Calibration and characterization of the ELVIS hydrophones

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Abstract

Calibration is an important field and is used everywhere from education, research and industry. Every electrical equipment has to be calibrated during manufacturing and even over time as it is worn down. The purpose of calibration is to come as close as possible to the true value. The question is how close is close enough and how close is possible? Because even the equipment used for calibration needs calibrating, which in turn also needs calibrating and so on.

This thesis will be about the hydrophones used by the system ELVIS. The method of choice is calibration by comparison. Its idea is to compare the signal received by the uncalibrated transducer with the same signal received by an already calibrated one. This might seem trivial but there are many things to be considered.

ELVIS uses 47 hydrophones. The frequency range subjected to calibration is 30-250 kHz which leads to a huge amount of data to be recorded, analysed and presented. The result shows that each individual hydrophone performs similar to each other. Because of the insecurities regarding the reference hydrophone, no absolute measurements will be presented.

Sammanfattning

Kalibrering är ett väldigt viktigt område och används dagligen inom olika verksamheter. I stort sätt allting behöver kalibreras dels vid tillverkning men också efterhand det åldras, slits, skadas eller byter användningsområde. Meningen med kalibrering är att komma så nära det absoluta värdet som möjligt. Frågan är hur nära det absoluta värdet man behöver komma för bra resultat och framförallt, hur nära det är möjligt att komma? För även mätutrustningen behöver kalibreras, och mätutrustningen som kalibrerar mätutrustningen och så vidare.

Detta examensarbete kommer handla om att kalibrera hydrofonerna som används till mätsystemet ELVIS. Metoden som används kallas jämförelsemetoden och går ut på att man jämför signalen som hydrofonen man vill kalibrera tar emot med en signal som en känd(kalibrerad) hydrofon tar emot, vid samma tillfälle. Vid första anblick kan det låta rätt trivialt men det kan bli en del komplikationer.

ELVIS använder sig av 47 hydrofoner. Frekvensområdet som ska kalibreras ligger mellan 30-250 kHz, detta leder till stor mängd data som ska analyseras och presenteras. Resultatet visar att varje enskild hydrofon presterar bra i förhållande till varandra. På grund av osäkerheter kring referenshydrofonen presenteras inga absoluta mätningar.

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1 Introduction

Calibration is fundamental for accurate measurements and to eliminate systematic errors. Systematic errors may occur during fabrication or over time, more commonly it is caused by damage or interference from the environment, for example temperature. This makes continuous calibration necessary with the industrial standards being once a year, it is a balance of cost and accuracy [1]. Most of the time, a calibration requires an already calibrated reference. It is of utmost importance that you can trust your reference. This is known as traceability and means that the calibration that is performed is traceable to the "absolute truth".

1.1 Goal and purpose

The goal and purpose of this master's thesis is to design a procedure to determine how accurate the hydrophones will perform during different conditions and how to compensate for any errors that might occur. The reason to have calibrated hydrophones is to be able to draw more final conclusion of the field measurements of real animals using ELVIS.

The following questions will be investigated:

- Will each of the hydrophones perform similar under similar conditions?
- How will they respond to different frequencies?
- How good is the chosen method compared to industrial calibration?
- Can the calibration be automated during field usage?

1.2 Previous Studies

There has been several previous studies in the field of hydrophone calibration. Most other studies involve a certain point of interest such as phase characteristics, non-linearity or a specific frequency range.

1.2.1 Calibration through self-reciprocity

This methods is valid if the hydrophone that is subjected to calibration is reciprocal (can be used as both transmitter and receiver) [2, 3]. Its main purpose is to provide a simple and solid method that can be used in the field. The idea is to let the hydrophone transmit a signal towards a plane surface and measure the voltage from the received reflection. In other words, the transducer is calibrated against itself.

$$M_H = \sqrt{J_x * \frac{v_r}{v_t} * 2d} \tag{1}$$

Where $\mathrm{M_H}$ is the receiving response factor, $\mathrm{v_t}$ is the voltage of the transmitted pulse, $\mathrm{v_r}$ is the voltage of the receiving pulse and d is the distance to the surface. $\mathrm{J_x}$ is reciprocity parameters and depends on the geometry of the transducer and the acoustic radiation.

$$Plane : J_p = \frac{2}{\rho c} A \tag{2}$$

$$Cylindrical : J_c = \frac{2}{\rho c} \sqrt{\lambda r} L \tag{3}$$

$$Spherical : J_s = \frac{2}{\rho c} \lambda r \tag{4}$$

Where ρ is the density of the medium, c is the velocity of the sound in the medium, A is the area of a plane hydrophone, λ is wavelength of the pulse, r is the distance between the transmitter and the projected receiver $r = 2d$ and L is the length of a cylindrical hydrophone.

1.2.2 Non-linearity measurements

There is a method using a separate projector to determine the linearity of hydrophones. This method assumes that every hydrophone has a non-linear factor [3].

$$e \approx mp + \eta p^2 \tag{5}$$

Where e is the response to a pressure p, m is related to the first order of sensitivity and η related to the second. Every hydrophone has a fundamental frequency f_0. The technique uses a dual-frequency pulse transmitted by a projector. The two primary frequencies are produced by modulating a carrier at centre frequency f_0 by a pulse at half the difference frequency, *f*. This produces the two primary components at $f_0 \pm f/2$. By letting a signal pass through a passive low-pass filter, the non-linear component will be eliminated. Then by comparing the filtered signal with the non-filtered signal, the non-linear component can be determined.

1.2.3 Calibration by Brüel & Kjær

Two hydrophones were sent to Brüel & Kjær for an external calibration and to compare their results with the results of this thesis. Because of privacy policy, their method will not be discussed.

1.2.4 Calibration by comparison

The method of calibration uses an unknown projector that sends pulses towards the transducer subjected to calibration as well as an already calibrated reference [2]. It is the most common and straightforward method but it requires a known reference. This method will be used in this thesis.

1.3 ELVIS

ELVIS (EchoLocation Visualization and Interface System) is a measurement system used to study the echolocation beam of marine animals, such as dolphins. ELVIS uses an array of 47 hydrophones connected to 6 data acquisition boards. The recordings are then visualized in real-time and saved to a hard drive. Each hydrophone has its own channel and the data is saved separately. The software is created and run through LabVIEW.

1.4 Problem discussion

The main problem of this thesis is to make the measurements accurate enough to draw any conclusions from the result regarding frequency behaviour. It is required to create a measurement environment that is identical for each of the different hydrophones and settings.

The first task is to extract the data in its rawest form from the data acquisition boards using ELVIS. The data will then be exported for analysis using MATLAB. Because of the large data size the analysis has to be done in a way that is easily replicated numerous times and takes into account a limited amount of time for processing.

The initial measurements will be made in a water tank. Because of this, one has to take into account that every surface will have its own near-field and will produce reflections. It is also possible that the system will detect reflections in the hydrophones themselves. To perform the measurements, an independent program will control a waveform generator. The program will generate bursts of sinuses with different frequencies and amplitudes. The ELVIS program will then measure the known signal.

Something else to take into consideration is that it can be hard to find a reliable reference since the frequency range that is going to be investigated is uncommon. This applies to the projector as well. The measurements will require a projector with a broad band to transmit on every frequency or several projectors to make up for it.

Another problem is to construct a rack for the projector, the reference and the hydrophones. It has to be robust and stable but it must still be easy to exchange the hydrophone to be measured without altering the conditions.

At last but not least, the water has to be kept clean during the measurements since particles in the medium can cause unwanted reflections.

1.5 Delimitations

There are a number of other things that could affect the hydrophones measurements that will not be investigated. For example, temperature and salinity of the water and movement such as a current. A proper field test of the system will not be performed.

The system will not be made automated and the calibration interface is for lab purpose only and will not be made more user friendly than needed.

2 Theory

To understand ultrasonic calibration it is necessary to understand the fundamental physical laws as well as the technical limitations that are involved.

2.1 Acoustics

The understanding of how force is transmitted by waves is essential when working with transducers relying on pressure.

2.1.1 The wave equation

On a macroscopic level, sound is a series of waves of pressure that propagates through a compressible medium such as water or air [5, 6]. On a microscopic level, it is an oscillatory system of particles moving back and forth. A particle in a wave can be considered a mass suspended around an equilibrium influenced by a force, for example a mass on a spring

$$F = -kx \tag{6}$$

where k is the spring constant and x is the displacement from equilibrium. When the particle is oscillating it is under the effect of Newton's second law, $F = ma$. When inserted into (6) it gives

$$m\frac{\delta^2 x}{\delta t^2} = -kx \tag{7}$$

the differential equation (7) has the solution

$$x(t) = a\cos(\omega t) \tag{8}$$

where $\omega = \sqrt{\frac{k}{m}}$ and the constant a depends on the initial condition. In this case the distance from the equilibrium. This means that if we move the mass a distance x and release it, it will oscillate with the angular frequency ω. When looking at sound propagation it is not enough to look at a single mass, but a whole system of n masses connected with springs, resulting in n differential equations. The position of each mass now depends on all the surrounding masses as well.

When one mass m_i starts to move, the surrounding masses will start to move with a delay that depends on their mass, the spring constant and the distance between the masses. The force F that is required to move masses, travels through the system as a compression of the springs

$$F = \frac{kul}{v} \tag{9}$$

where $\frac{ul}{v}$ is the displacement of a mass (compare with (6)), u is the particle velocity, l is the distance between two masses and v is the wave velocity. From $t = 0$ to $t = T$ where $T = \frac{nl}{v}$, the mechanical work is

$$W = Fs = FuT = Fu\frac{nl}{v} \tag{10}$$

The total kinetic energy through the system can be expressed as

$$F_k = n * \frac{1}{2}mu^2 \tag{11}$$

and the energy stored in all the springs as

$$F_p = n * \frac{1}{2}kx^2 \tag{12}$$

where $x = \frac{ul}{v}$. Combining equations (9) to (12) gives the total force of the system

$$W_{out} \equiv \frac{kul}{v} * u\frac{nl}{v} = n * \frac{1}{2}mu^2 + n * \frac{1}{2}k(\frac{ul}{v})^2 \tag{13}$$

from this v can be derived as

$$v = l\sqrt{\frac{k}{m}} \tag{14}$$

if and only if $u < v$ and the masses start their movement in unison. In practice the wave velocity is dependant on the frequency. Because of this the expression in (14) can be compared to the relationship

$$v = f\lambda = \frac{\omega}{k} \tag{15}$$

where f is the frequency and λ is the wavelength.

In a homogenous media the wave is mathematically described with the following differential equation:

$$\frac{\delta^2 p}{\delta x^2} = \frac{1}{v^2}\frac{\delta^2 p}{\delta t^2} \tag{16}$$

where p is the pressure in the wave, x is the space coordinate, v the velocity of the wave and t the time parameter. (16) works for any equation that satisfies (15) and is a function of time and spatial position for example, amplitude of the wave or the particle velocity. (16) has the general solution:

$$p(x,t) = p_+(x - vt) + p_-(x + vt) \tag{17}$$

where p_+ travels in the positive direction and p_- travels in the negative direction. For a sinusoidal wave travelling only in the positive direction the solution can be written as

$$p(x,t) = A_0 \sin(\omega t - kx) \tag{18}$$

2.1.2 Acoustic impedance and intensity

Acoustic impedance is defined as

$$z = \frac{p}{u} = \sqrt{\frac{\rho}{\kappa}} \tag{19}$$

where ρ is the density and κ is the compressibility. This means that it is harder for the particles in a heavy material to move. The intensity of an acoustic wave is given by

$$\vec{I} = p\vec{v} \tag{20}$$

Note that $\vec{I}$ and $\vec{v}$ are vectors and therefore have both magnitude and direction. The direction of the intensity is the average direction in which the energy is flowing. The following formula is used to determine the average acoustic intensity during time T

$$I = \frac{1}{T}\int_0^T p(t)v(t)dt \tag{21}$$

For a plane progressive wave this can be reduced to

$$I = \frac{p^2}{z} = zu^2 \tag{22}$$

2.1.3 Reflection and transmission

Reflection occurs when a wave travels to a material with different properties. This can be compared to a mass colliding with a smaller or larger mass. This is where acoustic impedance describes how easy a medium is for a wave to travel in. If the second medium has higher impedance, and therefore heavier masses, a reflection occurs [5, 7]. The lighter masses will bounce against the heavier and create a reflected wave in the opposite direction. At the same time, the heavier masses will be put in motion and create a wave of their own propagating in its original direction. The amplitude of the waves will have the following relation

$$P_i = P_t - P_r \tag{23}$$

where P_i is the incoming wave, P_t the transmitted wave and P_r the reflected wave. The reflection will depend on the difference in acoustic impedance between the two mediums.

$$R_a = \frac{Z_2 - Z_1}{Z_1 + Z_2} \tag{24}$$

where R_a is the reflection coefficient that is the quota between the reflected wave and the incoming wave ($R_a = \frac{P_r}{P_i}$) and Z the impedance of the two mediums. The same goes for the transmission

$$T_a = \frac{2Z_2}{Z_1 + Z_2} \tag{25}$$

where T_a is the transmission coefficient that is the quota between the transmitted wave and the incoming wave ($T_a = \frac{P_t}{P_i}$). Equations (23) to (25) is only true for waves perpendicular to the surface between the mediums. For oblique incoming waves, the angel has to be accounted for [8].

$$\theta_i = \theta_r \tag{26}$$

$$\frac{P_i}{Z_1}\cos(\theta_i) - \frac{P_r}{Z_1}\cos(\theta_r) = \frac{P_t}{Z_2}\cos(\theta_t) \tag{27}$$

$$R_a = \frac{Z_2\cos(\theta_i) - Z_1\cos(\theta_t)}{Z_1\cos(\theta_t) + Z_2\cos(\theta_i)} \tag{28}$$

$$T_a = \frac{2Z_2\cos(\theta_i)}{Z_1\cos(\theta_t) + Z_2\cos(\theta_i)} \tag{29}$$

Up until now all waves has been considered lossless. In reality this is not the case. A wave will lose amplitude the following way [5]

$$p = p_0 e^{-\alpha f x} \tag{30}$$

where α is the dampening coefficient [dB/MHz*cm], f is the frequency [MHz] and x is the distance travelled [cm]. The dampening coefficient for water is 0.0022 [8]. Also to note, for a pulse containing more than one frequency, the high-frequency components will experience a heavier dampening and therefore the central frequency for the pulse will shift downwards while the wave travels.

2.1.4 In 3 dimensions

Equation (18) is the one-dimensional wave equation. To apply it in a three-dimensional world it has to be extended from *p(x)* to *p(x,y,z)*. This is done by using the Laplace-operator

$$\nabla^2 p = 2 = \frac{1}{v^2}\frac{\delta^2 p}{\delta t^2} \tag{31}$$

where

$$\nabla^2 = \frac{\delta^2}{\delta x^2} + \frac{\delta^2}{\delta y^2} + \frac{\delta^2}{\delta z^2} \tag{32}$$

In practice this represents the difference is pressure in and around a point. When considering a point source, the angel can be disregarded and the wave equation can be reduced to

$$\frac{1}{r^2}\frac{\delta}{\delta r}(r^2\frac{\delta p}{\delta r}) = \frac{1}{v^2}\frac{\delta^2 p}{\delta t^2} \tag{33}$$

where r is the distance from the source. This equation has the solution

$$p(r,t) = \frac{1}{r}p(\omega t \pm kr) \tag{34}$$

Compare this to the one-dimensional case (18), the only difference is the factor $\frac{1}{r}$.

2.2 Hydrophones

Hydrophone comes from the Greek words *hydro* and *phone* which means *water* and *sound*. It is a microphone designed for underwater use. Most hydrophones are used for navigation, communication or target localization. Different hydrophones uses different methods to detect sound, or in other words, pressure in water and convert it to an electric signal. Every hydrophone can be used as a receiver but not every hydrophone can be used as a transmitter. There are a few different types of hydrophones, here follows a few common types.

2.2.1 Piezoelectric

Piezoelectric hydrophones are the most common ones [9]. Piezo materials will change its electrical attributes when deformed. The deformation is a result of a change in pressure. There are two types of piezo material, piezoresistive and piezoelectric. Piezoresistive will change its resistance and piezoelectric materials will generate voltage when deformed, see Figure 1.

