Absolute calibration of hydrophones immersed in sandy sediment

Gary B. N. Robb
National Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, United Kingdom

Stephen P. Robinson, Pete D. Theobald, and Gary Hayman
National Physical Laboratory, Teddington, Middlesex TW11 0LW, United Kingdom

Victor F. Humphrey, Timothy G. Leighton, and Lian Sheng Wang
Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, United Kingdom

Justin K. Dix and Angus I. Best
National Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, United Kingdom

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An absolute calibration method has been developed based on the method of three-transducer spherical-wave reciprocity for the calibration of hydrophones when immersed in sandy sediment. The method enables the determination of the magnitude of the free-field voltage receive sensitivity of the hydrophone. Adoption of a co-linear configuration allows the acoustic attenuation within the sediment to be eliminated from the sensitivity calculation. Example calibrations have been performed on two hydrophones inserted into sandy sediment over the frequency range from 10 to 200 kHz. In general, a reduction in sensitivity was observed, with average reductions over the frequency range tested of 3.2 and 3.6 dB with respect to the equivalent water-based calibrations for the two hydrophones tested. Repeated measurements were undertaken to assess the robustness of the method to both the influence of the sediment disturbance associated with the hydrophone insertion and the presence of the central hydrophone. A simple finite element model, developed for one of the hydrophone designs, shows good qualitative agreement with the observed differences from water-based calibrations. The method described in this paper will be of interest to all those undertaking acoustic measurements with hydrophones immersed in sediment where the absolute sensitivity is important. [DOI: 10.1121/1.3106530]

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I. INTRODUCTION

Marine engineers require a detailed knowledge of the physical properties of seafloor sediments to site foundations for oil and gas drilling rigs and pipelines, offshore wind farms, and telecommunication cables. At present these properties are predominantly obtained using techniques for analyzing acoustic reflection/refraction data that require ground-truthing cores and samples.[1–3] A thorough understanding of the relationships between the acoustical and physical properties of seafloor sediments would negate the need for ground-truthing. Unfortunately, the nature of these relationships is still under debate, with a variety of equally valid geoacoustic theories in circulation for both saturated sediment[4–6] and sediment containing free-gas bubbles.[7–9]

In situ experiments allow the acoustical properties of well-defined sediment volumes to be measured, the physical properties of which can be determined through the laboratory analysis of sediment samples.[10–15] The examination of acoustical and physical data obtained using *in situ* techniques therefore offers a valuable way of refining our knowledge of the acoustical-physical relationships required for more effective inversion of acoustic data. While a variety of more complex *in-situ* experimental techniques exist, which require the insertion of three or more acoustic probes into the sediment, the use of a single source-receiver pair is still frequently adopted owing to its relatively simple deployment and a reduced sediment disturbance.[11,12,14,16] The processing techniques necessary for the analysis of the resulting transmit-receive data require knowledge of the transmitting current response of the source and sensitivity of the receiver, both of which are commonly determined through water-based calibrations. It has, however, been noted that these transducer-based properties may vary with the acoustic impedance of the medium into which the transducer is inserted.[8,11,17] This is particularly true for frequencies where the radiation impedance is a significant contribution to the overall device impedance such that the impedance of the medium can affect the hydrophone performance (typically, this would be at frequencies close to the resonance frequency). The characteristic acoustic impedance of sediment (for example, 1.7×10^6 kg m^{-2} s^{-1} for a mud to 3.8×10^6 kg m^{-2} s^{-1} for a sand) may considerably exceed that of water (i.e., $(1.4-1.5) \times 10^6$ kg m^{-2} s^{-1} for water with temperatures from 0 to 20 °C and salinities from 0‰ to 35‰). Therefore, calibration data derived from water-based measurements may not be valid when the hydrophone is used in sediment. This motivates the work described here to develop a method which may be applied to sediment-based calibrations. The method will be beneficial to sediment acousticians relying on the absolute sensitivity of sediment-immersed hydrophones.

This paper describes and illustrates the calibration method with results from two types of hydrophone which were calibrated while immersed in sandy sediment. Section II presents the calibration technique which is based on a modified version of the three-transducer spherical-wave reciprocity method originally described by Luker and Van Buren for use in hydrophone phase calibration in water.[18] The method allows sediment-based absolute calibrations of receive sensitivity and transmit current response to be determined without knowledge of the acoustic properties of the sediment. Section III presents the results of reciprocity calibrations performed in saturated fine sands under laboratory conditions. Section IV shows a comparison of the results with a simple finite element (FE) model of one of the hydrophones, while conclusions are drawn in Sec. V.

II. SEDIMENT-BASED RECIPROCITY CALIBRATION TECHNIQUE

At present, the primary method in which hydrophones are calibrated is that of three-transducer spherical-wave reciprocity.[19] The method provides free-field values for both the receive voltage sensitivity and transmitting current response of the hydrophones under test. Throughout the work described here, the definitions used are those that are common in the calibration of electroacoustic transducers and are defined by the International Electrotechnical Commission.[19] Specifically, the free-field receive voltage sensitivity in a given direction and for a given frequency is the ratio of the open-circuit voltage developed by the hydrophone to the sound pressure that would exist in the undisturbed free-field at the position of the hydrophone if the hydrophone were absent. The SI units are V Pa^{-1}, but the sensitivity is commonly expressed in decibels as dB re 1 V μPa^{-1}. The transmitting current response in a given direction and for a given frequency is the ratio of the sound pressure at a reference distance from the transducer to the electrical current flowing through the terminals. The reference distance is defined as 1 m. The SI units are Pa m A^{-1}, but the sensitivity is commonly expressed in decibels as dB re 1 μPa A^{-1} at 1 m. Note that this is a far-field quantity, and a spherical-wave field is implied with the sound pressure being inversely proportional to the distance from the source. In the work described here, only the magnitude of the hydrophone response is considered.

