level that will be used, the magnitude of the transfer impedance shall remain constant within 5 %.

Take care that during the actual calibration, the **signal** levels are kept within the range of linearity. As this range can be different for each pair of **transducers**, careful observation of the **signal** levels is necessary.

NOTE Distortion can manifest itself by the presence of higher harmonics in the **signal**, evident from an inspection of the spectral levels. Ideally, any harmonics will be more than 10 dB lower in amplitude than the fundamental.

8.2.9.4 Inclusion of calibrated reference transducers in the transducer triad

If one or more of the **transducers** used in the calibration are reference **transducers** with sensitivity known from previous calibrations, good agreement obtained with the known values of sensitivity for the reference devices will provide extra confidence in the results for the **transducer** under test.

NOTE In a reciprocity calibration, absolute sensitivities are obtained for all three **transducers** used in the triad. There is no requirement to rely on the sensitivity of one **transducer** when calibrating another. However, if the aim of the calibration is to derive the sensitivity of a specific **transducer** of unknown performance, the use of calibrated reference **transducers** as the other devices in the **transducer** triad can provide an extra check on the accuracy of the results for the **transducers** under test (assuming stability for the reference **transducers**).

8.2.10 Uncertainty

If conducted with care and in accordance with above procedures, the expanded uncertainty (95 % confidence level) shall be in the range 4 % to 10 %.

NOTE The evaluation of uncertainty for the free-field reciprocity calibration method involves many components (see Annex F for details) [40] to [43].

8.3 Calibration to determine phase of the hydrophone sensitivity

8.3.1 General principle

For determination of the phase angle of the **hydrophone** sensitivity, the measurement configuration adopted shall be the co-linear arrangement depicted in Figure 2 [44] to [46]. This arrangement is designed to minimize phase errors due to positioning errors. In the arrangement, the three **transducers** P, T and H are mounted in a straight line with H located between P and T such that $d_2 = d_1 + d_3$.

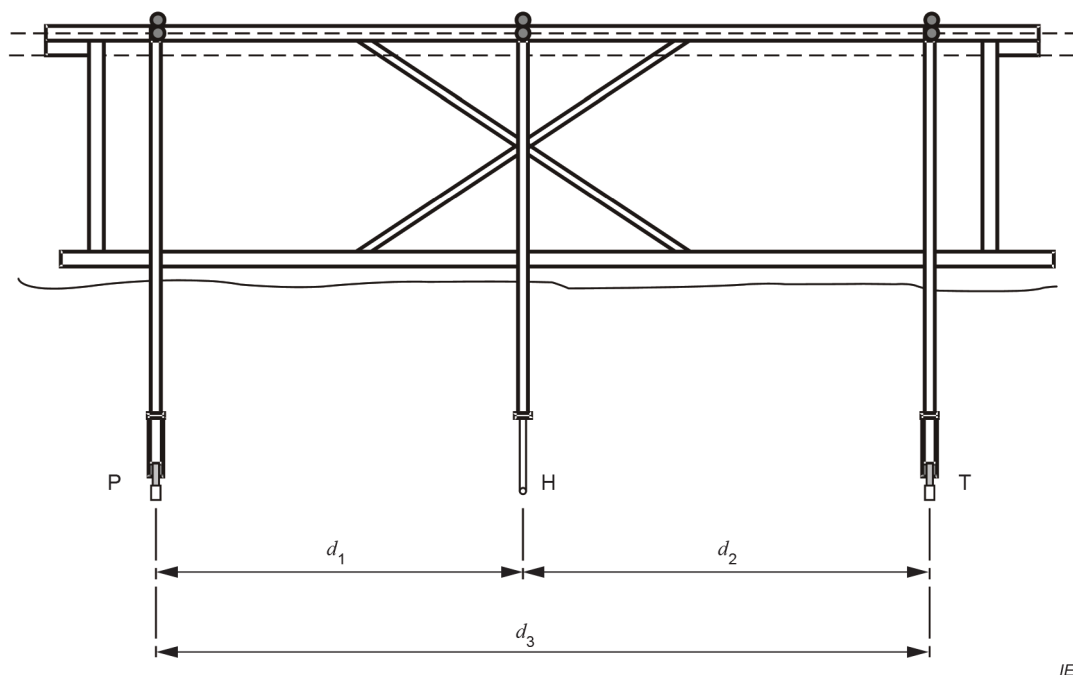


Figure 2 – Measurement framework for supporting in-line the three transducers: a projector P, a reciprocal transducer T, and a hydrophone H to be calibrated

Measurements shall be made as follows.

Mount the **transducers** as shown in Figure 2 with their reference centres separated by the distances d_1 , d_2 and d_3 , where $d_2 = d_1 + d_3$.

Align their reference directions with P pointing toward H and T. Determine the complex **electrical transfer impedance** $\underline{Z}_{PH}$ from the input current to P and the output voltage from H.

Remove the **hydrophone** with its hanger from the framework. Determine the complex **electrical transfer impedance** $\underline{Z}_{PT}$ from the input current to P and the output voltage from T.

Replace the **hydrophone** with its hanger in the framework and rotate about its reference centre so that T now points toward H and the distance d_3 is maintained between the reference centres of H and T. Determine the complex **electrical transfer impedance** $\underline{Z}_{TH}$ from the input current to T and the output voltage from H.

Calculate the modulus and phase angle of the free-field sensitivity of the **hydrophone** according to the instructions in 8.3.6 using the measured electrical transfer impedances [44] to [46].