A conductive material that is subjected to stress or strain will change its innate resistance because of the change in length or area as well as change in molecular structure. By running a current through the material and measure the difference in resistance it is possible to determine stress or strain on the transducer [10].

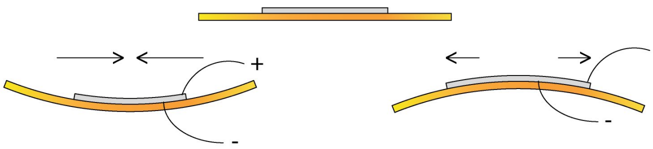


Figure 1: The principle on how piezoresistive material changes its length and therefore resistance.

A piezoelectric transducer uses the asymmetry of the molecular structure. Metallizing two opposite areas will allow the transducer to collect two equal electrical charges with opposite polarity on each side. Common materials with these properties includes lithium sulphate, ADP (ammonium dihydrogen phosphate), ferroelectric ceramics, Rochelle salt, quartz, tourmaline and polyvinylidenfluroid [9, 10]. Piezoelectric transducers are known for good linearity which is why they can produce accurate measurements even when the measurand is only a fraction of the measured value.

Stress or strain will generate a charge

$$Q = K * \Delta L \tag{35}$$

where Q is the generated charge, K is the transducer constant and ΔL the stress or strain. Because of elasticity, Hooke's Law is applicable

$$\sigma = E * \epsilon \tag{36}$$

where $\sigma = F/A$ is the stress, E is the stiffness of the material and $\epsilon = \Delta L/L$ the relative strain. Combining equation (35) and (36) will give [10]

$$Q = K\frac{L * F}{A * E} \tag{37}$$

This shows that Q is proportional to the applied force F.

2.2.2 Moving-Coil

The moving-coil transducer for underwater use is similar in principle to the air loudspeaker and is primary used as a wide-band sound source. Its basic components are a diaphragm, one or more moving coils and the associated electrical circuit. When the diaphragm is subjected to force it will move the coils, changing the magnetic field and therefore the current, see Figure 2

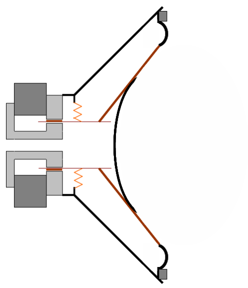


Figure 2: When pressure changes around the diaphragm, the coils will move and the magnetic field will be submitted to change.

The moving-coil transducer uses three conditions, transduction of energy, mechanical impedance and the radiation of sound from a small diaphragm [9].

$$F = BLi \tag{38}$$

$$F = j\omega mu \tag{39}$$

$$p \propto \omega u \tag{40}$$

where F is the force, B is the magnetic flux, L is the length of the wire that moves, i is the current, ω is the angular frequency, m is the total mass, u is the velocity of the coil and p is the radiated sound pressure. Combining (38) to (40) yields

$$p \propto \omega u = \omega(\frac{F}{j\omega m}) = \frac{BLi}{jm} \propto i \tag{41}$$

The equation are valid when the diaphragm is small in comparison to the wavelength. To make it more useful at low frequencies, the spring suspension can be made less stiff. This however makes it mechanically fragile. Consequently, moving-coil transducers have an automatically compensating system for equalizing the gas pressure inside the transducer with the hydrostatic pressure on the outside. Even with proper compensation system, moving-coil transducers are fragile components.

2.2.3 Magnetostrictive Transducers

A more robust transducer is the magnetostrictive transducer. Magnetostrictive materials has the similar principles as the piezoelectric ones. The material will deform when subjected to magnetic flux and vice versa, it will produce a magnetic flux when deformed. It has low impedance and good mechanical strength although with several drawbacks, such as inherent non-linearity, hysteresis and the need for a biasing magnetic field.

2.3 Calibration

To calibrate a transducer means to observe the sensitivity-versus-frequency characteristics, also known as the response. When talking about bandwidth and transducers it is referring to the useful frequency range. It is determined by the sensitivity level, the electrical impedance and the mechanical limitations [9]. These limitations are flexible and there are no simple rules for minimum useful sensitivity or maximum useful impedance and so forth. However, these parameters are important to know when using the transducer for measurements.

2.4 ELVIS

The measurement system used is called ELVIS (EchoLocation Visualization and Interface System). It uses 6 NI PXI-5105 digitizer cards with 12 bits resolution. The cards are controlled with the NI PXI-8106 controller mounted in a NI PXI-1042 rack. This accounts for a total of 48 channels. These are hooked up to 47 piezoelectric hydrophones and synchronized through a trigger channel. The system was developed with the following requirements [11]:

- 47 channels individually amplified in two settable gain levels (35 dB and 50 dB)
- Dynamic voltage range 12 V
- Band pass filtering, allowing for full signal dynamics in the frequency range 20-500 kHz
- A separate signal summation circuit for use as trigger source for the A/D-converter
- Mountable in a shielded box
- Connectors into and out from the amplification/filter box, D-sub50

The circuitry was designed using 48 individual low noise operational amplifiers (OP) of the type LMH6622. Each integrated circuit package (8-lead SOIC) contained two individual OP amplifiers and were surface mounted (size 1206). The signal from each hydrophone was amplified in either one or two steps using two non-inverting amplifiers connected in series. The first step had a gain level of 35 dB. The second one had a gain level of 15 dB for a total of 50 dB. The filters have the components

$$R_1 = 560\Omega, C_1 = 330pF, R_2 = 10\Omega, C_2 = 0.68\mu F$$

this gives the cut-off frequencies $f_1 = 816kHz$ and $f_2 = 23kHz$ using the formula

$$f = \frac{1}{2\pi RC} \tag{42}$$

The software was created with LabVIEW (National Instruments, Natick, USA). The system is designed to run several loops simultaneously that includes acquisition, streaming, analysis and display. ELVIS uses a pre-trigger recording method. It means that the system is always recording data but it will only save it once the signals reaches the determined trigger level.

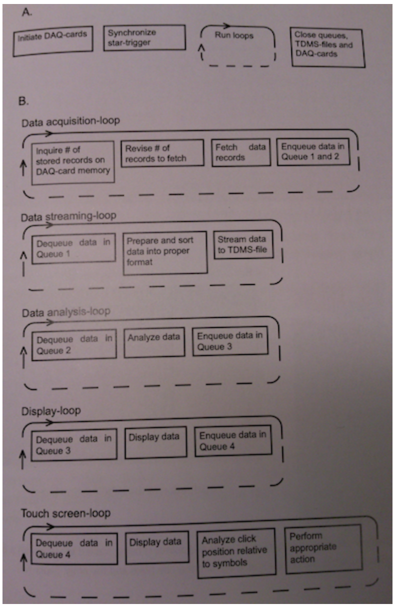


Figure 3: A flow chart that explains how ELVIS works, the loops run independently.

ELVIS uses a sample rate of 1 MSa/s which, according to the Nyquist-Shannon sampling theorem [13], this should be enough to recreate a 500 kHz sinusoid.

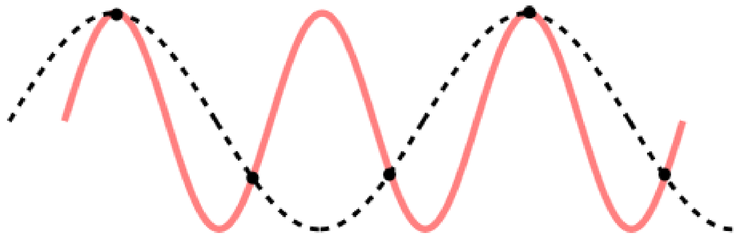


Figure 4: With too low sample rate, a higher frequency sinusoid can appear as a lower frequency.

3 Method

This section will explain how the measurements were performed. It is divided into physical set-up, measuring, data collection and data analysis.

3.1 Calibration by comparison

The method used in this thesis is calibration by comparison. A projector was chosen to send ultrasonic pulses towards both an already calibrated hydrophone as well as an unknown transducer subjected to calibration. This method is chosen because of its ability to produce good results while still being very simple.

3.2 Set-up

The hydrophone used as a reference is a Brüel & Kjær hydrophone type 8103 (from now on, 8103). It is a well-known and appreciated model for most of the frequencies of interest. According to Brüel & Kjær's calibrations, 8103 is supposed to be linear up to 180 kHz with a receiving sensitivity of -211dB re 1V/µPa. It is omnidirectional, has a high sensitivity relative to its size and good all-around characteristics which makes it good for industrial and educational use [12]. By default, ELVIS summarizes the signals from all 47 channels for triggering purpose. It is useful in field testing, but in a lab environment with only two hydrophones it causes the system to trigger more easily on noise. Instead ELVIS was modified to only trigger on 8103.

The 8103 that was used had a 10-32 UNF Microdot plug. A converter to BNC was found, so to connect the 8103 to ELVIS a home made adapter was designed. A soldering iron was used to connect a pin on the D-sub50 to the cable of a BNC and then made ELVIS read from that particular pin, see Figure 5

The projector used was a sonar projector model NBM50-118-6 (from now on, projector). It has an excitation frequency at 118 kHz and is most effective between 60-180 kHz but usable for all the frequencies of interest.

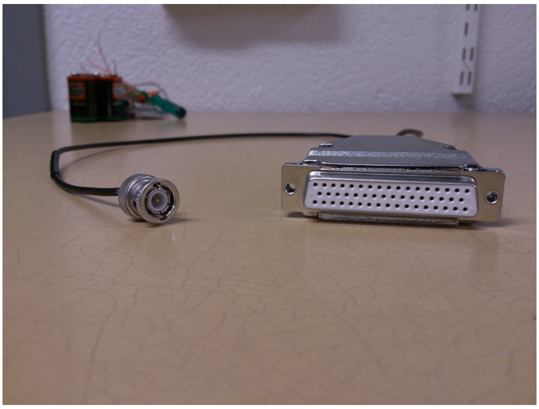


Figure 5: The home made adaptor, BNC to D-sub50.

The projector and 8103 was put in a 0.5x0.5x1.3 m^3 water tank. The water tank had been thoroughly cleaned and filled with filtered water. The water tank was at all time covered with an oilcloth. All this was done to ensure that there would be as few particles as possible in the water that could disturb the measurements.

Measurement set-up

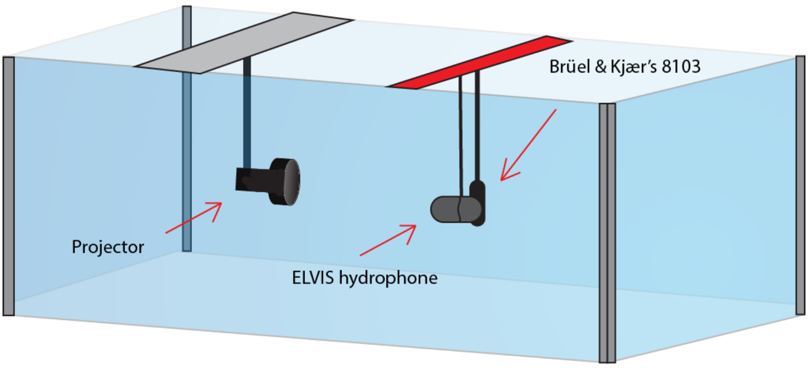


Figure 6: Illustration of the set-up.

8103 and the hydrophone subjected to measurement was placed next to each other in the middle of the tank because of two reasons. One, the reflection would be as weak as possible. Two, if the system recorded any reflections, the time between the actual signal and the reflected signal would be long enough to easily be filtered. The projector was put 40 cm away from its targets, see Figure 6. The hydrophones were fastened by their cord on rods made of acrylic glass. Acrylic glass was chosen because it has similar acoustic impedance as water and therefore weaker reflections.

3.3 The measuring

Because ELVIS already had all the acquisition features needed, it was used it to record the measurements. 8103 and the hydrophone to be measured was plugged into the amplifier of ELVIS. The projector was connected to a waveform generator, Agilent 33250A. The waveform generator used a sinusoid. To make sure the resolution on the measurements was good, all the settings were optimized for each sent frequency, such as trigger level, vertical range, record length, amplitude and number of cycles. This was mainly done by trial and error. The projector and the hydrophone was kept at a distance long enough for the according wavelengths. See Appendix B for the configurations.

To control the waveform generator, a GPIB-USB adapter was used to connect it to ELVIS. An additional LabVIEW program was written to run in parallel. The program was designed with a number of options. Starting frequency, frequency increment, number of increments for frequency, starting amplitude, amplitude increment, number of increments for amplitude, number of cycles of the sinusoid and number of pulses for each setting, see Figure 7.

For the results in this thesis, each setting was triggered ten times to be able to perform averaging while still keeping down the time consummation. One hydrophone took about 30 minutes of recording mainly because of the numbers of options needed to be changed between frequencies.

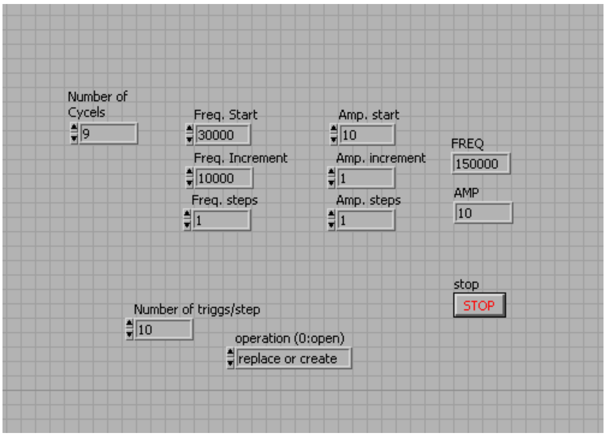


Figure 7: The front panel of the program that controlled the waveform generator.

3.4 Extracting the data

The system is collecting data by the acquisition loop and stores the data in queues for extraction later on. The data was wanted in its rawest form to avoid as many influences as possible from the system, therefore it was recorded as early as possible. It was possible to record it just before it was put into the queues. A new a subVI was created and all the input signals was lead unaffected through it. Inside the subVI it was made possible to pick exactly the wanted signal.

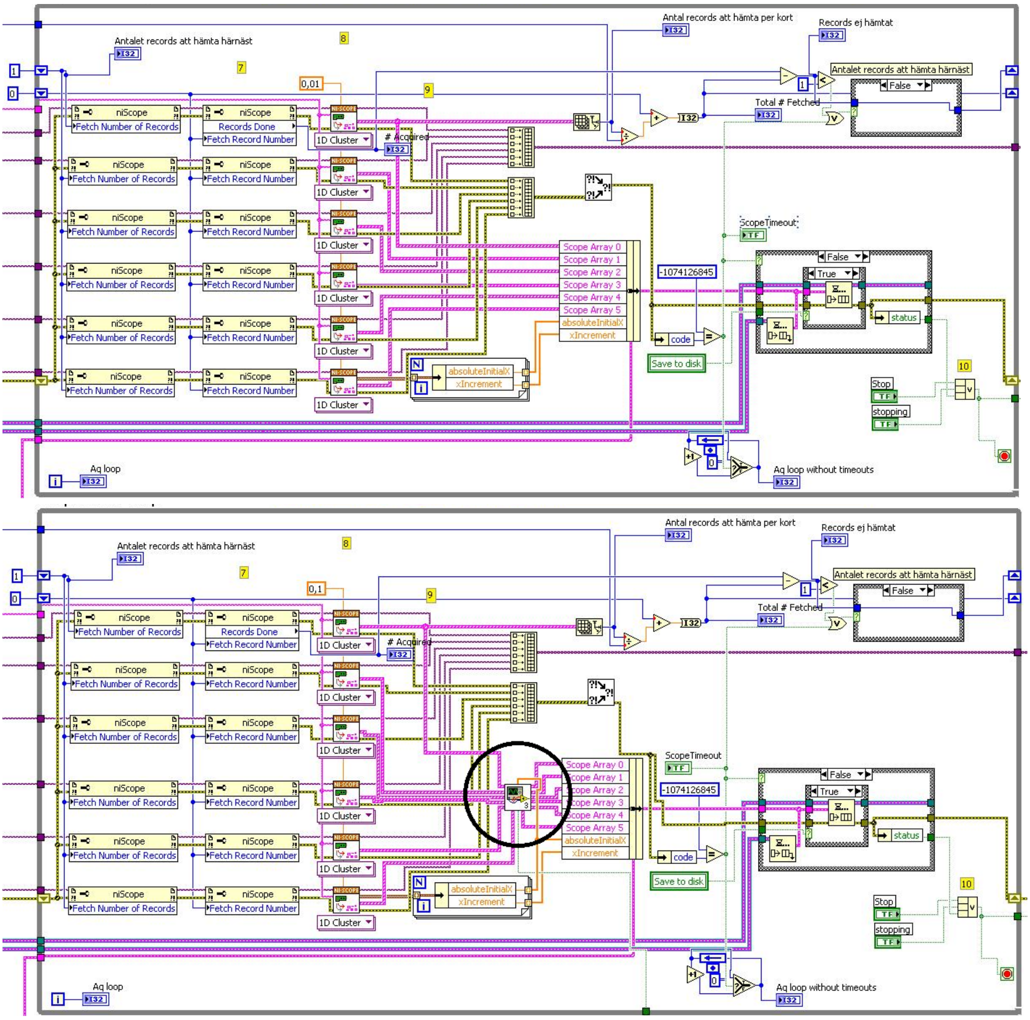


Figure 8: The upper picture shows the ELVIS acquisition loop before modification, the lower one after. As apparent, it is only a minor modification

ELVIS saves the recordings as a TDMS-file (technical data management system). It is a file type created by National Instruments to be used when a really large amount of data needs to be saved onto a hard drive, as in the case when 47 hydrophones records simultaneously. It is however a complicated structure to use when only a small piece of the data is wanted. When only two hydrophones were recording, a text file was suffice. Text files are easily imported into MATLAB for analysis.

