Calibration of Dual Accelerometer Vector Sensor (DAVS2) at the Alfeite Arsenal Tank

N. Pinto and S.M. Jesus

Rep 05/20 - SiPLAB
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<td>This report discusses the acoustic calibration of the Dual Accelerometer Vector Sensor version 2 (DAVS2) at the Arsenal tank, in Lisbon. The measurements took place on the 9\textsuperscript{th}, 10\textsuperscript{th} and 11\textsuperscript{th} of January 2018 and aimed at the calibration of the device in the frequency range of 1 to 4kHz. The calibration was carried out for sensitivity and directivity in two dimensions for the DAVS2 hydrophones and accelerometers.</td>
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Abstract

This report discusses acoustic the calibration of the Dual Accelerometer Vector Sensor - version 2 (DAVS2) at the Alfeite Arsenal tank, in Lisbon. The measurements took place on the 9th, 10th and 11th of January 2018 and aimed at the calibration of the device in the frequency range of 1 to 4kHz. The calibration was carried for sensitivity and directivity in two dimensions for the DAVS2 hydrophones and accelerometers.
Chapter 1

Introduction

The Dual Accelerometer Vector Sensor version 2 (DAVS2) was developed at CINTAL during EU H2020 project WiMUST in 2016-17 [1]. It is a complete autonomous underwater digital recorder based on DAVS device [2], with similar electronics but different sensing elements. DAVS2 consists in two parts: a) the recorder body with all the electronic support circuits and batteries, b) the sensing element containing the transducers. Figure 1.1 shows the DAVS2 while at the calibration facilities: digital recorder (the white cylinder on the bottom) and moulded sensor black tip fixed to a Delrin pole (top). The pole is used to attach sensing nose to support structures.

Figure 1.1: DAVS2 system: digital recorder white cylinder (bottom) and moulded sensor black tip (top) fixed to a white Delrin pole (top), connected through an umbilical cable.

DAVS2 uses 4 sensing elements composed of 2 custom made hydrophones and 2 accelerometers from PCB Piezotronics, model 356A17. All transducer are aligned inside
nose with the spacing dimensions seen on figure 1.2 a). The identification of transducers and the device axis orientation can also be seen. All these sensing elements are moulded into a black Polyurethane enclosure. Figure 1.2 b) show part of the moulding process, during device fabrication. This sensing element is connected to the digital recorder through a cable that can be detached and extended if needed.

![DAVS2 Axis.jpg](attachment:DAVS2 Axis.jpg)

(a) Transducers placement inside sensor black tip and axis orientations (b) Sensor tip in construction phase orientations

Figure 1.2: DAVS 2 nose schematic and construction detail

This report describes the results obtained for the calibration of the DAVS version 2, performed in the Arsenal do Alfeite acoustic tank, from 9th to 11th January, 2018, in Lisbon. The tank is covered on all sides including the surface by anechoic panels and it has dimensions of 8 m length, 5 m wide and 5 m depth. The calibration test was divided into two phases:

1. Sensitivity test: where it was checked the various frequency responses of sensors’ elements according to different sensor positioning, relative to an acoustic source;

2. Directivity test: where the DAVS2 device was fixed to the carriage rotating system in two different planes, vertical to measure the Y-Z directivity and horizontal to measure X-Y directivity, considering four different tonal frequencies.

This report is organized as follows: section 2 describes the signal path, including gains and compensations, from the physical sensor up to the digital file for both hydrophones and accelerometers of the DAVS2; section 3 describes the experimental methodology used during the calibration test; section 4 gives and analyses the results obtained through the calibration testing; and finally section 5 draws some conclusions and recommendations for future calibration tests.
Chapter 2

DAVS2 Signal Path

Since DAVS2 is a compact acquisition system there is no direct access to transducer terminals, in order to obtain output voltages and compare with the reference hydrophone output. The alternative is to convert the final digital WAVE file values to the voltage at transducer output, by inverting the signal path, to perform sensitivity estimation. Therefore in order to correctly calibrate DAVS2 we need to determine the exact signal path from transducers’ output to the stored WAVE file and which changes do the signal suffers through this path. Depending on signal source, the accelerometer or hydrophone, a different path is followed. The next sections will detail each of the signals path and the conversions to obtain the real input physical quantity, based on the information from DAVS device [2].

2.1 DAVS2 Hydrophone Forward and Backward path

The hydrophone signal path (figure 2.1) starts at the hydrophone sensitive input where the incident sound pressure waves are transformed into an electric voltage. This voltage will go through a pre-amplifier with two fixed gain options: 2x or 40x, selected in a device switch. The 2x gain is useful in order to avoid saturation for high intensity signals (close to source or explosive), whereas the 40x is the normal gain for general purpose recording. Through our experiments only the 40x gain was used. Following there is an user programmable gain amplifier (PGA), with an output range from -5 to 5 Volt. Depending on the gain selected by user from the available options (1x, 2x, 4x, 8x, 16x, 32x or 64x), the signal gets amplified and forwarded to a single ended to differential output circuit, which is responsible for adapting the output ranges of the PGA (± 5 V) to the input ranges of the analog to digital ADC converter (0-5 V). By using a differential input, the ADC require that 2 signals are used to represent the original signal we want to digitize. These signals will be 2 opposite signals, whose amplitudes are symmetrical around some reference value. The single ended to differential circuit creates these 2 signals from the PGA signal by dividing it by two and adding an offset of 2.5 Volt. This way, the differential signals will oscillate around 2.5 V and the extreme values will be 0 and 5 V, the maximum electrical ranges of the ADC input. This corresponds to an input range of ± 2.5 Volt, considering that both signals will oscillate around the 2.5 V offset. The output of the ADC is a digital signal, that is saved into a WAVE file by the micro-controller. Since
the WAVE file does not have information about the input range of the ADC, the digital
data is normalized in ±1 Volt. In the backward path, to obtain the calibrated value at
the input of ADC we need divide the normalized value read in the digital file by a
scale factor of 2.5, corresponding to the maximum value at the input. Division of 1 by
2.5 corresponds to a multiplying factor of 0.4. To simplify the math, the single ended
and ADC gains are expressed together as a division by 5 or a gain of 0.2x (0.5*0.4 = 0.2x) and
is termed throughout this report as ADC sensitivity. The selected PGA gain is obtained
from the WAVE file header, which stores this information. To better detail this path the
mathematical expressions that represent the signal passing through each component are
given below.

![DAVS2 Signal Paths Hyd.jpg](image)

Figure 2.1: Hydrophone signal path: from physical sensor input (left) to WAVE digital
file (right).

### 2.1.1 Voltage at hydrophone terminals

The voltage $V_{\text{hyd}}$ is usually referred as to Open Circuit Receiving Response (OCRR)
or Open Circuit Voltage (OCV). The OCRR/OCV is the frequency dependent voltage
generated by a transducer with nothing connected to its terminals, per $\mu$Pa of sound
pressure applied and its input. It is commonly referred to 1 Volt [dB re 1V],

$$V_{\text{hyd}}[\text{dB re} \ 1\text{V}] = 20 \times \log_{10}\left(\frac{V_{\text{hyd}}}{1[V]}\right) = 20 \times \log_{10}(V_{\text{hyd}}), \quad (2.1)$$

where $V_{\text{hyd}}[V]$ is the root mean square (rms) voltage, which correspond to the peak to
peak voltage $V_{\text{hyd}_\text{p2p}}$ divided by twice the square root of 2,

$$V_{\text{hyd}}[V] = \frac{V_{\text{hyd}_\text{p2p}}}{2 \times \sqrt{2}}. \quad (2.2)$$

When directly measuring the hydrophone output with an oscilloscope, the peak voltage
is an easy and practical value to obtain. However, in the DAVS2 we don’t have direct
access to hydrophone terminals, so this value must be obtained from the final digital raw
WAVE file.
2.1.2 DAVS2 hydrophone pre-amplifier gain

The purpose of the pre-amplifier stage is to amplify the very weak signal from the output terminals of the hydrophone. The DAVS2 has 2 fixed gains at pre-amplifier stage with 2X or 40X, meaning that when the signal goes through the pre-amplifier it is multiplied by 2 or 40. Since we are not using the 2X mode, the output voltage of the pre-amplifier $V_{pa}$ will then be

$$V_{pa}[V] = V_{hyd}[V] \times 40$$  \hfill (2.3)

2.1.3 DAVS2 hydrophone programmable gain amplifier (PGA)

The PGA is the stage that follows the pre-amplifier, and where the gain value $G_{pga_{hyd}}$ is software selected by the user and can be retrieved from the WAVE file header. The gain options are 1x, 2x, 4x, 8x, 16x, 32x or 64x. In a similar way to the pre-amplifier calculations, the PGA output $V_{pga_{hyd}}$ in Volt units is

$$V_{pga_{hyd}}[V] = V_{pa}[V] \times G_{pga_{hyd}}$$  \hfill (2.4)

2.1.4 DAVS2 hydrophone single ended to differential

The single ended to differential circuit adapts the amplitude of the signal by reducing the PGA output $V_{pga_{hyd}}$ by a factor of 2

$$V_{se2d_{hyd}}[V] = V_{pga_{hyd}}[V] \times 0.5$$  \hfill (2.5)

2.1.5 DAVS2 hydrophone ADC / WAVE file

The ADC does not change signal amplitude, however the normalized digital data in the WAVE file needs to be converted into a voltage at ADC input, while doing the backward path. So, the output of single ended to differential circuit $V_{se2d_{hyd}}$ is divided by 2.5 (or multiplied by 0.4) while passing through the ADC to the normalized WAVE data $WAVE_{V_{hyd}}$:

$$WAVE_{V_{hyd}} = V_{se2d_{hyd}}[V] \times 0.4$$  \hfill (2.6)

Note that we are not considering the digital value obtained at the output of the ADC (the raw digital sample present in the WAVE file) but the converted float value from that digital sample, which is normalized between -1 and 1. This is the value that we obtain while performing a plain read of the WAVE file in a software like Matlab.