NOTE 1 The difficulty of determining the phase of $\underline{M}_H$ by this method lies in accurately determining both the sound speed and the measurement distances d_1 , d_2 and d_3 . For example, at 100 kHz in water, an error of only 1,0 mm in any one of the distances gives a phase error of about 12° [45].

NOTE 2 The resulting sensitivity is representative of both the **hydrophone** and its mount.

NOTE 3 The calibration is ideally performed using the same mount that will support the **hydrophone** when it is used for field measurements.

8.3.2 Transducer preparation

Before commencing the measurements, the requirements for soaking (7.1) and wetting (7.2) of the **transducers** shall be met.

8.3.3 Acoustic field requirements

For all measurements, the requirements for acoustic free-field conditions (5.2), far-field conditions (5.3) and steady-state conditions (5.4) shall be met.

8.3.4 Signal type

The **signal** type shall be in accordance with 6.1.

8.3.5 Transducer mounting and alignment

The distance between the **projector** and the **hydrophone** shall be decided and measured according to the requirements of 5.6.5.

In the choosing the separation distance the requirements of acoustic free-field conditions (5.2), and **acoustic far-field** conditions (5.3) shall be met.

8.3.6 Measurement of electrical transfer impedance

For each measurement configuration illustrated in Figure 1, at each acoustic frequency the complex-valued **electrical transfer impedance** shall be determined by measuring the **hydrophone** voltage in accordance with 6.3 and the **projector** drive current in accordance with 6.4.

Each complex **electrical transfer impedance** (for example, Z_{PH}) shall be measured (see 3.2) and calculated from:

$$Z_{PH} = \frac{\mathcal{F}(U_H(t))}{\mathcal{F}(I_P(t))} \quad (17)$$

NOTE 1 For highest accuracy, the **projector** drive current can be measured through the same measuring channel as the **hydrophone** voltage (the measuring channel consists of an amplifier, filter, and digitizer). In this case, the instruments used in the measuring channel will not require absolute calibration since only ratios of electrical quantities are required.

NOTE 2 If required, a calibrated attenuator can be used to equalize the voltage representing the **projector** current with the **hydrophone** voltage. This will minimize errors due to non-linearity in the measuring channel.

NOTE 3 If very high acoustic frequencies are used, each **electrical transfer impedance** can be corrected for loss due to sound absorption by water. Further details are given in 5.8.1 and in Annex E.

8.3.7 Calculation of sensitivity phase angle

At each acoustic frequency, the complex-valued **free-field receive sensitivity** $\underline{M}_H$ of the **hydrophone** shall be calculated from:

$$\underline{M}_H = \sqrt{\frac{2d_1d_3}{j\rho f d_2} \frac{Z_{PH}Z_{TH}}{Z_{PT}}} \quad (18)$$

The modulus alone of the sensitivity $|\underline{M}|_H$ can be calculated from:

$$|\underline{M}_H| = \sqrt{\frac{2d_1d_3}{\rho f d_2} \frac{|Z_{PH}||Z_{TH}|}{|Z_{PT}|}} \quad (19)$$

The phase angle alone of the sensitivity, θ_H , can be calculated from:

$$\theta_H = \frac{1}{2} \left(\Delta\theta_{PH} + \Delta\theta_{TH} - \Delta\theta_{PT} - \frac{\pi}{2} \right) \quad (20)$$

where θ_{PH} is the phase angle of Z_{PH} , etc [45].

NOTE Since the distances and sound speed do not appear explicitly in a phase term in Formula (18), the accuracy of the calculated phase of $\underline{M}_H$ is only limited by accuracy of the phase measurements of the voltages and currents and by positioning. A special measurement framework that can minimize positioning errors is illustrated by Figure 2.

8.3.8 Repeatability

The calibration shall be repeated several times and the mean of the results at each frequency shall be used as the final value of sensitivity. The repeated calibrations shall be fully independent, with the **transducers** removed from the water and remounted between each calibration.

The standard deviation shall be determined and used in the calculation of uncertainties, see Annex F.

It is recommended that at least four repeated measurements are made.

NOTE 1 If a different separation distance is used for some of the repeated calibrations, this will be of assistance in assessing some of the assumptions in the method (free-field conditions, spherical-wave field, etc.) since the sensitivity is invariant with separation distance for spherically-spreading wave in free-field conditions (with corrections made for absorption by water at high frequencies).

NOTE 2 Lack of good repeatability indicates a problem with the calibration. Causes can include poor **signal**-to-noise ratio, the presence of acoustic reflections, poor precision with positioning and alignment, poor temporal stability in the performance of the acoustic **transducers** or instrumentation. With care, it is possible to achieve standard deviations as low as 1 % for **hydrophones** over their operating range.

8.3.9 Verification and checking

The verification checks for reciprocal behaviour shall be undertaken in accordance with 8.2.9.1.

The spherical-wave field checks shall be undertaken in accordance with 8.2.9.2.

The **transducer** linearity checks shall be undertaken in accordance with 8.2.9.3.

If possible, **transducers** with a known sensitivity shall be included in the **transducer** triad in accordance with 8.2.9.4.

8.3.10 Uncertainty

Under good conditions with precise positioning, it is possible to obtain an overall expanded uncertainty of less than 5° in phase for frequencies up to 50 kHz, rising to 10° in phase for frequencies up to 100 kHz, and rising to 20° in phase for frequencies up to 300 kHz [44] to [46].