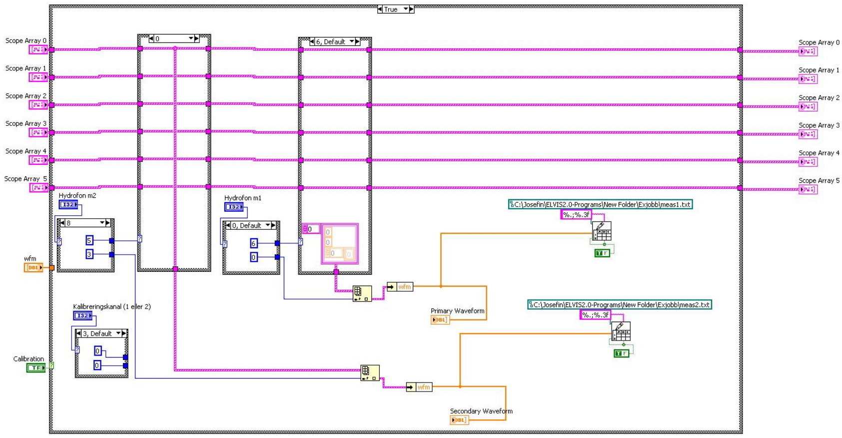


Figure 9: The subVI showing in the lower picture of Figure 8

The hydrophones were measured every 5 kHz from 30-100 kHz and every 10 kHz from 110-250 kHz. An exception from this was hydrophone 1 that was measured every 2.5 kHz over the entire range. Hydrophone 1 was used as a test subject to determine the configuration settings and step size for the remaining hydrophones.

3.5 Visualizing and analysing the data

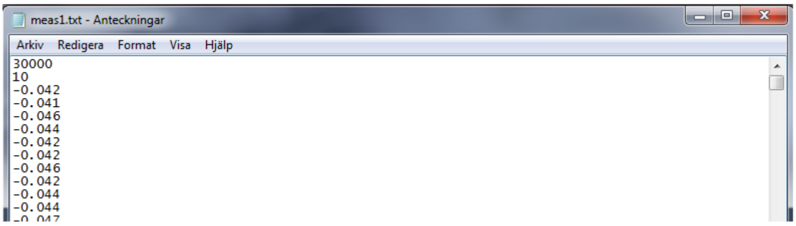


Figure 10: Example of a measurement text file from LabVIEW.

The text file from LabVIEW looks like Figure 10. Each pulse is preceded by the sent out frequency and amplitude. At the start this was mainly used to check for missed pulses but later on used to separate the different pulses and identifying them. Any eventual offset of a pulse is removed.

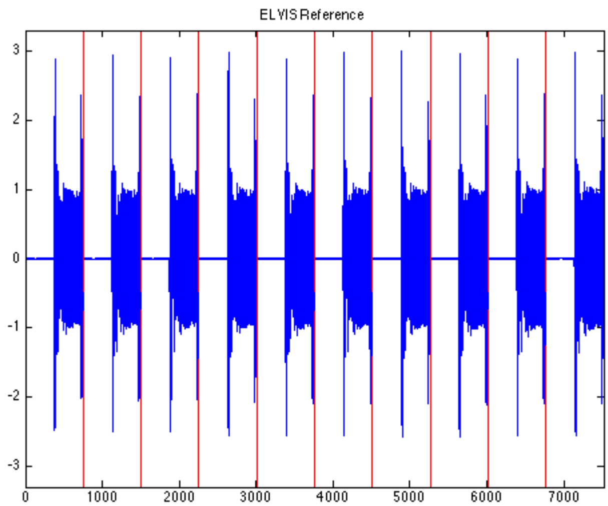


Figure 11: The red lines indicate a start of each pulse. The flat area is the pre-trig recording.

When plotting the measurement text file in MATLAB using a created script it will appear as Figure 11. The MATLAB-script will then perform a FFT because of the frequency behaviour of the projector. The FFT is not really used for the measurement results but more of an indicator that everything is working well and that the frequency of interest is present.

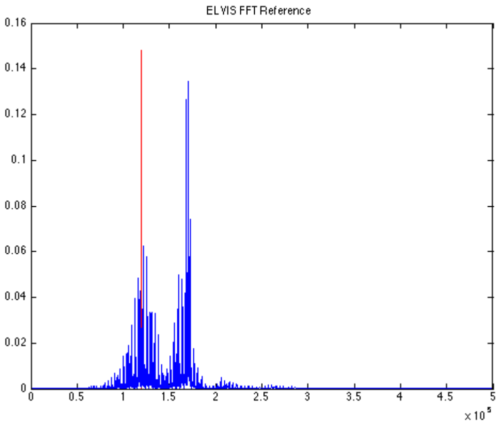


Figure 12: As apparent in the picture, even if the transmitted signal is mainly 170 kHz, there is a significant contribution from a 118 kHz signal.

Each pulse is then put into its own vector and each vector is then put into a matrix. Because the signal has more than one significant frequency, the frequency of interest had to be manually picked out. There are filter functions in MATLAB, but they were applicable to the data for any improved results. After choosing the relevant part of the pulse, all subpulses were averaged and the result derived.

The interesting segment (Figure 13) from all of the pulses were extracted and an average number for the signal strength was derived. The signal strength was then compared to the power of the transmitted pulse and plotted in MATLAB on a logarithmic scale. The entire analysis in MATLAB took about 20 minutes for each hydrophone.

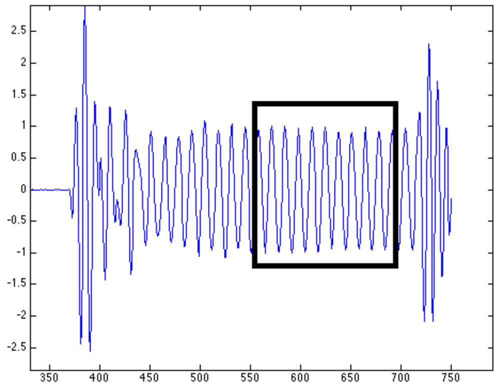


Figure 13: The figure shows the general appearance of a single pulse. The black square shows the area of interest. The large spikes in the beginning and the end are due to the 118 kHz excitation pulses from the projector.

However this representation includes everything that is distorting the signal such as system circuits, projector behaviour and water attenuation. This is why a known reference is used. By subtracting the recorded signal from 8103 it was possible to remove those exterior influences. If the signal then is compensated for the frequency response of 8103 the result will be absolute.

3.6 Miscellaneous

As mentioned in the theory chapter, a wave propagating in a medium will lose its strength depending on distance travelled and its frequency. To see if this affected the results, the different levels of attenuation were calculated.

Since the amplifier box consists of a broad band pass filter (23-816 kHz), it was of interest to measure its frequency response. All frequencies of interest, 30-250 kHz, were checked. The waveform generator was connected straight into the amplifier box by using the BNC to D-Sub50 adapter.

The effect of the cable impedance were investigated to see if it had any influence to the signal. This was estimated by first looking at a signal in ELVIS. Then an identical signal was sent to the hydrophone connected an oscilloscope. After subtracting the amplification from ELVIS the two signals were compared.

4 Results

This section will cover the results for this master's thesis. It will show a summary of the hydrophone measurement, for full individual results see Appendix A.

4.1 Results from the work environment

All data from sources that could interfere with our measurements will be represented here.

4.1.1 Attenuation in water

The distance was fixed at 40 cm and the frequency range was 30-250 kHz which gives a received signal strength of 99.7-97.8%. For the purpose of this thesis, this attenuation is negligible. Figure 14 shows the general attenuation in water.

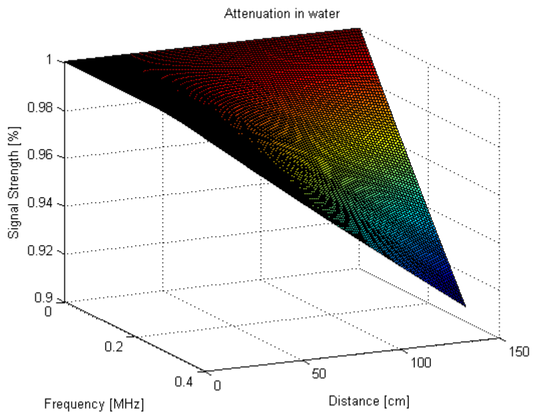


Figure 14: The graph shows the attenuation in water depending on distance and frequency. The graph ranges from 0-150 cm and 0-0.4 MHz

4.1.2 The amplifier and the cables

The amplifier box contained a broad band pass filter (23-816 kHz).The frequency response was measured from 30-250 kHz to see if the filter would affect the signal and how the amplifier performed under different frequencies.

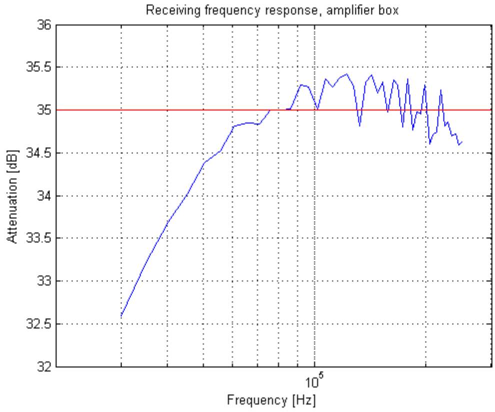


Figure 15: The frequency response from the amplifier. The red line shows the theoretical amplification of 35 dB.

To see the largest effect the amplifier box had for the result, the difference between the maximum and minimum value of Figure 15 was calculated.

$$max - min = 2.8dB$$

After 55 kHz the difference was less than $\pm 0.5dB$.

The effect of the impedance of the cable was $<1\%$ of the signal strength.

4.2 Hydrophone measurement

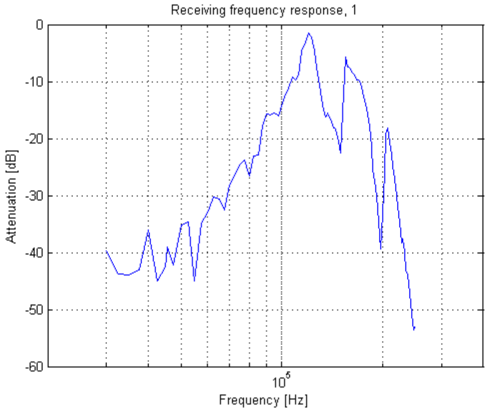


Figure 16: The plot shows the frequency response for hydrophone 1.

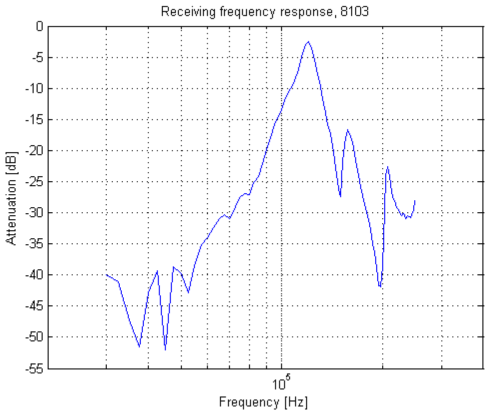
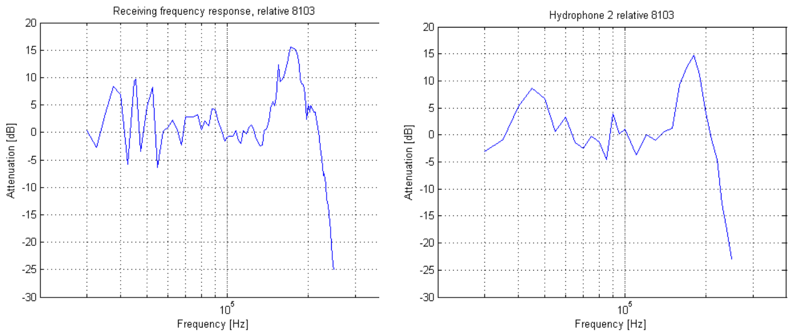


Figure 17: The plot shows the frequency response for 8103.

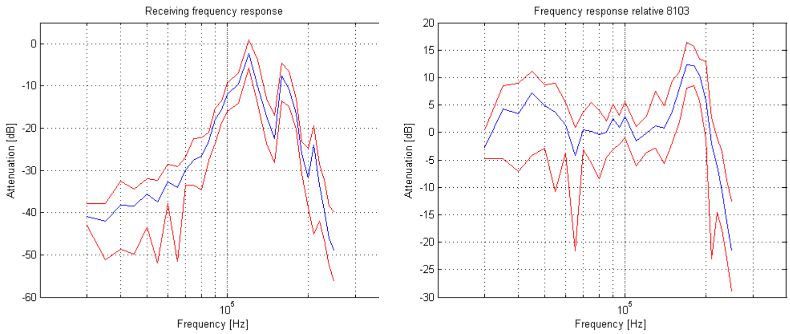
Both results include the frequency behaviour of the projector, the amplifier box and other influences, that is why they look similar. When subtracting the graph in Figure 16 with the graph in Figure 17 those influences are removed.



(a) Hydrophone 1 (b) Hydrophone 2

Figure 18: The plots show the comparing response for the respective hydrophones

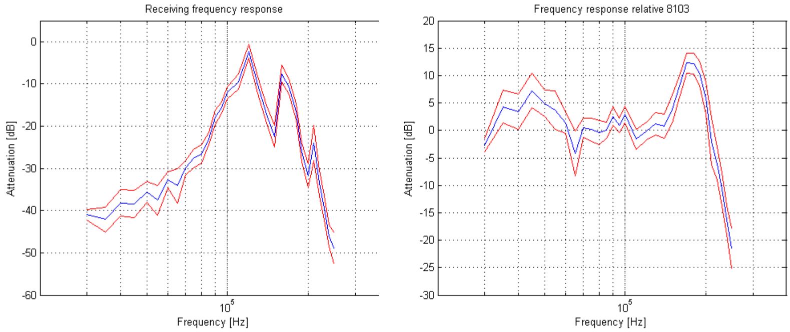
These calculations were done for every single hydrophone, see Appendix A.



(a) Measured values (b) Compared values

Figure 19: The red lines show the minimum and maximum value from all hydrophones, the blue line is the average value.

To lessen the effect of individual extreme values it is better to look at the standard deviation, see Figure 20.



(a) Measured values (b) Compared values

Figure 20: This figure shows the standard deviation instead of the maximum and minimum values.

By subtracting the graph in Figure 20b with the calibration curve of 8103 showing in Figure 21 the absolute calibration of the ELVIS hydrophones should be given.

