National Physical Laboratory

NPL REPORT AC 17

REVIEW OF METHODS FOR THE CALIBRATION OF VECTOR SENSORS FOR THE MEASUREMENT OF UNDERWATER ACOUSTIC FIELDS

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APRIL 2016

National Measurement System

Review of methods for the calibration of vector sensors for the measurement of underwater acoustic fields

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Acoustics and Ionising Radiation

ABSTRACT

This report was published as an output of Project AIR/2014/UA5 of the National Measurement System 2014-2017 Programme for Acoustics and Ionising Radiation Metrology to review the methods for calibration of underwater acoustic vector sensors, and consider other methods with the potential to provide calibration solutions in the future. The scope includes all vector sensor types which are currently available for the measurement of underwater acoustic vector quantities, and is not limited in scope to a particular frequency range. Whilst sensors design for the measurement of seabed vibration and their calibration is excluded from the scope, the requirements for seabed vibration instrumentation are considered in limited detail in this report.

ISSN 1754-2936

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CONTENTS

1 INTRODUCTION

For underwater acoustics, a vector sensor can be considered a passive device (receiver) for the measurement of sound intensity, through the measurement of sound particle velocity and sound pressure, although the term could apply to any device which measures a vector component (amplitude and direction) of the sound field, i.e. sound particle acceleration, velocity, or displacement. Vector sensor application in underwater acoustics is wide ranging, from geoacoustic inversion to determine seabed properties, to tracking of acoustic targets such as cetaceans and naval vessels (Santos et al., 2010; Thode et al., 2010; Stein et al., 1996).

There are a number of vector sensor designs for the measurement of sound intensity (Guigné, and Atkins, 1991; Gabrielson et al., 1995; Bastyr et al., 1999; Kim et al., 2004; Akal et al., 2008; Barnard and Hambric, 2011), with the more common designs employed for underwater acoustic applications based on either a pressure gradient receiver or direct measurement of the motion of the water due to the sound field using an accelerometer or geophone, which are discussed in more detail in Section 2.

Underwater acoustic vector sensors provide two main advantages over conventional pressure sensitive hydrophones:

I) Directivity or directional discrimination;
II) Signal to noise ratio gain, as a result of I).

The measurement of vector components of underwater sound fields allows discrimination of direction, which is much more difficult to achieve with the measurement of a scalar quantity such as pressure, as demonstrated theoretically by Cray et al. (2003). Directional discrimination of an underwater sound field can be achieved using arrays of conventional pressure hydrophones, although similar arrays of acoustic vector sensors can provide improved directivity performance without the same demands on array dimensions (Cray and Nuttall, 2001; Hehorai and Paldi, 1994). It is this advantage that has led to the development of the vector sensor and vector sensor arrays for use in target tracking applications (Stein et al. 1996). The use of a receiving array, through the forming of a receiving beam, will generally lead to improvements in the signal to noise ratio through the 'array gain'. Similarly, the good receiving 'directivity index' of a vector hydrophone results in an improved signal to noise ratio over traditional pressure hydrophones, with advantages in the use of arrays of vector hydrophones over conventional pressure hydrophone arrays (Hawkes and Nehorai, 1998).

Recently, the demand for underwater acoustic vector sensors for the measurement of sound fields resulting from anthropogenic sound sources has increased, with increased awareness of the potential impact of underwater noise on aquatic fauna (Sigray and Andersson, 2011). This has generally been related to specifics taxa, such as fish, which have been shown to be sensitive to sound particle velocity (Hawkins, 2009; Popper and Hastings, 2009; Popper et al. 2014), and other fauna, such as crustaceans and cephalopods, which are understood to also be sensitive to sound particle motion (Packard et al., 1990; Mooney et al., 2010; Andrè et al., 2011). Efforts have been made to describe sound particle velocity of sound fields resulting from man-made sources, in relation to the impact of sound on fish (Mueller-Blenkle et al., 2010; Sigray and Andersson, 2011; Hawkins et al., 2014). In addition, concerns have been raised over the potential affects that motion of the bottom (seabed, riverbed, for example) might pose for sensitive marine life (Hazelwood, 2012). The requirement for the measurement of sound particle motion in relation to its impact on marine fauna was the topic of an international workshop that brought together experts in acoustics and marine biology. A synopsis of this discussion is available in a workshop summary report (Pangerc and Theobald, 2015).

