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INTERNATIONAL STANDARD

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inside

Underwater acoustics – Calibration of acoustic wave vector receivers in the frequency range 5 Hz to 10 kHz

Acoustique sous-marine – Étalonnage des récepteurs vectoriels d’ondes acoustiques dans la plage de fréquences de 5 Hz à 10 kHz

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UNDERWATER ACOUSTICS – CALIBRATION OF ACOUSTIC WAVE VECTOR RECEIVERS IN THE FREQUENCY RANGE 5 Hz TO 10 kHz

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Draft	Report on voting
87/839/FDIS	87/843/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

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INTRODUCTION

Unlike traditional piezoelectric **hydrophones** which are sensitive to sound pressure, **vector receivers** measure **sound particle** motion (velocity, acceleration or displacement) or **sound pressure gradient**, and have strongly **directional response** in their working frequency range. The calibration of these **vector receivers** which measure **sound particle** motion or **sound pressure gradient** is considered in this document.

The output voltage of a **vector receiver** channel to be calibrated is proportional to the **sound particle** motion or **sound pressure gradient** at the reference centre of the receiver. The directivity of the **vector receiver** channel is independent of acoustical frequency, and the ratio of the output voltage of the receiver channel at angle θ to the maximum output voltage on the axial direction is equal to $|\cos\theta|$ [1][1].

Recent developments of **acoustic wave vector receivers** for ocean acoustics, such as those that measure **sound particle velocity**, have led to a number of commercial systems being made available on the market. In addition to providing sensors which possess some useful directivity for low-frequency applications, they are increasingly used for measurement of underwater noise exposure for marine fauna that are sensitive to sound particle motion rather than sound pressure (for example, fish and invertebrates). However, calibration of such sensors poses technical challenges, and is not covered by the existing international standards such as IEC 60565 [2], [3]. Building on work begun in China and Russia [4], where a successful bilateral comparison has recently been concluded, this work establishes an International Standard on calibration of **vector receivers** in the frequency range 5 Hz to 10 kHz.

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[1] Numbers in square brackets refer to the Bibliography.

UNDERWATER ACOUSTICS – CALIBRATION OF ACOUSTIC WAVE VECTOR RECEIVERS IN THE FREQUENCY RANGE 5 Hz TO 10 kHz

1 Scope

Usually, **acoustic wave vector receivers** are designed and constructed based on one of two principles. One is the sound pressure difference (gradient) principle. When measuring with this sensor, the **vector receiver** is rigidly fixed on a mount and supported in water. The other is the co-vibrating (**inertial**) principle. When measuring with this sensor, the **vector receiver** is suspended on a mount and supported in water in a non-rigid manner, which allows the **vector receiver** co-vibrate in the same direction as the **sound particle** in the sound wave field.

Many methods have been used to calibrate **vector receivers**, such as free-field calibration, calibration in standing wave tube and calibration in a travelling wave tube. This document specifies methods and procedures for calibration of **vector receivers** in the frequency range 5 Hz to 10 kHz, which are applicable to **vector receivers** based on the two different principles. In addition, it describes an absolute method of **inertial vector receiver** calibration in air using optical interferometry.

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

IEC 60565-1:2020, *Underwater acoustics – Hydrophones – Calibration of hydrophones, Part 1: Procedures for free-field calibration of hydrophones*

ISO 80000-8:2020, *Quantities and units – Part 8: Acoustics*

ISO 18405:2017, *Underwater acoustics – Terminology*

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60500:2017, IEC 60565-1:2020, ISO 80000-8:2020, ISO 18405:2017 and the following apply.

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

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
sound particle
material element
smallest element of the medium that represents the medium's mean density

[SOURCE: ISO 80000-8:2020, 3.1]

3.2
sound particle displacement
$\boldsymbol{\delta}$
displacement of a **sound particle** caused by the action of sound

Note 1 to entry: **Sound particle displacement** is a function of time, t, which is indicated by means of an argument t, as in $\boldsymbol{\delta}(t)$.

Note 2 to entry: **Sound particle displacement** is expressed in metres, m.

Note 3 to entry: **Sound particle displacement** is a vector quantity. Spatial components of the **sound particle displacement** can be indicated by assigning subscripts to the symbol. For example, in Cartesian coordinates, $\boldsymbol{\delta} = (\delta_x, \delta_y, \delta_z)$. By convention in underwater acoustics, the z axis is usually chosen to point vertically down from the sea surface, with x and y axes in the horizontal plane. If the **sound particle displacement** is in the same direction in which the sound wave propagates, its symbol can be simply δ.

[SOURCE: ISO 18405:2017, 3.1.2.9, modified – In the definition, "material element" has been replaced by "sound particle".]

3.3
sound particle velocity
$\boldsymbol{u}$
contribution to velocity of a **sound particle** caused by the action of sound

Note 1 to entry: **Sound particle velocity** is a function of time, t, which is indicated by means of an argument t, as in $\boldsymbol{u}(t)$.