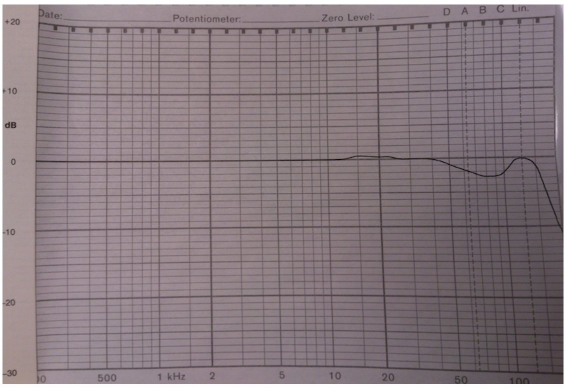
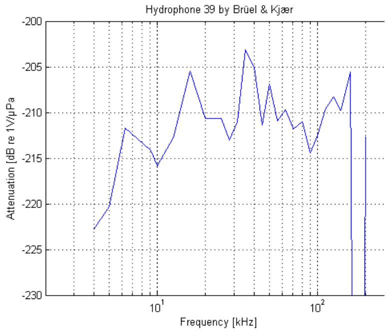


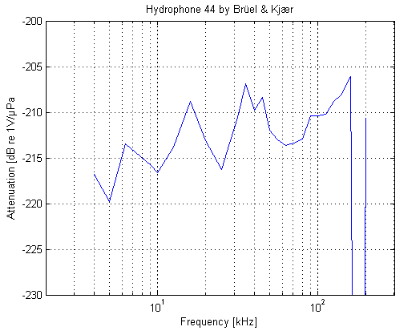
Figure 21: The calibration graph that was delivered together with 8103. 0 in this graph is normalized around -211.3 dB re 1V/µPa or 27.2 µV/Pa.

4.3 Brüel & Kjær's results

Figure 22 shows measurement done by Brüel & Kjær and Figure 23 show the measurement done by during this thesis. It is not compensated for the 8103's frequency behaviour, therefore the axis cannot be compared. Brüel & Kjær started their measurement at 4.0 kHz and stopped at 200.1 kHz.

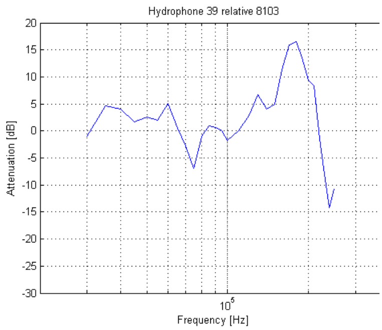


(a) Hydrophone 39

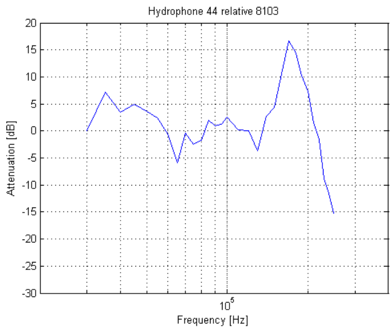


(b) Hydrophone 44

Figure 22: Brüel & Kjær's results



(a) Hydrophone 39



(b) Hydrophone 44

Figure 23: Thesis results

5 Discussion

Here we will discuss our results and present our conclusion.

5.1 Our results

It is difficult to draw any conclusions from Figure 16 and 17 because of the large impact of the projector. They can be used to compare hydrophones with each other but will not yield any absolute results. For this purpose we use Figure 18. As seen in Figure 21, between 30-170 kHz the largest difference is 3 dB. The graph provided was too bad to put into numbers and the effect too small to take into consideration. Their calibration was made in 1989 and our own experience shows that it might not be completely accurate, therefore we chose to ignore it.

Even though the influence of the amplifier box as well as the attenuation in water was relatively small they are compensated for in Figure 18. Both hydrophone 1 and 2 shows similar frequency behaviour with peaks around 45 and 170 kHz and rapidly dropping after 170 kHz. When comparing the two graphs, hydrophone 1 seems a lot more jittery but this could be because of the small steps in frequency hitting unfortunate wavelength causing bad interference. For example, when we measured 8103 we got zero response at 45 kHz but good results at both 42.5 and 45.5 kHz.

Looking at Figures 19, it is apparent that the hydrophones differs mostly around 30-70 kHz. The mean curve follows the maximum curve quite good which means that most of the values are close to the maximum values. The minimum curve is mostly made out of a few specific low sensitivity results. For example, the lower peaks in the 30-70 kHz range is made from hydrophones number 7, 8, 13, 19 and 24. The large difference at 210 kHz is caused by hydrophone 39, see Appendix A.

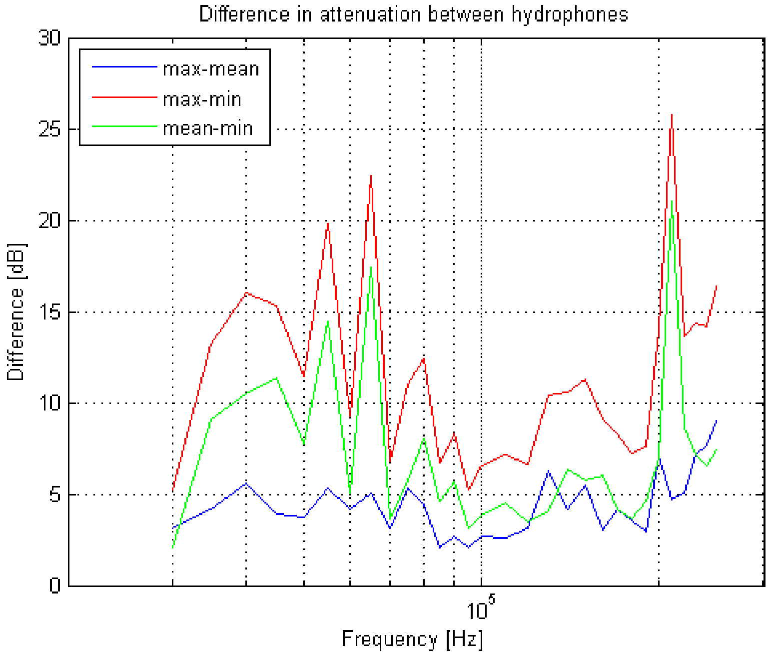


Figure 24: Plotting the differences between the maximum, minimum and mean curves.

The largest difference in measurements is because certain hydrophones has negative peaks shown by the minimum graph in Figure 19. In general most hydrophones are close to each other and therefore the maximum values, this is shown by the blue line in Figure 24. This is why the standard deviation shown in Figure 20 is relatively small compared to maximum and minimum graphs.

5.2 Brüel & Kjær's results

Just as our results showed, Brüel & Kjær's results show a large deviation for frequencies less than70 kHz. However right after our resonance peak at 170 kHz, Brüel & Kjær has an anti-resonance peak with an attenuation of over 100 dB. We do not know exactly what causes this difference but their pre-study showed the following phase graph:

Frequency [kHz]	Phase [Deg.]
4,0	1,1
5,0	0,1
6,3	0,1
8,1	0,7
10,0	0,6
12,5	0,3
16,0	0,9
20,0	1,4
25,0	1,1
28,0	0,8
31,5	2,1
35,5	0,0
40,1	1,6
45,1	0,1
50,0	0,1
56,1	1,0
63,0	1,3
71,0	0,6
80,0	1,1
90,0	1,7
100,0	2,0
112,0	2,3
125,1	2,0
140,0	2,6
160,0	2,3
180,0	100,3
200,1	2,7

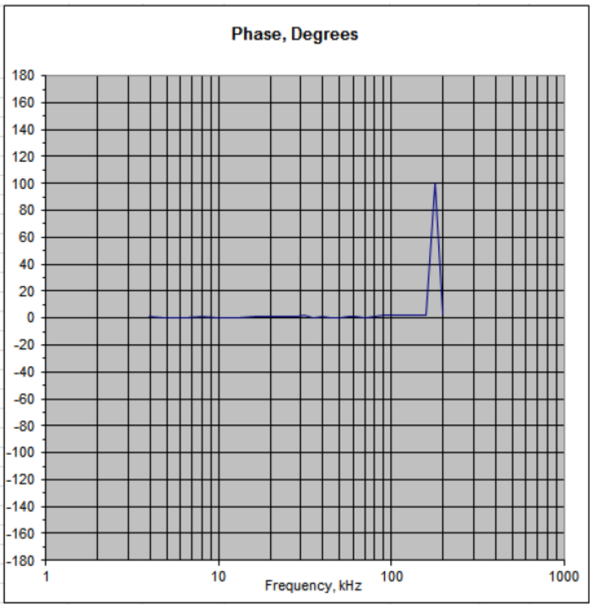


Figure 25: Brüel & Kjær's result when measuring the phase response. This was given to us in their pre-study but excluded from their final results.

Since a phase graph was not published in the final results and we have no option of measuring the phase ourselves, we believe that their system somehow ran into a compatibility problem with the ELVIS hydrophones. Since we do not know what measurement method they used because of privacy policies it is difficult to investigate it any further.

Apart from the anti-resonance, our measurements showed similar contours which support our results.

5.3 Problems

One of the largest insecurities with our results is that we cannot rely on the information we have about 8103. The calibration curve is too inaccurate and has shown more than once to be incorrect. In theory, by subtracting the calibration curve for 8103 (Figure 21) with our measured values (Figure 23) they should appear like Brüel & Kjær's results (Figure 22). It is easy to see that this is not true.

Another large factor is the projector. It is designed to transmit around 118 kHz which is very prominent at excitation and relaxation of the projector, see Figure 13. Our own method was to manually pick out the part of the pulse, some human error must be considered.

Because of the set-up we have, we can only measure one hydrophone at a time. Each time that a hydrophone is exchanged the rack is moved a small distance. Even turning it one degree could have impact on the results. Because of the time consuming measurements we were forced to do it over several days meaning that we had to put it up and take it down every day. The time was also a limitation on how thorough our measurements could be.

For higher frequencies we experienced a limitation of the sampling rate even thou the cards used 1 MSa/s which for our highest frequency, 250 kHz, is 4 time as large. Compare to the Nyquist-theorem described in the theory chapter, which says that sample rate must be twice the frequency to recreate a sinusoid.

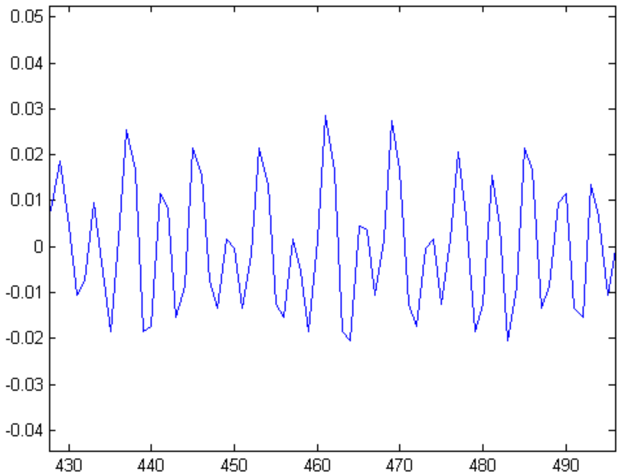


Figure 26: Close-up on the plot from a 240 kHz sinusoid.

While the sampling rate is good enough to measure the sinusoid, it will result in some missed peaks which might effect the result. However, with numerous iterations followed by averaging this effect should be minimal.

We also experienced some external distortions from unexpected sources. For example when the elevator was running we got a 50 Hz signal on all channels and at sometimes the elevator would cause the software to trig prematurely. Another one was when the toilet next door was flushing, it could cause the measurements to be messed up. We suspect it has to do with vibrations.

5.4 Improvements

To enable the measuring of absolute values, a properly calibrated and fully known reference would yield the largest improvement. Especially if its data was provided numerically and applicable after our own measurements. A second huge improvement would be to have different projectors for different frequencies to make them all work in the range they were created for, so we would get a clean as possible signal. This spectrum is not widely used and therefore the options for both reference and projector are very limited.

The impact of the projector could be lessened by using a moving band pass filter on the measurement results to make sure that we only take into account the frequency of interest. This should be possible in MATLAB but our efforts did not provide any results.

The rack we had could also be made a lot better. By using no mobile parts and instead doing all the small adjustments with stepper motors to make sure every measurement would have the same condition. It could also be used to measure the hydrophones from different angels, and the possibility to measure the phase.

5.4.1 Automation

Our first idea was to make the calibration possible at field. This would improve the measurements a lot for example when you do not know how strong of a signal you are expecting. However under the condition ELVIS is running today and the method we chose this is not possible. Mainly because of having a moving reference calibrated for the actual condition. The best course of action would be to modify ELVIS to make each hydrophone work as a projector in addition to its current features and then calibrate using the self-reciprocity method.

5.5 Conclusion

The method we chose requires a lot of the measurement set-up. If we would have known how difficult it will be to implement maybe we would have chosen another method, for example self-reciprocity. All things considered, the results are good and show how the system behaves for different frequencies.

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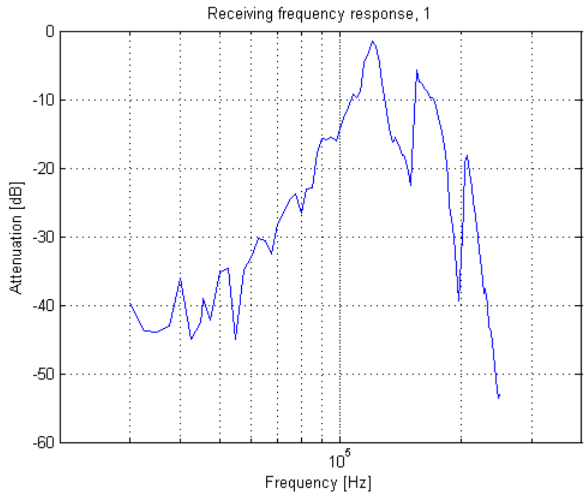
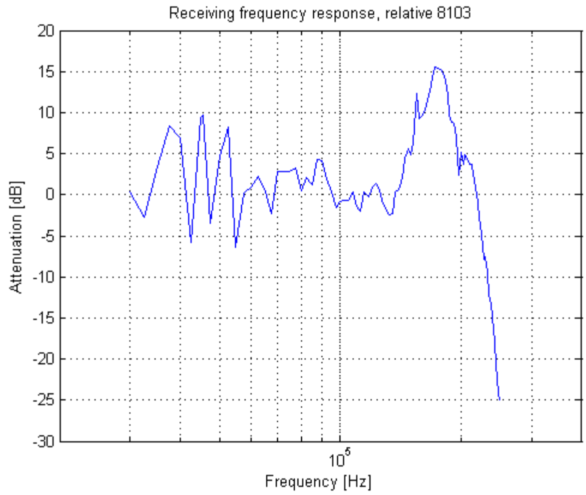
Appendix A

Appendix A will contain all graphs from the hydrophone measurements as well as notes. Hydrophones were measured every 5 kHz from 30-100 kHz and every 10 kHz from 110-250 kHz. Hydrophone 3 is not included in the analysis because a broken cable. For table of configuration, see Appendix B.

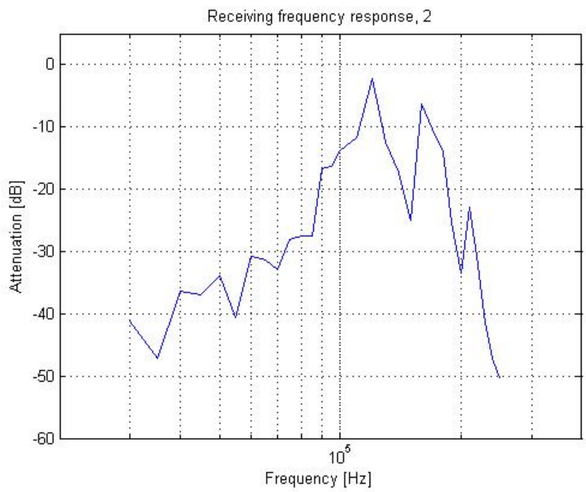
Hydrophone 1

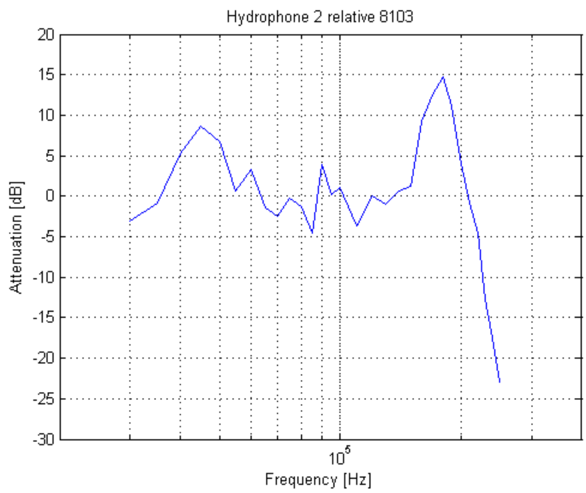




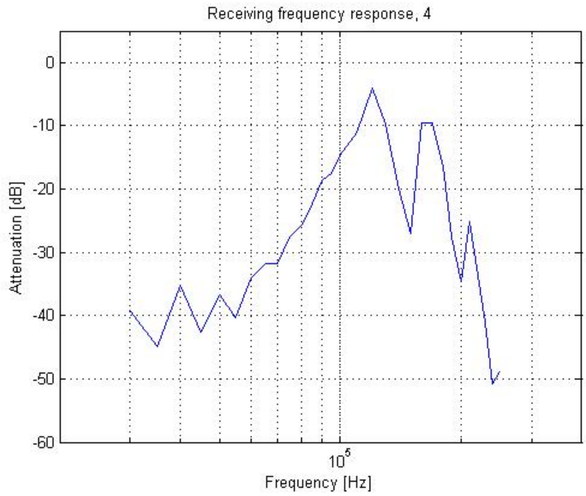
Hydrophone 1 was measured every 2,5 kHz from 30-250 kHz plus an additional recording at 45,5 kHz.