Whilst the use of underwater acoustic vector sensors is fairly widespread, methods for their calibration are not extensively developed or employed. The availability of primary calibration methods for these devices is limited to a few National Metrology Institutes and, at present, no international standard exists for the calibration of underwater acoustic vector sensor devices, as is the case for the pressure hydrophone (IEC 50656).

This report considers the available methods for the calibration of vector sensors, which are used for the measurement of vector components of the sound field in water. Whilst the calibration of instruments for the measurement of sound particle motion of the bottom boundary, to which aquatic organisms may be sensitive, is not the primary purpose of this report, Section 4 does provide some information on vibration sensor calibration. To help distinguish sound particle motion in the water column from sound particle motion of the bottom, the latter will hereafter be referred to as vibration, as is customary for movement in solids.

2 UNDERWATER ACOUSTIC VECTOR SENSORS

2.1 PRESSURE GRADIENT HYDROPHONE (P-P VECTOR SENSOR)

Sound particle velocity can be calculated from the sound particle acceleration, in a given direction, obtained by measurement of the pressure gradient of an acoustic field between two points, where the gradient is the pressure difference divided by the distance between the two measurement points. Two hydrophones can be used to achieve this, and sound intensity calculated from the product of the sound particle velocity and the sound pressure (Kinsler and Frey, 1962). The directional discrimination obtained from the use of pressure gradient devices is described by Oslon (1946), in relation to pairs of microphones.

Vector sensors based on the pressure gradient principle, generally referred to as pressure gradient hydrophones, usually provide an arrangement of orthogonal pairs of hydrophones (Guigné and Atkins, 1991), of fixed separation, to determine the sound intensity to be calculated as a function of direction.

The sensitivity of the device is dictated by the separation distance over which the pressure gradient is calculated, and this separation limits the operational frequency range of the devices, with the maximum sensitivity achieved where the hydrophone separation distance is equal to one half of the wavelength of the incident sound field. The relatively high, low-frequency noise resulting from using pairs of hydrophones as pressure gradient (Keller, 1977) may also limit their application, particularly in the presence of flow.

2.2 NEUTRALLY BUOYANCY TYPE (P-A VECTOR SENSOR)

This type of vector sensor works by physically measuring the movement of the water in the presence of a sound field. This is achieved by using a velocity sensitive measuring device mounted within a rigid, spherical shell, with the whole structure being neutrally buoyant and free to follow the movement of the water. This type of sound particle velocity sensor was first described by Kendall (1951) and Leslie et al. (1956) and numerous designs have been published in the literature since, many of which incorporate a hydrophone to also measure the sound pressure, in addition to multi-axis geophones, to allow determination of the sound intensity (Henriquez, 1981; Gabrielson et al., 1995; Bastyr et al., 1999; D'Spain et al., 1991; Kim et al., 2004; Sigray and Andersson, 2011; Barnard and Hambric, 2011).

Unlike the pressure gradient device, the neutrally buoyant vector sensor will also be sensitive to any oscillatory motion present in the water, which may be unrelated to the acoustic field. In comparison to a pressure gradient device, where the response, as function of frequency and direction, is defined by the hydrophone spacing, a neutrally buoyant vector sensor has no such limitation. Rather, the operational frequency range is limited by the geophone/accelerometer performance, the hydrophone performance, or the ability of the neutrally buoyant sphere to faithfully follow the particle velocity of the sound field. This latter requirement places particular demands on the way in which the device is deployed and restrained in the field, to achieve accurate measurements, and floating rotational resonances can result in low frequency contamination.

The use of neutrally buoyant vector sensor devices has been demonstrated in open water environments for the measurement of acoustic particle velocity of ambient noise and of operational wind turbines (D'Spain et al., 1991 and Sigray and Andersson, 2011). D'Spain et al. (1991) also demonstrated good agreement, *in situ*, of the plane wave equivalent pressure calculated from the sound particle velocity, with the measurements of sound pressure.