Note 2 to entry: For small-amplitude sound waves in an otherwise stationary medium, the **sound particle velocity** and **sound particle displacement** are related by

$$\boldsymbol{u}(t) = \frac{\partial \boldsymbol{\delta}(t)}{\partial t} \qquad (1)$$

where $\boldsymbol{\delta}(t)$ is the **sound particle displacement** at time, t, and the partial derivative is evaluated at a fixed position.

Note 3 to entry: **Sound particle velocity** is expressed in units of metre per second, $\text{m} \cdot \text{s}^{-1}$.

Note 4 to entry: **Sound particle velocity** is a vector quantity. Spatial components of the **sound particle velocity** can be indicated by assigning subscripts to the symbol. For example, in Cartesian coordinates, $\boldsymbol{u} = (u_x, u_y, u_z)$. By convention in underwater acoustics, the z axis is usually chosen to point vertically down from the sea surface, with x and y axes in the horizontal plane. If the **sound particle velocity** is in the same direction in which the sound wave propagates, its symbol can be simply u.

[SOURCE: ISO 18405:2017, 3.1.2.10, modified – In the definition, "material element" has been replaced by "sound particle".]

3.4
sound particle acceleration
$\boldsymbol{a}$
contribution to acceleration of a **sound particle** caused by the action of sound

Note 1 to entry: **Sound particle acceleration** is a function of time, t, which is indicated by means of an argument t, as in $\boldsymbol{a}(t)$.

Note 2 to entry: For small-amplitude sound waves in an otherwise stationary medium, the **sound particle acceleration** and **sound particle velocity** are related by

$$\boldsymbol{a}(t) = \frac{\partial \boldsymbol{u}(t)}{\partial t} \tag{2}$$

where $\boldsymbol{u}(t)$ is the **sound particle velocity** at time, t, and the partial derivative is evaluated at a fixed position.

Note 3 to entry: **Sound particle acceleration** is expressed in units of metre per second squared, $\text{m}\cdot\text{s}^{-2}$.

Note 4 to entry: **Sound particle acceleration** is a vector quantity. Spatial components of the **sound particle acceleration** can be indicated by assigning subscripts to the symbol. For example, in Cartesian coordinates, $\boldsymbol{a} = (a_x, a_y, a_z)$. By convention in underwater acoustics, the z axis is usually chosen to point vertically down from the sea surface, with x and y axes in the horizontal plane. If the **sound particle acceleration** is in the same direction in which the sound wave propagates, its symbol can be simply a.

[SOURCE: ISO 18405:2017, 3.1.2.11, modified – In the definition, "material element" has been replaced by "sound particle".]

3.5
sound pressure gradient

∇p

spatial derivative of sound pressure with respect to distance caused by the action of sound

Note 1 to entry: **Sound pressure gradient** is expressed in units of pascal per metre, $\text{Pa}\cdot\text{m}^{-1}$.

Note 2 to entry: **Sound pressure gradient** is a vector quantity. In Cartesian coordinates, spatial components of the **sound pressure gradient** can be indicated as $\nabla p = (\partial p / \partial x, \partial p / \partial y, \partial p / \partial z)$. By convention in underwater acoustics, the z axis is usually chosen to point vertically down from the sea surface, with x and y axes in the horizontal plane.

3.6
vector receiver
acoustic wave vector receiver

receiving transducer whose output voltage of its receiving channel is proportional to the **sound particle** motion (displacement, velocity or acceleration) or **sound pressure gradient** on the position of the reference centre of it in water

Note 1 to entry: Due to the different constructions, the **vector receiver** can be one-dimensional **vector receiver**, two-dimensional orthogonal **vector receiver** or three-dimensional orthogonal **vector receiver**, and it has different receiving channels. For a three-dimensional orthogonal **vector receiver**, the channels are usually named as x-channel, y-channel and z-channel.

Note 2 to entry: The receiving channel of the **vector receiver** has very strong **directional response**, which is independent of the frequency.

Note 3 to entry: According to the vector values which are perceived, there are different **vector receivers**, including **inertial vector receiver** and **sound pressure gradient receiver**.

Note 4 to entry: Sometimes, the **vector receiver** has a sound pressure (scalar) receiving channel, and open-circuit voltage of the sound pressure channel is proportional to the sound pressure on the position of the reference centre of the **vector receiver**.

Note 5 to entry: The phase of the output signal of the vector receiving channel changes by 180 degrees when the direction of sound wave incidence changes to the opposite direction, which can be found using the output signal of a sound pressure receiving channel as a reference signal when the **vector receiver** has a sound pressure receiving channel in it.

3.7
inertial vector receiver

receiving transducer that senses **sound particle** motion by measuring the reaction of a proof mass in response to motion of the sensor body (e.g. accelerometer, geophone)

3.8
hydrophone

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

[SOURCE: IEC 60500:2017, 3.17, modified – In the definition, "electrical signals" has been replaced with "electrical voltages", and "pressure signals" with "sound pressure signals".]