NOTE 1 The evaluation of uncertainty involves many components (see Annex F).

NOTE 2 For a discussion of ways to reduce the uncertainty of phase measurement caused by inaccuracy in the distance between the acoustic centres of the **hydrophone** and the **projector**, as well as determining the displacement of the acoustic centre relative to the reference centre, see reference [46].

9 Free-field calibration by comparison with an acoustic reference device

9.1 Principles

The calibration of **hydrophones** or **projectors** in free-field conditions can be accomplished by use of a reference acoustic **transducer** which has previously been subject to an absolute

calibration. Such a calibration requires the use of either a calibrated **hydrophone** or a calibrated **projector** [3] to [6].

NOTE Calibration by a comparison method will in general have higher uncertainty than a primary method (such as a method based on free-field reciprocity) since the uncertainty in the calibration of the reference device will inevitably introduce an extra Type B component of uncertainty. More guidance on assessment of uncertainties is given in Annex F.

9.2 Types of comparison calibration method

9.2.1 Hydrophone calibration using a calibrated reference hydrophone

The sound field generated by an auxiliary **projector** in water is measured at a point in the **acoustic far-field** with a calibrated reference **hydrophone**. The reference **hydrophone** is then replaced by the **hydrophone** under test. The ratio of the open circuit voltages of the two **hydrophones** is equal to the ratio of their free-field sensitivities, enabling the **free-field receive sensitivity** of the **hydrophone** under test to be determined. The auxiliary **projector** need not be calibrated, and needs to be stable only for the duration of the calibration.

9.2.2 Hydrophone calibration using calibrated reference projector

The sound field generated in water by a calibrated reference **projector** is measured by the **hydrophone** under test at a point in the **acoustic far-field**. The free-field sensitivity of that **hydrophone** is determined from measurement of the open circuit voltage of the **hydrophone**, the **projector-hydrophone** separation distance, the transmit sensitivity of the calibrated **projector**, and the electrical drive **signal** applied to the **projector**. For the calibrated **projector**, either the **transmitting response to current** or the **transmitting response to voltage** can be used, requiring the measurement of the electrical drive current or drive voltage, respectively.

9.2.3 Projector calibration using a calibrated reference hydrophone

The sound field generated in water by the **projector** under test is measured by a calibrated reference **hydrophone** at a point in the **acoustic far-field**. The free-field transmit sensitivity of the **projector** is determined from measurement of the open circuit voltage of the **hydrophone**, the **projector-hydrophone** separation distance, the **free-field receive sensitivity** of the calibrated reference **hydrophone**, and the electrical drive **signal** applied to the **projector**. For the **projector**, either **transmitting response to current** or the **transmitting response to voltage** can be determined, requiring the measurement of the electrical drive current or drive voltage, respectively.

9.3 Hydrophone calibration by comparison with a reference hydrophone

9.3.1 Acoustic field requirements

For all measurements, the requirements for acoustic free-field conditions (5.2), far-field conditions (5.3) and steady-state conditions (5.4) shall be met.

9.3.2 Separation distance

The distance between the auxiliary **projector** and the **hydrophone** shall be decided and measured according to the requirements of 5.6.5.

In the choosing the separation distance the requirements of acoustic free-field conditions (5.2), and **acoustic far-field** conditions (5.3) shall be met.

It is recommended that each repeated calibration be conducted at a different separation distance.

NOTE A distance smaller than that required for free-field conditions can be acceptable when the **hydrophone** under test is compared with a calibrated **hydrophone** at the same place in the sound field. This is possible when the two **hydrophones** are exposed to the same acoustic pressure and neither **hydrophone** responds to acoustic pressure

gradients. To achieve this, the two **hydrophones** will be essentially identical (or very similar) in structure and size, or both will have dimensions less than an acoustic wavelength [4].

9.3.3 Transducer preparation, mounting and alignment

Before commencing the measurements, the requirements for soaking (7.1) and wetting (7.2) of the **transducers** shall be met.

For each measurement of electrical transfer impedance, the requirements for **transducer** mounting (5.6.3) and **transducer** alignment (5.6.4) shall be met.

9.3.4 Signal type

The **signal** type shall be chosen in accordance with 6.1.

9.3.5 Measurement of electrical voltage

For both the **hydrophone** under test and the reference **hydrophone**, the **hydrophone** voltage shall be measured in accordance with 6.3. Both voltages shall be expressed in the same metric (for example, both as peak voltages, or both as root-mean-square voltages).

During the measurements, as a check on the stability of the source **transducer** between measurement runs, the **projector** drive current shall be measured in accordance with 6.4.

NOTE 1 For highest accuracy, the **hydrophone** voltages can be measured through the same measurement channel (the measuring channel consists of an amplifier, filter, and digitizer). In this case, the instruments used in the measuring channel will not require absolute calibration since only ratios of electrical quantities are required.

NOTE 2 If required, a calibrated attenuator can be used to equalize the voltages. This will minimize errors due to non-linearity in the measuring channel.