2.1.6 DAVS2 hydrophone full forward and backward path

Joining all linear formulas above into one single formula, based on hydrophone OCR voltage $V_{hyd}$ and the user selected gain of PGA $G_{pga_{hyd}}$:

$$WAVE_{V_{hyd}} = V_{hyd}[V] \times 40 \times G_{pga_{hyd}} \times 0.5 \times 0.4 = V_{hyd}[V] \times G_{pga_{hyd}} \times 8$$  \hfill (2.7)
To convert the normalized values from a DAVS2 WAVE file $WAVE_{V_{hyd}}$ into the voltage at hydrophone terminals $V_{hyd}$, we can use (2.7) which simplifies to

$$V_{hyd}[V] = \frac{WAVE_{V_{hyd}}}{G_{pga_{hyd}} \times 8}$$

(2.8)

### 2.2 DAVS2 accelerometer forward and backward path

The accelerometer forward signal path (Figure 2.2) starts at the output of the IEPE power source, which has a voltage excursion of $\pm$ 5 Volt, gets through the PGA, where the signal is amplified by the user selected value (1x, 2x, 4x, 8x, 16x, 32x or 64x). Then the output PGA signal ($\pm$ 5 Volt) is conditioned in the single ended to differential converter for the ADC input range 0-5 Volt. At that stage the signal is divided by two and an offset of 2.5 Volt is applied. In this way, the signal will oscillate around 2.5 Volt and the minimum and maximum values will be 0 and 5 Volt, respectively, as in the hydrophone signal path. Then the signal is digitised and saved by the micro-controller to a digital WAVE file. Here, the ADC sensitivity will have the same value as in the hydrophone case with a gain of 0.2x.

![DAVS2 Signal Paths Acc.jpg](image)

Figure 2.2: Accelerometers’ signal path: accelerometer on the left hand side and the digital WAVE file output on the right hand side.

#### 2.2.1 DAVS2 accelerometer PGA, Single Ended to Differential and ADC/WAVE file

The signal path from the output of the IEPE power source $V_{acc}$ will be exactly the same as that from the output of hydrophone pre-amplifier, so the equations will be similar,

$$V_{pga_{acc}}[V] = V_{acc}[V] \times G_{pga_{acc}},$$

(2.9)

$$V_{se2d_{acc}}[V] = V_{pga_{acc}}[V] \times 0.5,$$

(2.10)

$$WAVE_{V_{acc}} = V_{se2d_{acc}}[V] \times 0.4.$$  

(2.11)
2.2.2 DAVS2 accelerometer full forward and backward path

Joining all linear formulas into one single formula, based on accelerometer output voltage $V_{acc}$ and the user selected gain of PGA $G_{pgaacc}$:

$$ WAVE_{V_{acc}} = V_{acc}[V] * G_{pgaacc} * 0.5 * 0.4 = V_{acc}[V] * G_{pgaacc} * 0.2. \quad (2.12) $$

To converts the normalized WAVE file values $WAVE_{V_{acc}}$ on to a voltage at the accelerometer terminals $V_{acc}$ we have

$$ V_{acc}[V] = \frac{WAVE_{V_{acc}}}{G_{pgaacc} * 0.2} \quad (2.13) $$

where this is based on the accelerometer PGA gain, retrieved from WAVE file header.
Chapter 3

DAVS2 Calibration experiment

The Arsenal do Alfeite facilities have a large tank, 8 m long, 5 m wide and 5 m deep, which was used for the DAVS2 calibration experiment. The main objectives of the experiment were to test the directional response of the accelerometers and to obtain the hydrophone frequency response. To find the transducers sensitivities the comparison method was used, acquiring data from DAVS2 and two reference hydrophones, as seen on Figure 3.1. The additional equipment can also be seen in the figure.

Figure 3.1: Setup used for sensitivity calculation, Z axis pointing to the source. The same setup was used for X and Y axis, only by rotating DAVS2 position on the carriage rail.
3.1 Used Equipment

To obtain the required data, the following equipment was used through these experiments.

3.1.1 Red Pitaya

For generating signals and acquiring hydrophone outputs, a RedPitaya StemLab was used, allowing for the synchronized signal generation and capture. A series of 20 cycles pulses were generated, at the desired tone frequency (1, 2, 3 and 4 kHz) and the respective responses captured. The received signals were stored in a text file, containing a single pulse. This text file has 32768 lines, where the first 16384 are the first channel voltage amplitude values (where the Reson near the source was connected) and the last 16384 were obtained from the second channel (the Reson near DAVS2). Each line has a time difference of 8.192 $\mu$seconds, based on the RedPitaya sampling frequency and decimation factor used (125 Msps/1024).

3.1.2 Source projector

The used projector was a Sensortech SX05 dogbone source, connected to an amplifier and to a signal generator (RedPitaya). The TVR of this device can be seen on Appendix A.

3.1.3 Reference hydrophones

Two reference Reson TC4033 hydrophones were used, one at 1 meter of the source and the other at 0.5 m of DAVS2. These hydrophones have a sensitivity for the used frequency of approximately -202 dB re V/$\mu$Pa. The individual sensitivity calibration data can be seen on Appendix B (placed near source) and C (placed near DAVS2).

3.1.4 Hydrophone amplifier

The amplifier used to amplify the reference hydrophone has an unknown gain, so some tests have been performed to determine its value. For each used frequency (1, 2, 3 and 4 kHz) the hydrophone signal was measured at the input and output of the amplifier. The measured RMS values was then related to determine the gain of the device. The results show that the amplifier has a gain of approximately 19.21 dB, as seen from Table 3.1. This gain must be considered when processing the reference hydrophones.
<table>
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<tr>
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<th>Voltage [mV]</th>
<th>Voltage ∆[dB]</th>
</tr>
</thead>
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<tr>
<td>Out 1</td>
<td>1</td>
<td>24.93</td>
<td>18.8</td>
</tr>
<tr>
<td>In 1</td>
<td></td>
<td>2.86</td>
<td></td>
</tr>
<tr>
<td>Out 2</td>
<td>2</td>
<td>28.10</td>
<td>18.9</td>
</tr>
<tr>
<td>In 2</td>
<td></td>
<td>3.20</td>
<td></td>
</tr>
<tr>
<td>Out 3</td>
<td>3</td>
<td>35.13</td>
<td>19.9</td>
</tr>
<tr>
<td>In 3</td>
<td></td>
<td>3.55</td>
<td></td>
</tr>
<tr>
<td>Out 4</td>
<td>4</td>
<td>17.99</td>
<td>19.3</td>
</tr>
<tr>
<td>In 4</td>
<td></td>
<td>1.95</td>
<td></td>
</tr>
<tr>
<td><strong>Average Gain</strong></td>
<td></td>
<td><strong>19.2</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Reference hydrophone amplifier gain tests and obtained gains.

### 3.1.5 DAVS2 Base Station

DAVS base station was used to capture DAVS2 output and save the WAVE files. This device connects to DAVS2 and allow the remote configuration and the direct saving of captured data into WAVE files. More information about this device can be seen on [2].

### 3.2 DAVS2 Sensitivity experiments

To determine the DAVS2 sensitivity, several tests were done by changing the DAVS2 direction plane pointing to source, as seen on Figure 3.2. There were acquisitions with only the accelerometer channels being recorded and others with both accelerometer and hydrophone channels turned on. In all experiments 20 cycles pulses were used, with a tone frequency of 1, 2, 3 or 4 kHz. For each experiment, 5 or 10 groups of oscilloscope captures were recorded, to be used for sensitivity calculation. The experiment axis respect the accelerometer axis, a X axis experiment means that the accelerometer positive X axis is pointing to source. Only the positive axis was tested. For Y and Z experiments (Y-Z plane) the sensing nose is placed vertically in the support structure, while for X-Y it is in the horizontal position.

