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A method for calibrating hydrophones immersed in sandy sediment

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Hydrophones are frequently used as receivers for *in situ* sediment acoustic experiments. At present, processing techniques use receiver sensitivities measured from water-based calibrations. It is, however, accepted that the receive sensitivity will depend, to some degree, on the medium surrounding the hydrophone, particularly at frequencies close to the transducer's resonance. To assess this effect, the receive sensitivity of two types of hydrophones immersed in a saturated medium sand were measured using a modified three-transducer reciprocity technique. This technique uses a co-linear arrangement to allow the sediment attenuation to be omitted from the sensitivity calculation. The insertion of the hydrophones into the sediment reduced the measured receive sensitivities with respect to the equivalent water-based calibrations by between 3.2 and 3.8 dB for the two devices examined. The co-linear arrangement adopted allowed the transmission between the outer devices to be recorded with and without the central hydrophone present. Repeat measurements indicated that the sediment disturbance associated with the removal of the central hydrophone caused sensitivity differences of less than 1.2 dB, while the inclusion of the central hydrophone caused a shadowing effect which increased sensitivities by between 1.3 to 4.0 dB.

1 Introduction

In situ acoustic experiments [1-6] are frequently used to measure the acoustical properties of well-defined sediment volumes and, therefore, generate the data required for both the ground-truthing of remote acoustic surveys and the validation of geoacoustic theories. While a variety of relatively complex *in situ* experimental techniques exist, which require the insertion of three or more transducers into the sediment, the use of a single source / receiver pair is still frequently adopted [2, 3, 6, 7] owing to its relatively simple deployment and the associated reduction in sediment disturbance. In order to process the transmit-receive data obtained from a single source/receiver pair, knowledge of the sensitivity of the receiver is required. At present, these receiver sensitivities are determined through water-based calibrations. It has, however, been noted that receiver sensitivities depend to some degree on the acoustic impedance of the surrounding medium [1, 8]. For the bubble-free conditions assumed throughout this paper, typical sediment-based acoustic impedances, which vary between 1.7 x 10^6 kg·m^{-2}·s^{-1} for a typical mud and 3.8 x 10^6 kg·m^{-2}·s^{-1} for a typical sand, are considerably greater than water-based acoustic impedances, which vary from 1.4 x 10^6 kg·m^{-2}·s^{-1} to 1.5 x 10^6 kg·m^{-2}·s^{-1} for temperatures from 0 to 20 ^{o}C and salinities from 0 to 35 ‰. It is, therefore, feasible that hydrophone sensitivities in sediment and water may differ, in which case a technique for measuring the *in situ* sensitivities of receivers immersed in sediment would be beneficial.

This paper presents a modified three-transducer reciprocity technique which uses a co-linear arrangement to measure the *in situ* sensitivity of hydrophones immersed in sediment. Laboratory-based calibrations performed using this technique are presented for two hydrophone types, while uncertainties associated with sediment disturbance and shadowing by the central hydrophone are quantified.

2 Sediment-based reciprocity technique

At present the primary manner with which the receive sensitivity of hydrophones are measured is water-based three-transducer reciprocity [9]. This involves the transmission of signals between three individual transducer pairs, namely source P to receiver T, source P to receiver H and source T to receiver H. For each measurement the required pair of transducers is placed in a water tank at a separation that satisfies free-field, far-field and steady-state conditions. The receive sensitivity of transducer H (denoted by M_{HW}) can then be derived from transfer impedances Z of each pair (i.e., the received voltage divided by the driving current). This sensitivity is computed using

$$M_{HW} = \sqrt{\left(\frac{2 d_2 d_3}{\rho f d_1}\right)\left(\frac{Z_{PH} Z_{TH}}{Z_{PT}}\right)} \qquad (1)$$

where d_1, d_2 and d_3 are the distances between P and T, P and H and T and H respectively, f is the insonifying frequency and ρ is the bulk density of the surrounding medium. This technique assumes that transducer T is reciprocal and that the absorption of the water is negligible. This final assumption is valid for frequencies of order kHz, e.g., absorptions at 200 kHz are 8.6x10^{-3} nepers·m^{-1} or less [10].