2.3 ALTERNATIVE VECTOR SENSING METHODS

One alternative approach, capable of measuring vector sound field quantities is based on a principle used in hot wire anemometry. Anemometers of this type are based on the relationship between the electrical resistance of a heated wire and the convective effects of a surrounding air flow on the wire, thus measurement of the electrical resistance change in the hot wire allows the velocity of the air flow to be determined. These devices have a long history of use for flow measurements (Corrsin, 1947), and have recently been used for the measurement of sound particle velocity in air, using the same fundamental principle of operation. Whilst these 'acoustic' devices were originally designed for use in air (de Bree, 2003), proprietary devices designed for underwater acoustic applications have been described in the literature (Akal et al., 2008). Such instruments were developed to measure sound intensity, with the potential advantage being small size and the ability to measure over a wide bandwidth.

Optical interferometry methods can be used to directly measure the sound particle velocity or displacement in an acoustic field, both in air and water. These are primarily, i) methods based on homodyne interferometer for sound particle displacement measurement and heterodyne for sound particle velocity measurement, using an optically reflective, acoustically compliant membrane (Preston et al., 1999; Yuebing and Yongjun, 2001; Theobald et al., 2005); and ii) and methods based on laser Doppler anemometry, which measures the acoustic oscillations of particles in air or water, in the interference region of two laser beams (Crickmore et al., 1999; Campbell et al., 2000; Koukoulas et al., 2008). Whilst the laser Doppler anemometry is well suited to measurements in air, it is more difficult in water due to incoherent sound pressure induced refractive index changes in the two incident beams (Theobald et al., 2002). Furthermore, Cranch et al. (2012) demonstrated a practical optical approach to measurement of in-situ sound vector field quantities with the design of a fibre-optic cantilever to measure sound particle velocity.

Other technologies have been used in air for the measurement of vector sound field quantities, for example, the ribbon microphone (Olson, 1931), which works by detecting the movement of a metallic ribbon, in a magnetic field, which fluctuates in the sound field due to the pressure difference on each side of the metallic ribbon (the principle of the ribbon movement detection being induction), thus its operation is similar, in principle, to a pressure gradient hydrophone.

3 UNDERWATER ACOUSTIC VECTOR SENSOR CALIBRATION METHODS

At present, no international standard exists for the calibration of underwater acoustic vector sensors. In contrast, calibration of pressure hydrophones is the subject of an international standard between 0.01 Hz to 1 MHz (IEC 60565), and an American national standard over nominally the same frequency range (ANSI/ASA S1.20-2012). Whilst underwater acoustic vector sensors are not as widely used as conventional pressure hydrophones, their use is widespread and the requirements for the measurement of underwater vector acoustic quantities is becoming more prominent, primarily due to concerns relating to noise exposure and environmental impacts of underwater sound. Although there is no international standard describing the calibration methodology, calibration of underwater acoustic vector sensors have been performed, and some of the methods used are reviewed in this section. This section also considers alternative methods that would be suitable as a primary method for calibration.

3.1 FREE-FIELD RECIPROCITY OR COMPARISON

Hydrophone calibrations are generally performed to establish their free-field pressure sensitivity, carried out using i) the free-field reciprocity method or ii) the comparison method if a calibrated hydrophone is available (IEC 60565). Establishing the free-field pressure sensitivity relies on the absence of reflections from boundaries. This can be approximated in a laboratory environment by removing the reflections from the measured signal, which is commonly achieved by time-gating the measured test signal, although other methods, including signal processing for removal of reflections, are also used (Isaev and Matveyev, 2009).

The requirement to approximate a free-field condition in a calibration environment generally limits the lowest frequency to which hydrophone calibrations can be performed, due to the requirement for a reflection free time window. This will be equally true for calibration of vector sensors in a free-field environment. Free-field reciprocity hydrophone calibrations are performed at VINIFTRI (National Research Institute for Physical-Technical Measurements), Russia, for example, down to 500 Hz in a 6 m tank; at NPL in the UK down to 1 kHz in a 5 m tank (smallest dimension); and at USRD (NAVSEA Underwater Sound Reference Division) down to 1 kHz in a ~4.6 m tank (smallest dimension). It is also possible to carry out calibrations at larger open water facilities such as a reservoir, marine facility, or a lake, enabling a free-field calibration at lower frequencies, although this would not provision testing under controlled temperature conditions. The NPL open water facility supports measurements down to tens of Hz, and the USRD open water facility enables measurements down to 5 Hz.