During the first day, measurements with Z axis pointing to source were done, at depths of 2.9 m and 2.5 m for DAVS2 and source, respectively. The distance between source and DAVS2 was 3 m.

For the second day, the Y axis was tested, with both devices at 3.2 m depth and at 3 m range. The measurement of the Z axis was repeated with the same placement as for the Y axis.

On the third and last day, the X axis was tested with both devices placed at the centre of the tank (2.5 m depth) and at 3 m range.

### 3.3 DAVS2 directivity experiments

For the DAVS2 directivity several tests were performed, using various frequencies of the tone signal of 1, 2 3 and 4 kHz. During these tests the DAVS2 was fixed on a rotating
3.3. DAVS2 DIRECTIVITY EXPERIMENTS

Figure 3.2: Three tank setups used during DAVS2 sensitivity calibration (not on scale).

The experiments did rotate DAVS2 more than 360 degrees, so that there might be some overlap into the heading. During rotation a series of pulses were emitted by the source and no reference hydrophones were used in the tank. Figure 3.3 shows the setups used for the two plane experiments.

For the Z-Y plane, DAVS2 was placed at 2.9 m depth while the source was at 3.2 m. The source and DAVS2 were 3 m apart. Each frequency was tested, by rotating DAVS2 in clockwise (CW) and counter clockwise (CCW) directions, and doing a full rotation on each test. A total of 16 measurements were done, repeating each measurement twice.

For the plane X-Y DAVS2 and “dogbone” source were placed at 2.5 m depth and at a range of 3 m. The same 16 measurements were done, two experiments for each frequency-rotation direction combination.

Figure 3.3: Directivity experiments' schematic.
Chapter 4

DAVS2 Calibration Results

In order to perform DAVS2 calibration, MATLAB® was used to process the WAVE, compass and oscilloscope files. For each test the required files were grouped in a folder and a MATLAB script created to process each file. The folder naming follows the day of experiment (day 1, day 2 or day 3), the experiment number (as test 1, 2 3 or 4) and some experiment characteristic to easily recognize the folder content (e.g. X meaning that experiment was done for X axis). The experiments are identified by Dxy, meaning experiment y of day x. Below we detail the processing of each data file and the results obtained.

4.1 DAVS2 sensitivity calculation method

To obtain the hydrophone and accelerometer sensitivities, the MATLAB® script works as follows:

1. The first step is to convert WAVE channels data into voltages at respective transducer terminals with (2.8) and (2.13),

   \[ V_{\text{hyd}}[V] = \frac{\text{WAVE}_E_{V_{\text{hyd}}}}{G_{\text{pga}_{\text{hyd}}} * 8} \]  

   \[ V_{\text{acc}}[V] = \frac{\text{WAVE}_E_{V_{\text{acc}}}}{G_{\text{pga}_{\text{acc}}} * 0.2} \]

   These equations use the gains read in the WAVE file header.

2. The first pulse is isolated from the complete WAVE data and band passed between 500 and 5 kHz.

3. The reference hydrophones data is loaded from the RedPitaya text file. The data from Reson near DAVS or near the acoustic source is band pass filtered filtered. 20 peaks are identified and the first 9 are discarded (transient time), using only the following 9 peaks to determine the RMS voltage (\( V_{\text{RMS}_{\text{ref}}} \)). These 9 peaks are averaged before RMS. The last peaks are not used in order to minimize disturbances.
caused by the reflections of the tank. The 19 dB gain from amplifier is removed from the RMS value, obtaining the real voltage at reference hydrophone terminals.

4. From the DAVS2 hydrophones 20 peaks are also identified, discarding the first 9 and determining the RMS value from the following 9 peaks average ($V_{RMS_{hyd}}$).

5. The DAVS2 hydrophone sensitivities can now be obtained from RMS values ($V_{RMS_{hyd}}$ and $V_{RMS_{ref}}$), considering the reference Reson sensitivity $S_{ref}$ (-202 dB re V/µPa):

$$S_{hyd} = S_{ref} + 20log10(V_{RMS_{hyd}}) - 20log10(V_{RMS_{ref}})$$ (4.3)

6. For the acceleration sensitivity the same pulse of the front axis (the axis pointing to source, X, Y or Z) was isolated from the two accelerometers. The same 20 peaks are identified, the first 9 discarded and the following 9 averaged and root mean squared.

7. The accelerometer sensitivity is obtained from the pressure equivalent sensitivity $S_{peq}$, based on accelerometer voltage $V_{RMS_{acc}}$, reference hydrophone RMS voltage $V_{RMS_{ref}}$ and reference hydrophone sensitivity $S_{ref}$:

$$S_{peq} = S_{ref} + 20log10(V_{RMS_{acc}}) - 20log10(V_{RMS_{ref}})$$ (4.4)

This value is then linearised and referred to µPa units:

$$M_p = 10^{S_{peq}/20} * 10^6$$ (4.5)

8. And finally the accelerometer sensitivity $M_a$ is obtained through the relation of the acoustic impedance $\rho c$ and the frequency of the pulse signal $f$ (Hz), with the pressure equivalent sensitivity $M_p$ ($\rho$=1026, $c$=1500):

$$M_a = \frac{\rho c}{\omega} * M_p = \frac{\rho c}{2\pi f} * M_p$$ (4.6)

9. Several graphs are plotted with different measurements of DAVS2 hydrophones, accelerometers and reference hydrophones.

4.2 DAVS2 sensitivity

Several files were analysed for the sensitivity calculations as listed on Tables ??, 1 and 2 (in appendix D). The following results were obtained, based on the methods described above.

4.2.1 Hydrophone sensitivity

For the hydrophones, the obtained sensitivity values are those shown in Figure 4.1 and Table 4.1. There’s no valid data for the Y axis 2 kHz test which has a corrupted WAVE file. Figure 4.1 shows the results obtained into each hydrophone when DAVS2 was pointing to source in the three axis (X,Y,Z).
Can be seen on Figure 4.1 that each axis the two hydrophones have a relatively different value, even if they follow a similar curve shape. The X axis test put both hydrophones into a perpendicular position relative to wavefronts, that can cause changes in the device response. The shape of the device response for X axis is very different from the one of Y and Z axis. The Y and Z axis should have a similar response, since they’re on the same alignment inside DAVS2 sensing tip, but they show relatively large differences. When testing Y-Z plane the sensing tip is in a vertical position and the wave front should reach both hydrophones at the same time. However, the Y and Z experiments have differences in the devices depth, that can change the incident wave angle, and cause some variation on the amplitudes. In general hydrophone 1 has a higher sensitivity than hydrophone 2.

Figure 4.1: Hydrophone sensitivities obtained from the 3 distinct experiments. The accelerometer 1 is represented in X1, Y1 and Z1 while accelerometer 2 is represented by X2, Y2 and Z2

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Axis front</th>
<th>Sens. Hyd 1 (dB re V/µPa)</th>
<th>Sens. Hyd 2 (dB re V/µPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>-221.1</td>
<td>-222.8</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>-213.1</td>
<td>-214.7</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>-216.1</td>
<td>-220.1</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>-219.4</td>
<td>-221.9</td>
</tr>
<tr>
<td>1</td>
<td>Y</td>
<td>-220.2</td>
<td>-219.2</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>-223.3</td>
<td>-227.6</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>-221.4</td>
<td>-221.3</td>
</tr>
<tr>
<td>1</td>
<td>Z</td>
<td>-219.5</td>
<td>-217.4</td>
</tr>
<tr>
<td>2</td>
<td>Z</td>
<td>-224.3</td>
<td>-230.0</td>
</tr>
<tr>
<td>3</td>
<td>Z</td>
<td>-221.1</td>
<td>-223.3</td>
</tr>
<tr>
<td>4</td>
<td>Z</td>
<td>-216.3</td>
<td>-216.4</td>
</tr>
</tbody>
</table>

Table 4.1: Hydrophone sensitivities for each frequency and front axis combination experiments.

When looking at obtained waveforms some details can be seen. For X axis, the 1 (figure D.11 on appendix) and 2 kHz (figure D.21) waveforms shows a relatively good waveform shape, even considering the tank reflections, and following the expected shape without too much interference. However, when looking at 3 and 4 KHz (figure D.31 and figure D.41), more interferences are present and the hydrophone 2 shows a lower amplitude value. These
interferences can be caused by the device structure itself or by some refracting waves from the support structure.

For the Y axis a similar behaviour occurs. For 1 kHz (figure D.48) a good-looking waveform is present, while for 3 (figure D.58) and 4 kHz (figure D.65) there’s some significant noise in the waveforms. Both hydrophone amplitudes are similar.

Equally, Z axis have the same results (check figures D.76, D.80, D.90, D.100, D.104, D.114, D.118).