The method of three-transducer spherical-wave reciprocity involves the transmission of signals between three pairs of transducers, commonly designated P, T, and H. The typical measurement configurations used require successive acoustic transmission from P to T, P to H, and T to H (see Fig. 1). The sensitivity of hydrophone H, which is denoted by M_{HW}, can then be derived from the measured transfer impedance (i.e., the quotient of the received voltage divided by the driving current) for each the transmitter pair using

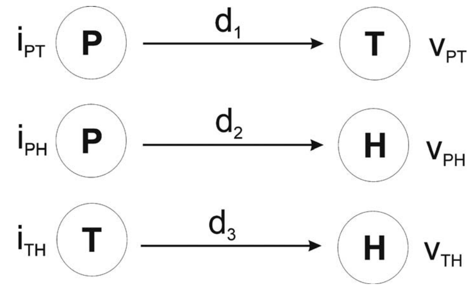


FIG. 1. Measurement configurations required for a standard water-based three-transducer reciprocity calibration. To obtain the sensitivity of hydrophone H, two additional transducers are required, namely, P and T, and measurements are required between the three transducer pairs of P to T, P to H, and T to H, which are separated by the distances d_1, d_2, and d_3, respectively. The respective driving currents for these three pairs are denoted by i_{PT}, i_{PH}, and i_{TH}, while the received voltages are denoted by v_{PT}, v_{PH}, and v_{TH}.

$$M_{HW} = \sqrt{\left(\frac{2d_2d_3}{\rho f d_1}\right)\left(\frac{Z_{PH}Z_{TH}}{Z_{PT}}\right)}, \quad (1)$$

where d_1, d_2, and d_3 are, respectively, the distances between P and T, P and H, and T and H, f is the acoustic frequency, ρ is the bulk density of the surrounding medium, and Z_{PH}, Z_{TH}, and Z_{PT} are the respective measured transfer impedances for transmission from P to H, T to H, and P to T. The transmitting current response of hydrophone H, which is denoted by S_{HW}, can also be determined through the spherical-wave reciprocity parameter J using

$$J = \frac{M_{HW}}{S_{HW}} = \frac{2}{\rho f}. \quad (2)$$

This standard reciprocity method makes a number of assumptions. First, the conditions are assumed to be free-field. This limits the time-window that can be included in the analysis since measurements must be made before the arrival of boundary reflections. Second, all receivers are assumed to lie in the far-field of the corresponding projector where, for a simple source, pressure is inversely proportional to the distance from the source. Third, it is necessary that transducer T be reciprocal, i.e., it is electrically passive, linear, and reversible. Fourth, it is assumed that the signals analyzed are steady-state, and therefore any initial transducer transients must be allowed to settle before any measurement window is applied. A final assumption present in Eq. (1) is that the attenuation of sound in water, which arises from absorption losses only, is negligible. This assumption is generally valid for kilohertz frequencies (for example, absorption at 200 kHz is 8.6×10^{-3} Np m^{-1} or less[20]) while the homogeneous nature of water allows correction factors to be determined for higher frequencies.[19]

In contrast to water, the attenuation of acoustic waves in the range 16–100 kHz in saturated sediment, which consists of absorption and scattering losses, can reach values of 2.9 Np m^{-1} in muds and 9.5 Np m^{-1} in sand (predictions from the grain-shearing theory[5] for typical sediment properties[21,22]). If this attenuation could be accurately predicted, suitable correction factors could be obtained. However, this is not practical owing to the highly variable nature

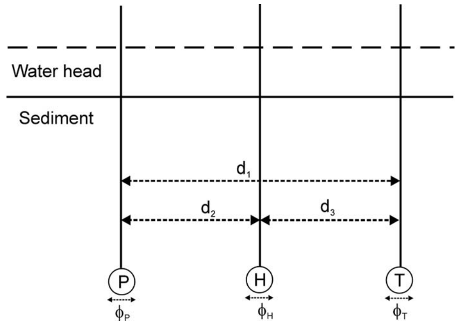


FIG. 2. Co-linear arrangement for three-transducer reciprocity required for sediment-based measurements which utilizes a projector P and reciprocal transducer T to calibrate hydrophone H.

of these attenuations. For example, a compilation of attenuation data from marine sediment displays a scatter of $\pm 31\%$ for a unique mean grain size,[6] while attenuation coefficients measured in sandy sediment varies by up to 2.8 Np m^{-1} for sediments with similar physical properties lying within a 100 m distance of one another.[22] This variability makes it extremely difficult to predict, and to account for, the attenuation losses in sediment. It is therefore preferable to devise a calibration method which does not critically depend on the need to correct for attenuation losses. This may be achieved through the co-linear arrangement displayed in Fig. 2, based on the configuration originally used by Luker and Van Buren for hydrophone phase calibration in water.[18] The method is described below.

Consider the general case of a pair of transducers that are embedded in sediment, comprising a projector P and hydrophone H whose reference centers are separated by a distance d. If a driving current i_p is applied to the projector, and it is assumed that spherical spreading losses apply and the sediment is homogeneous, the voltage v_H received by the hydrophone can be expressed as

$$v_H = \frac{M_H S_P i_P}{d} e^{-\alpha d}, \quad (3)$$

where S_P is the transmitting current response of the projector, M_H is the sensitivity of the hydrophone, and α is the attenuation coefficient of the sediment (in Np/m). The specific transfer impedances for transducer pairs P to $T(Z_{PT})$, P to $H(Z_{PH})$, and T to $H(Z_{TH})$ are therefore given by

$$Z_{PT} = \frac{M_{TS} S_P}{d_1} e^{-\alpha[d_1 - (\phi_P + \phi_T)/2]},$$

$$Z_{PH} = \frac{M_{HS} S_P}{d_2} e^{-\alpha[d_2 - (\phi_P + \phi_H)/2]},$$

$$Z_{TH} = \frac{M_{HS} S_T}{d_3} e^{-\alpha[d_3 - (\phi_T + \phi_H)/2]}, \quad (4)$$

where M_{HS} and M_{TS} are the sediment-based sensitivities of hydrophone H and transducer T, respectively, and S_T and S_P are the transmitting current responses of the transducers T and P, respectively. The separations between the reference centers of P and T, P and H, and T and H are denoted by d_1, d_2, and d_3, respectively, while the diameter of transducers P, T, and H are denoted by ϕ_P, ϕ_T, and ϕ_H, respectively. Equation (4) assumes that the acoustic reference center of each transducer lies at the geometric center of the device. Using the reciprocity parameter J, as described in Eq. (2), it is possible to combine the expressions for the transfer impedances Z_{PH}, Z_{PT}, and Z_{TH} to derive an expression for the sensitivity M_{HS} of the hydrophone H:

$$M_{HS} = \sqrt{\left(\frac{2d_2 d_3}{\rho f d_1}\right) \exp[\alpha(d_2 + d_3 - d_1 - \phi_H)] \left(\frac{Z_{PH} Z_{TH}}{Z_{PT}}\right)}. \quad (5)$$