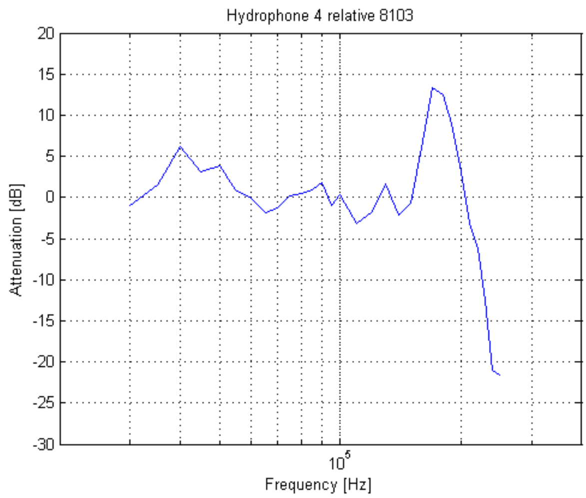
Hydrophone 2





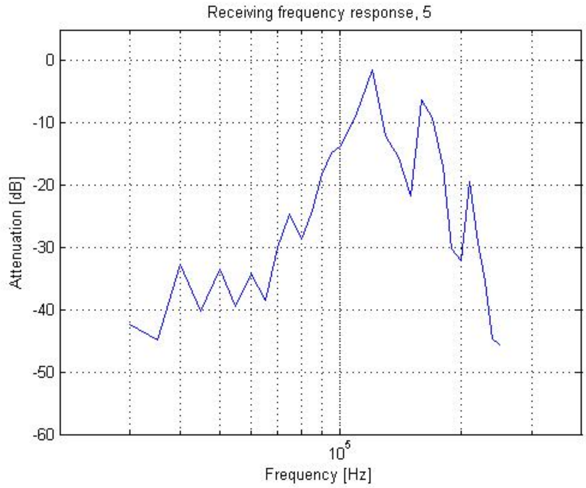
Hydrophone 4

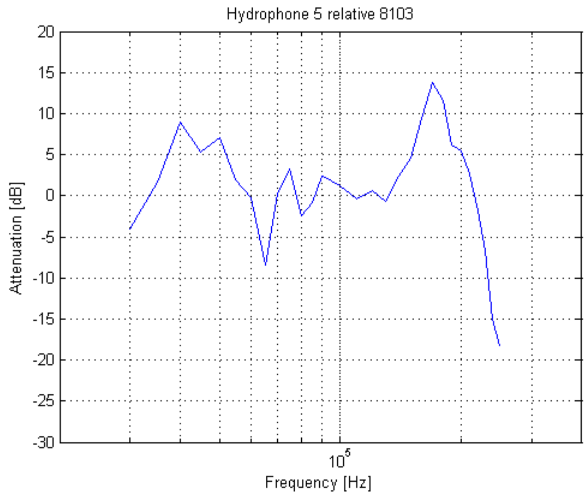




Good performance on lower frequencies.

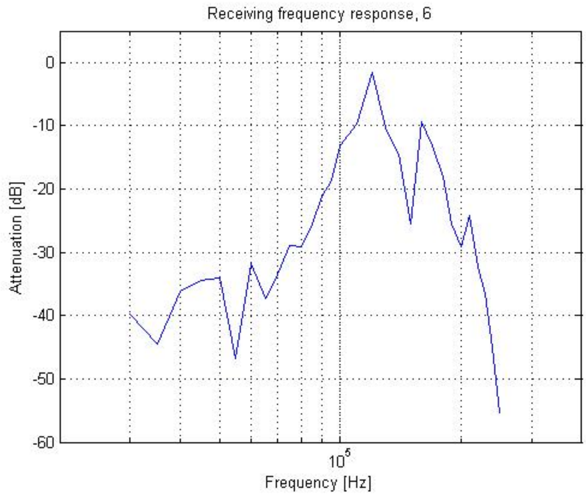
Hydrophone 5

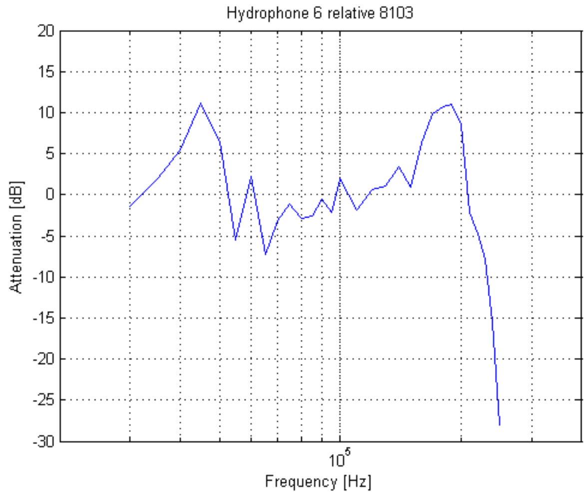




Unusually high at 40 kHz but low at 65 kHz.

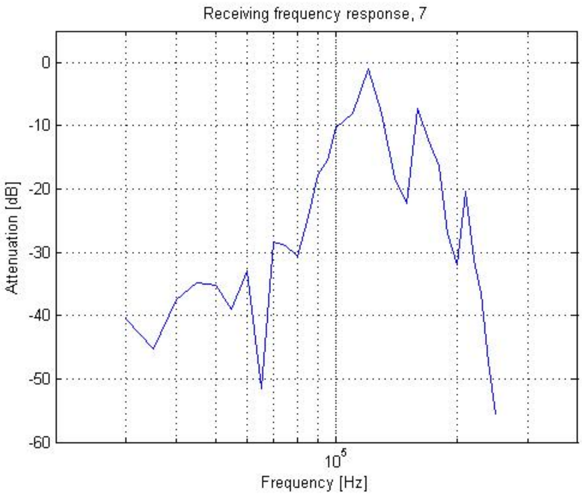
Hydrophone 6

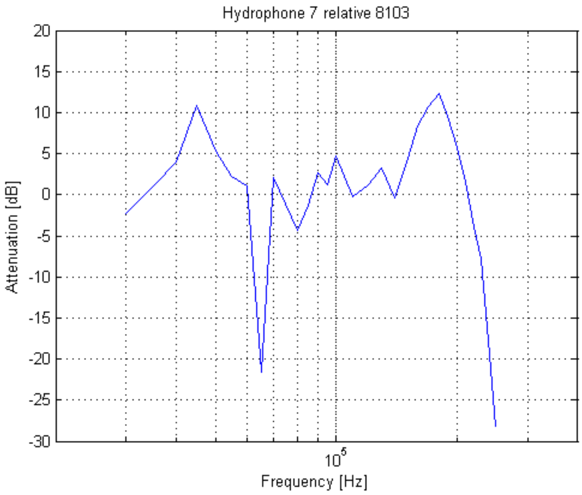




Large peak at 45 kHz.

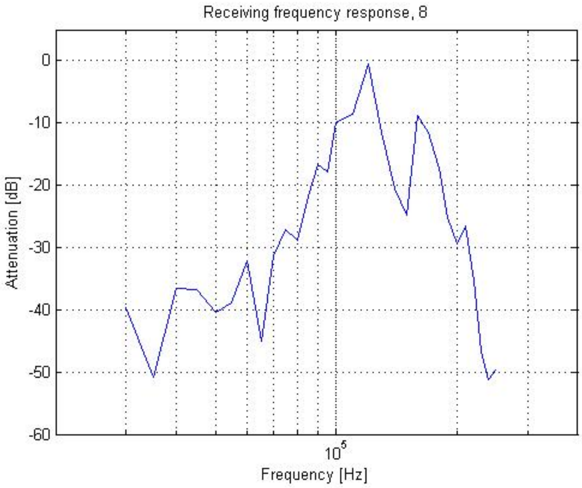
Hydrophone 7

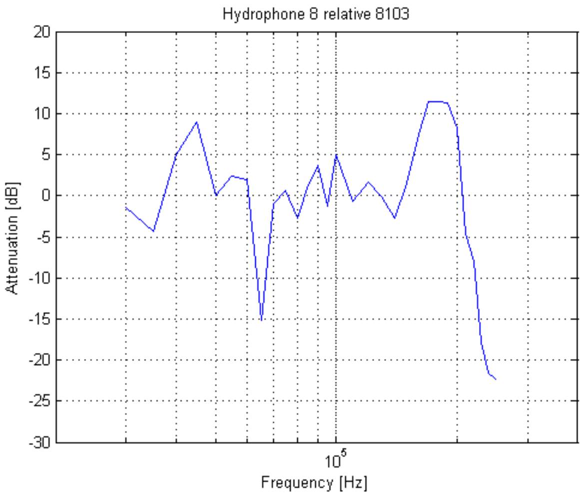




Large peak at 45 kHz but extreme attenuation at 65 kHz.

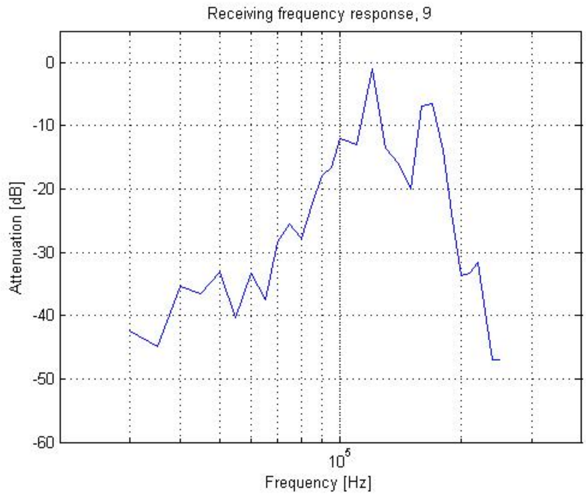
Hydrophone 8

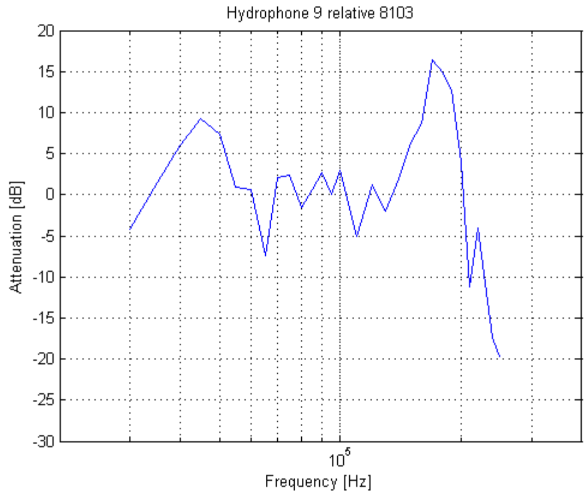




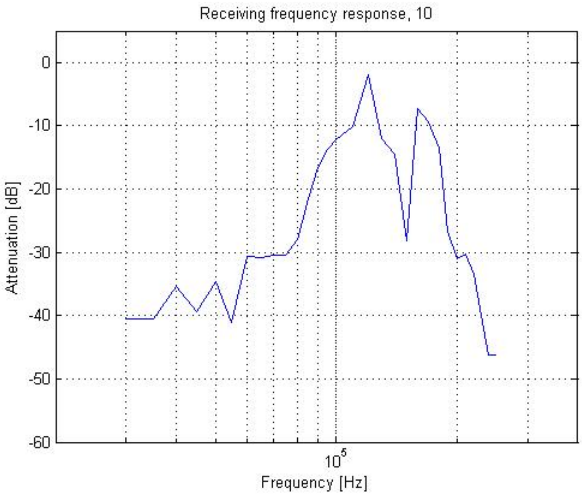
Uneven for lower frequencies.