To obtain the hydrophone sensitivity curves for the Y-Z plane (DAVS2 in vertical position), the values from table 4.1 was averaged for each frequency and accelerometer, which resulted in the following figure 4.2 and table 4.2. Can be seen that hydrophone 1 presents a higher sensitivity than hydrophone 2, for 2 and 3 kHz. At 4 kHz they have an identical value, while at 1 kHz hydrophone 2 is more sensitive than 1. A negative peak can be seen at 2 kHz, where the response shows a lower sensitivity, specially for hydrophone 2.

<table>
<thead>
<tr>
<th>Frequency [kHz]</th>
<th>Hyd 1 [dB re V/uPa]</th>
<th>Hyd 2 [dB re V/uPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-219.8</td>
<td>-218.3</td>
</tr>
<tr>
<td>2</td>
<td>-224.3</td>
<td>-230.0</td>
</tr>
<tr>
<td>3</td>
<td>-222.2</td>
<td>-225.4</td>
</tr>
<tr>
<td>4</td>
<td>-218.9</td>
<td>-218.8</td>
</tr>
</tbody>
</table>

Table 4.2: Hydrophone sensitivities values for Y-Z plane and for each frequency.

4.2.2 Accelerometer sensitivity

For the accelerometers, the tests done for each axis X, Y and Z pointing to the acoustic source, are plotted in Figures 4.3, 4.4 and 4.5. The RMS voltage values for the reference hydrophone and accelerometer output are shown in tables ??, 1 and 2 on appendix.
The three tests performed for the X axis calibration (D3T1, D3T2 and D3T3 of Figure 4.3) showed that the sensitivity values of each accelerometer are almost identical and follow the same curve shape. The accelerometer 1 and 2 present however a distinct shape, with the #1 showing a higher sensitivity than #2, for frequencies higher than 1 kHz. Exception made for test 2 of the 3rd day at 4 kHz, where reference Reson voltage have a higher value than for the other tests (see Figure D.1). The voltage output of the accelerometers was always identical, so that difference in the sensitivity was caused by some interference into reference hydrophone values.

![Excel Graphs Ax.jpg](Excel Graphs Ax.jpg)

**Figure 4.3:** Accelerometers X axis sensitivity curves, for the 3 experiments done

Looking at the waveforms (on appendix) for 1 kHz can be seen that for the accelerometer 1 there is some cross talk, slowly appearing into Y axis but reaching a high amplitude. The signal has an intensity of the same order of magnitude as the one from X axis (around 2 mV). This is consistent through the 3 experiments as seen on figures D.4, D.7 and D.10. The accelerometer 2 is fine, with a lower cross talk between X and Y/Z axis. When we look for the amplitudes at 2 kHz, accelerometer 1 X axis amplitude reaches 8 mV but Y and Z axis are near 4 mV. For accelerometer 2 all the axis are at approximately 4 mV. The amplitude of the X axis for accelerometer 2 is nearly half of accelerometer 1, with a distinct pattern between them (D.15). This behaviour is consistent between all three tests as seen on figures D.14, D.17 and D.20. At 3 kHz the X axis output reaches 20 mV, for both accelerometers, with the Y axis reaching half that value (10 mV). However, accelerometer 2 has some large attenuation at the middle of the pulse, which lower the RMS value, as seen in figures D.24, D.27 and D.30. At 4 kHz the Z axis has the same amplitude as the X axis for accelerometer 1. For accelerometer 2 Z axis reaches half the X value. Once again this happens for the 3 experiments, as seen on figures D.34, D.37 and D.40. The amplitude of accelerometer 2 is also half of accelerometer 1 (D.35).

The Y axis experiments showed a similar behaviour than the X axis, where the sensitivity curves of each accelerometer have a distinct shape. On figure 4.4 can be seen the obtained values for the 2 experiments done (D2T1 and D2T2). Note a lack of the 2 kHz values from experiment 1 of second day (D2T1), due to WAVE file corruption.

For the Y axis and 1 kHz experiment, the accelerometer 1 amplitudes are identical for each axis (reaching 1.5-2 mV), while accelerometer 2 has an Y amplitude of 2.3 mV and X of 1.1 mV (see D.44 and D.47). For 2 and 3 kHz the Z axis of accelerometer 1 decreases but X and Y have the same amplitudes (see D.14 and D.24). In accelerometer 2, the
4.2. DAVS2 SENSITIVITY

X axis also decreases amplitude. At 4kHz the Y axis has the larger amplitude but in accelerometer 2 the Z axis has increased its value as seen in D.34.

The four Z axis experiments done have a large difference between the voltage values of reference hydrophone for first day (D1T2 and D1T3) and the values for second day (D2T3 and D2T4), which results in the figure D.3 on appendix. Positions have changed between days, as well as accelerometer gains (from 4x to 64x). Drive voltages of the Reson hydrophone didn’t changed between days, so the difference that exists between 2 and 3 kHz should be caused by the change of position. The differences of the accelerometer curves (Figure D.3a) between the two days can also be related to the response of the PGA, for the different gains settings used. From the experiments the values from figure 4.5 were obtained.

When looking at waveforms, the Z axis has a low output for 1kHz test on accelerometer 1. In all 4 experiments done it has always a lower value than the other axis. For the experiments done over the second day, accelerometer 2 has the Z axis value higher than the other axis (D.71, D.78). These differences can be caused by the change in the position of DAVS2 (depth in the tank). The same happens for 2kHz (D.82, D.85), 3kHz (D.92, D.95) and 4kHz (D.106, D.109). Even if the second day experiments have a stronger
信号在 Z 轴，X 轴有相似的振幅。

如果平均获得实验值，校准曲线如图 4.6 所示并在表 4.3 中呈现。对于 1, 2 和 3 kHz, 加速度计 1 和 2 的响应接近（差值小于 8 mV/(m/s²)）对于 Y 和 Z 轴，而 4 kHz 时的差值分别为 35.45 或 21.77 mV/(m/s²)，对于 Y 和 Z 轴分别。Y 轴在 2 和 4 kHz 有两个峰值，而 Z 轴在 1 kHz 时最小。对于 X 轴，存在显著差异，1 号传感器的灵敏度最高。2 号传感器在 34.24 和 54.27 mV/(m/s²) 附近呈相对平坦曲线，最小值出现在 1 kHz，最大值出现在 3 kHz。1 号传感器的范围更大，为 34.82 至 94.03 mV/(m/s²)，曲线形状在 2 kHz 时最大，在 1 kHz 时最小。这种行为并不反映探头的定位，即 2 号传感器应具有更高的灵敏度，因为它是前波的第一个传感器。

<table>
<thead>
<tr>
<th>频率 (kHz)</th>
<th>加速度计 1</th>
<th>加速度计 2</th>
<th>加速度计 1</th>
<th>加速度计 2</th>
<th>加速度计 1</th>
<th>加速度计 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34.82</td>
<td>34.24</td>
<td>18.15</td>
<td>23.86</td>
<td>14.65</td>
<td>15.74</td>
</tr>
<tr>
<td>2</td>
<td>94.03</td>
<td>46.01</td>
<td>38.20</td>
<td>46.09</td>
<td>17.78</td>
<td>22.78</td>
</tr>
<tr>
<td>3</td>
<td>76.12</td>
<td>54.27</td>
<td>32.12</td>
<td>27.89</td>
<td>28.71</td>
<td>24.25</td>
</tr>
<tr>
<td>4</td>
<td>84.55</td>
<td>40.44</td>
<td>75.23</td>
<td>39.78</td>
<td>53.16</td>
<td>74.93</td>
</tr>
</tbody>
</table>

表 4.3: 加速度计灵敏度值

图 4.6: 加速度计灵敏度

4.3 DAVS2 直向性计算方法

为了获得直向性图，MATLAB® 软件被用于单独处理每个 WAVE 文件。用于直向性响应的通道与投影面平行。如果我们旋转 DAVS2 并且 X-Y 平面，所用的文件来自 X 和 Y 加速度计轴。流程如下：

To obtain the directivity plots, MATLAB® software was used and each WAVE file processed individually. The used channels for directivity response correspond to the accelerometer axis that are in the plane of projection. If we are rotating DAVS2 around X-Y plane, the used files are from the X and Y accelerometer axis. The workflow is as follows:
4.4 DAVS2 DIRECTIVITY

1. Load WAVE file and isolate each channel. Create time arrays from acquisition date and time. Do not convert data using the WAVE normalized values.

2. Load compass file “DeviceDetect0_dddhhmmss.csv” and find the heading information relative to WAVE file time (using the first and the last WAVE sample times). Remember that compass file has all information from that day or capture, so the need to filter only the information’s relative to that WAVE file. When using the WAVE times, the process can be automated.

3. Find the start and finish rotation points by looking at compass heading information. The times, angles and indexes of that points are stored to separate each channel full rotation data.