As a consequence of the co-linear arrangement adopted, the separation distances are related by the expression $d_1 = d_2 + d_3$ and Eq. (5) reduces to

$$M_{HS} = \sqrt{\left(\frac{2d_2 d_3}{\rho f d_1}\right) \exp(-\alpha \phi_H) \left(\frac{Z_{PH} Z_{TH}}{Z_{PT}}\right)}. \quad (6)$$

For an infinitesimally thin hydrophone, the exponential term in Eq. (6) will reduce to unity and the sensitivity of the central hydrophone can be determined from the approximate form

$$M_{HS} = \sqrt{\left(\frac{2d_2 d_3}{\rho f d_1}\right) \left(\frac{Z_{PH} Z_{TH}}{Z_{PT}}\right)}, \quad (7)$$

which corresponds to the water-based scenario displayed in Eq. (1). For the sands examined in the present work, the maximum attenuation coefficient for the frequency range examined (10–200 kHz) was estimated using the grain-shearing model[5] to be 8.16 Np m^{-1}. Combined with the diameters of the hydrophones used, which are 20–21 mm, respectively (see Sec. III A), the sensitivities determined from the exact equation [Eq. (6)] will vary from those determined from the approximate equation [Eq. (7)] by a maximum of 8.9%, i.e., sensitivity levels will deviate by less than 0.74 dB. As this deviation lies within the variability associated with sediment disturbance (see Sec. III B), the approximate equation is assumed valid for sediment-based reciprocity calibrations and is used throughout the remainder of this paper. Although the attenuation coefficients, frequency ranges and transducer diameters used in this work are typical of *in-situ* experiments, future users are advised to assess the validity of Eq. (7) for their own situations.

There are, however, certain alignment problems that arise from the co-linear arrangement shown in Fig. 2. First, hydrophones cannot be assumed to be omni-directional and so must be calibrated in a reference direction. The receiving device must therefore be aligned such that its reference direction is pointing toward the transmitting device. For the co-linear arrangement, this means that the central device H must be rotated between measurements of Z_{PT} and Z_{TH} so that H is facing the transmitting hydrophone in each case. Second, when measuring Z_{PT} or Z_{TP}, the central device should ideally be removed to avoid any "shadowing" effect on the acoustic field. While both the rotation and removal of H will have no effect for water-based measurements, for sediment-based measurements these adjustments may introduce some degree of disturbance into sediment and therefore alter the propagation loss between consecutive measurements used in the same calibration. The impact of these disturbance and shadowing effects is examined in Sec. III.

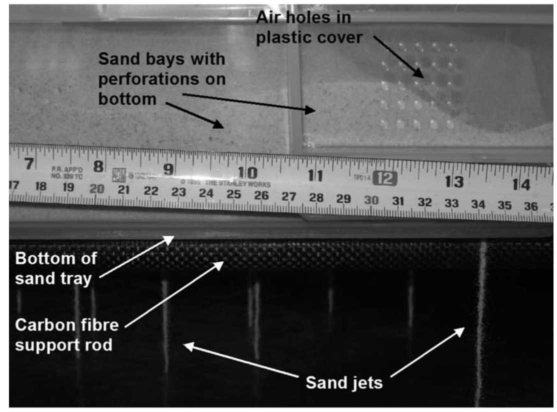
III. SEDIMENT-BASED RECIPROCITY MEASUREMENTS

A. Experiment

A series of reciprocity calibrations was performed on transducers inserted into saturated sands contained in two laboratory tanks. Initial measurements were made in a small test tank located at the National Physical Laboratory to validate the sediment-based reciprocity technique detailed in Sec. II. A second laboratory tank located at the University of Southampton was used for calibrations over a larger frequency range, the use of two test tanks providing a test of the robustness of the method. These tanks have been designated as Tank 1 and Tank 2, respectively.

The manner in which the sand was placed in both tanks was designed to minimize the possibility of trapping or forming air bubbles within the sediment. The inclusion of such bubbles would introduce strongly frequency-dependent compressional wave velocities and attenuations,[7] which would disrupt the waveforms received and, therefore, make it extremely difficult to identify the time-windows over which the signals are steady-state. To minimize the possibility of introducing air bubbles, the sand was sprinkled into degassed water (degassed using a vacuum pump prior to filling the tank) using a large container with 5 mm diameter holes drilled in the bottom, see Fig. 3(a), and the sediment was left to settle for a week prior to the measurement phase. The method used for inserting the transducers was also chosen to prevent the entrapment of air bubbles. This involved inserting an open-ended tube into the sediment and excavating the sand within it using a smaller tube. The transducer was then placed in the excavated hole through the outer tube, and the tube was then removed to allow the sediment to envelop the transducer. After each insertion, the sediment was given a few hours to settle.

The physical properties of the sand were measured through the collection and analysis of sediment cores. Bulk density, porosity, and compressional wave velocity were measured at 1 cm depth increments using a multi-sensor core logger,[23] while grain size distributions were measured at 5 cm intervals using a laser particle analyser. The sand was classified as a medium sand with a mean grain size of 304 ± 49 μm, a porosity of $33\% \pm 1.0\%$, a bulk density of 2177 ± 18 kg m^{-3}, and a compressional wave velocity of 1746 ± 8 m s^{-1} (all values quoted are mean values with standard deviations as the corresponding uncertainties). Here, the mean grain size is expressed as $-\log_2(d/d_0)$, where $d_0 = 1$ mm and d is the grain diameter for each class determined by sieving (i.e., the maximum grain diameter that can pass through a sieve mesh, assuming spherical grains). The mean grain size was determined from the cumulative frequency curve of percentage mass of the sample passing through each sieve against grain size fraction (sieve size) by reading off the grain sizes corresponding to the 16, 50, and 84 quartiles (i.e., 16% of the sample mass has a grain size less than D16,



(a)

(b)

FIG. 3. (a) Manner in which sediment tank was filled (through sprinkling of sand from container at top of image into degassed water. (b) Reciprocity experiment being performed on Tank 1, with the poles attached to three transducers clearly visible.