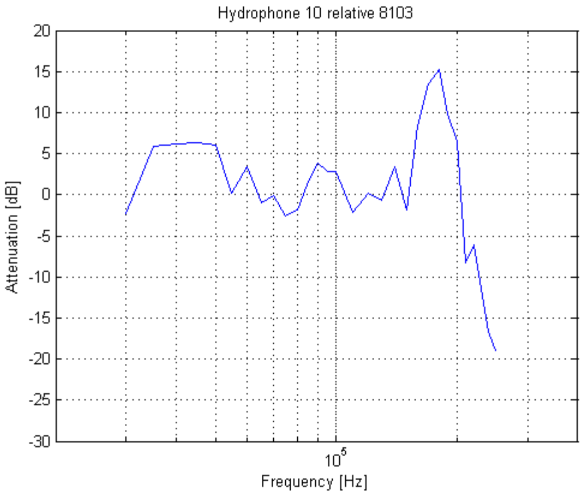
Hydrophone 9



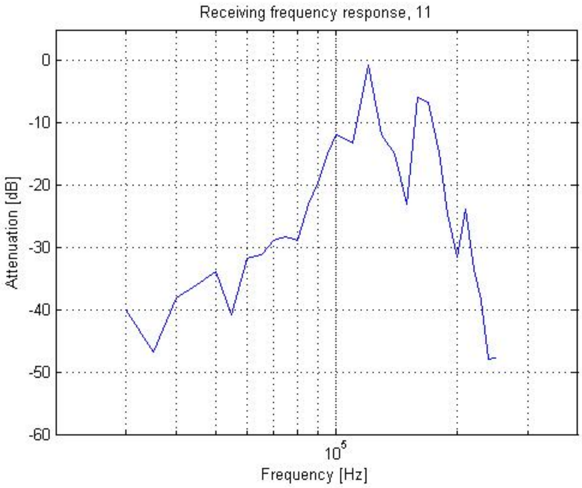


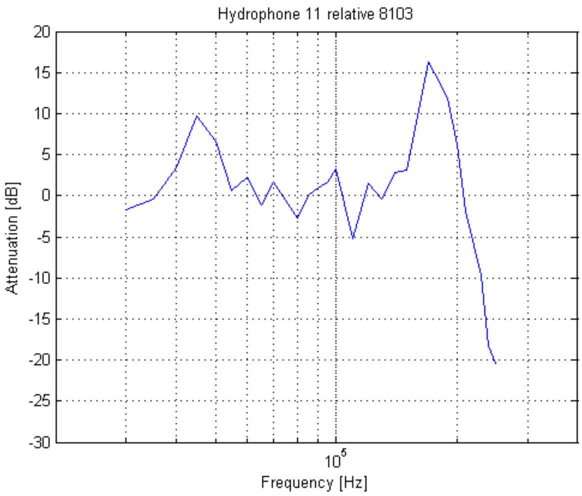
Hydrophone 10



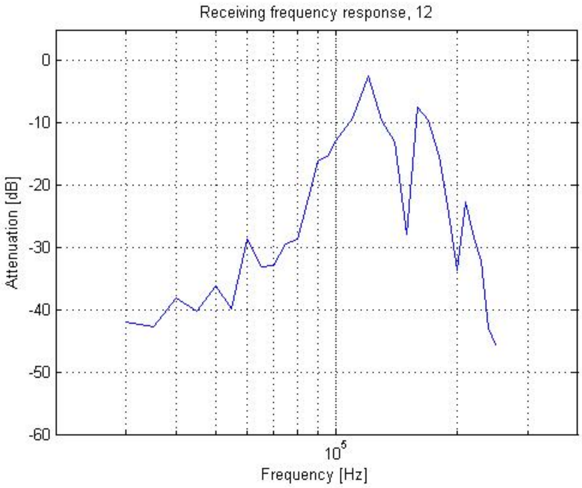


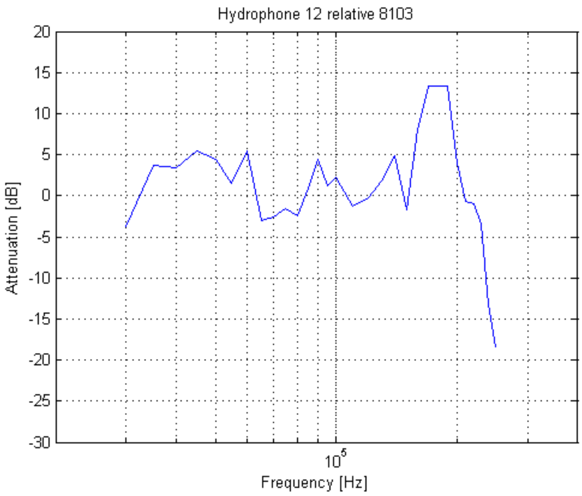
Hydrophone 11





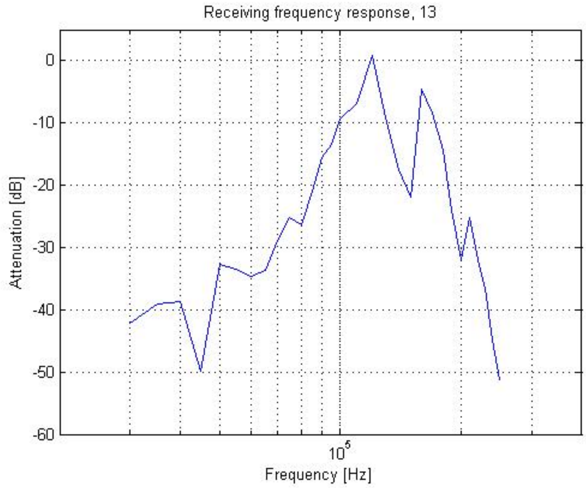
Hydrophone 12

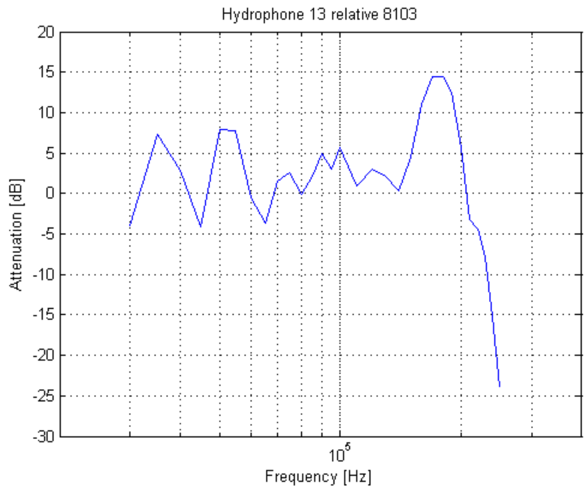




Good performance.

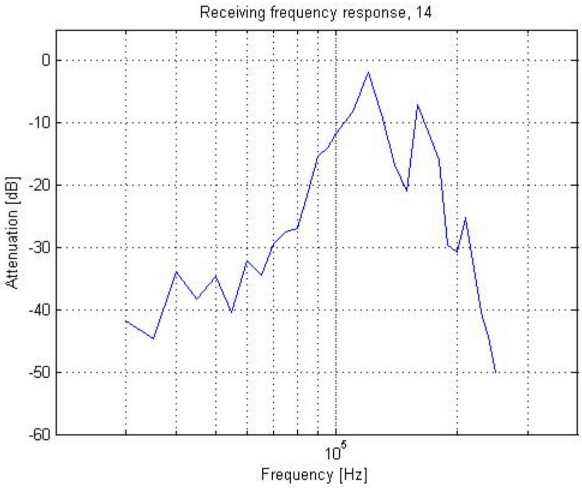
Hydrophone 13

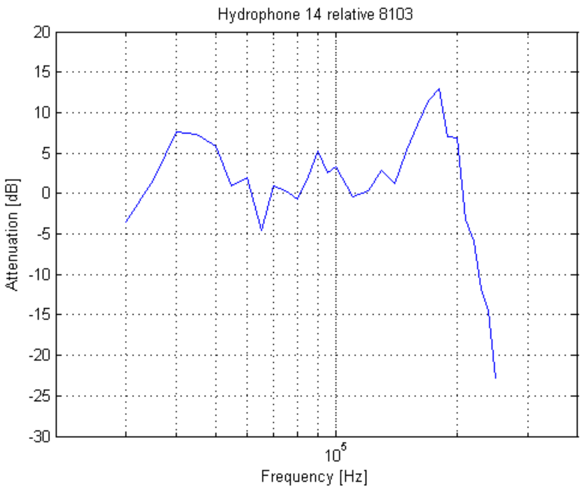




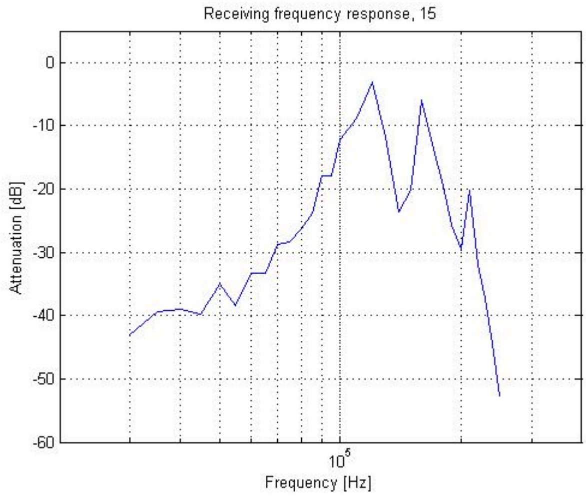
Unusually low at 45 kHz.

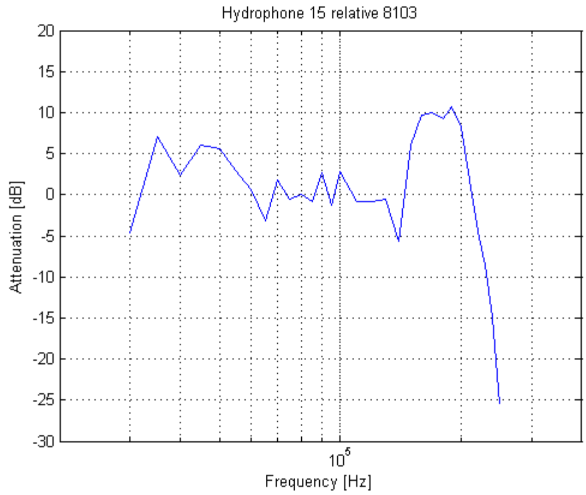
Hydrophone 14



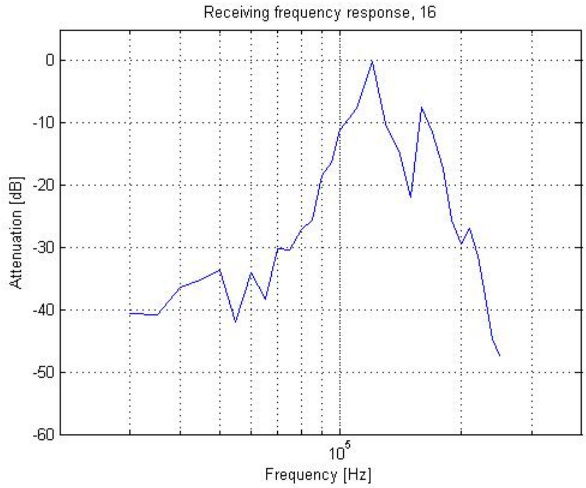


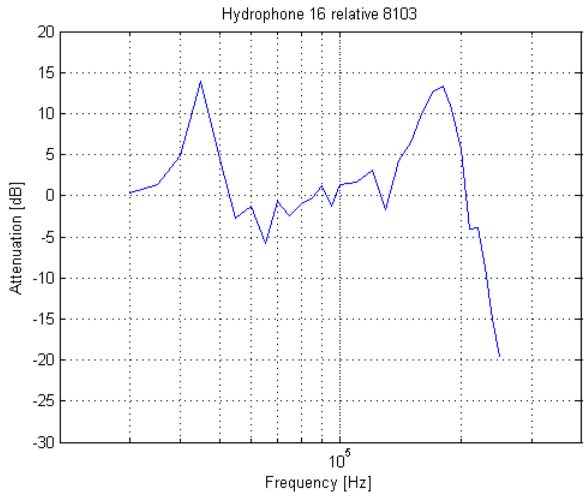
Hydrophone 15





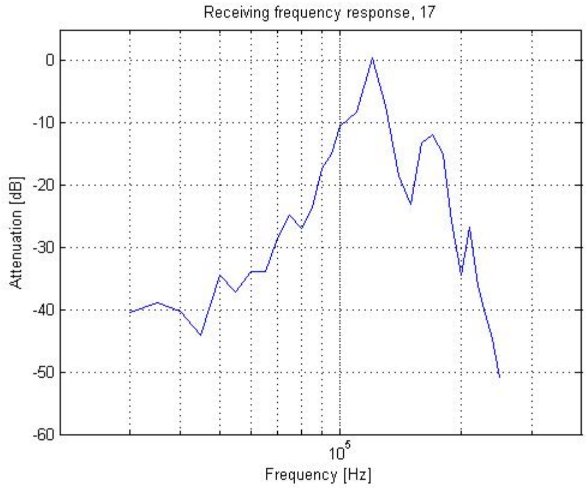
Hydrophone 16

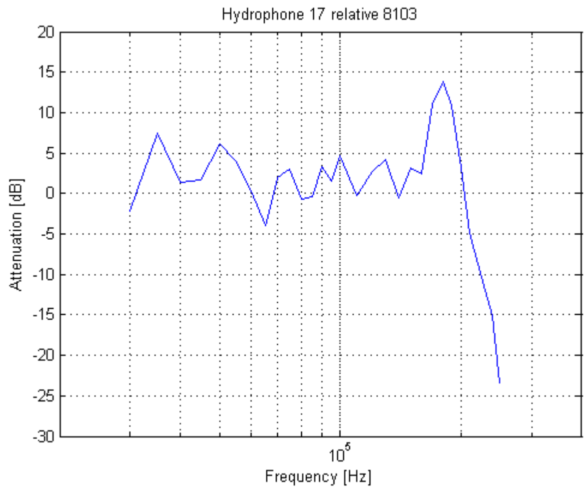




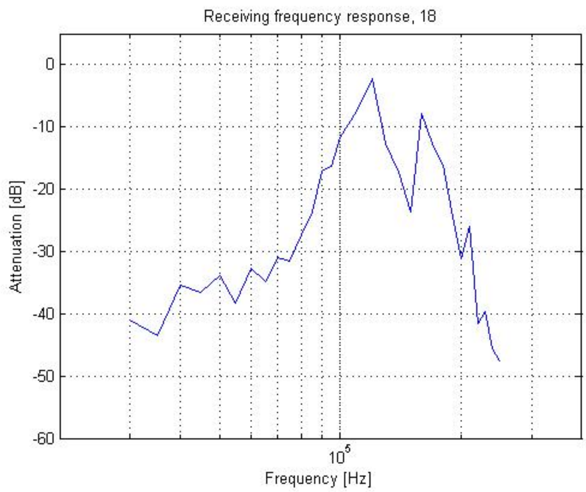
Unusually high at 45 kHz, even higher than 170 kHz.

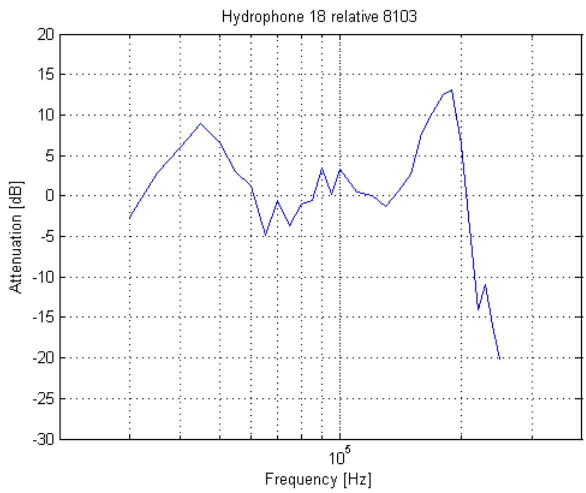
Hydrophone 17





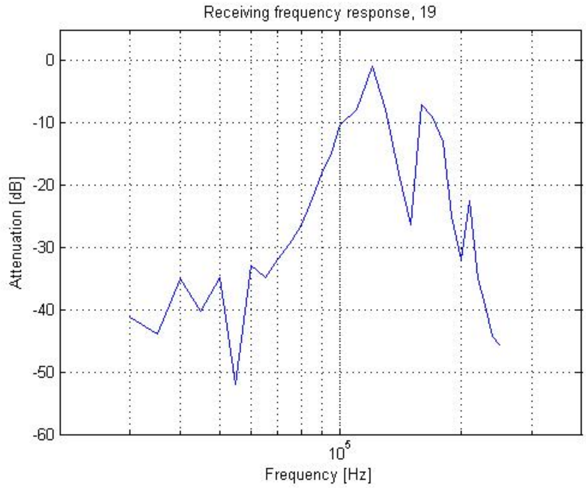
Hydrophone 18

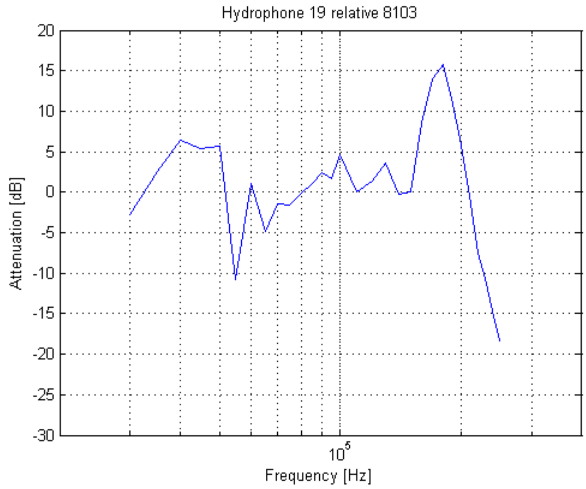




Broad lower frequency peak.

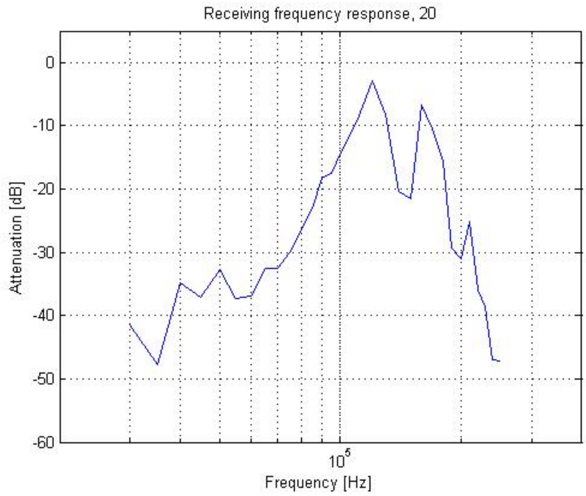
Hydrophone 19

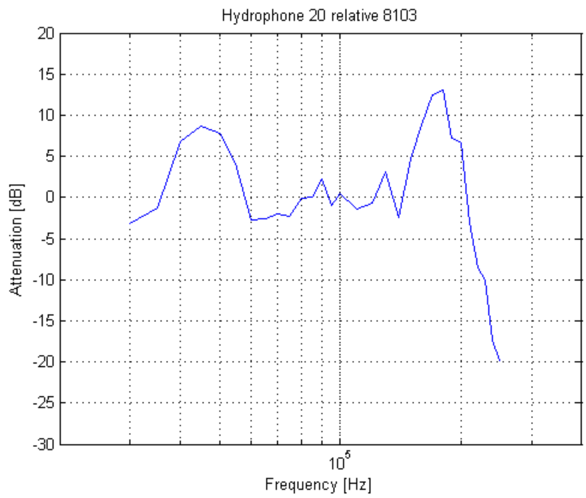




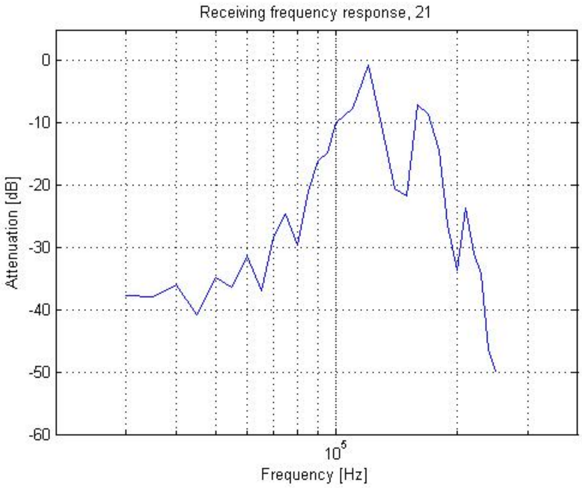
Really low for 55 kHz.