4. Band-pass [0.5-5] kHz each channel and get it’s envelope, based on peak values.

5. Normalize each channel by it’s maximum value and convert it to logarithmic scale.

6. Isolate the full rotation data from each logarithmic data arrays. The WAVE file contains more data than that needed for a full rotation.

7. Plot graphs and directivity diagrams. This is done also through each of the previous steps, to obtain additional information’s about WAVE files.

All the process is automated, but some settings can be fine-tuned as e.g. for peak values or rotation detection. For the rotation detection, it’s known that the rotation speed was approximately 1.4 degrees per second and the compass sample rate is 1 Hz. When searching for the start of rotation, the adjacent heading values are compared to determine whether the difference between them is higher than 1 degree, assuming that DAVS2 is rotating when it happens. The end of rotation happens when the heading value crosses the start rotation angle.

4.4 DAVS2 directivity

To find the directivity response, the files listed on Table 3 (in appendix E) were analysed and the following results were obtained. For each plane and frequency, 4 captures were done, 2 for clockwise rotation direction and 2 for counter clockwise direction. For each frequency two groups were done, containing 2 files with the same frequency and the 2 rotation directions (CW and CCW). The 2 files was then overlapped and plotted on the same graph. Some individual experiments have noisy data or have missing information, so they were not used here. The following directional plots shows only data from one of the good groups, while the other group images are in appendix E. When the second group has valid data the results are similar to those of the first group.

The polar plot of figures 4.7 and 4.8 shows the obtained responses for the 2 rotation planes and the position of DAVS2 in the experiment. The CW and CCW rotation data are overlapped, for each accelerometer and the same frequency. The blue and purple lines are from accelerometer 1 while the red and green are the accelerometer 2 data. The DAVS2 position allows to easily compare the response of accelerometers with the device position. Note that when rotation start (0 degrees in polar plot axis) DAVS2 axis was
not exactly pointing to source, but around 20-40 degrees in clockwise direction. Positive angles denote the clockwise rotation direction, while the counter clockwise direction is in the negative angles direction. Note also that there are some small discontinuities at start and end of rotation due to bad alignment of acoustic data samples and heading data.

![XY Dir Compare.jpg](image)

**Figure 4.7:** Comparison of directional plots for X-Y axis.

For the X-Y plane, we found that when the X axis is pointing to source, the obtained amplitude change with higher frequencies. At 1 kHz, the response have a higher value than at 2, 3 or 4 kHz, and follows an “8” shape with some small attenuation on the opposite lobe. These last frequency values shows that the response attenuates significantly (always more than 4 dB) when pointing to source, which was not the expected. For the 1 kHz the response is the expected one, with the lobe pointing to source showing the higher amplitude, while the opposite lobe having some attenuation (2-4 dB) caused by the support structures. To confirm that this was the behaviour and that none device rotation in support have happened during experiments or any error during processing steps, the heading angle of all files was analysed. For the 1 kHz experiments the heading
4.4. DAVS2 DIRECTIVITY

angles (which can be seen on figures E.5 and E.6), was compared with the ones of 2 kHz (E.11 and E.12), 3 kHz (E.17, E.18), and 4 kHz (E.23 and E.24). All files have the same rotation pattern, so DAVS2 shouldn’t have been moved into support and no errors occurred when processing data. Compared also with the second experimental data (figures E.2, E.8, E.14, E.20), but the patterns are identical.

When Y axis is perpendicular to wave fronts the accelerometers also show a distinct response, depending on the positive or negative axis position (relative to accelerometer internal axis). When DAVS2 have Y axis pointing to source, the amplitudes always present some attenuation that can reach -8 dB (3 kHz). At the same time there are some significant variations between accelerometers as seen at 1, 3 and 4 kHz. The opposite direction present a well-formed lobe for all frequencies, which was the expected behaviour for the two positions Y and -Y (Y rotated 180 degrees). This could be related to cross-talk but a more detailed study should be made to confirm it.

![Figure 4.8: Comparison of directional plots for Y-Z axis.](image-url)
CHAPTER 4. DAVS2 CALIBRATION RESULTS

The Y-Z plane experiments (figure 4.8) shows also some variation across the tested frequency range. For the 1 kHz experiment, when Y is pointing to source, accelerometer 2 (red line) present an amplitude higher than accelerometer 1 (blue line), which is attenuated around 5 dB. However, when rotated 180 degrees there is an inversion on amplitudes, having accelerometer 1 the highest amplitude lobe and accelerometer 2 an attenuation of 2 dB. Similarly, when Z is pointing to source, accelerometer 1 (purple line) shows a higher amplitude than accelerometer 2 (green line). Again, when rotated 180 degrees, there is an inversion of amplitudes, with accelerometer 1 attenuated around -8 dB. For accelerometer 2, the shape follows an “8” figure, while for other cases it’s not notorious. For 2 kHz, when Y is pointing to source the 2 accelerometers have the maximum amplitude while when rotated 180 degrees, there’s an attenuation around 2-6 dB. For Z axis pointing to source accelerometer 1 have the maximum amplitude, while accelerometer 2 is attenuated 4 dB. The opposite direction have the maximum amplitude for both transducers. The 3 kHz Z axis shows an ”8” shape, with a small attenuation (2 dB) for -Z direction. The same happens for Y direction, but with a less visible shape. The Z axis main lobe happens when pointing to source, while when in the opposite direction there’s a reduction of 1 to 3 dB. At 4 kHz, the Y axis shows that accelerometer 1 (blue line) have the highest amplitude when pointing to source, while when rotated 180 degrees the lobe has a diminution of 4 dB. The inverse happens for accelerometer 2 in Y axis. The Z axis main lobe happens when pointing to source, while when in the opposite direction there’s a reduction of 2 to 5 dB.

Starting at 2 kHz the Z axis suffers a gradual reduction of amplitude, when not pointing to source. For the Y axis when not pointing to source, only accelerometer 1 behaves like that, the accelerometer 2 decreases in 1 and 2 kHz but then increase through 3 and 4 kHz. The lobe of Y axis accelerometer 1 pointing to source increase from 1 to 2 kHz maintaining the values across 3 and 4 kHz. The lobe of Y axis accelerometer 2 maintain the maximum value for 3 kHz but shows some reduction at 4 kHz.
Chapter 5

Results and Conclusions

After the analysis of the DAVS2 data, obtained from sensitivity and directivity experiments, the following conclusions may be drawn. The first is the importance of evaluating a device response when deployed, and not only consider the expected sensitivities from transducers. When developing such a complex underwater device, the transducers placement and device structure will affect significantly all the responses, as seen through this report. It’s also important to check how the waveforms are affected considering distinct frequencies.

The hydrophones’ response in Y-Z plane varies from -219.8 to -224.3 dB re V/µPa for hydrophone 1 and -218.3 to -230 dB re V/µPa for hydrophone 2. It was expected that hydrophone showed an omnidirection response on this plane, but some big variations were found. Specially for second hydrophone there’s a big variation of 11.7 dB, across tested frequencies. The first accelerometer only present a variation of 4.5 dB. For 3 and 4 kHz frequencies, the waveform analysis showed some interference’s that distorted the received signal. For lower frequencies the reflections from the tank don’t show any remarkable interference in the signal. The source of these interference’s is not known.

The accelerometers sensitivity response show that each axis have a distinct shape, in a broad range as 14.65-94.03 mV/(m/s²). The obtained values are in some case higher than the ones given by manufacturer for air applications. For the X axis, accelerometer 1 have a higher sensitivity than accelerometer 2, but with a difference as high as 48.02 mV at 2 kHz. This behaviour is probability caused by transducers placement distance inside nose, as well as by the structure itself. When sensing nose is pointing to source (X axis facing projector), the wave front reach first the accelerometer 2, then the accelerometer 1. It was supposed that the #2 have a higher sensitivity than #2, but the 3 experiments showed the inverse situation. More tests must be done to check this and also test DAVS2 in the reverse position (X axis pointing to wave propagation direction). For Y axis till 3 kHz both accelerometers have a similar amplitude and curve shape, with a maximum difference between them of 7.89 mV/(m/s²) at 2 KHz. At 4 kHz there’s a difference of 35.45 mV/(m/s²), with the higher sensitivity at accelerometer 1. For Z axis, accelerometers also showed a similar curve and amplitude till 3 kHz, while at 4 kHz a 21.77 mV/(m/s²) difference appears, with highest sensitivity at accelerometer 2. However, the curve shape for Y and Z are distinct, even if they are on the same plane and the responses theoretically should be identical. The Y axis have a peak at 2 kHz that Z axis have not. When testing this plane, the sensing element is placed at a vertical position, and if correctly aligned to
CHAPTER 5. RESULTS AND CONCLUSIONS

projector both transducer should receive the wave front at similar times. The rotation from Y to Z will not change transducers position inside nose, relative to projector distance (maintain the same distance) as occurs at X-Y plane. This difference between Y and Z axis can be attributed to some mechanical resonances in device body, due to fixation supports or uneven weight distribution of internal components. But further study should be carried out to find the real causes of these behaviors. These tests must be reproduced, taking some care in the device alignment and testing both the front of the axis (+X/+Y/+Z) as well as the opposite side (rotating the accelerometer front axis 180 degrees, -X/-Y/-Z). Also, the projector settings must be maintained between experiments. Some variation occurred between first and second day of experiments, that can affect the final results.