50% less than D50, and 84% less than D84) and calculating (D16+D50+D84)/3. The Friedman & Sanders scale was then used to categorize the sediment according to mean grain size.[24] For the work here, the mean grain size was measured on a number of samples from an assumed homogeneous sediment, thus getting a standard deviation ± linear error.

The absence of gas bubbles was confirmed through a number of observations. First, the high fraction of the 500 kHz pulses that were transmitted though the core during the core analysis indicated a bubble-free medium. Second, all signals acquired during the reciprocity measurements displayed clean waveforms, without any additional frequency components that would be indicative of scattering from bubbles. Third, upon gentle stirring of the sediment no bubbles were observed to emerge from the sediment.

Tank 1 contained a sediment volume measuring 0.67 m by 0.49 m with a depth of 0.45 m and a 50 mm head of water, see Fig. 3(b). All transducers were inserted to a depth of 0.22 m in the sediment, with the central hydrophone H placed at the centre of the tank and, to maximize the echo-free time, the outer devices P and T placed 0.13 m on either side of H. To determine the transfer impedances required to calculate the sensitivity of hydrophone H, the steady-state driving current and received voltage were measured for each transducer pair (namely, P to T, P to H, and T to H). These measurements were acquired for tone-burst signals with frequencies that covered the range from

20 to 150 kHz in 2 kHz steps. The steady-state voltage of the received signal was measured using standard techniques,[19] which involve the application of a time-window to select the portion of the received signal that satisfies both steady-state conditions (i.e., contains no ringing affects associated with the start of the received signal) and free-field conditions (i.e., contains no reflected signals). Least squares fitting techniques were then applied to this windowed signal to measure the amplitude of the received voltage, with reliable results obtained when the duration of the time-window contained at least half a period of the received signal.[25] A type 8104 transducer (manufactured by Brüel and Kjær, Denmark) with a diameter of 21 mm was selected as the central hydrophone (H) because the minimal ringing effects associated with this relatively heavily damped device allowed a relatively long time-window (32.9 μs) to be used and therefore frequencies as low as 20 kHz to be examined. In order to allow signals with sufficient amplitude to be transmitted over the required frequency range an ITC 1042 transducer with a diameter of 35 mm (manufactured by International Transducer Corporation) was selected as the projector (P) and a Brüel and Kjær 8100 with a diameter of 21 mm was used as the reciprocal transducer (T).

While the transfer impedances Z_{PH} and Z_{TH} required to derive the sensitivity of H from Eq. (7) can only be measured with H present, Z_{PT} was measured under three sets of conditions. First, the use of Z_{PT} measured before H was inserted allowed a "reference" sensitivity to be calculated that was subject to no shadowing effect and only relatively minor disturbances associated with the insertion of P and T. Second, a "shadowed" sensitivity was calculated through the use of Z_{PT} measured with H present, which introduces both a shadowing effect and an additional disturbance associated with the insertion of H. Third, on the removal of H, a final measure of Z_{PT} was obtained; while this measurement will have no shadowing effects associated with it, it will be affected by the sediment disturbance associated with the insertion and removal of H and is therefore referred to as the "disturbed" sensitivity. In addition, the transfer impedance between the outer transducers was measured in both directions, i.e., from P and $T(Z_{PT})$ and from T and $P(Z_{TP})$. This allowed the sensitivity to be calculated with either Z_{PT} or Z_{TP} in the denominator of Eq. (7), and the validity of the reciprocal assumption to be tested (if both P and T are reciprocal then both sensitivities should be the same).[19]

Calibrations were also performed in Tank 2, with the aim of repeating the earlier work and obtaining sensitivities at a wider range of frequencies. Here, the hydrophone under test consisted of a spherical element with a diameter of 12.5 mm embedded in a cylindrical polyurethane boot with an outer diameter of 20 mm. This hydrophone was manufactured by Neptune Sonar Ltd. UK, and consisted of a modified version of their D140 design (the design used here has the same spherical element, but is encapsulated in a cylindrical boot). This hydrophone was designed for *in-situ* fieldwork over the frequency range 10–200 kHz. Tank 2 was cylindrical, with a diameter of 0.97 m, a sediment depth of 0.87 m, and water head of 0.10 m. The slightly larger dimensions of Tank 2 allowed the length of the time-window over which the received signal satisfied steady-state and free-field conditions to be extended to 50 μs, enabling measurements to be made at somewhat lower frequencies than for Tank 1. The central hydrophone was placed at a depth of 0.45 m in the center of the tank and, to maximize echo free time, with P and T placed in a co-linear arrangement 0.17 m on either side of H. Other details of the experiment, such as the transducers used for P and T and the pulse lengths, remained as described above for Tank 1. However, since degassed water was not available, a submersible pump was used to assist with degassing of water and sediment. This pump, capable of driving a 30 m head of water, had a constricting valve fitted to the inlet which was used to throttle the flow. The resulting pressure drop allowed the water/sediment mixture to degas by drawing dissolved gases out of the water. The outlet was vented to atmospheric pressure at the water surface with a glass beaker used to collect the exiting gas (allowing the gas production to be monitored). This degassing pump was used to degas the water prior to filling the tank with sand, with steadily decreasing amounts of gas harvested from the tank and captured in the glass beaker as the water reached a degassed state. Once degassed, the water tank was filled with sediment to envelop the degassing pump which was protected by a flooded cylindrical column. As the column lay below the water surface, degassing continued during sand filling of the tank and prior to measurements. A small increase in the amounts of gas harvested from the tank during sand filling provided some evidence that the filling process did indeed introduce air/gas into the water. The degassing pump was used for several hours in the saturated sediment prior to measurements until the volume collection rate of gas reached an equilibrium. While there remains the possibility that small fractions of gas were present in both sediment tanks, the evidence presented earlier indicates that these gas fractions were not sufficient to impact on the measurement technique presented here.