The calibration of underwater acoustic vector sensors could be performed in these facilities, to establish free-field sensitivity, either through the comparison method with a reference hydrophone (Isaev et al., 2013), or directly using reciprocity (Isaev et al., 2014). The work by Isaev et al. (2014) has demonstrated the reciprocity calibration of a vector sensor for its sensitivity to sound pressure and the sound pressure gradient. Sensitivity to sound particle acceleration/velocity is determined indirectly.

The use of anechoic facilities designed for microphone calibration may also provide a viable solution. This would allow calibration down to the tens of hertz range. In this case, a primary calibrated microphone would be used as the reference against which the comparison calibration would be performed. For hydrophone calibration, this can be done at low frequencies where the diffraction effects of the receiving device can be neglected. Assuming that the acoustic impedance of the device being calibrated is high enough that its radiation impedance can be considered to be negligible, then the sensitivity in water would be equivalent to that determined in air (Levin, 1973). If a plane wave can be approximated, the sound particle velocity sensitivity can be determined through knowledge of the acoustic impedance of air. However, it should be noted that the coupling aspects would not be the same and this would preclude calibration of neutrally buoyant type vector sensor systems.

3.2 LOW-FREQUENCY CALIBRATION

Due to the extended test tank dimensions required to approximate a free field in a laboratory environment, it is often preferred to use alternative approaches for the calibration of pressure hydrophones at lower frequencies. There are a number of approaches which can be used, generally reliant on either the use of an enclosed volume (chamber) where the dimensions are very small compared to the wavelength (Isaev and Shchelkunov, 2008), or the use of a vibrating water column which effectively varies the height of the water around the hydrophone (Schloss and Strasberg, 1962). The first is not appropriate for acoustic vector sensor calibration, as such a quasi-static pressure variation has negligible spatial pressure gradient and therefore no sound particle motion component. The vibrating water column, however, can be used for the calibration of pressure hydrophones and underwater acoustic vector sensors due to the spatial and temporal pressure variation relative to a stationary point within the chamber. At higher frequencies, where the wavelength approaches the length of the chamber, the uniformity of motion in the chamber will be compromised and the pressure and motion in the chamber will be dictated by wave effects (Schloss and Strasberg, 1962). In conditions where a standing wave is present, due to termination reflections, an acoustic sensor can be exposed to both sound pressure and/or sound particle velocity, depending on the location of the sensor along the longitudinal axis of the standing wave.

The vibrating water column approach is well established for the calibration of pressure hydrophones at lower frequencies. VINIFTRI, for example, use the vibrating water column method to provide primary calibration of hydrophones between 5 Hz and 1 kHz. Similarly, USRD, have a number of standing wave facilities which provide hydrophone calibration from 1 Hz to 50 Hz. This approach is also being used by the Hangzhou Applied Acoustic Research Institute (HAARI) to calibrate vector sensors at low frequencies and a standing wave method for vector sensor calibration has also been described by Bastyr et al. (1999), and further used by Barnard and Hambric (2011). It would also be possible to use standing wave or plane wave waveguides in air to provide calibration by microphone comparison. However, the same limitations will apply as those described in Section 3.1 for free-field calibrations in air.

3.3 OPTICAL METHODS FOR CALIBRATION

Optical methods, based on either homodyne or heterodyne interferometry have been demonstrated for the measurements of either sound particle displacement or velocity, respectively, of underwater acoustic fields and have furthermore been applied to the free-field calibration of hydrophones (Preston et al., 1999; Yuebing and Yongjun, 2001; Theobald et al., 2005). Homodyne optical interferometric methods have been used predominantly for the calibration of high frequency hydrophones associated with medical ultrasound fields (Preston et al. 1999), whereas heterodyne methods have been demonstrated for the calibration of hydrophones at lower frequencies, down to a few kilohertz (Theobald et al., 2005).