In contrast to water, the attenuation of compressional waves at kHz frequencies in sediment can reach values of 2.9 nepers·m^{-1} in muds and 9.5 nepers·m^{-1} in sands (values predicted using the grain-shearing theory [11] with typical sediment properties [12]). The possibility of correcting for these attenuations in the reciprocity technique described above, as is done for water-based calibrations at MHz frequencies [9], is prevented by the highly variable nature of sediments. Attenuations from marine sediment can vary by $\pm$ 31 % for a single mean grain size [13], while attenuation coefficients measured in sandy sediment have been observed to vary by up to 2.8 nepers·m^{-1} for sediments with similar physical properties lying within a horizontal range of 100 m of one another [14]. It is therefore necessary to develop a calibration technique which does not require knowledge of the sediment attenuation. This is achieved by modifying the above water-based technique to incorporate a co-linear transducer arrangement (see Fig. 1).

Consider the general case of a pair of transducers that are embedded in sediment, comprising of 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 that the sediment is homogeneous, the voltage v_H received by the hydrophone can be expressed as:

$$v_H = \frac{M_H S_P i_P}{d} e^{-\alpha d} \qquad (2)$$

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 nepers·m^{-1}).

The specific transfer impedances for transducer pairs P to T (Z_{PT}), P to H (Z_{PH}), T to H (Z_{TH}) are therefore given by

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

$$Z_{PH} = \frac{M_{HS}\,S_P}{d_2} e^{-\alpha\left[d_2 - (\Phi_P + \Phi_H)/2\right]} \qquad (3)$$

$$Z_{TH} = \frac{M_{HS}\,S_T}{d_3} e^{-\alpha\left[d_3 - (\Phi_T + \Phi_H)/2\right]}$$

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. Eqs. (3) assume that the reference center of each transducer lies at the geometric center of the device. Using the reciprocity parameter J it is possible to combine the expressions for the transfer impedances Z_{PH}, Z_{PT} and Z_{TH} to derive an expression for the complex sensitivity M_{HS} of the hydrophone H:

$$M_{HS} = \sqrt{\left(\frac{2d_2 d_3}{\rho f d_1}\right)\exp\left[\alpha\left(d_2 + d_3 - d_1 - \phi_H\right)\right]\left(\frac{Z_{PH} Z_{TH}}{Z_{PT}}\right)} \qquad (4)$$

As a consequence of the co-linear arrangement adopted, $d_1 = d_2 + d_3$ and Eq. (4) therefore simplifies to

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

For an infinitesimally thin hydrophone Eq. (5) reduces to Eq. (1).

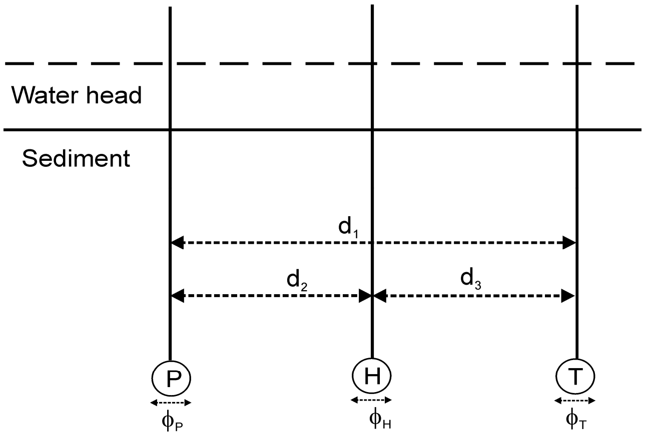

Fig. 1. The co-linear arrangement adopted for sediment-based reciprocity calibrations which utilises a projector P and a reciprocal transducer T to calibrate hydrophone H.

For the present work, which uses hydrophones with diameters of 20 and 21 mm immersed in a medium sand with attenuations less than 8.16 nepers·m^{-1} (computed for the required frequency range of 10 to 200 kHz using grain-shearing theory [11]), the sensitivities determined by assuming infinitesimally thin hydrophones, i.e. Eq. (1), differ from those determined from Eq. (5) by less than 8.9 %. As the resulting deviation in sensitivity levels (<0.74 dB) lies within the variability associated with sediment disturbance (see Section 4) Eq. (1) is assumed to be valid for these sediment-based reciprocity measurements and is used throughout the remainder of this paper. It is interesting to note that a similar co-linear arrangement is adopted for calibrations that require the information on hydrophone phase [15].

