STUDY OF A TRUE FREE FIELD CALIBRATION METHOD OF AN ACCELEROMETER BASED VECTOR SENSOR FOR UNDERWATER USE

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Abstract: *Hearing is the main sensory organ for many marine species. Fish without swim bladder as well as Crustaceans and Cephalopods are known to be sensitive only to particle motion. Thus, sole measurement of acoustic pressure is not enough to assess the impact on marine species since particle motion cannot easily be derived from pressure. With the launch of the European Marine Strategy Framework Directive focus was directed to the low-frequency range where anthropogenic activities interfere with living conditions of marine animals. Most studies have been dealing with acoustic pressure but lately a shift towards particle motion has been observed, with the introduction of commercially available vector sensors. With this shift it will be necessary to develop calibration methods for particle motion. One alternative at hands is to perform calibration in-situ in free field conditions, provided that a stable, homogenous and large volume of water mass is available.*

Herein are the results from a three-axis calibration check of an accelerometer-based vector sensor presented. Prior to the calibration a reciprocal free-field calibration was done of a transducer which was used as a transmitter for the calibration of the vector sensor. The vector sensor was lowered to the same depth as the transmitter at 45 m depth with a horizontal separation distance of 25 m. Approximately 40 ms long continuous wave pulses in the frequency range of 400 Hz to 1200 Hz were used. Since the orientation of the vector sensor axis was unknown the resulting acceleration measurements from the three axes of the sensor were combined to give the total acceleration of the particle motion in the water. The calibration was repeated three times with varying incidence angles. The results were compared with the free field assumption of the acceleration of the particle motion resulting from the transducer.

Keywords: *Calibration, Vector Sensor*

1. INTRODUCTION

The vector sensor was developed for measurements of a large variety of applications with relatively high sound levels, for example measurement of energy produced by seismic airguns [1][2] and exposure experiments on cuttlefish [3]. These anthropogenic sources have in common that the majority of the energy is found below 1000 Hz.

The vector sensor was mainly optimized for the frequency band 0.5 Hz to 1000 Hz. The upper limit of the frequency band was limited by the size of the sensor. This broad frequency band makes calibrations of the sensor challenging. The classical way of calibrating underwater sensors is to use a time-gated tone burst of certain frequency and length and to measure the signals before the reverberation interferes with the direct field. Free field calibrations below 1000 Hz sets limits on which minimum water tank dimensions are usable. One solution is to use large water volumes like that of an ice-covered lake. The ice provides a stable platform to work from as well as reducing motional induced errors on the calibration results. It also makes it possible to measure horizontal distances with a relatively high precision. Thus, the vector sensor was calibrated in the lake Hornavan in Swedish Lapland in March 2018. The thickness of the ice was approximately 40 cm and the lake has a maximum depth of 200 m.

In order to calibrate the vector sensor, the sensor output was compared to the free field estimate of the acceleration field generated by a transducer, i.e. a comparison calibration technique is utilized in this study.

2. THE VECTOR SENSOR SYSTEM

The sensor of the system is a near neutrally buoyant (weakly positive) sphere with a diameter of 60.0±0.2 mm with a mass of 110±5 g. The sphere contains a three-axis accelerometer (PCB piezotronics model 356B18). The accelerometer is attached to a small aluminium support suspended to the sphere with screws and epoxy glue. The support has the additional function to provide the freedom to co-locate the mass at the buoyancy centre, see Fig.1. The sensitivity of the accelerometer is 1 V/g=-140 dB re 1 V/µm/s^2, g being the gravitational constant, with a flat sensitivity (±5%) in the frequency range of 0.5 Hz to 5.0 kHz. The noise floor at 100 Hz is approximately 1.2 µg/$Hz^{1/2}$ or 22 dB re 1 µm/s^2/$Hz^{1/2}$. The noise floor at 1000 Hz is approximately 0.4 µg/$Hz^{1/2}$ or 12 dB re 1 µm/s^2/$Hz^{1/2}$. The Vector Sensor system was custom built, based on the technique described in [4], the difference in this system being a smaller sphere and an autonomous recording system.

Fig. 1: The open sensing head of the vector sensor system showing its interior.

The sampling frequency of the data acquisition system was 14400 Hz, and the resolution of the Analog-to-Digital converter was true 21 bit. The recorded data were stored on a 32 Gb SD-card.

3. THE FREE FIELD MEASUREMENT SITE

Lake Hornavan is situated in the North of Sweden at the elevation of 425 m. The lake water is fresh with a little anthropogenic activities in the area.