For comparison purposes, water-based reciprocity measurements were also performed in a water tank measuring 2.0 m long by 1.5 m wide and 1.5 m deep for both the Brüel and Kjær 8104 and the spherical test hydrophone. In order to ensure that the water and sediment calibrations are directly comparable the transducer configurations, mounting, drive voltage, and pulse lengths remained unchanged. The P to T and T to P stages were again measured both with and without H present, i.e., under reference and shadowed conditions. For the water-based reciprocity calibrations, the overall measurement uncertainties (expressed for a confidence level of 95%) were estimated to be typically 0.5 dB.[26]

It is normal for three-transducer spherical-wave reciprocity calibrations to be undertaken with hydrophone separation distances that are sufficiently large to ensure that far-field conditions are achieved and that the acoustic field is sufficiently close to a spherically- diverging wave.[19] For the sediment-based calibrations reported here, relatively short transducer separations were used because of the use of relatively small test tanks (separations of 0.13 and 0.17 m, respectively). For the higher frequencies used here, the strictest acoustic far-field criterion is violated, for example, that specified in the international standard IEC 60565.[19] This

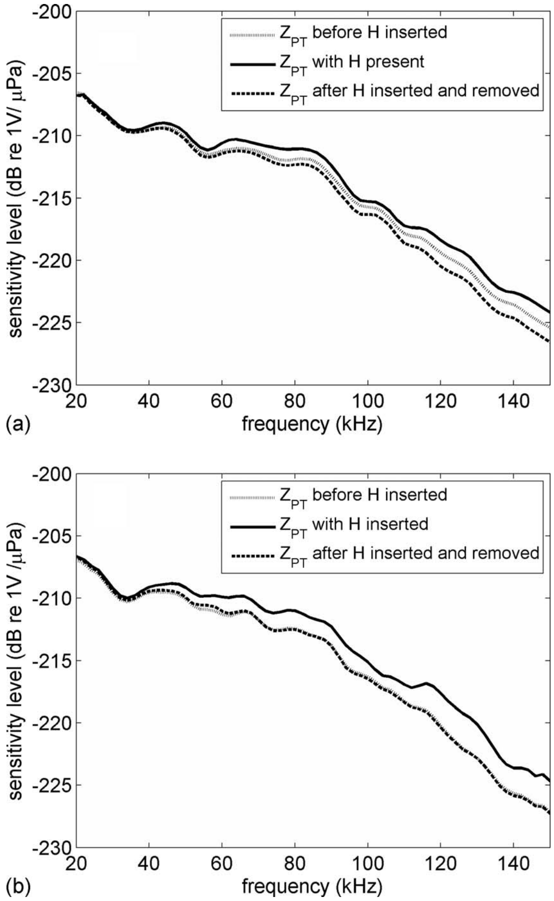


FIG. 4. An examination of the impact of shadowing and disturbance effects for the Brüel and Kjær 8104. Two sets of repeat measurements are displayed in (a) and (b), respectively. These measurements include reference sensitivity levels calculated using Z_{PT} measured before H was inserted (dotted line), shadowed sensitivity levels calculated using Z_{PT} measured with H present (solid line), and disturbed sensitivity levels calculated using Z_{PT} measured after H was inserted and then removed (dashed line). All measurement used the same P to H and T to H measurements. Note that the repeatability of the measurements with repeated insertion of the hydrophones was estimated to be between ± 0.1 and ± 0.4 dB (expressed as a standard deviation).

means that the acoustic field will not approximate to a spherical-wave to within a maximum tolerance of $\pm 2\%$ over the full frequency range, as required by the standard. With the relatively small transducer elements used here, this was not considered to be a significant source of error. However, to ensure that any observed differences in the calibration results were not due to this factor, the water-based calibrations were undertaken at the same separation distances as were used in the sediment-based calibrations. In addition, extra calibrations were undertaken in water at large separation distances (minimum of 1.1 m), so that comparisons were also possible with full far-field water-based results.

B. Results

Sensitivity levels measured on the Brüel and Kjær 8104 in Tank 1, which are used to validate the technique described in Sec. II, are displayed in Figs. 4 and 5. The sensitivities are expressed in decibels relative to a reference value of 1 V/μPa. It should be noted that the agreement between the sensitivity levels calculated using Z_{PT} and Z_{TP} was excellent,

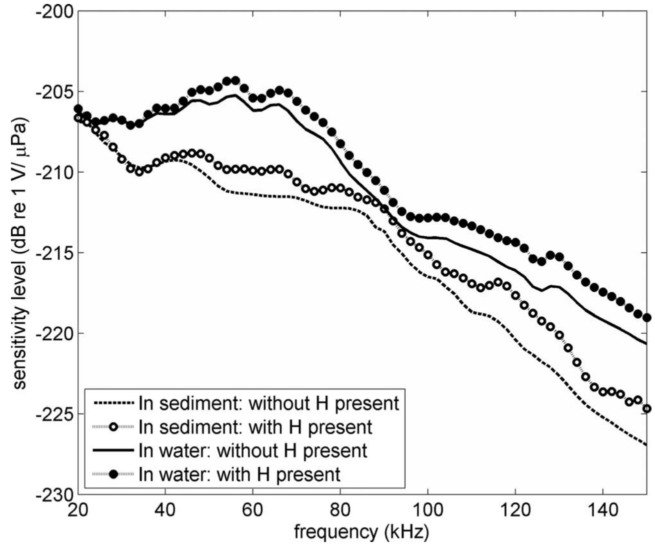


FIG. 5. Sensitivity levels measured on the Brüel and Kjær 8104 hydrophone in sediment and water. Sediment-based sensitivity levels measured in Tank 1 are displayed using P and T measurements both with H present (open circles) and without H present (dashed line). Water-based measurements performed in a larger water filled tank (measuring $2\times1.5\times1.5$ m^3) are also displayed for P and T measurements both with H present (closed circles) and without H present (solid line). Note that the overall uncertainty for the calibrations were estimated to be ± 0.5 dB for the water-based calibrations, and between ± 0.9 and ± 1.5 dB for the non-shadowed sediment-based calibrations (expressed for confidence levels of 95%).