3 Experiment

Laboratory based reciprocity measurements were performed on hydrophones inserted into water-saturated medium sands. It was essential that the manner in which the sand volumes were prepared prevented the trapping or formation of air bubbles within the sediment. The inclusion of such bubbles would introduce strongly frequency-dependent compressional wave velocities and attenuations [16-18] which would disrupt the waveforms received and, therefore, make it extremely difficult to identify the time windows over which the signals are stationary. The sediment was prepared by sprinkling the sand into water that had been previously degassed using vacuum pump techniques, which create extremely low absolute pressures at which the dissolved gasses form bubbles that coalesce and escape from the water surface. The sediment was then left to settle for a week prior to the measurement phase, with a minimum water head of 50 mm maintained at all times.

To minimise the possibility of introducing air bubbles the transducers were deployed by 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 and the tube slowly removed to allow the sediment to envelop the transducer. After each insertion, the sediment was given at least two hours to settle. The absence of gas bubbles was confirmed through a number of observations. First, the high relative amplitude of the 500 kHz pulses that were transmitted though core samples (see below) indicated a bubble free medium. Second, all of the signals acquired during the reciprocity measurements displayed clean waveforms, as opposed to earlier measurements performed in a sand tank which had not been degassed and in which no steady state signals could be observed. Third, upon gentle stirring of the sediment no bubbles were observed to emerge from the sediment.

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 [17] while grain size distributions were measured at 5 cm depth 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 33.2 ± 1.0 %, a bulk density of 2177 ± 18 kg·m^{-3} and a compressional wave velocity of 1745.9 ± 7.8 m·s^{-1} (all values quoted are mean values with standard deviations as the corresponding errors).

Reciprocity measurements were performed on two hydrophone types, namely a Brüel and Kjær 8104 transducer with an outer diameter of 21 mm and a cylindrical element and a test hydrophone with an outer diameter of 20 mm and a spherical element. For both hydrophones the same methodology was applied, with an ITC 1042 transducer with a diameter of 35 mm used as P and a Brüel and Kjær 8100 with a diameter of 21 mm used as T (see Fig. 1). For each transducer pair (namely P to T, P to H and T to H) the steady-state driving current and received voltage were measured using tonal pulses, with the hydrophone rotated to face the respective source. The steady-state voltage of the received signal was measured using standard techniques [9] which involve time windowing the received signal to select the portion of the received signal which satisfies both steady-state and free-field conditions. Least squares fitting techniques were then applied to measure the received voltage, with reliable results obtained when the duration of the time window contained at least half an oscillation of the received signal.

While the same methodology was used for both hydrophone calibrations, the different locations at which each device was tested required the use of two sediment tanks. The Brüel and Kjær 8104 was calibrated in a parallelepiped sediment volume measuring 0.67 m by 0.49 m by 0.45 m deep. In this case echo-free times were maximised by deploying all transducers to a sediment depth of 0.22 m, with the Brüel and Kjær 8104 placed at the center of the tank and the outer devices P and T placed co-linearly 0.13 m on either side. This allowed a frequency range of 20 to 150 kHz to be examined, using 2 kHz steps. The test hydrophone was calibrated in a cylindrical tank with a diameter of 0.97 m and a sediment depth of 0.87 m. In this case all devices were deployed to a sediment depth of 0.45 m, with the test hydrophone placed at the center of the tank and P and T placed co-linearly 0.17 m on either side. This second arrangement allowed the frequency range that could be investigated to be extended to 10 to 200 kHz, again using 2 kHz steps.

While the transfer impedances Z_{PH} and Z_{TH} required to compute the sensitivity of H can only be measured with H present, Z_{PT} could be measured under three sets of conditions. First, the use of Z_{PT} measured before H was inserted allowed a "reference" sensitivity to be calculated which suffers from no shadowing effects associated with the central hydrophone and only relatively minor disturbances associated with the insertion of P and T. Second, a "shadowed" sensitivity was calculated using 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.

For comparison purposes water-based reciprocity measurements were also performed in a water tank measuring 2.0 m by 1.5 m by 1.5 m deep for both the Brüel and Kjær 8104 and the test hydrophone. In order to ensure that the water and sediment calibrations are directly comparable the transducer configurations, mounting, drive voltage and pulse length 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.

The near-to-far field transitions D were computed using

$$D = \frac{\Phi_P^2}{\lambda} \qquad (6)$$

where Φ_P is the diameter of the projector and λ is the wavelength of the insonifying signal. Eq. (6) confirmed that the transducer arrangements adopted for both the Brüel and Kjær 8104 and the test hydrophone satisfy far-field conditions for all frequencies examined. Further evidence that far-field conditions are satisfied is supplied by the strong agreement between the water-based sensitivities measured using the transducer arrangements described above and sensitivities measured in a larger open water facility with a minimum transducer separation of 1.1 m, with these two measurements differing by less than 1.1 dB for all frequencies examined.