The calibrations took place at two sites (see Table 1). The calibration of the vector sensor was conducted at site 1, and the transmitter, which had to be calibrated as well, was calibrated at both sites. The water temperature was logged at site 1 and site 2 using a Valeport Datalog X2. The temperature as a function of depth showed a monotonic increase from surface 0.65 degrees to the lake floor 3.6 degrees. The accuracy of the sound velocity meter was 0.06 m/s.

All the auxiliary instruments were kept in a measurement hut, which was heated to room temperature. The power for the data acquisition and signal generation units was generated using a portable power generator placed at a distance of approximately 100 m from the measurement hut. The generator was placed on top of vibration insulation materials in order to minimize sound leakage in to the water.

The weather during the calibration was stable, -15°C in the morning and -10°C at noon. The atmospheric temperature change did not affect the temperature of the water.

	Coordinates	Water depth [m]	Calibration depth [m]	Temperature at calibration depth [°C]	Sound velocity at calibration depth [m/s]
Site 1	N 66,194, E 17,664	90	45	3.3	1419.4
Site 2	N 66,183, E 17,774	45	20	2.6	1415.9

Table 1: Measurement sites.

4. CALIBRATION

The calibration was performed in two steps. In the first step, the Transmit Voltage Responses, TVR, was calibrated in a reciprocity scheme including two ITC-1007 and one ORT-1014. One of the ITC-1007 transducers was later used for the calibration of the vector sensor in the second step.

Step 1 was repeated eight times with the same transducers. The calibration was done in the frequency intervals 80 Hz - 20 kHz, 120 Hz – 5 kHz. 120 Hz – 10 kHz and 120 Hz- 20 kHz. At site 1, the distance between the three elements was 25 m. At site 2, the distance between the three elements was 20 m. The calibrations were conducted over a time period covering approximately two weeks. In Fig. 2 the TVR level is presented for frequencies up to 1.2 kHz. The presented TVR value is generated by taking the mean of all eight calibrations.

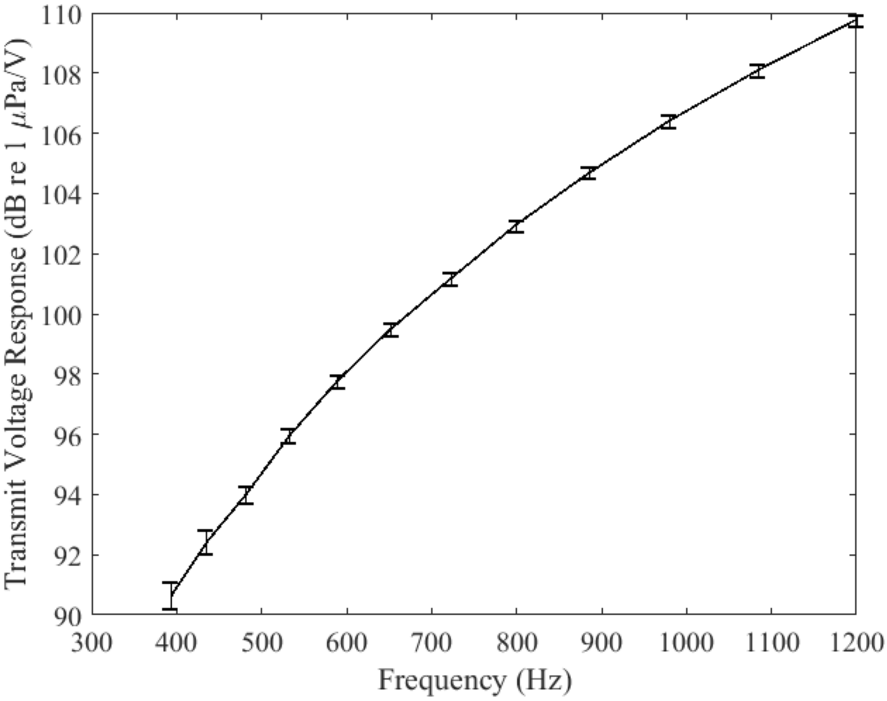

Fig. 2: The mean Transmit Voltage Response of the ITC-1007 used in the vector sensor calibration.

In step 2 the vector sensor was calibrated by using the newly calibrated ITC-1007 transducer. The vector sensor was placed at 25 m distance from the transducer. The deployment depth was 45 m, the same as for the transducer. The transducer generated 40 ms long tone bursts with discrete frequencies in the frequency range 392 Hz up to 1200 Hz. The following frequencies were used: 392 Hz, 434 Hz, 481 Hz, 532 Hz, 589 Hz, 652 Hz, 722 Hz, 799 Hz, 885 Hz, 979 Hz, 1084 Hz and 1200 Hz. Each tone was repeated ten times with a time separation of 1.5 s.