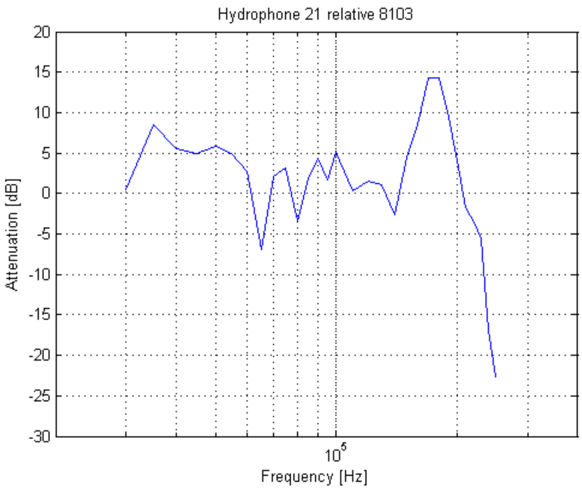
Hydrophone 20



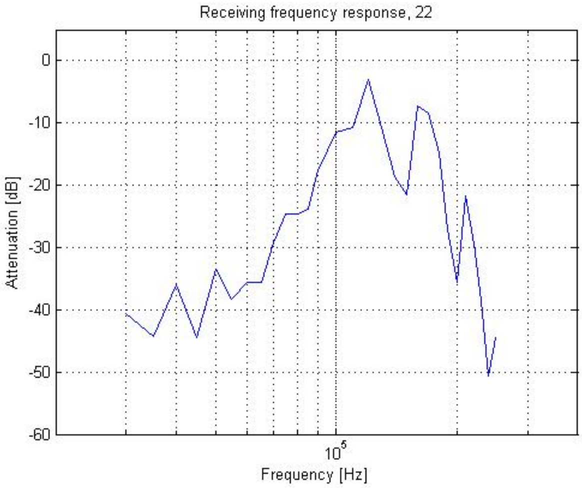


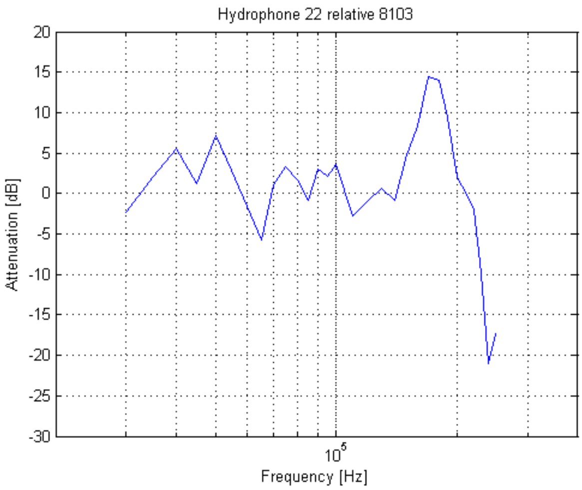
Hydrophone 21



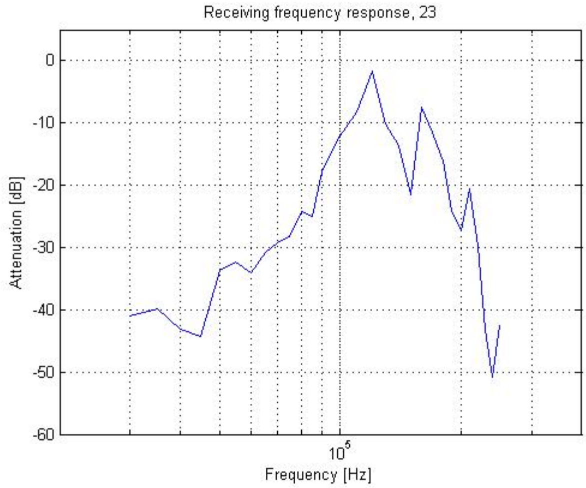


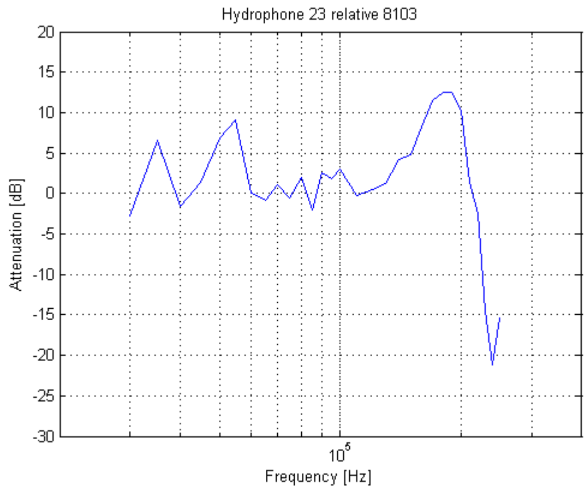
Hydrophone 22



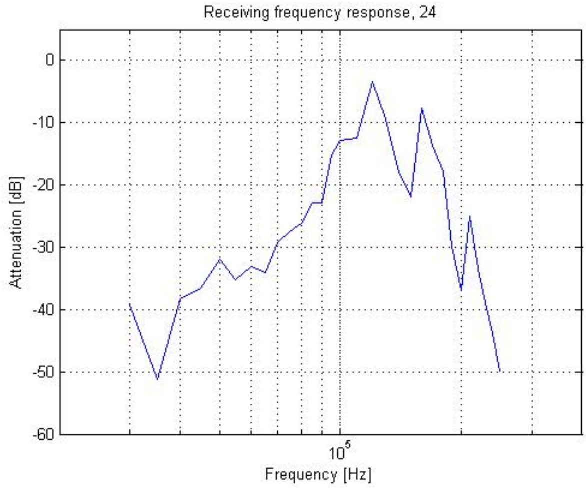


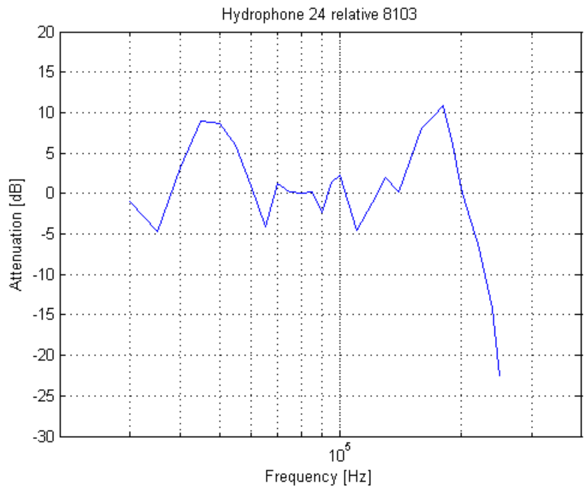
Hydrophone 23





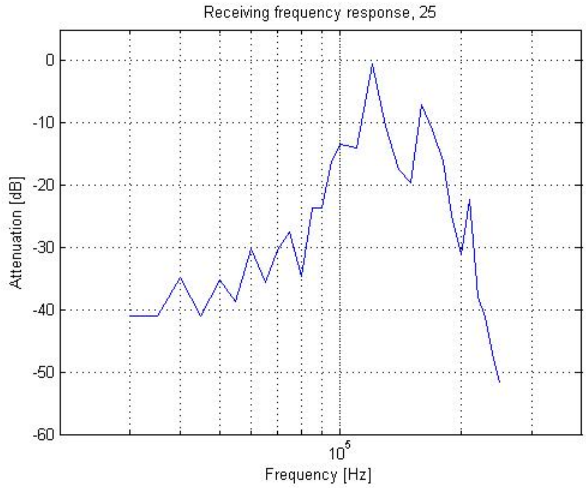
Hydrophone 24

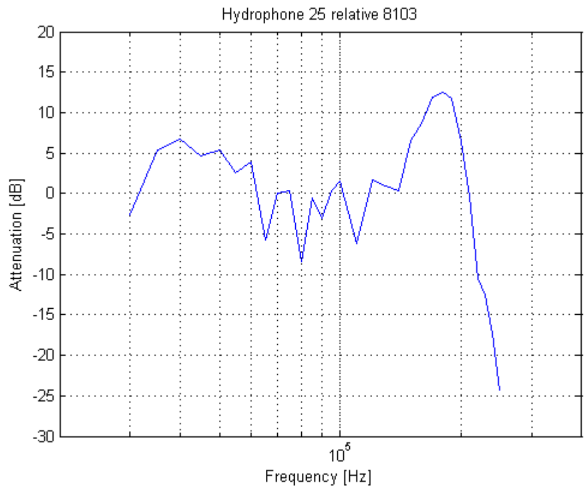




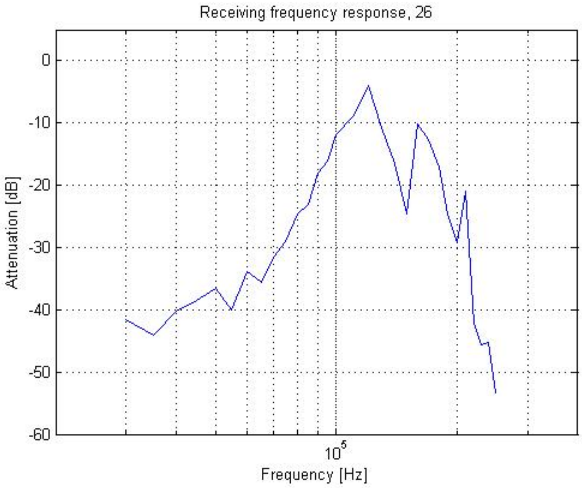
Relatively low for 35 kHz.

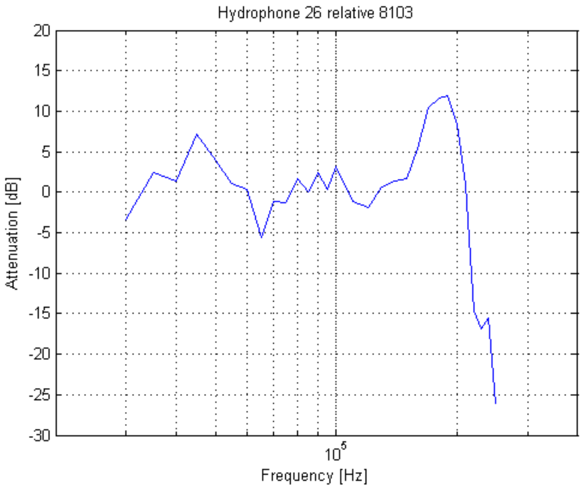
Hydrophone 25



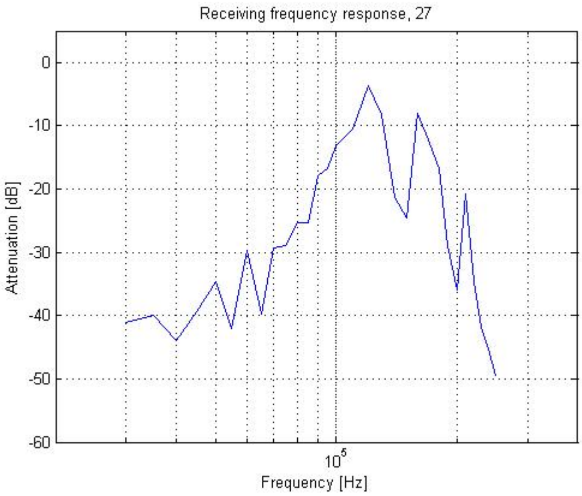


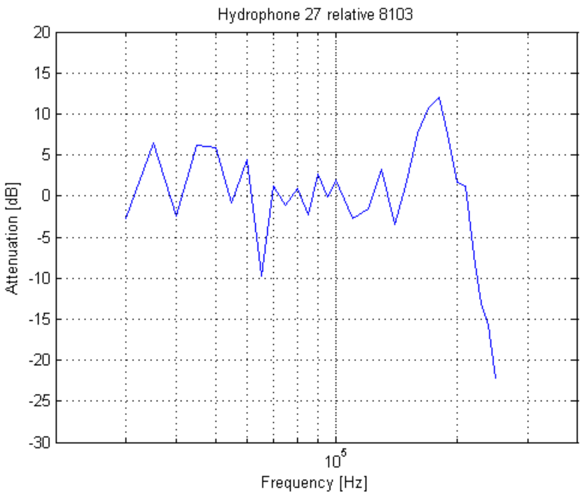
Hydrophone 26





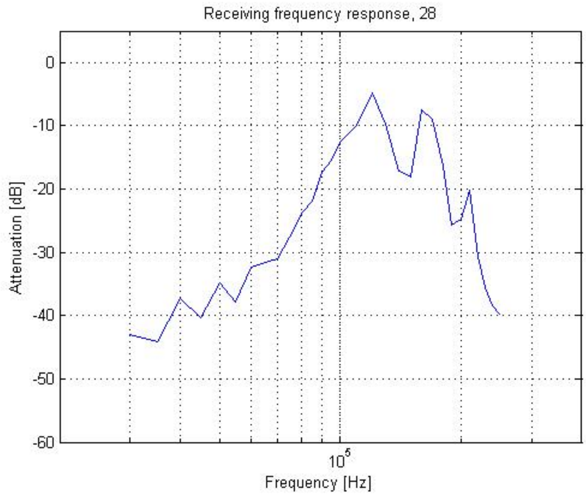
Hydrophone 27

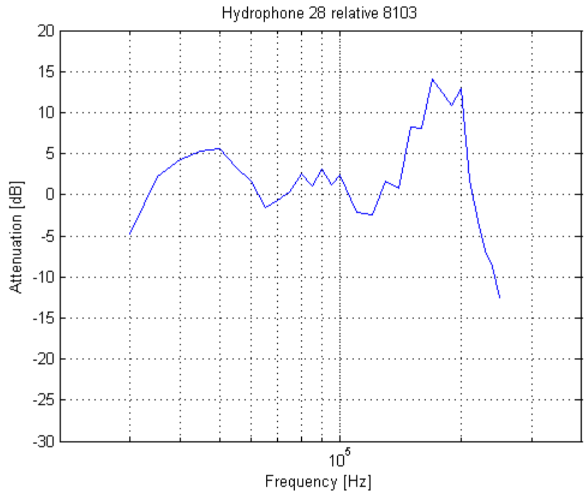




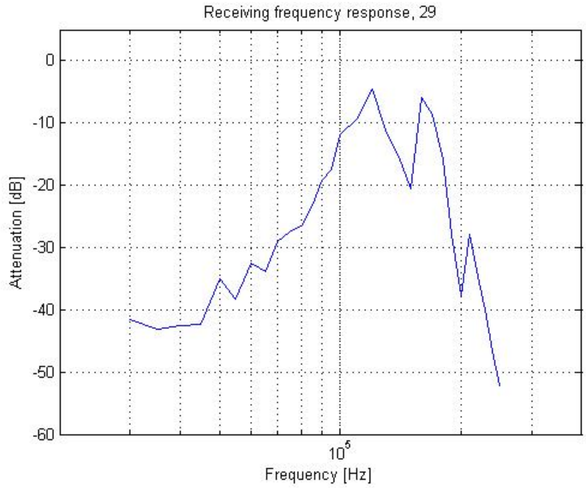
Unusually jittery for most of the frequencies.