4 Results

In order to validate the sediment-based reciprocity technique, the impact of shadowing and disturbance effects on the Brüel and Kjær 8104 sensitivity levels are displayed in Fig. 2, through the use of "reference", "shadowed" and "disturbed" sensitivity levels. This set of sensitivities levels was computed for two deployments of H, which were separated by a period of 48 hours to allow the sediment to resettle.

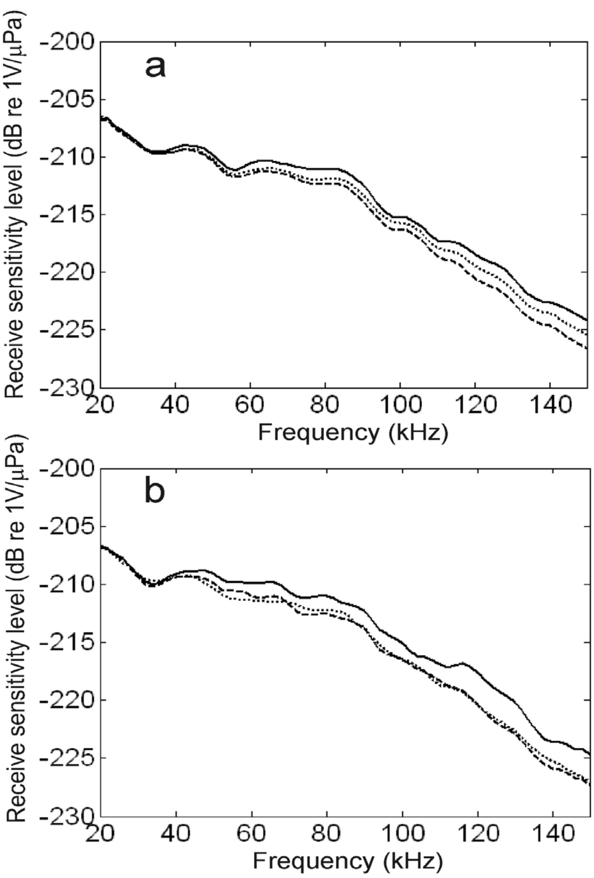

Fig. 2. Repeated measurements (a and b) that display the impact of shadowing and disturbance effects for the Brüel and Kjær 8104. These measurements include reference sensitivity levels (dotted line), shadowed sensitivity levels (solid line) and disturbed sensitivity levels (dashed line). All sensitivities use the same P to H and T to H measurements.

The combined shadowing / 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 deployment and 2.8 dB for the second deployment, 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 which reduces the Z_{PT} term in Eq. (1). 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 is, again, more pronounced at higher frequencies. This general reduction can be explained through the removal of H reducing the compaction of sediment in this region. The resulting increase in porosity causes a reduction in the sediment attenuation and subsequent increase in the amplitude of the signal transmitted from P to T, which increases Z_{PT}. Finally, the observation that the reference sensitivity levels in the second set of measurements are slightly lower than those observed in the first set indicates that the sediment had not fully recovered between the two deployments.

In order to assess if transducer T is reciprocal, an assumption made by the sensitivity calculation, 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}). As sensitivity levels calculated using Z_{PT} and Z_{TP} agreed to within 1% for the majority of the frequency range for both water-based and sediment-based measurements, P and T can be assumed to be behaving reciprocally.

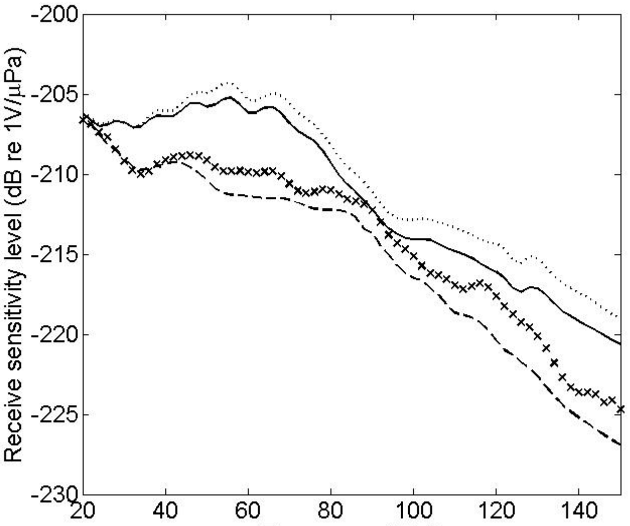

Fig. 3. Receive sensitivity of the Brüel and Kjær 8104 hydrophone in sediment and water. Sediment-based sensitivity levels measured in a sediment volume measuring 0.67 m by 0.49 m by 0.45 m deep are displayed using P and T measurements with (crosses) and without (dashed line) H present. Water-based measurements performed in a water volume measuring 2 m by 1.5 m by 1.5 m deep are displayed for P and T measurements with (dotted line) and without (solid line) H present.