The directivity response patterns for X-Y shows an unexpected behaviour when sensor nose is back facing the emitter projector, for the X-Y plane. It was expected that this position have the higher intensity, but for frequencies higher than 2 kHz a huge attenuation occurs. The Y-Z rotation plane have some more stable patterns, recalling the typical ”8” shape. However, the attenuation value is not constant across the frequencies and axis. No significant differences were found in the two rotation directions. A similar analysis should be done using the hydrophones channels. It was seen that Y and Z axis, although are on the same plane, the responses have a significant difference between them. The directivity response analysis will allow to confirm and quantify this behaviour.

After this analysis there are some identified errors in the measurement data, which we must be aware when considering these results. These errors, caused by noises in the facilities or corrupted WAVE files, decrease the data reliability. This is something that should be taken into account for future experiments, and always trying to double the experiments to achieve redundant data under the same settings.

The attachment and placement setups should also be chosen and maintained during experiments, since they will influences the measurements. The experiments should align the source and DAVS axis, and be done consistently in the same positions. The changes in position during the different experiments, will influence the results and the devices response. A calibration experiment should be as uniform as possible, in terms of positioning. Also, with these devices containing several transducers, can be difficult to subject all transducers to the same wavefront. Some effort must be made when preparing the experiments, trying to leave the sensors equally spaced around the projection axis. The attachment pole of device can also be a cause of interference. Depending on the fixation structures, some very small vibrations around that fixation point can occur, that will interfere with the accelerometer response.

Since this is an experimental device, the expected performance can be very distinct from the real performance. The device construction, materials used and transducer placement can have a huge impact on the expected performance. The proximity between transducers and the sensor structure can cause mutual interferences, that affect the devices response. That can easily be seen when comparing the hydrophones response for Y-Z plane, where theoretically they should have identical values but in real data is not the case. Some changes in the design and placement of transducers inside sensors nose may improve the device performance, however further studies on this must be made.

For future experiments, the use of more tone frequencies to cover intermediate zones, and increasing the tested range to higher frequencies are good options. This will allow us to increase the sensitivity resolution and see how DAVS2 perform between the frequencies
used in this work.
Bibliography


Appendices

A SX05 Source typical TVR

Nominal TVR curve of the barrel stave flexi-tensional transducer (dogbone)

![Nominal TVR curve of the barrel stave flexi-tensional transducer (dogbone)](image)

Figure A.1: Nominal TVR curve of the barrel stave flexi-tensional transducer (dogbone source)
B  Reference Reson 1 Calibration report

Receive sensitivity response of the Reson hydrophone TC4033 with serial number 4715101.
C Reference Reson 2 Calibration report

Receive sensitivity response of the Reson hydrophone TC4033 with serial number 4715102.
D  DAVS2 Sensitivity Additional Plots

For the sensitivity calculations the tables below resumes the used files, the grouping made for processing and the values obtained (RMS voltages and sensitivities). The grouping of files were done based on frequency and axis pointing to source. Table shows also the filenames of scope and WAVE and the group folder name. Note that are missing the 2 kHz from day 2 tests 2 and 4, because the WAVE files was corrupted and didn’t load into Matlab (or any other software).

Then, the first subchapter D.1 shows the voltages values used for accelerometer sensitivity calculations. The graphs present the values from the tables belows, grouped by accelerometer and experiment. The following subchapter shows the voltage waveforms from WAVE and scope files, plotted from Matlab. For an experiment without hydrophone, first figure shows accelerometers output with the three axis overlapped into each graph. The second figure shows the waveforms of the interest axis (the one pointing to source) with peaks and RMS values identified. The third image shows the output of scope file, with the two Reson hydrophone waveforms and the peaks identified. The higher amplitude is the hydrophone near source while the other is the one near DAVS2. For an experiment with hydrophone capture, first and second figures shows the same accelerometer waveforms, third figure shows two hydrophone output and the last figure shows the three hydrophone peaks and RMS values. Note that the Reson voltage was captured after the amplifier, so have a gain of 19 dB. The green trace shows the real value, used for sensitivity calculation.

<table>
<thead>
<tr>
<th>Group Folder</th>
<th>WAVE File</th>
<th>Scope file</th>
<th>f [kHz]</th>
<th>Ref RMS[mV]</th>
<th>Hyd1 RMS[mV]</th>
<th>Hyd2 RMS[mV]</th>
<th>Hyd1 Sens[dBV/uPa]</th>
<th>Hyd2 Sens[dBV/uPa]</th>
<th>Acc1 RMS[mV]</th>
<th>Acc2 RMS[mV]</th>
<th>Acc1 Sens[mV/m/s²]</th>
<th>Acc2 Sens[mV/m/s²]</th>
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<td>91249</td>
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</tbody>
</table>

Table 1: Used files for X axis sensitivity
### Table 2: Used files for Y axis sensitivity

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<thead>
<tr>
<th>Group Folder</th>
<th>WAVE File</th>
<th>Scope file</th>
<th>f [kHz]</th>
<th>Ref RMS[mV]</th>
<th>Hyd1 RMS[mV]</th>
<th>Hyd2 RMS[mV]</th>
<th>Hyd1 Sens[dBV/uPa]</th>
<th>Hyd2 Sens[dBV/uPa]</th>
<th>Acc1 RMS[mV]</th>
<th>Acc2 RMS[mV]</th>
<th>Acc1 Sens[mV/m/s²]</th>
<th>Acc2 Sens[mV/m/s²]</th>
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<tbody>
<tr>
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<td>1.7775</td>
<td>1.6388</td>
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### Table 3: Used files for Z axis sensitivity

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<thead>
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<th>Group Folder</th>
<th>WAVE File</th>
<th>Scope file</th>
<th>f [kHz]</th>
<th>Ref RMS[mV]</th>
<th>Hyd1 RMS[mV]</th>
<th>Hyd2 RMS[mV]</th>
<th>Hyd1 Sens[dBV/uPa]</th>
<th>Hyd2 Sens[dBV/uPa]</th>
<th>Acc1 RMS[mV]</th>
<th>Acc2 RMS[mV]</th>
<th>Acc1 Sens[mV/m/s²]</th>
<th>Acc2 Sens[mV/m/s²]</th>
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<tr>
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<tr>
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<tr>
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<td>5.8038</td>
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<td>5.8455</td>
<td>77.1498</td>
<td>39.974</td>
</tr>
</tbody>
</table>
D.1 Accelerometer voltages used for sensitivity calculations

Figure D.1: Accelerometers X axis RMS voltages, grouped by accelerometer and experiment

(a) Accelerometer X axis experiments Voltages
(b) Ref. Hydrophone Voltage

Figure D.2: Accelerometers Y axis RMS voltages, grouped by accelerometer and experiment

(a) Accelerometer Y axis experiments Voltages
(b) Ref. Hydrophone Voltage
Figure D.3: Accelerometers Z axis RMS voltages, grouped by accelerometer and experiment.

(a) Accelerometer Z axis experiments Voltages

(b) Ref. Hydrophone Voltage
D.2 X Axis at 1 kHz

Day 3 test 1 without hydrophone

![Figure D.4: Accelerometer Waveforms for 1 kHz (No Hydrophone)](at-P10216011091212Acc.jpg)

Day 3 test 3 without hydrophone
Figure D.5: X axis Accelerometer Waveforms for 1 kHz with RMS value marked

Figure D.6: Reson reference hydrophone waveform for X axis, 1 kHz
Figure D.7: Accelerometer Waveforms for 1 kHz (No Hydrophone)

Figure D.8: X axis Accelerometer Waveforms for 1 kHz with RMS value marked
Figure D.9: Reson reference hydrophone waveform for X axis, 1 kHz
Day 3 test 2 with hydrophone

Figure D.10: Accelerometer Waveforms for 1 kHz (With Hydrophone)

Figure D.11: X axis Accelerometer Waveforms for 1 kHz with RMS value marked
Figure D.12: DAVS2 Hydrophone waveform for X axis, 1 kHz

Figure D.13: Reson reference and DAVS2 hydrophone waveform for X axis, 1 kHz
D.3 X Axis at 2 kHz

Day 3 test 1 without hydrophone

Figure D.14: Accelerometer Waveforms for 2 kHz (No Hydrophone)

Day 3 test 3 without hydrophone
Figure D.15: X axis Accelerometer Waveforms for 2 kHz with RMS value marked