with discrepancies of less than 1% seen over much of the frequency range for both water-based and sediment-based measurements. This strongly suggests that both P and T were behaving reciprocally. The impact of shadowing and disturbance effects on the sensitivity levels are displayed in Fig. 4 through the use of the reference, shadowed, and disturbed sensitivity levels discussed in Sec. III A. These three sensitivity levels were derived for two sets of measurements obtained from two deployments of H, with a period of 48 h allowed between the first and second sets to allow the sediment to re-settle. The combined shadowing and disturbance effects associated with the insertion and presence of H causes sensitivity levels to increase from the reference sensitivity level by a maximum of 1.3 dB for the first set of measurements and 2.8 dB for the second set, with the effect more pronounced at higher frequencies. This increase can be primarily explained by the presence of H reducing the amplitude of the signal that is transmitted from P to T and, therefore, reducing the value of Z_{PT} in Eq. (7). The disturbed sensitivity levels lie a maximum of 1.2 dB below the reference sensitivity level for the first set of measurements and deviate from the corresponding reference values by less than 0.3 dB for the second set, which again is more pronounced at higher frequencies. This reduction can be explained by considering that the removal of H reduced the compaction of sediment in the region around the hydrophone position. The resulting increase in porosity causes the attenuation of the sediment to be reduced and the amplitude of the signal transmitted from P to T to be increased. The subsequent increase in the value of Z_{PT} in Eq. (7) leads to lower sensitivity levels.

The water-based and sediment-based sensitivities of the Brüel and Kjær 8104 are compared in Fig. 5. While reference

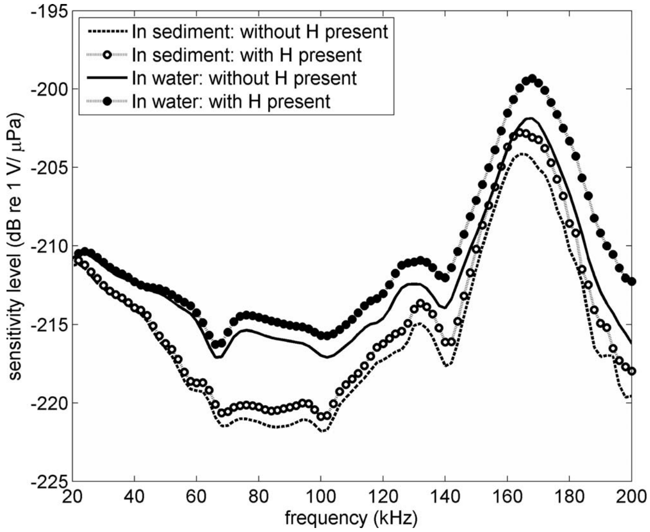


FIG. 6. Sensitivity levels measured for the spherical test hydrophone in sediment and water. Sediment-based sensitivity levels measured in Tank 2 are displayed using *P* and *T* measurements with *H* present (open circles) and without *H* present (dashed line). Water-based measurements performed in a larger water filled tank (measuring 2 m by 1.5 m by 1.5 m) are also displayed for *P* and *T* measurements with *H* present (closed line) and without *H* present (solid line). Note that the overall uncertainty for the calibrations were estimated to be ±0.5 dB for the water-based calibrations, and between ±0.9 and ±1.5 dB for the non-shadowed sediment-based calibrations (expressed for confidence levels of 95%).

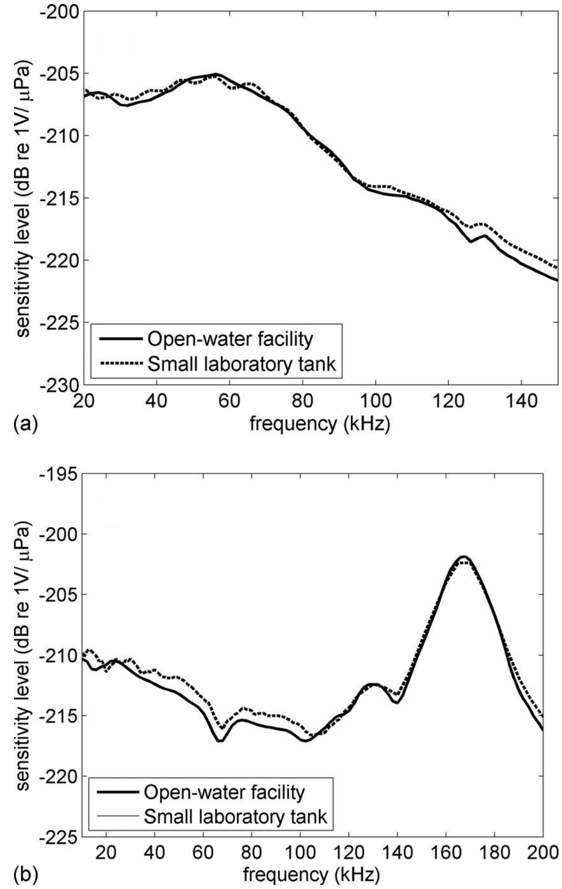


FIG. 7. Comparison of free-field sensitivity levels measured using large separations in an open-water facility (solid line) with water-based sensitivity levels measured in a small laboratory tank using the shorter transducer separation required for sediment-based work (dashed line) for (a) Brüel and Kjær 8104 and (b) spherical test hydrophone. Note that the overall uncertainty for the water-based calibrations were estimated to be ±0.5 dB (expressed for confidence levels of 95%).

sensitivity levels (i.e., those that use *P* to *T* measurements without *H* inserted) are traditionally used for water-based calibrations, shadowed measurements (i.e. those that use *P* to *T* measurements with *H* present) may be a more practical scenario for *in-situ* calibrations, as these would allow the three transducers to be attached to a single rig with well-defined separations for a single insertion into the sediment. For this reason both shadowed and non-shadowed sensitivities have been included in the following discussion. Comparison of the reference and shadowed sensitivity levels for each medium display a maximum increase from shadowing effects of 2.7 dB in sediment and 1.9 dB in water, both of which are more pronounced as frequency increases. The sensitivity levels in sediment are generally significantly lower than that in water, with a mean reduction across the frequency range of 3.8 dB for the shadowed measurements and 3.6 dB for the reference measurements. This reduction in sensitivity is greater than the degree of variability associated with disturbance effects, which, as discussed above, is less than 1.2 dB. The difference between sediment-based and water-based sensitivity levels varies with frequency, with this difference less than 2 dB for the range 20–28 kHz and 84–98 kHz, and greatest between these regions in the vicinity of the water-based resonance frequency of *H* (65 kHz).