The water-based and sediment-based sensitivities of the Brüel and Kjær 8104 are compared in Fig. 3. Both "reference" and "shadowed" sensitivities have been included as both possess certain benefits that warrant their discussion. Reference sensitivity levels (i.e., those that use P to T measurements without H inserted) correspond to those traditionally used for water-based calibrations. Alternatively, shadowed measurements (i.e., those that use P to T measurements with H present) may be more practical for *in situ* calibrations, as these would allow the three transducers required for the calibration to be attached to single rig with well-defined separations for a single insertion into the sediment.

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-sensitivity levels varies with frequency and is greatest in the vicinity of the water-based resonance frequency of H, i.e. 65 kHz.

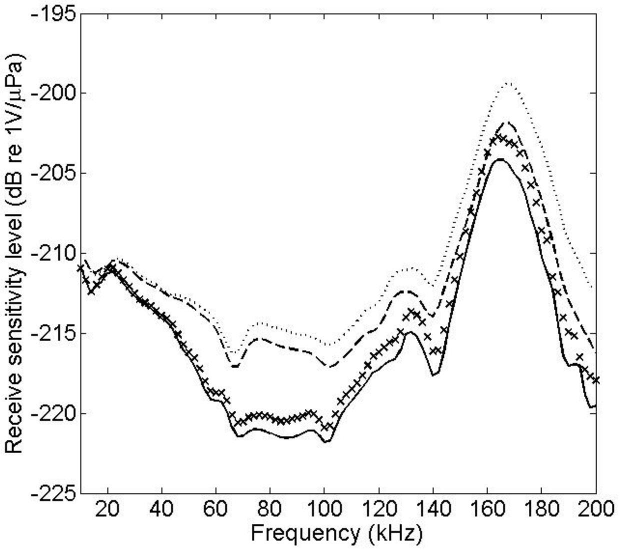

Fig. 4. Receive sensitivity measured for the test hydrophone in sediment and water. Sediment-based sensitivity levels measured in a cylindrical sediment volume with diameter of 0.97 m and depth of 0.87 m are displayed using P and T measurements with (crosses) and without (solid line) H present. Water-based measurements performed in a water volume measuring 2 m by 1.5 m by 1.5 m deep are displayed for P and T measurements with (dotted line) and without (dashed line) H present.

The measured sensitivities of the test hydrophone are displayed in Fig. 4, which again includes both reference and shadowed measurements. As for the Brüel and Kjær 8104 sediment-based sensitivity levels are lower that water-based values, with a mean reduction of 3.6 dB for shadowed measurements and 3.2 for non-shadowed measurements. This reduction is most pronounced between 70 and 100 kHz, which, in contrast to the Brüel and Kjær 8104, is less than the water-based resonance frequency of the test hydrophone (i.e. 170 kHz). The increase in sensitivity caused by shadowing effects is observed to be considerable greater for water-based measurements (maximum increase of 4.0 dB) than sediment-based measurements (maximum increase of 2.0 dB).

5 Conclusion

This paper has presented a modified three-transducer reciprocity technique for measuring the *in situ* sensitivity of hydrophones immersed in sediment. For the two devices examined, the change in the medium loading arising from the insertion of the transducers into sediment reduced the receive sensitivity by between 3.2 and 3.8 dB. These reductions exceeded variations introduced by sediment disturbance effects (which were less than 1.2 dB) and were more pronounced for shadowed sensitivity levels. The reduction in sensitivity is probably consequence of the increased miss-match between the acoustic impedance of the hydrophone boot material and the impedance of the sand (3.79×10^6 kg·m^{-2}·s^{-1}) when compared with that for water. Future work on this subject will involve the use of transducer-based models to develop a more thoroughly understand the mechanisms behind the observed changes in sensitivity.

Acknowledgments

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