When used for the calibration of hydrophones, a plane wave is approximated so that the sound pressure in the water, to which the hydrophone being calibrated is subsequently exposed, can be inferred from a *direct* measurement of sound particle motion. This *direct* measurement of particle motion is achieved through the positioning of a thin plastic membrane in the water. The membrane is acoustically compliant, coated with a thin layer of optically reflective material. The design of the membrane is such that it follows the acoustic motion of the water without introducing any residual vibrations or modes into the membrane, supported such that it does not contribute any acoustic reflections which compromise the free-field condition. This was demonstrated by Theobald et al. (2005) down to 10 kHz using a 2 mm wide pellicle consisting of 23 µm thick Mylar coated with 40 nm of aluminium suspended in the water using an aluminium frame measuring approximately 1.3 m by 1.3 m. The size of the frame (and the water tank in which the measurements were performed) was the primary limitation dictating the low-frequency limit. Other factors, such as modes in the membrane and the acoustic compliance of the membrane, are uncertainties that require consideration at higher frequencies. Whilst the work by Theobald et al. (2005) was primarily concerned with the calibration of a hydrophone for its sound pressure sensitivity, the method involved the direct measurement of sound particle velocity along the plane of the acoustic projector to achieve this.

The use of optical heterodyne interferometry to directly measure the sound particle velocity in water offers a potential solution to the calibration of underwater acoustic vector sensors, which is independent of the indirect determination of sound particle velocity from a measurement of pressure. Development of this method would be required to achieve a solution for calibration at the lower frequencies which would be required for vector sensors, and would ultimately be subject to the same limitations as described in the Section 3.1 for the free-field calibration. Whilst it has not been demonstrated, it would be possible to apply this method to a standing wave, to directly measure the sound particle motion antinode. Optical measurement of sound particle motion has been demonstrated for a standing wave in air using an interferometric method using photon correlation with an optical setup similar to that used in laser Doppler anemometry – i.e. measurement of light scattered from particles passing through an interference fringes resulting from two intersecting coherent laser beams (Koukoulas et al., 2008). This method allows direct interrogation of the velocity of light scattering particles in the air or water, which are assumed to follow the oscillations of the acoustic field. Whilst this method could be used in a free-field environment, it is more suited to measurement in standing wave tube, vibrating water column, or travelling wave tube etc., due to the potential for incoherence between the intersecting laser beams resulting from passage through the acoustic field.

3.4 VIBRATION, SHAKER METHOD

For vector sensors which are based on the use of accelerometers or geophones, it is possible to calibrate these following existing standards for calibration of vibration sensors or accelerometers. These methods generally rely on the use of a sinusoidal exciter or shaker and provide a calibration either through reciprocity or comparison to a reference device. For example, ISO 16063-11:1999 describes this method for reference against an interferometer providing traceability to units of length and time. The advantage of this approach is the ability to provide calibrations at very low frequencies, below 1 Hz. However, it should be noted that this method would not be applicable to all underwater acoustic vector sensors, and it would not include the loading and coupling aspects of water. It would essentially only calibrate the individual accelerometer components as mounted in the device. The benefit of this method is that it is generally easy to perform and would highlight any unloaded (by the water) structural resonances in the device.

4 VIBRATION SENSOR CALIBRATION

Measurement of seabed vibration is a particular case of particle motion which is also of interest when considering seabed dwelling aquatic fauna such as demersal fish and crustaceans, due to their sensitivity to sound particle motion (Hawkins, 2009; Popper and Hastings, 2009; Popper et al., 2014). The effect of seabed vibration has been of particular concern for sound sources which are coupled to the seabed, such as pile-driving (Hazelwood, 2012).

The technology for measuring seabed vibration is based on accelerometer or geophone technology, with the instruments coupled to the seabed, and measuring the motion of the seabed in the vertical and horizontal planes.

The methods described in Section 3.4 (see ISO 16063-11:1999), for calibration of accelerometers would be particularly applicable for calibration of seabed vibration sensors. Similarly, the calibration would only be applicable to the individual accelerometer components as mounted in the device i.e. it would not include the effects of loading and coupling. The structure on which the sensor elements are mounted to couple to the seabed will have natural resonances and contribute to the overall system response. Ideally, these resonances should be designed to be either above or below the frequency range of interest, but characterisation of the whole system will be an important aspect of the calibration. As the loading and coupling effects will not be inherent to the calibration, determination the absolute seabed vibration from the measured output signal and the calibration sensitivity could therefore be subject to substantial uncertainty, depending on the device and coupling conditions. A feasible solution for calibration *in situ* is not obvious.