The measured sensitivities of the spherical test hydrophone are displayed in Fig. 6, which again includes both reference and shadowed measurements. As for the Brüel and Kjær 8104, sediment-based sensitivity levels are lower than water-based values, with a mean reduction of 3.6 dB for shadowed measurements and 3.2 dB for non-shadowed measurements. This reduction is most pronounced for frequencies between 70 and 100 kHz, which, in contrast to the Brüel and Kjær 8104, are below the water-based resonance frequency of the hydrophone (i.e., 170 kHz). The increase in sensitivity caused by shadowing effects is observed to be considerably greater for water-based measurements (maximum increase of 4.0 dB at 200 kHz) than sediment-based measurements (maximum increase of 2.0 dB at 200 kHz).

In addition, to examine the effect of the restricted acoustic far-field conditions, water-based sensitivity levels measured at the short separation distances were compared to those obtained at larger separations, the latter measurements being undertaken in an open-water facility. The use of larger facilities allowed a minimum transducer separation of 1.1 m to be used and the resulting sensitivities to represent true far-field conditions. For the Brüel and Kjær 8104 transducer arrangement [see Fig. 7(a)] sensitivity lie within 0.6 dB of the free-field values from 20 to 122 kHz, and deviated from these free-field values by less than 1.1 dB as frequency increases to 150 kHz. The spherical test hydrophone displayed a similar deviation [see Fig. 7(b)] from true free-field values, with deviations less than 1 dB from 10 to 200 kHz.

The above results indicate that, for the two transducers examined, the change in the medium loading arising from the insertion of transducers into sediment will reduce sensitivity levels, averaged over the frequency range tested, by

3.2 and 3.6 dB respectively. These reductions exceed variations introduced by sediment disturbance effects (which are less than 1.2 dB) and are more pronounced for shadowed sensitivity levels. The reduction in sensitivity is probably a consequence of the increased acoustic impedance of the fine sand (3.79×10^6 kg m^{-2} s^{-1}) with respect to the acoustic impedance of the water (1.45×10^6 kg m^{-2} s^{-1}) and the resulting increased mismatch with the boot material used to protect the hydrophone element.

C. Uncertainties

For free-field reciprocity calibrations performed in water, the overall uncertainty is typically ± 0.5 dB (expressed for a 95% confidence level). A comprehensive description of the sources of uncertainty is provided elsewhere in the literature.[19,26] Many of these sources of uncertainty are common to the calibrations performed in sediment, examples being lack of steady-state conditions, lack of spherical-wave propagation, instrument calibration uncertainty, and lack of far-field conditions. The values of these uncertainties can vary with frequency, for example, the contribution from lack of steady-state conditions is greater at the lower limit of the frequency range where there are fewer cycles available within the echo-free time-window for analysis. Conversely, the lack of far-field conditions contributes greater uncertainty at higher frequencies where the near-field region extends for a greater distance.

In addition, there are additional uncertainties specific to the calibrations in sediment, a number of which have already been the subject of discussion in the previous sections. These include the residual effect of the finite size of the hydrophones, which was estimated to be a maximum value of 0.74 dB in Sec. II. The influence of shadowing caused by the central hydrophone has already been discussed in Sec. III B. The reduced separations used for the sediment calibrations introduced the potential for increased contributions from lack of far-field conditions. This was assessed by undertaking two sets of water-based calibrations, one set at the same marginal separations used for the sediment work, and one set at increased separations where far-field conditions were comfortably satisfied. This contribution was estimated in Sec. III B at between 0.6 and 1.1 dB.

Any calibration method will also suffer from a "random" uncertainty due to the lack of perfect repeatability in the measurements. This will be exacerbated for the sediment calibrations due to disturbance of the sediment on repeated immersion of the hydrophones. This was examined experimentally by measuring the transfer impedance between hydrophones under repeated immersion, extraction, and re-immersion of the Brüel and Kjær 8104 hydrophone. The repeatability obtained varied relatively little with frequency and was typically in the range 0.1–0.4 dB (expressed as a standard deviation).

An additional potential contribution specific to the sediment-based calibrations is that of lateral variations in attenuation (causing the value of α to be different for paths d_2 and d_3). Such a variation can be incorporated in to the analysis by using different attenuations in Eq. (4). As the total attenuation over the sediment part of the path d_1 is equal to the total attenuation over the paths d_2 and d_3 then the resulting equations will reduce to Eq. (6) indicating that such lateral variations should not be an issue. The experimental protocol (including the method of lying down a uniform degassed sediment described in Sec. III A) makes lateral variation in α far less likely than would occur in real shallow marine sediment, with its potential for the presence of flora and fauna (including shells), gas, and mineral inclusions. Assessment of any lateral variation in α would require removal and re-insertion of hydrophones into the sediment, which introduces another error that is potentially at least as large as the one being measured. To investigate the potential for any lateral variation in α to affect the results of this work, during the initial measurements using the Brüel and Kjær 8104, the roles of P and T (and the identity of the hydrophones) were interchanged. This provided a test of the robustness of the method to any lateral variations since the transducer pairs associated with the separations d_2 and d_3 (and the corresponding transfer impedances) were now interchanged. Although these measurements were only undertaken at a subset of frequencies within the overall frequency range, the results showed that the differences obtained were within the repeatability obtained from simply removing and re-inserting the hydrophones (typically between 0.1–0.4 dB as indicated above). This provided confidence that lateral variations in attenuation were not a significant source of error for the sediment tanks used here.

Although the work described here is mainly intended as a statement of the methodology rather than a definitive study of uncertainties, the additional sources of uncertainty have been combined with those common sources from the water-based calibrations in an attempt to make a provisional estimate of the overall uncertainty for sediment-based calibrations at a subset of frequencies within the overall frequency range. Combining the uncertainties according to the ISO Guide to Uncertainties in Measurement,[27] overall values of between ± 0.9 and ± 1.5 dB (depending on frequency) are obtained when using the reference "non-shadowed" method (expressed for a confidence level of 95%).