9.3.6 Free-field sensitivity

The modulus of the **free-field receive sensitivity** of the **hydrophone** under test, $|\underline{M}_H|$, shall be calculated from the ratio of the open-circuit voltages of the **hydrophone** under test, U_H , and the reference **hydrophone**, U_R , and the sensitivity of the calibrated reference **hydrophone**, $|\underline{M}_R|$, according to the following:

$$|\underline{M}_H| = \frac{U_H}{U_R} |\underline{M}_R| \quad (21)$$

9.3.7 Repeatability

The calibration shall be repeated several times and the mean of the results at each frequency shall be used as the final value of sensitivity. The repeated calibrations shall be fully independent, with the **transducers** removed from the water and remounted between each calibration.

The standard deviation shall be determined and used in the calculation of uncertainties, see Annex F.

It is recommended that at least four repeated measurements are made. If two different reference **hydrophones** are used, it is recommended that each is utilized for two of the repeats.

NOTE 1 If a different separation distance is used for some of the repeated calibrations, this will be of assistance in assessing some of the assumptions in the method (free-field conditions, spherical-wave field, etc.) since the sensitivity is invariant with separation distance for spherically-spreading wave in free-field conditions (with corrections made for absorption by water at high frequencies).

NOTE 2 Lack of good repeatability indicates a problem with the calibration. Causes can include poor **signal**-to-noise ratio, the presence of acoustic reflections, poor precision with positioning and alignment, poor temporal stability in the performance of the acoustic **transducers** or instrumentation. With care, it is possible to achieve standard deviations as low as 1 % for **hydrophones** over their operating range.

9.3.8 Verification and checks

The measured **signals** shall be checked for distortion during the calibrations. If there is significant distortion present, the drive level of the **projector** shall be reduced.

The use of two different reference **hydrophones** for the repeated measurement runs will mitigate the risk of temporal instability in the sensitivity of the reference **hydrophone** since its last primary calibration.

In order to mitigate the possibility of the reference **hydrophone** changing sensitivity since its last absolute calibration, it is recommended that two different reference **hydrophones** be used for different repeated calibrations. The sensitivities calculated will be the same when using either reference **hydrophone**. The degree to which the results disagree provides an indication of the stability of the two reference **hydrophones** (it is highly unlikely that both **hydrophones** would change sensitivity by the same amount).

Take care that during the actual calibration, the **signal** levels are kept within the range of linearity.

NOTE 1 Distortion can manifest itself by the presence of higher harmonics in the **signal**, evident from an inspection of the spectral levels. Ideally, any harmonics will be more than 10 dB lower in amplitude than the fundamental.

NOTE 2 If the calibrated reference **hydrophone** is used under significantly different environmental conditions to those used during its primary calibration, this can cause a change in the sensitivity and add to the calibration uncertainty. Environmental conditions that are relevant include the depth of immersion and water temperature.

9.3.9 Uncertainty

The overall uncertainty for the calibration shall be determined and expressed with the value for the sensitivity. With care and when using **hydrophones** within their main operating range, an overall uncertainty (95 % confidence levels) can be achieved which is in the range 7 % to 15 %.

NOTE **Hydrophone** calibration by a comparison method will in general have higher uncertainty than a primary method (such as a method based on free-field reciprocity) since the uncertainty in the calibration of the reference **hydrophone** will inevitably introduce a large Type B component of uncertainty [43]. More guidance on assessment of uncertainties is given in Annex F.

9.4 Hydrophone calibration using a calibrated projector

9.4.1 Acoustic field requirements

For all measurements, the requirements for acoustic free-field conditions (5.2), far-field conditions (5.3) and steady-state conditions (5.4) shall be met.

9.4.2 Separation distance

The distance between the **projector** and the **hydrophone** shall be decided and measured according to the requirements of 5.6.5.

In the choosing the separation distance the requirements of acoustic free-field conditions (5.2), and **acoustic far-field** conditions (5.3) shall be met.

It is recommended that each repeated calibration be conducted at a different separation distance.

The **projector** might itself have been calibrated at a certain distance or within a given range of distances. If so, it is recommended that these separation distances are used for this calibration also.

9.4.3 Transducer preparation, mounting and alignment

Before commencing the measurements, the requirements for soaking (7.1) and wetting (7.2) of the **transducers** shall be met.

For each measurement of electrical transfer impedance, the requirements for **transducer** mounting (5.6.3) and **transducer** alignment (5.6.4) shall be met.

9.4.4 Signal type

The **signal** type shall be chosen in accordance with 6.1.

If the **projector** has been calibrated with a specific type of **signal**, it is recommended to use the same type when that **projector** acts as a calibrated sound source.

9.4.5 Measurement of electrical transfer impedance

At each acoustic frequency, the **electrical transfer impedance** shall be determined by measuring the **hydrophone** voltage in accordance with 6.3 and the **projector** drive current in accordance with 6.4. Both the voltage and current shall be expressed in the same metric (for example, both as peak quantities, or both as root-mean-square quantities).

NOTE 1 For highest accuracy, the **projector** drive current can be measured through the same measuring channel as the **hydrophone** voltage (the measuring channel consists of an amplifier, filter, and digitizer). In this case, the instruments used in the measuring channel will not require absolute calibration since only ratios of electrical quantities are required.

NOTE 2 If required, a calibrated attenuator can be used to equalize the voltage representing the **projector** current with the **hydrophone** voltage. This will minimize errors due to non-linearity in the measuring channel.

NOTE 3 If very high acoustic frequencies are used, each **electrical transfer impedance** can be corrected for loss due to sound absorption by water. Further details are given in 5.8.1 and in Annex E.