Figure D.16: Reson reference hydrophone waveform for X axis, 2 kHz
Figure D.17: Accelerometer Waveforms for 2 kHz (No Hydrophone)

Figure D.18: X axis Accelerometer Waveforms for 2 kHz with RMS value marked
Figure D.19: Reson reference hydrophone waveform for X axis, 2 kHz
Day 3 test 2 with hydrophone

Figure D.20: Accelerometer Waveforms for 2 kHz (With Hydrophone)

Figure D.21: X axis Accelerometer Waveforms for 2 kHz with RMS value marked
Figure D.22: DAVS2 Hydrophone waveform for X axis, 2 kHz

Figure D.23: Reson reference and DAVS2 hydrophone waveform for X axis, 2 kHz (ERROR in presented RMS, need to remove 19 dB Amplifier)
D.4  X Axis at 3 kHz

Day 3 test 1 without hydrophone

Figure D.24: Accelerometer Waveforms for 3 kHz (No Hydrophone)

Day 3 test 3 without hydrophone
Figure D.25: X axis Accelerometer Waveforms for 3 kHz with RMS value marked

Figure D.26: Reson reference hydrophone waveform for X axis, 3 kHz
Figure D.27: Accelerometer Waveforms for 3 kHz (No Hydrophone)

Figure D.28: X axis Accelerometer Waveforms for 3 kHz with RMS value marked
Figure D.29: Reson reference hydrophone waveform for X axis, 3 kHz
Day 3 test 2 with hydrophone

Figure D.30: Accelerometer Waveforms for 3 kHz (With Hydrophone)

Figure D.31: X axis Accelerometer Waveforms for 3 kHz with RMS value marked
Figure D.32: DAVS2 Hydrophone waveform for X axis, 3 kHz

Figure D.33: Reson reference and DAVS2 hydrophone waveform for X axis, 3 kHz
D.5  X Axis at 4 kHz

Day 3 test 1 without hydrophone

Figure D.34: Accelerometer Waveforms for 1 kHz (No Hydrophone)

Day 3 test 3 without hydrophone
Figure D.35: X axis Accelerometer Waveforms for 4 kHz with RMS value marked

Figure D.36: Reson reference hydrophone waveform for X axis, 4 kHz
Figure D.37: Accelerometer Waveforms for 4 kHz (No Hydrophone)

Figure D.38: X axis Accelerometer Waveforms for 4 kHz with RMS value marked
Figure D.39: Reson reference hydrophone waveform for X axis, 4 kHz
Day 3 test 2 with hydrophone

Figure D.40: Accelerometer Waveforms for 4 kHz (With Hydrophone)

Figure D.41: X axis Accelerometer Waveforms for 4 kHz with RMS value marked
Figure D.42: DAVS2 Hydrophone waveform for X axis, 4 kHz

Figure D.43: Reson reference and DAVS2 hydrophone waveform for X axis, 4 kHz
D.6 Y Axis at 1 kHz

Day 2 test 2 without hydrophone

Figure D.44: Accelerometer Waveforms for 1 kHz (No Hydrophone)

Day 2 test 1 with hydrophone
Figure D.45: Y axis Accelerometer Waveforms for 1 kHz with RMS value marked

Figure D.46: Reson reference hydrophone waveform for Y axis, 1 kHz
Figure D.47: Accelerometer Waveforms for 1 kHz (With Hydrophone)

Figure D.48: Y axis Accelerometer Waveforms for 1 kHz with RMS value marked
Figure D.49: DAVS2 Hydrophone waveform for Y axis, 1 kHz

Figure D.50: Reson reference and DAVS2 hydrophone waveform for Y axis, 1 kHz
D.7 Y Axis at 2 kHz

Day 2 test 2 without hydrophone

![Waveform Graph](Waveforms/y/DATA_Tx_P10216010104417_Acc.jpg)

Figure D.51: Accelerometer Waveforms for 2 kHz

Day 2 test 1 with hydrophone

Corrupted WAVE
Figure D.52: Y axis Accelerometer Waveforms for 2 kHz with RMS value marked

Figure D.53: Reson reference hydrophone waveform for Y axis, 2 kHz
D.8 Y Axis at 3 kHz

Day 2 test 2 without hydrophone

![Waveform plots for 3 kHz](image.png)

Figure D.54: Accelerometer Waveforms for 3 kHz

Day 2 test 1 with hydrophone
Figure D.55: Y axis Accelerometer Waveforms for 3 kHz with RMS value marked

Figure D.56: Reson reference hydrophone waveform for Y axis, 3 kHz
Figure D.57: Accelerometer Waveforms for 3 kHz (With Hydrophone)

Figure D.58: Y axis Accelerometer Waveforms for 3 kHz with RMS value marked
Figure D.59: DAVS2 Hydrophone waveform for Y axis, 3 kHz

Figure D.60: Reson reference and DAVS2 hydrophone waveform for Y axis, 3 kHz
D.9  Y Axis at 4 kHz

Day 2 test 2 without hydrophone

Figure D.61: Accelerometer Waveforms for 4 kHz

Day 2 test 1 with hydrophone
Figure D.62: Y axis Accelerometer Waveforms for 4 kHz with RMS value marked

Figure D.63: Reson reference hydrophone waveform for Y axis, 4 kHz
Figure D.64: Accelerometer Waveforms for 4 kHz (With Hydrophone)

Figure D.65: Y axis Accelerometer Waveforms for 4 kHz with RMS value marked
Figure D.66: DAVS2 Hydrophone waveform for Y axis, 4 kHz

Figure D.67: Reson reference and DAVS2 hydrophone waveform for Y axis, 4 kHz
D.10 Z Axis at 1 kHz

Day 1 test 2 without hydrophone

Figure D.68: Accelerometer Waveforms for 1 kHz

Day 2 test 3 without hydrophone
Figure D.69: Z axis Accelerometer Waveforms for 1 kHz with RMS value marked

Figure D.70: Reson reference hydrophone waveform for Z axis, 1 kHz
Figure D.71: Accelerometer Waveforms for 1 kHz

Figure D.72: Z axis Accelerometer Waveforms for 1 kHz with RMS value marked
Figure D.73: Reson reference hydrophone waveform for Z axis, 1 kHz
Day 1 test 3 with hydrophone

Figure D.74: Accelerometer Waveforms for 1 kHz (With Hydrophone)

Figure D.75: Z axis Accelerometer Waveforms for 1 kHz with RMS value marked
D. DAVS2 SENSITIVITY ADDITIONAL PLOTS

Figure D.76: DAVS2 Hydrophone waveform for Z axis, 1 kHz

Figure D.77: Reson reference and DAVS2 hydrophone waveform for Z axis, 1 kHz
Day 2 test 4 with hydrophone

Figure D.78: Accelerometer Waveforms for 1 kHz (With Hydrophone)

Figure D.79: Z axis Accelerometer Waveforms for 1 kHz with RMS value marked
D. DAVS2 SENSITIVITY ADDITIONAL PLOTS

Figure D.80: DAVS2 Hydrophone waveform for Z axis, 1 kHz

Figure D.81: Reson reference and DAVS2 hydrophone waveform for Z axis, 1 kHz
D.11 Z Axis at 2 kHz

Day 1 test 2 without hydrophone

Figure D.82: Accelerometer Waveforms for 2 kHz

Day 2 test 3 without hydrophone
D. DAVS2 SENSITIVITY ADDITIONAL PLOTS

Figure D.83: Z axis Accelerometer Waveforms for 2 kHz with RMS value marked

Figure D.84: Reson reference hydrophone waveform for Z axis, 2 kHz
Figure D.85: Accelerometer Waveforms for 2 kHz

Figure D.86: Z axis Accelerometer Waveforms for 2 kHz with RMS value marked
Figure D.87: Reson reference hydrophone waveform for Z axis, 2 kHz
Day 1 test 3 with hydrophone

Figure D.88: Accelerometer Waveforms for 2 kHz (With Hydrophone)

Figure D.89: Z axis Accelerometer Waveforms for 2 kHz with RMS value marked
Figure D.90: DAVS2 Hydrophone waveform for Z axis, 2 kHz

Figure D.91: Reson reference and DAVS2 hydrophone waveform for Z axis, 2 kHz
Day 2 test 4 with hydrophone

Corrupted WAVE file
D.12 Z Axis at 3 kHz

Day 1 test 2 without hydrophone

Figure D.92: Accelerometer Waveforms for 3 kHz

Day 2 test 3 without hydrophone
Figure D.93: Z axis Accelerometer Waveforms for 3 kHz with RMS value marked

Figure D.94: Reson reference hydrophone waveform for Z axis, 3 kHz
Figure D.95: Accelerometer Waveforms for 3 kHz

Figure D.96: Z axis Accelerometer Waveforms for 3 kHz with RMS value marked
Figure D.97: Reson reference hydrophone waveform for Z axis, 3 kHz
Day 1 test 3 with hydrophone