As a first step in the analysis the estimated acceleration was deduced using the TVR values generated in step 1, in combination with the measured voltages from the power amplifier to the transducer. The estimated acceleration, a_e, at the vector sensor was calculated using the following relations:

$$a_e=p\cdot w/Z, \text{ where } p=TVR\cdot v_o/d, \quad (1)$$

where p is the pressure generated by the transducer, w is the angular frequency of the generated wave, Z is the acoustic impedance in the water, V_o is the voltage generated by the power amplifier and d is the distance to the vector sensor. In this measurement the acoustic impedance was estimated to be 1419800 ± 60 Rayl.

The vector sensor output was compared to the generated acceleration levels. This analysis was done by measuring the peak-to-peak voltage of the signal from the recorded tone bursts. The measured voltages were scaled with the sensitivity, given by the accelerometer manufacturer, of -140 dB re 1 V/μm/s^2.

Since the orientation of the vector sensor axis was unknown the resulting acceleration measurements from the three axes of the sensor were combined to give the total acceleration of the obtained particle motion in the water. In Fig. 3 the estimated acceleration is shown with the measured acceleration from the vector sensor.

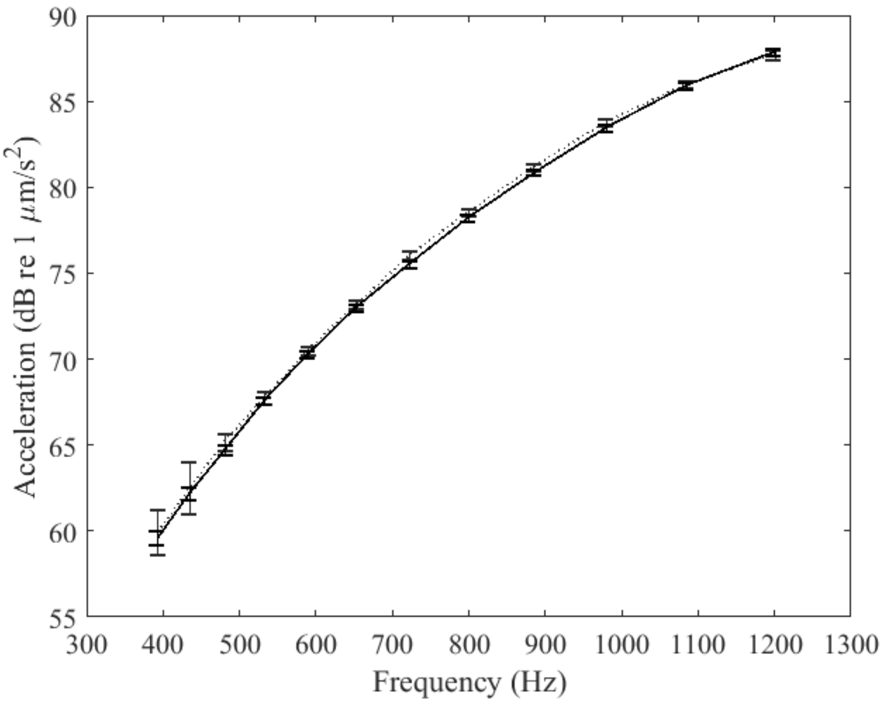

Fig. 3: The estimated acceleration using pressure and assuming that the free-field estimate is valid (solid line), and the measured acceleration (dotted line) using the output voltage from the accelerometer and manufacturer's sensitivity.

The solid line represents the estimated acceleration and the dotted line represents the measured acceleration. The calibration was repeated two times after rotating the vector sensor roughly 50-100 degrees between the measurements, supervised by using an underwater video camera. The measured accelerations were comparable to the one presented in Fig 3. Assuming that the relations and assumptions behind the estimated acceleration is correct, the sensitivity of the vector sensor can be rescaled according to:

$$M_e=M_m \cdot a_m/a_e\,, \tag{2}$$

where M_m is the sensitivity specified by the manufacturer, a_m is the measured acceleration and a_e the estimated acceleration. In Fig. 4, the resulting sensitivity for vector sensor is presented. This correction is advocated by the fact that the buoyance will change the sensitivity of the sensor [5].