9.4.6 Calculation of the receive sensitivities

With the measured values of d , U_{PH} , I_P , and with the known transmit current sensitivity $\underline{S}_{I,P}$ of the calibrated **projector**, the modulus of the **free-field receive sensitivity** $|\underline{M}_H|$ of the **hydrophone** shall be calculated with the following formula:

$$|\underline{M}_H| = \frac{d U_{PH}}{|\underline{S}_{I,P}| I_P} = \frac{d |\underline{Z}_{PH}|}{|\underline{S}_{I,P}|} \quad (22)$$

9.4.7 Repeatability

The calibration shall be repeated several times and the mean of the results at each frequency shall be used as the final value of sensitivity. The repeated calibrations shall be fully independent, with the **transducers** removed from the water and remounted between each calibration.

The standard deviation shall be determined and used in the calculation of uncertainties, see Annex F.

It is recommended that at least four repeated measurements are made.

NOTE 1 If a different separation distance is used for some of the repeated calibrations, this will be of assistance in assessing some of the assumptions in the method (free-field conditions, spherical-wave field, etc.) since the sensitivity is invariant with separation distance for spherically-spreading wave in free-field conditions (with corrections made for absorption by water at high frequencies).

NOTE 2 Lack of good repeatability indicates a problem with the calibration. Causes can include poor signal-to-noise ratio, the presence of acoustic reflections, poor precision with positioning and alignment, poor temporal stability

in the performance of the acoustic **transducers** or instrumentation. With care, it is possible to achieve standard deviations as low as 1 % for **hydrophones** over their operating range.

9.4.8 Verification and checks

The measured **signals** shall be checked for distortion during the calibrations. If there is significant distortion present, the drive level of the **projector** shall be reduced.

As far as possible, the calibrated **projector** shall be used in the manner and conditions that pertained to its primary calibration.

The use of a calibrated reference **hydrophone** to check the **projector** performance will mitigate the risk of temporal instability in the sensitivity of the **projector** since its last primary calibration.

NOTE 1 Take care that during the actual calibration, the **signal** levels are kept within the range of linearity. Distortion can manifest itself by the presence of higher harmonics in the **signal**, evident from an inspection of the spectral levels. Ideally, any harmonics will be more than 10 dB lower in amplitude than the fundamental.

NOTE 2 The calibrated reference **projector** will ideally be used under operating conditions to those used during its primary calibration. These conditions include a similar applied drive voltage; and similar separation distance and a similar mounting configuration.

NOTE 3 If the calibrated reference **projector** is used under significantly different environmental conditions to those used during its primary calibration, this can cause a change in the sensitivity and add to the calibration uncertainty. Environmental conditions that are relevant include the depth of immersion and water temperature.

NOTE 4 As a check on the stability of the **projector** sensitivity (since its last primary calibration), a calibrated **hydrophone** can be used to measure the sound field produced by the **projector**.

9.4.9 Uncertainty

The overall uncertainty for the calibration shall be determined and expressed with the value for the sensitivity. With care and when using **hydrophones** within their main operating range, an overall uncertainty (95 % confidence levels) can be achieved which is in the range 10 % to 20 %.

NOTE **Hydrophone** calibration by use of a standard **projector** will in general have higher uncertainty than a primary method (such as a method based on free-field reciprocity) since the uncertainty in the calibration of the reference **projector** will inevitably introduce a large component of uncertainty. The stability of the **projector** and the potential lack of free-field conditions can also contribute to overall uncertainty [39]. More guidance on assessment of uncertainties is given in Annex F.

9.5 Projector calibration using a calibrated hydrophone

9.5.1 Acoustic field requirements

For all measurements, the requirements for acoustic free-field conditions (5.2), far-field conditions (5.3) and steady-state conditions (5.4) shall be met.

9.5.2 Separation distance

The distance between the **projector** and the **hydrophone** shall be decided and measured according to the requirements of 5.6.5.

In the choosing the separation distance the requirements of acoustic free-field conditions (5.2), and **acoustic far-field** conditions (5.3) shall be met.

It is recommended that each repeated calibration be conducted at a different separation distance.

9.5.3 Transducer preparation, mounting and alignment

Before commencing the measurements, the requirements for soaking (7.1) and wetting (7.2) of the **transducers** shall be met.

For each measurement of **electrical transfer impedance**, the requirements for **transducer** mounting (5.6.3) and **transducer** alignment (5.6.4) shall be met.

9.5.4 Signal type

The **signal** type shall be chosen in accordance with 6.1.

9.5.5 Measurement of electrical transfer impedance

At each acoustic frequency, the **electrical transfer impedance** shall be determined by measuring the **hydrophone** voltage in accordance with 6.3 and the **projector** drive current in accordance with 6.4. Both the voltage and current shall be expressed in the same metric (for example, both as peak quantities, or both as root-mean-square quantities).

NOTE 1 For highest accuracy, the **projector** drive current can be measured through the same measuring channel as the **hydrophone** voltage (the measuring channel consists of an amplifier, filter, and digitizer). In this case, the instruments used in the measuring channel will not require absolute calibration since only ratios of electrical quantities are required.

NOTE 2 If required, a calibrated attenuator can be used to equalize the voltage representing the **projector** current with the **hydrophone** voltage. This will minimize errors due to non-linearity in the measuring channel.

NOTE 3 If very high acoustic frequencies are used, each **electrical transfer impedance** can be corrected for loss due to sound absorption by water. Further details are given in 5.8.1 and in Annex E.