When considering the differences observed between the water-based and sediment-based results, it should be remembered that as far as possible the same instrumentation and experimental procedure were used for both media. This means that any systematic bias introduced into the results due to uncertainty contributions which are common to both experiments will be the same for both media and so will not influence the *differences* between the results. As can be seen from the results presented in Sec. III B, sensitivity differences are observed which exceed the estimated uncertainties, and therefore it is believed that these differences are real for the hydrophones used here and are not experimental artifacts.

IV. COMPARISON WITH HYDROPHONE MODEL

In order to investigate the effect of immersion in sand on a hydrophone performance and confirm that the observed changes in sensitivity were realistic, preliminary FE calculations were performed using a simplified model of the spheri-

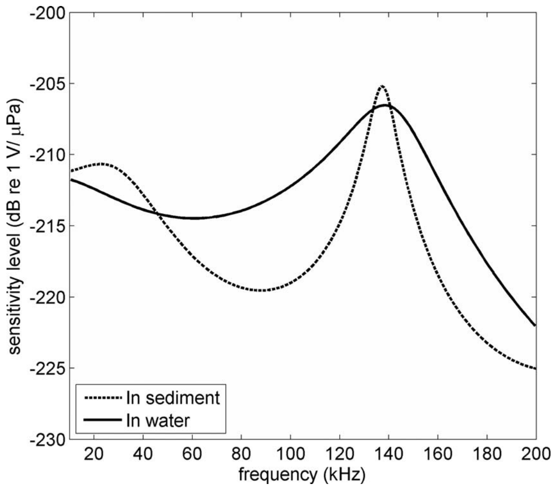


FIG. 8. Absolute sensitivity of spherical hydrophone with spherical boot in water and sand calculated using FE model.

cal hydrophone. These used a commercial FE code (PAFEC, PACSYS Ltd., Nottingham, UK). For reasons of simplicity, the model was only developed for the spherical hydrophone. The Brüel and Kjær 8104 hydrophone was not modeled since the complex element design, consisting of four coaxial rings, was not readily amenable to a simplified model.

The model consisted of a radially-poled spherical shell of PZT 5 piezoelectric ceramic with inner and outer radii of 5.0 and 6.35 mm, respectively, covered by a uniform coating layer of outer radius 10 mm (the hydrophone boot), based on information provided by the hydrophone manufacturer. The hydrophone was modeled when immersed in water, with a speed of sound 1500 m s^{-1} and density 1000 kg m^{-3}, and in sand, with a speed of sound 1746 m s^{-1} and density 2176 kg m^{-3}. The parameters for the piezoelectric material were taken from the database within PAFEC and the coating layer was assumed to have a compressional wave speed of 1626 m s^{-1} and a density of 1040 kg m^{-3}. In the model, the coating and the sediment were assumed to act as fluids (and so would not support shear waves). However, realistic values of the compressional wave speed have been used which correspond to those for the sediment. The model utilized boundary elements on the outer surface of the coating to simulate the effect of the infinite fluid medium (water or sand). These properties are considered to be reasonable estimates of the properties of the tested device.

In order to evaluate the performance of the hydrophone as a receiver, the transmit voltage sensitivity of the device was initially calculated. This was then converted into a current sensitivity using the predicted impedance of the device. Finally, the receive sensitivity was calculated by use of the principle of reciprocity [see Eq. (2)]. It should be noted that no attempt has been made to correct the resulting element receive sensitivities to end of cable sensitivities.

The resulting receive sensitivities are shown in Fig. 8 as a function of frequency from 10 to 200 kHz. These results show that the sensitivities in sediment and water are very similar at the lowest frequency considered, but that the sensitivity in sand is much lower in the region of 90 kHz, being some 6 dB lower than in water. However, the sensitivities in the region of the resonance at 140 kHz are very similar, with that in sand being about 1.5 dB higher. The peak in response has a higher Q for the in-sand measurements than the in-water measurements. It should be noted that changes to the Q factor of the resonance have been predicted elsewhere for hydrophones immersed in sediment.[28]

The qualitative features displayed by the model are in very good agreement with those displayed by the experimental measurements of sensitivity (Fig. 6). In particular, the similar low frequency sensitivities, the significantly reduced sensitivity in the midfrequency region in sand, and similar sensitivity in the resonance region are all well replicated. This gives added confidence that these features are real and not the result of systematic uncertainties.

It should be noted that this FE model was not intended to model exactly the tested hydrophone with its complex construction of a spherical element in a truncated cylindrical boot. It is intended to develop a more extensive model in the future in order to understand in more detail how sediment affects the performance of buried hydrophones.

V. CONCLUSIONS

An absolute calibration method has been developed to investigate hydrophone performance in sediment. The method is based on the method of three-transducer spherical-wave reciprocity with a co-linear transducer arrangement which enables the sensitivity of the central hydrophone to be determined without *a priori* knowledge of the sediment properties. A series of reciprocity calibrations has been performed in sediment and in water for two types of hydrophone. Through comparison with equivalent water-based measurements, the immersion of the hydrophones into the sediment was observed to reduce their sensitivity levels by varying amounts depending on the frequency. The observed reductions varied between a minimum of less than 1 dB and a maximum of just over 7 dB, the average reduction in sensitivity for the two hydrophones being 3.2 and 3.6 dB, respectively (averaged over the all measurement frequencies). The effect of the sediment disturbance associated with the necessary insertion, rotation, and removal of the central hydrophone caused measured sensitivities to deviate from reference sensitivity levels by less than 1.2 dB. Shadowing effects associated with the use of P to T measurements with the central hydrophone present increased sensitivity levels by between 1.3 and 4.0 dB. Despite the relatively short transducer separations that were required for the sediment-based measurements, the lack of perfect far-field conditions for part of the frequency range did not cause significant error in the measurements. The reduction in sensitivity levels associated with insertion into sediment can be explained through the higher impedance of the sediment and increased mismatch with the hydrophone boot material. A simple FE model has been developed for one of the hydrophones, the results of which show good qualitative agreement with the measured data and indicate that the observed changes are realistic.

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