Figure D.98: Accelerometer Waveforms for 3 kHz (With Hydrophone)

Figure D.99: Z axis Accelerometer Waveforms for 3 kHz with RMS value marked
Figure D.100: DAVS2 Hydrophone waveform for Z axis, 3 kHz

Figure D.101: Reson reference and DAVS2 hydrophone waveform for Z axis, 3 kHz
Day 2 test 4 with hydrophone

Figure D.102: Accelerometer Waveforms for 3 kHz (With Hydrophone)

Figure D.103: Z axis Accelerometer Waveforms for 3 kHz with RMS value marked
Figure D.104: DAVS2 Hydrophone waveform for Z axis, 3 kHz

Figure D.105: Reson reference and DAVS2 hydrophone waveform for Z axis, 3 kHz
D.13 Z Axis at 4 kHz

Day 1 test 2 without hydrophone

Figure D.106: Accelerometer Waveforms for 4 kHz

Day 2 test 3 without hydrophone
Figure D.107: Z axis Accelerometer Waveforms for 4 kHz with RMS value marked

Figure D.108: Reson reference hydrophone waveform for Y axis, 4 kHz
Figure D.109: Accelerometer Waveforms for 4 kHz

Figure D.110: Z axis Accelerometer Waveforms for 4 kHz with RMS value marked
Figure D.111: Reson reference hydrophone waveform for Z axis, 4 kHz
Day 1 test 3 with hydrophone

Figure D.112: Accelerometer Waveforms for 4 kHz (With Hydrophone)

Figure D.113: Z axis Accelerometer Waveforms for 4 kHz with RMS value marked
Figure D.114: DAVS2 Hydrophone waveform for Z axis, 4 kHz

Figure D.115: Reson reference and DAVS2 hydrophone waveform for Z axis, 4 kHz
Day 2 test 4 with hydrophone

Figure D.116: Accelerometer Waveforms for 4 kHz (With Hydrophone)

Figure D.117: Z axis Accelerometer Waveforms for 4 kHz with RMS value marked
Figure D.118: DAVS2 Hydrophone waveform for Z axis, 4 kHz

Figure D.119: Reson reference and DAVS2 hydrophone waveform for Z axis, 4 kHz
E  DAVS2 Directivity Directional Plots

For the directivity calculations, the Table 3 resumes the used files and the grouping made for processing. The grouping of files were done based on time of acquisition and setup used (with or without hydrophone turned on). Table contains also orientation axis, frequency, placement distances and additional notes for each file.

<table>
<thead>
<tr>
<th>WAVE File name</th>
<th>Rot. plane</th>
<th>f [kHz]</th>
<th>Rotation Direction</th>
<th>Setup</th>
<th>DAVS Depth [m]</th>
<th>Source Depth [m]</th>
<th>Notes</th>
<th>Group Folder</th>
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<td>No HYD</td>
<td>2.9</td>
<td>3.2</td>
<td>Merged these 2 files for a complete rotation</td>
<td>Day2 Test1</td>
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<td>No HYD</td>
<td>2.9</td>
<td>3.2</td>
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<td>With HYD</td>
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<td>3.2</td>
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<td>With HYD</td>
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<td>3.2</td>
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<td>With HYD</td>
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<td>3.2</td>
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<td>Clockwise</td>
<td>With HYD</td>
<td>2.9</td>
<td>3.2</td>
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<td>CounterClock</td>
<td>With HYD</td>
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<td>With HYD</td>
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<td>X - Y</td>
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<td>113146</td>
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</table>

Table 4: Used files for directivity calculations

Following subchapter contains the directional plot for each accelerometer, based on clockwise and counter clockwise rotations. The first 2 images shows the individual frequency polar plot, for each plane. The first one is the same from the main text, while the second use the data from the second experiment. Comparing the 2 images just show they have the same result and both curves have the same shape. Exceptions for 3 and 4 kHz for X-Y where a lack of full rotation and some interferences in the data were present, respectively.
Then, the following images are from individual. The first image was generated by P.J. Santos and is used for comparison only. The second image is the clockwise rotation and the third is the counter clockwise rotation. Each subchapter correspond to a specific frequency and rotation plane. Note that for 3 and 4 kHz there’s no P.J. Santos figures for comparison. The corresponding linear plot of all WAVE data with heading information overlaped, is also showed.
E. DAVS2 DIRECTIVITY DIRECTIONAL PLOTS

E.1 X-Y Axis at 1 kHz

Figure E.1: Directivity plot for X-Y 1 kHz experiments (CW and CCW rotations)

Figure E.2: Directivity plot for X-Y 1 kHz experiment 2 (CW and CCW rotations)
Figure E.3: Plot for X-Y 1 kHz experiment (CW rotation)

Figure E.4: Plot for X-Y 1 kHz experiment (CCW rotation)
Figure E.5: Time Plot for X-Y 1 kHz CW experiment

Figure E.6: Time Plot for X-Y 1 kHz CCW experiment
E.2 X-Y Axis at 2 kHz

Figure E.7: Directivity plot for X-Y 2 kHz experiments (CW and CCW rotations)

Figure E.8: Directivity plot for X-Y 2 kHz experiment 2 (CW and CCW rotations)
Figure E.9: Plot for X-Y 2 kHz experiment (CW rotation)

Figure E.10: Plot for X-Y 2 kHz experiment (CCW rotation)
Figure E.11: Time Plot for X-Y 2 kHz CW experiment

Figure E.12: Time Plot for X-Y 2 kHz CCW experiment
E.3 X-Y Axis at 3 kHz

Figure E.13: Directivity plot for X-Y 3 kHz experiments (CW and CCW rotations)

Figure E.14: Directivity plot for X-Y 3 kHz experiment 2 (CW and CCW rotations)
Figure E.15: Plot for X-Y 3 kHz experiment (CW rotation)

Figure E.16: Plot for X-Y 3 kHz experiment (CCW rotation)
Figure E.17: Time Plot for X-Y 3 kHz CW experiment

Figure E.18: Time Plot for X-Y 3 kHz CCW experiment
E.4 X-Y Axis at 4 kHz

Figure E.19: Directivity plot for X-Y 4 kHz experiments (CW and CCW rotations)

Figure E.20: Directivity plot for X-Y 4 kHz experiment 2 (CW and CCW rotations)
Figure E.21: Plot for X-Y 4 kHz experiment (CW rotation)

Figure E.22: Plot for X-Y 4 kHz experiment (CCW rotation)
Figure E.23: Time Plot for X-Y 1 kHz CW experiment

Figure E.24: Time Plot for X-Y 1 kHz CCW experiment
E.5  Y-Z Axis at 1 kHz

Figure E.25: Directivity plot for Y-Z 1 kHz experiments (CW and CCW rotations)

Figure E.26: Directivity plot for Y-Z 1 kHz experiment 2 (CW and CCW rotations)
Figure E.27: Plot for Y-Z 1 kHz experiment (CW rotation)

Figure E.28: Plot for Y-Z 1 kHz experiment (CCW rotation)
Figure E.29: Time Plot for Y-Z 1 kHz CW experiment

Figure E.30: Time Plot for Y-Z 1 kHz CCW experiment
E.6  Y-Z Axis at 2 kHz

Figure E.31: Directivity plot for Y-Z 2 kHz experiments (CW and CCW rotations)

Figure E.32: Directivity plot for Y-Z 2 kHz experiment 2 (CW and CCW rotations)
Figure E.33: Plot for Y-Z 2 kHz experiment (CW rotation)

Figure E.34: Plot for Y-Z 2 kHz experiment (CCW rotation)
Figure E.35: Time Plot for Y-Z 2 kHz CW experiment

Figure E.36: Time Plot for Y-Z 2 kHz CCW experiment
E.7 Y-Z Axis at 3 kHz

Figure E.37: Directivity plot for Y-Z 3 kHz experiments (CW and CCW rotations)

Figure E.38: Directivity plot for Y-Z 3 kHz experiment 2 (CW and CCW rotations)
Figure E.39: Plot for Y-Z 3 kHz experiment (CW rotation)

Figure E.40: Plot for Y-Z 3 kHz experiment (CCW rotation)
Figure E.41: Time Plot for Y-Z 3 kHz CW experiment

Figure E.42: Time Plot for Y-Z 3 kHz CCW experiment
E.8  Y-Z Axis at 4 kHz

Figure E.43: Directivity plot for Y-Z 4 kHz experiments (CW and CCW rotations)

Figure E.44: Directivity plot for Y-Z 4 kHz experiment 2 (CW and CCW rotations)
Figure E.45: Plot for Y-Z 4 kHz experiment (CW rotation)

Figure E.46: Plot for Y-Z 4 kHz experiment (CCW rotation)
Figure E.47: Time Plot for Y-Z 4 kHz CW experiment

Figure E.48: Time Plot for Y-Z 4 kHz CCW experiment