9.5.6 Calculation of the transmit sensitivity

With the measured values of d , U_{PH} , I_P , and with the known free-field sensitivity $|\underline{M}_H|$ of the **hydrophone**, the modulus of the **transmitting response to current** $|\underline{S}_{I,P}|$ of the **projector** shall be calculated with the following formula:

$$|\underline{S}_{I,P}| = \frac{dU_{PH}}{|\underline{M}_H|I_P} = \frac{d|\underline{Z}_{PH}|}{|\underline{M}_H|} \quad (23)$$

For calibration of the **projector** in terms of the measured electrical drive voltage, V_P , the modulus of the **transmitting response to voltage** $|\underline{S}_{V,P}|$ is calculated from:

$$|\underline{S}_{V,P}| = \frac{dU_{PH}}{|\underline{M}_H|V_P} \quad (24)$$

9.5.7 Verification and checks

The measured **signals** shall be checked for distortion during the calibrations. If there is significant distortion present, the drive level of the **projector** shall be reduced.

As far as possible, the **projector** shall be calibrated in the manner and conditions that will pertain to its intended use in the field.

The use of two different reference **hydrophones** for the repeated measurement runs will mitigate the risk of temporal instability in the sensitivity of the reference **hydrophone** since its last primary calibration.

Take care that during the actual calibration, the **signal** levels are kept within the range of linearity. Distortion can manifest itself by the presence of higher harmonics in the **signal**, evident from an inspection of the spectral levels. Ideally, any harmonics should be more than 10 dB lower in amplitude than the fundamental.

The **projector** under test will ideally be calibrated using a similar applied drive voltage, separation distance and mounting configuration that will pertain to its intended use in the field.

If the calibrated reference **hydrophone** is used under significantly different environmental conditions to those used during its primary calibration, this can cause a change in the sensitivity and add to the calibration uncertainty. Environmental conditions that are relevant include the depth of immersion, water temperature and mounting configuration.

In order to mitigate the possibility of the reference **hydrophone** changing sensitivity since its last absolute calibration, it is recommended that two different reference **hydrophones** be used for different repeated calibrations. The **projector** transmit sensitivities calculated will be the same when using either reference **hydrophone**. The degree to which the results disagree provides an indication of the stability of the two reference **hydrophones** (it is highly unlikely that both **hydrophones** would change sensitivity by the same amount).

9.5.8 Uncertainty

The overall uncertainty for the calibration shall be determined and expressed with the value for the sensitivity. With care and when using **transducers** within their main operating range, an overall uncertainty (95 % confidence levels) can be achieved which is in the range 10 % to 20 %.

NOTE Calibration of a **projector** will in general have higher uncertainty than a primary method (such as a method based on free-field reciprocity) since the uncertainty in the calibration of the reference **hydrophone** will inevitably introduce a large component of uncertainty. The potential lack of free-field conditions can also contribute to overall uncertainty to a greater degree than for **hydrophone** calibration. More guidance on assessment of uncertainties is given in Annex F.

10 Reporting of results

10.1 Sensitivity

The results for **projector** or **hydrophone** sensitivity shall be reported for each acoustic frequency of measurement.

The results for **free-field receive sensitivity** of a **hydrophone** shall be reported in units of volts per pascal (V/Pa).

The results for the transmit current response (TCR) of a **projector** shall be reported in units of pascal metre per ampere, $\text{Pa} \cdot \text{m} \cdot \text{A}^{-1}$.

The results for transmit voltage response (TVR) of a **projector** shall be reported in units of pascal metre per volt, $\text{Pa} \cdot \text{m} \cdot \text{V}^{-1}$.

Any allowed multiplier within the SI system of quantities and units is acceptable (for example, a common variant for **free-field receive sensitivity** in the underwater acoustics field is $\mu\text{V} \cdot \text{Pa}^{-1}$).

10.2 Sensitivity level

If the results for **projector** or **hydrophone** sensitivity are required to be expressed as a level, they shall be reported for each acoustic frequency of measurement.

The results for the **free-field receive sensitivity level** of a **hydrophone** shall be reported in units of decibels, with a reference value equal to $1 \text{ V} \cdot \mu\text{Pa}^{-1}$.

The results for the transmit current response level of a **projector** shall be reported in units of decibels, with a reference value equal to $1 \mu\text{Pa} \cdot \text{m} \cdot \text{A}^{-1}$.

The results for the transmit voltage response level of a **projector** shall be reported in units of decibels, with a reference value equal to $1 \mu\text{Pa}\cdot\text{m}\cdot\text{V}^{-1}$.

It is recommended that the sensitivity is included in SI units alongside the sensitivity level.

10.3 Calibration uncertainties

The calibration uncertainty shall be reported alongside the sensitivity, and shall be expressed as an expanded uncertainty for a coverage factor $k = 2$.

The uncertainty shall be evaluated in conformance with ISO/IEC Guide 98-3 [43]. See Annex F for guidance on sources of uncertainty in calibration of **hydrophones** and **projectors**.

NOTE The calibration uncertainty is ideally expressed as a relative uncertainty as a percentage.

10.4 Auxiliary metadata

Any calibration is only valid on the date of calibration and for the environmental conditions which existed during the calibration. When the result of the calibration of a **hydrophone** is reported, the environmental conditions that pertain to that calibration shall be stated, including all those conditions that can influence the sensitivity of the device [9], [47] to [51].