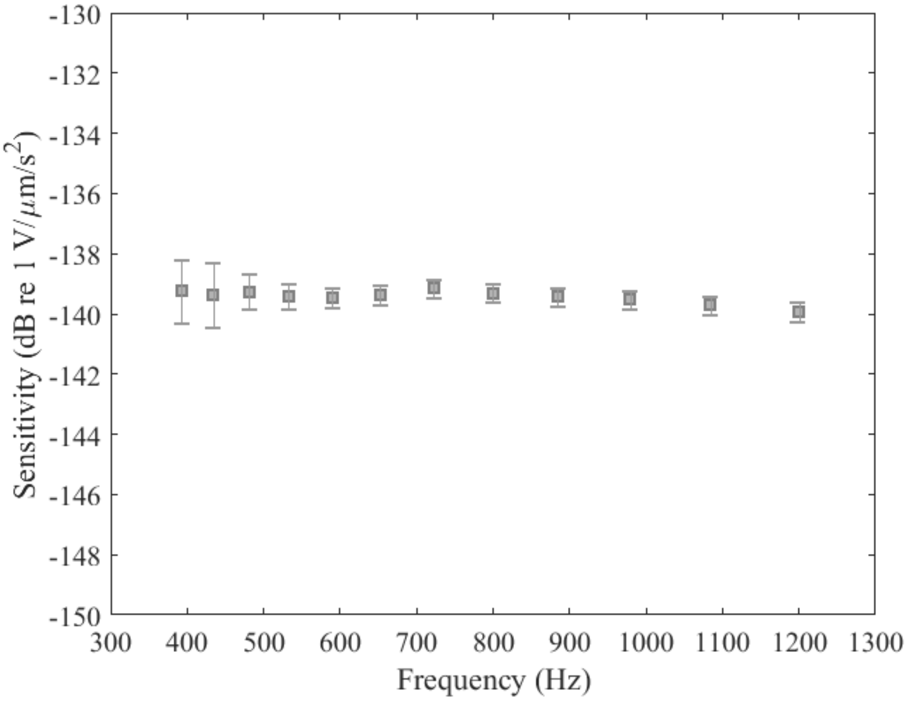

Fig. 4: The measured sensitivity of the particle motion sensor. The increase of the uncertainty for lower frequencies is explained by the decrease of SNR related to the transmitter and receiver.

5. SOURCES OF UNCERTAINTY

A number of sources contribute to the uncertainty in the estimated sensitivity. The uncertainties are listed and discussed briefly:

Transducer TVR uncertainty: The reciprocity calibration was done eight times. The repeated calibrations using the same frequency points gave a statistical spread, the standard deviation was evaluated and used as an uncertainty estimate. This uncertainty has its major impact at low frequencies where the signal to noise ratio was relatively low.

Vector sensor measurement uncertainty: The measurements were repeated 30 times for each frequency, when adding the three different impinging angles. The standard deviation was calculated for each frequency and this uncertainty has its major impact at frequencies close to 400 Hz where the signal to noise ratio was relatively low.

Distance: There is an uncertainty in the measurement of the distance between transmitter and receiver. Further, it occurs twice, both in the reciprocity calibration and in the vector sensor calibration. In the reciprocity scheme the uncertainty was estimated to 0.3 m or 0.11 dB. When conducting the vector sensor calibration this uncertainty was increased to 0.15 dB.

Directivity: The vector sensor was not oriented with the same side facing towards the ITC-1007 as was the case in the reciprocity calibration. It can be expected that there are small deviations from the omnidirectional response. According to the manufacturer of the ITC-1007 transducer there is a ±1 dB directional response at 10 kHz, however, this uncertainty is ±0.1 dB at 1 kHz.

Instrumentation: The resolution of both the vector sensor system and the reciprocity calibration instruments are 24 bit. The instrument accuracy, internal noise levels are <<0.1 dB. In this study a conservative uncertainty estimate of 0.1 dB is assumed for all the different instruments.

Thermal stabilization: The transducers used in the TVR calculation and the vector sensor were allowed to thermalize for at least three hours prior to the first measurements. No drift of electrical signals are observed over the course of measurements and these uncertainties are assumed to be hidden in the statistical variability in the measurements and thus covered by the two first entries in this list.

6. DISCUSSION

The measured acceleration was observed to be slightly higher than the estimated acceleration assuming free field conditions in the water volume. A positive buoyancy is known to amplify the amplitude of oscillations [5]. The mean density of the sensor head is 950± 50 kg/m^3, thus it is weakly positive. The resulting sensitivity for the vector sensor as presented in Fig. 4 indicates that there are no structural resonances apparent in the investigated frequency range. The sensitivity was offset by roughly +0.5 dB from the factory calibration, which is most probably explained by the positive buoyancy of the sensing head.

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