3.9
sound pressure gradient receiver

receiving transducer that senses the gradient of sound pressure using two or more **hydrophones** separated by distances that are small relative to the wavelength

3.10
directional response

<of a **vector receiver** channel> description of the response of a **vector receiver** channel, as a function of the direction of propagation of the incident plane sound wave, in a given channel direction through the reference centre, at a specified frequency

Note 1 to entry: The **directional response** pattern is usually presented in the form of a two-dimensional polar graph. The scale of the polar can be in terms of sensitivity level or in angular deviation loss (see Annex A).

Note 2 to entry: The **directional response** pattern of the **vector receiver** channel is a cosine function, that is the ratio of the output voltage of the **vector receiver** channel in the direction of angle θ to the maximum output voltage in the axial direction is equal to $|\cos\theta|$.

[SOURCE: IEC 60500:2017, 3.4, modified – In the definition, "hydrophone" has been replaced with "vector receiver channel", "a specified plane" has been replaced with "a given channel direction", and ", generally presented graphically," has been deleted.]

3.11
axial angular deviation loss

larger value of **directional response** of a **vector receiver** channel on the principal axis minus another value of **directional response** on the symmetrical direction

Note 1 to entry: The **axial angular deviation loss** is expressed as a level in decibels, dB (see Annex A).

Note 2 to entry: Sometimes, the **axial angular deviation loss** is named as asymmetry or maximum heterogeneity of **directional response** on the principal axis of a **vector receiver** channel.

3.12
lateral angular deviation loss

larger value of **directional response** of a **vector receiver** channel on the principal axis minus the smaller value of **directional response** on the lateral axis

Note 1 to entry: The **lateral angular deviation loss** is expressed as a level in decibels, dB (see Annex A).

3.13
sound particle displacement sensitivity

$\underline{M}_{\delta}$

<of a **vector receiver** channel> quotient of the Fourier transform of the output voltage signal $\mathcal{F}\left(U_{\mathrm{VR}}(t)\right)$ of a **vector receiver** channel to the Fourier transform of the **sound particle displacement** signal $\mathcal{F}\left(\delta(t)\right)$, for specified frequency and specified direction of plane wave sound incidence on the position of the reference centre of the **vector receiver** in the undisturbed free field if the **vector receiver** was removed

$$\underline{M}_{\delta} = \frac{\mathcal{F}\left(U_{\mathrm{VR}}(t)\right)}{\mathcal{F}\left(\delta(t)\right)} \tag{3}$$

Note 1 to entry: The **sound particle displacement sensitivity** of a **vector receiver** is a complex-valued parameter. The **sound particle displacement sensitivity** calculated by this equation is in the direction of the sound wave propagation. This calibration procedure can be performed for only one aligned channel, and each channel of the **vector receiver** is calibrated independently.

Note 2 to entry: The modulus of the **sound particle displacement sensitivity** is expressed in units of volt per metre, V·m^{-1}.

Note 3 to entry: The phase angle of the **sound particle displacement sensitivity** is expressed in radians and represents the phase difference between the output voltage of a **vector receiver** and the **sound particle displacement** (see IEC 60500).

3.14
sound particle displacement sensitivity level

$L_{\mathrm{M},\delta}$

twenty times the logarithm to the base 10 of the ratio of the modulus of the **sound particle displacement sensitivity** $\left|\underline{M}_{\delta}\right|$ of a **vector receiver** channel to a reference value of sensitivity, $M_{\delta,\mathrm{ref}}$, in decibels

$$L_{\mathrm{M},\delta} = 20\log_{10}\frac{\left|\underline{M}_{\delta}\right|}{M_{\delta,\mathrm{ref}}}\ \mathrm{dB} \tag{4}$$

Note 1 to entry: The unit of **sound particle displacement sensitivity level** is expressed as a level in decibels, dB.

Note 2 to entry: The reference value of sensitivity, $M_{\delta,\mathrm{ref}}$, is 1 V·pm^{-1}.

3.15
sound particle velocity sensitivity

$\underline{M}_{\mathrm{u}}$

<of a **vector receiver** channel> quotient of the Fourier transform of the output voltage signal $\mathcal{F}\left(U_{\mathrm{VR}}(t)\right)$ of a **vector receiver** channel to the Fourier transform of the **sound particle velocity** signal $\mathcal{F}\left(u(t)\right)$, for specified frequency and specified direction of plane wave sound incidence on the position of the reference centre of the **vector receiver** in the undisturbed free field if the **vector receiver** was removed

$$\underline{M}_{\mathrm{u}} = \frac{\mathcal{F}\left(U_{\mathrm{VR}}(t)\right)}{\mathcal{F}\left(u(t)\right)} \tag{5}$$

Note 1 to entry: The **sound particle velocity sensitivity** of **vector receivers** is a complex-valued parameter. The **sound particle velocity sensitivity** calculated by this equation is in the direction of the sound wave propagation. This calibration procedure can be performed for only one aligned channel, and each channel of the **vector receiver** is calibrated independently.

Note 2 to entry: The modulus of the **sound particle velocity sensitivity** is expressed in units of volt second per metre, V·s·m^{-1}.

Note 3 to entry: The phase angle of the **sound particle velocity sensitivity** is expressed in radians and represents the phase difference between the output voltage of a **vector receiver** and the **sound particle velocity** (see IEC 60500).