Conditions that shall be reported are:

- date of the calibration;
- water temperature;
- depth of immersion;
- type of mount or rigging used;
- length of soaking time and wetting procedure used;
- orientation of the **transducer** about any axis or alignment mark;
- alignment method (manually or acoustically aligned).

NOTE Other conditions that can need to be reported include:

- maximum acoustic pressure experienced by the **hydrophone**;
- separation distances used in the calibration;
- electrical drive voltages and/or currents;
- water (fresh water or sea water);
- any assumptions made about the device under test (e.g. the position of the reference centre).

11 Recalibration periods

Reference **hydrophones** used for absolute measurements shall be calibrated periodically in order to maintain a valid calibration status. An appropriate period between calibrations shall be chosen after consideration of the use that is made of the **hydrophone** and the likelihood for damage to the device.

NOTE 1 For reference **hydrophones**, which are used purely for calibration purposes, an annual recalibration is appropriate. Where **hydrophones** are used in the field and potentially could be subjected to abuse, calibrations are typically undertaken at shorter intervals (see IEC 60500:2017).

NOTE 2 The decision on the appropriate recalibration period depends upon the risk of any unobserved change to the sensitivity of the **hydrophone** or **projector**. If, during the period between full primary calibrations, other calibration checks are performed over all or part of the frequency range, then an ongoing assessment can be made of the temporal stability and the period between full calibrations can be extended. An example might be a **hydrophone** which is subject to periodic relative calibration checks by inclusion as one of the reference **hydrophones** in comparison calibrations along with another reference **hydrophone** or reference **projector** (see 9.3.8, 9.4.8 and 9.5.7). Another would be a **transducer** used over part of its frequency range in a triad for a reciprocity calibration of another **transducer** (8.2.9).

Annex A (informative)

Directional response of a hydrophone or projector

A.1 General principle

A complete determination of the performance characteristics of a **projector** or **hydrophone** should include a measurement of its **directional response** at representative frequencies above the range where it is still omnidirectional (see IEC 60500:2017, Clause 6).

The measurements require that a rotational stage be incorporated into the **transducer** support framework or positioning system, with the **transducer** mount aligned such that the **transducer** reference centre is located along the axis of rotation. The **transducer** under test (**hydrophone** or **projector**) is rotated about the axis and measurements are made of the received **signal** as a function of angle in a specified plane [3] to [6].

In practice, for efficiency and reliability, the control of the rotation stage and the **signal** acquisition is automated and under computer control.

A.2 Types of measurement implementation

Two methods of implementing the rotation are in general feasible:

a) Discrete rotation intervals

In this case, measurements are made at discrete angular intervals, with the rotation stage stopping at specified angular increments while measurements are made of the received voltage **signal** at the **hydrophone** for each known angle of rotation. This method ideally requires some form of stepper motor control. One disadvantage of this method is that it can be time-consuming. In addition, there is a disadvantage in that mechanical vibrations can occur in the **transducer** suspension system when the motion is stopped rapidly at a predetermined position. To avoid this issue, the acceleration and deceleration of the positioning system are reduced to provide a more gradual change of motion, and acoustic measurements are delayed for a time required to completely terminate any mechanical vibrations. The advantage of discrete rotation intervals is that, at each rotation angle, auto-scaling and **signal** averaging can be performed, enabling accuracy to be maintained for large fluctuations in received **signal** level (such as in nulls and for low amplitude side lobes). For highly directional **transducers** where the response varies strongly, this is desirable.

b) Continuous rotation

In this case, the rotation stage is rotated continuously but very slowly while making simultaneous measurements of the received voltage **signal** and the angle of rotation. Although the rotation is slow to enable readings of voltage and angle to be obtained, in a few minutes it is typically possible to obtain measurements at thousands of angles. The advantage of this method is increased speed compared to the discrete method. The disadvantage is that no **signal** averaging or auto-scaling is possible, which can limit the achievable uncertainty for responses of highly directional **transducers** that show high variation in received **signal** level with angle, and can also lead to greater electrical noise being apparent in the measured data. The **transducer** should be rotated slowly enough for the **signal** acquisition to pick up changes in the **signal** level around the nulls in the response. This method is best for **transducers** that exhibit a smooth **directional response** with no significant nulls, as can be obtained from small **hydrophones** at frequencies up to the resonance.

A.3 Coordinate system

The angular coordinate system chosen is that specified by IEC 60500:2017.

A.4 Acoustic field requirements

For all measurements, the requirements for acoustic free-field conditions (5.2), and steady-state conditions (5.4) shall be met.

With regard to far-field requirements, when measuring the **directional response** of a **transducer**, the distance between the **projector** and the **hydrophone** shall be larger than that for a calibration on axis. The distance shall be no less than twice that given by Formula (9) or Formula (10), whichever is larger (see 5.3). See Annex D and references [3], [4], [7] to [9].

A.5 Positioning and alignment

The requirements of 5.6 shall apply.

A.6 Signal type

The **signal** type shall be chosen in accordance with 6.1.

A.7 Measurement of transducer directional response

A.7.1 Projector

With the **projector** under test and **hydrophone** deployed in the water, the **projector** is driven with a **signal** of fixed amplitude and rotated about an axis through the reference centre through the required angular range, with measurements of the received voltage **signal** made at the **hydrophone** for each known angle of rotation and at the required angular resolution. The **hydrophone** voltage is measured in accordance with 6.3.

NOTE 1 The **hydrophone** need not be calibrated.