5 DISCUSSION

There is a clear requirement for the calibration of underwater acoustic vector sensors, and furthermore, a requirement for international standardisation. The challenges associated with calibration of underwater acoustic vector sensors are complicated by two main points:

i) there are substantial differences in the physical operation of these devices; and
ii) such devices are generally designed to operate at frequencies which extend below the lower frequency limit typically achievable for free-field hydrophone calibration.

The first point is less critical but may limit which calibration method can be adopted for a given device and perhaps more fundamentally, what quantity a given device should derive its traceability from. It will also limit the possibility to calibrate underwater acoustic vector sensors in air, either through calibration in anechoic facilities, low frequency plane wave tubes, or on shakers/exciters.

The second point is much broader and the availability of facilities will ultimately limit the calibration method used. Free-field calibration requires large bodies of water or post-processing, to allow removal of boundary reflections. Whilst this is also a fundamental limitation for free-field calibration of pressure hydrophone calibration, it generally only affects a small proportion of hydrophones on the market. This will not be true for underwater acoustic vector sensors, which are typically designed for frequencies below around 10 kHz, and in many cases, below a few kilohertz. Furthermore, interferometric methods which can provide direct traceability to units of length and time, are not proven at these lower frequencies. However, the frequency range over which pressure hydrophone free-field calibration is applicable will also be generally suitable for underwater acoustic vector sensor calibration, providing traceability through a reference hydrophone. Free-field calibration will therefore be possible in open tank facilities down to around 1 kHz to 0.5 kHz, requiring large open water facilities below these frequencies. None free-field calibrations, based on comparison against a reference hydrophone, are the most suitable alternative at these lower frequencies, and perhaps the only feasible way to achieve calibrations at frequencies below tens of hertz. Whilst optical interferometric methods could provide calibration solutions for none free-field methods, this has not been demonstrated in underwater acoustic measurements and is not a currently available option. The use of a reference hydrophone for comparison methods will ultimately limit the achievable calibration uncertainty due to the uncertainty of the reference hydrophone calibration, the comparison method, and the calculation of the sound particle velocity from the sound pressure.

Whilst methods for the calibration of underwater acoustic vector sensors already exist, and are in some laboratories carried out routinely, no standardisation exists. In this context, standardisation refers to two things: firstly a standard method which is used to provide traceability back to a common benchmark; and secondly a specification standard describing the method for undertaking the calibration (Robinson et al., 2014). Thus, any measurement made with an underwater acoustic vector sensor should be traceable to national or international standards, through an unbroken series of comparisons (JCGM 2012). To further ensure consistency between the calibrations carried out in different countries, there is also a need for comparisons such as that which is required for hydrophone calibration (Robinson et al., 2006), under the Consultative Committee on Acoustics, Ultrasound, and Vibration of the Comité International des Poids et Mesures.

6 CONCLUSIONS

Calibration of underwater acoustic vectors is carried out using a number of different methods dictated by either the type of sensor, or the available facilities. For a free-field calibration of underwater acoustic sensor sound particle velocity response, the dimensions of the test tank are a fundamental limitation. For lower frequency, the use of non-free-field methods, using a vibrating water column chamber for example, is the most common approach. Whichever method is used, the calibration is generally carried out by comparison with a pressure hydrophone, although reciprocity calibration has been applied to a pressure gradient device. There exists a requirement for primary calibration, ideally by direct comparison with a measurement of sound particle motion, traceable to units of length and time. Optical methods show potential for this, and have already been demonstrated for pressure hydrophone calibration by measurement of sound particle motion. However, further work is required as optical methods have not been demonstrated at the lower frequencies which are required for underwater acoustic vector sensor calibration. There is also a requirement for standardisation both in availability of primary methods providing traceability to National Metrology Institutes demonstrating equivalence to those of other countries by successful participation in key comparison exercises under the auspices of Bureau des Poids et Mesures (BIPM), and also for international standardisation of the procedure through standards bodies such as the International Electrotechnical Commission (IEC) or the International Organization for Standardization (ISO).

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