NOTE 2 The zero degree angle is normally chosen to be the reference direction of the principal axis of the **projector**.

A.7.2 Hydrophone

With the **projector** and **hydrophone** under test deployed in the water, the **projector** is driven with a **signal** of fixed amplitude and the **hydrophone** is rotated about an axis through the reference centre through the required angular range, with measurements of the received voltage **signal** made at the **hydrophone** for each known angle of rotation and at the required angular resolution. The **hydrophone** voltage is measured in accordance with 6.3.

NOTE 1 The **projector** need not be calibrated. However, any instability in its output throughout the measurements will contribute to the measurement uncertainty.

NOTE 2 The zero degree angle is normally chosen to be the reference direction of the **hydrophone**.

A.8 Calculation of the directional response level (angular deviation loss)

The **directional response** is calculated by normalizing the response to the response at a specified reference angle. The **directional response** level $L_{D\theta}$ expressed in decibels can be calculated from:

$$L_{D\theta} = 20 \log_{10} \left(\frac{V_{\theta}(\theta)}{V_{\text{ref}}} \right) \text{ dB} \quad (\text{A.1})$$

where $V_{\theta}(\theta)$ is the array of voltages measured at the range of angles, θ , and V_{ref} is the reference voltage used for the normalization.

NOTE 1 The reference voltage can be measured in the **hydrophone** reference direction or direction of the principal axis of the **projector**, but is most often chosen to be the maximum value of the voltage measured at any angle. The choice of reference voltage is stated with the results if it is not obvious.

NOTE 2 For a **projector**, often the maximum **signal** is obtained on or near the **transducer** principal axis. For a small and relatively omnidirectional **hydrophone**, the chosen reference direction can be arbitrary and will not necessarily be the direction of maximum sensitivity.

A.9 Uncertainty

The uncertainty in **directional response** measurement is affected by the same quantities that limit the accuracy of the sensitivity measurement, but there are some additional limitations. A larger separation distance is generally required (see Annex F). For directional **transducers**, the level of reflections and noise should ideally be lower than for sensitivity measurement on the principal axis because of the low level of the **signals** measured at off-axis angles.

If the reference centre is not located accurately on the axis of rotation, the varying separation distance (precession) can cause errors in the phase and the amplitude of the measured **directional response**.

For omnidirectional **transducers** showing weak variation with angle, and for directional **transducers** at angles close to the maximum of the main beam, uncertainties in the **directional response** are typically about 0,5 dB (for a confidence level of 95 %). An additional uncertainty of 1 dB for each **angular deviation loss** between 10 dB and 30 dB can be expected.

A.10 Graphic representation

A **directional response** is typically presented graphically, either in the form of a two-dimensional polar plot or as a Cartesian plot [3]. Examples are shown in Figure A.1.

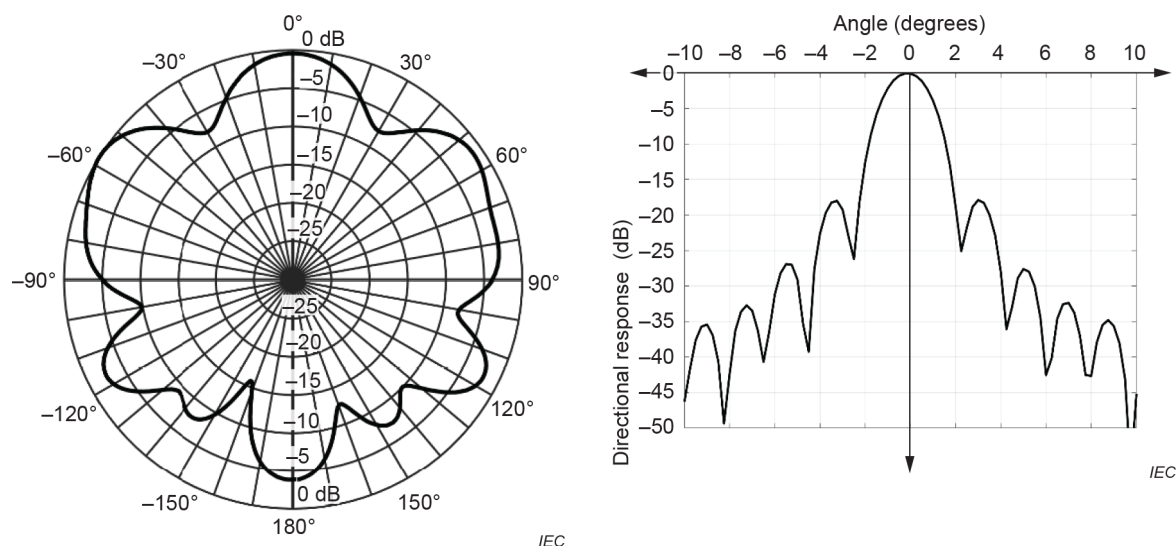


Figure A.1 – Examples of graphical representations of the level of the directional response: polar plot (left) and Cartesian plot (right)

For both plots, the amplitude scale is most often in terms of the normalized **directional response** expressed as a level in decibels (**angular deviation loss**). However, occasionally the normalized **directional response** is scaled by the sensitivity on axis to produce a response in terms of absolute sensitivity.

The reporting requirements of 10.4 apply. In addition, each **directional response** plot is identified to indicate the type of response, frequency or frequency band, and orientation within the specified co-ordinate system of IEC 60500:2017.