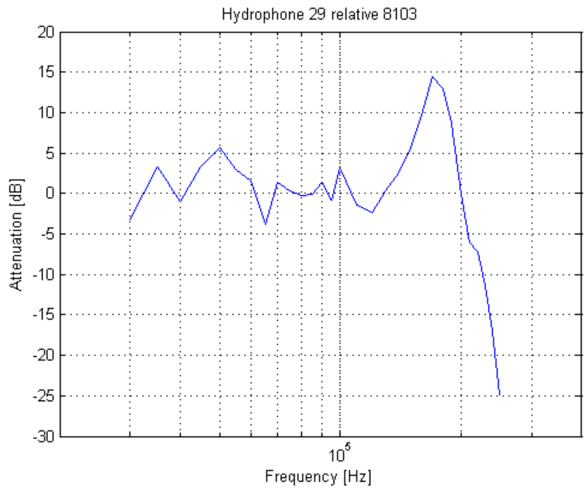
Hydrophone 28





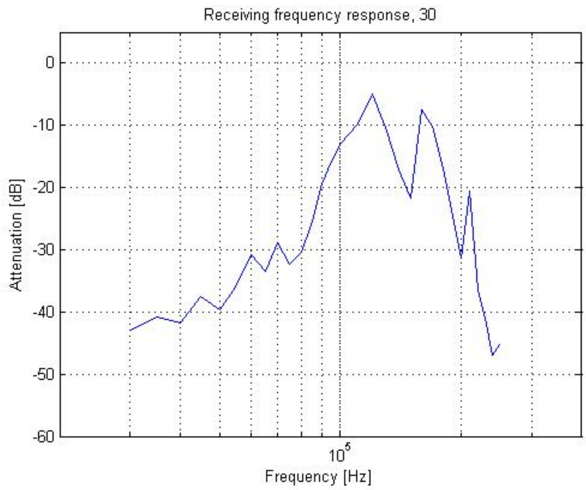
Hydrophone 29

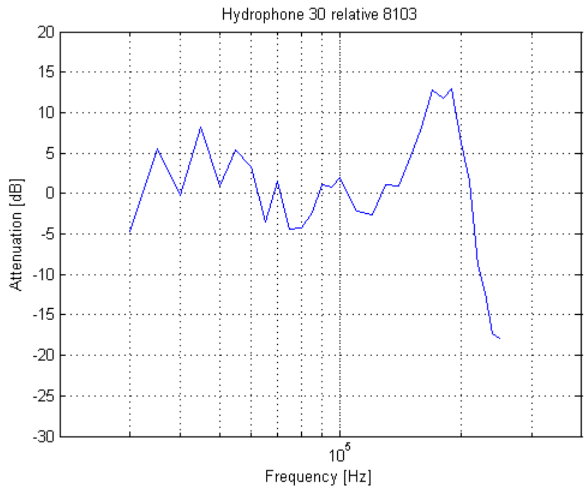




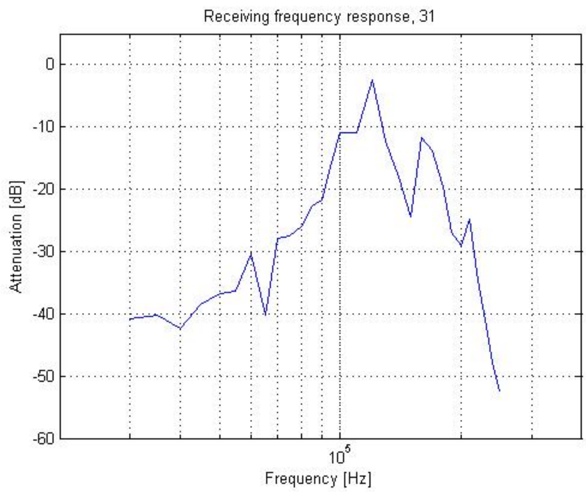
Good performance.

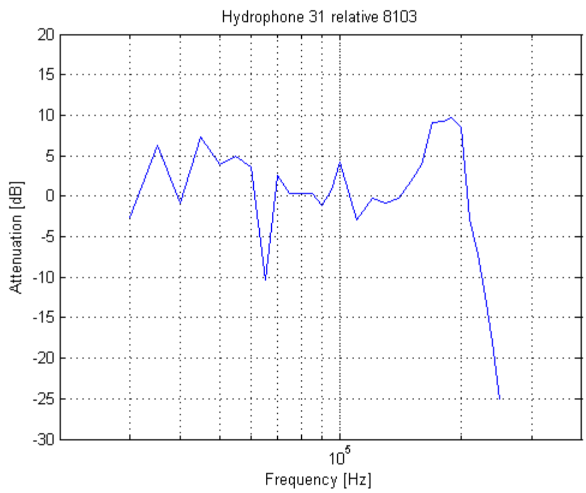
Hydrophone 30





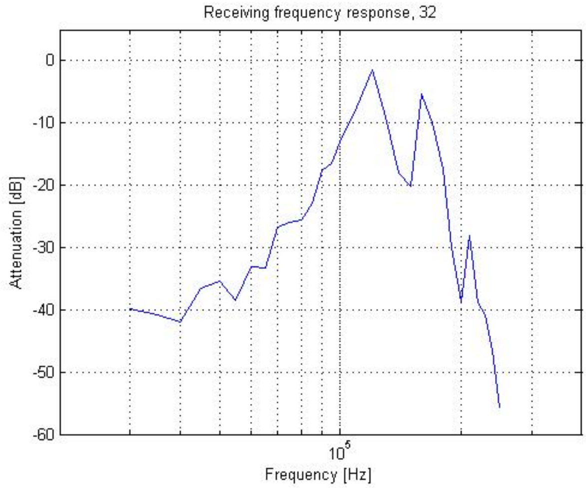
Hydrophone 31

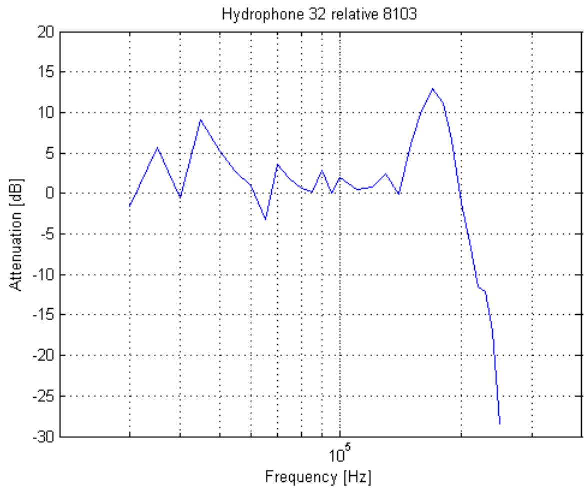




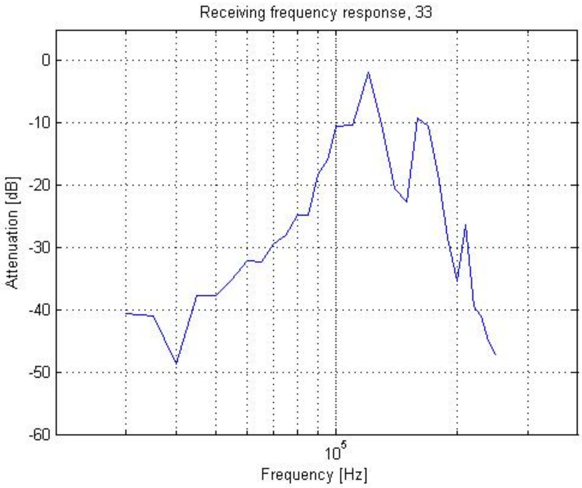
Low resonance peak at 170 kHz.

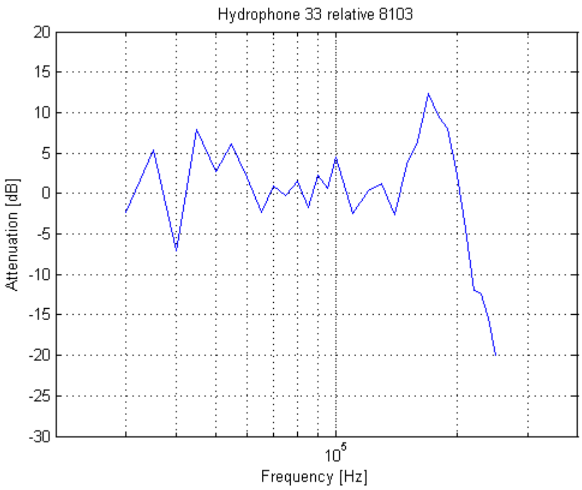
Hydrophone 32



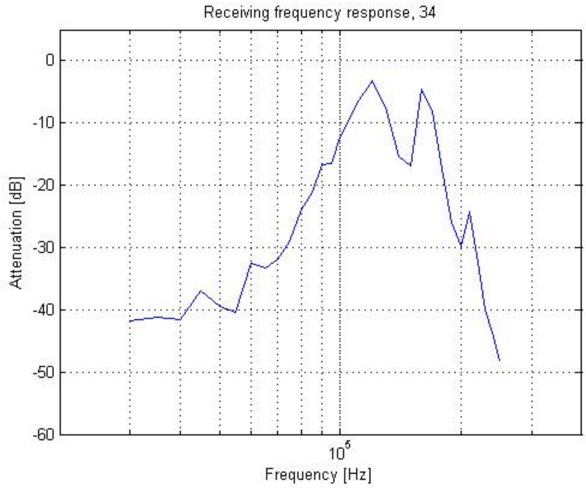


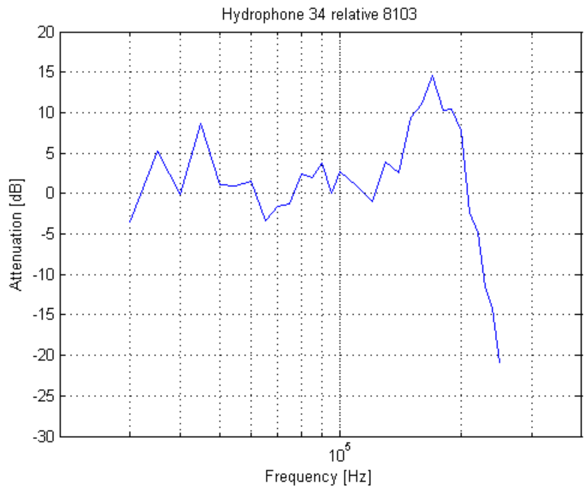
Hydrophone 33



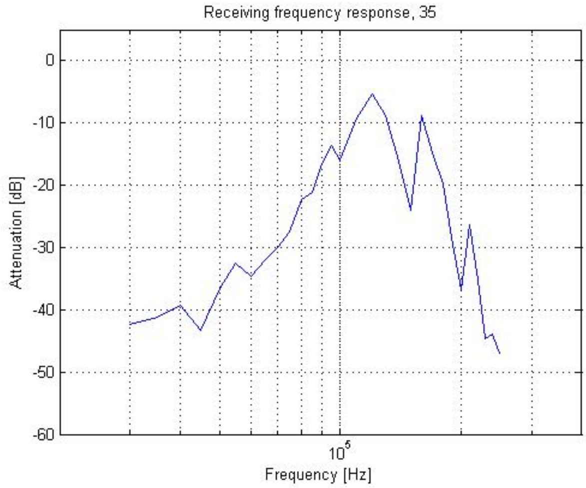


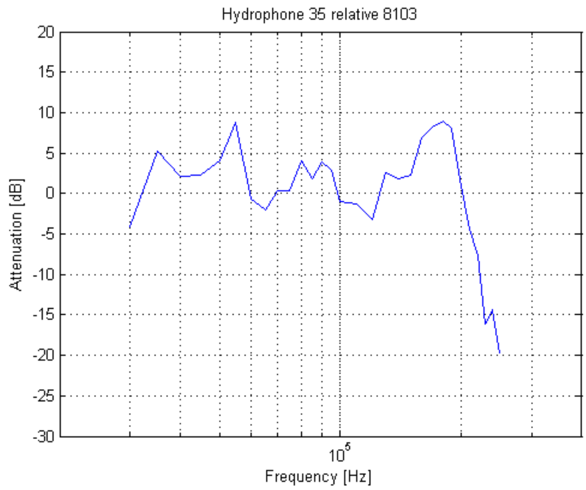
Hydrophone 34





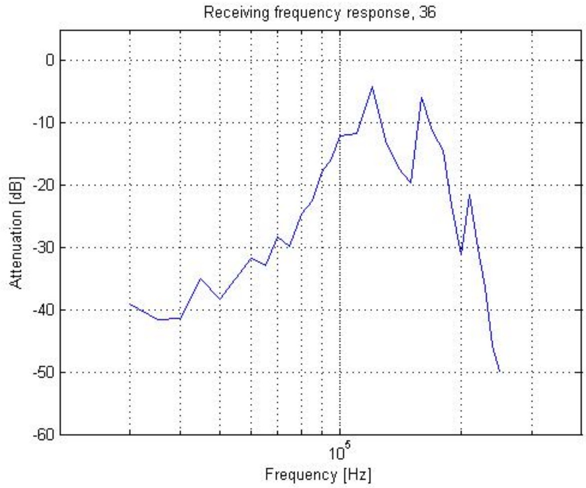
Hydrophone 35

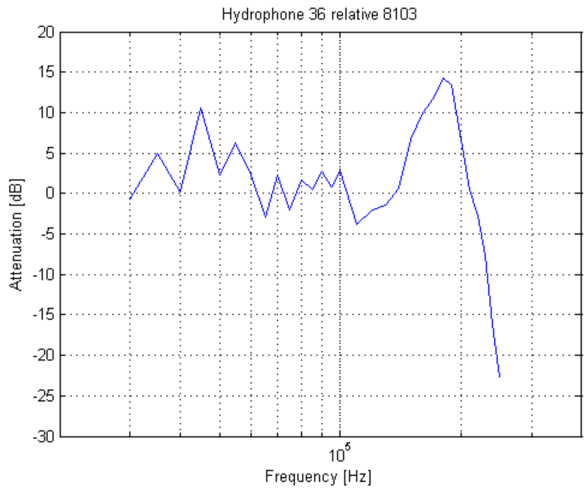




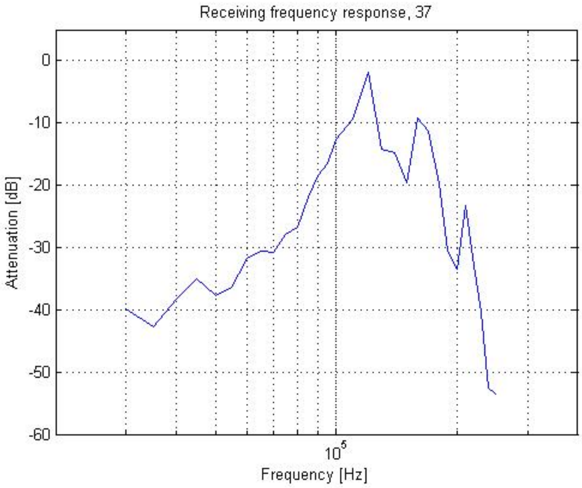
Low resonance peak at 170 kHz.

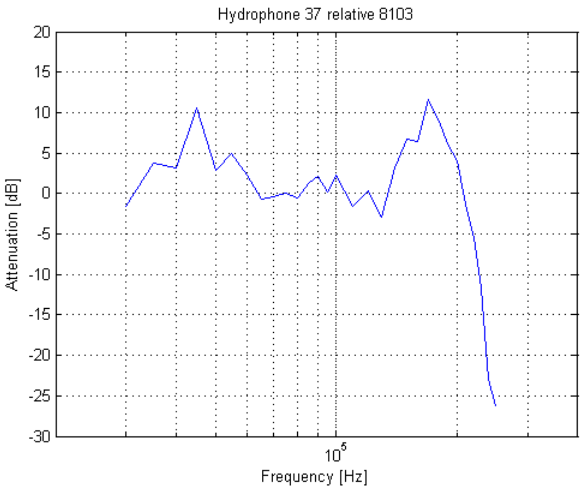
Hydrophone 36



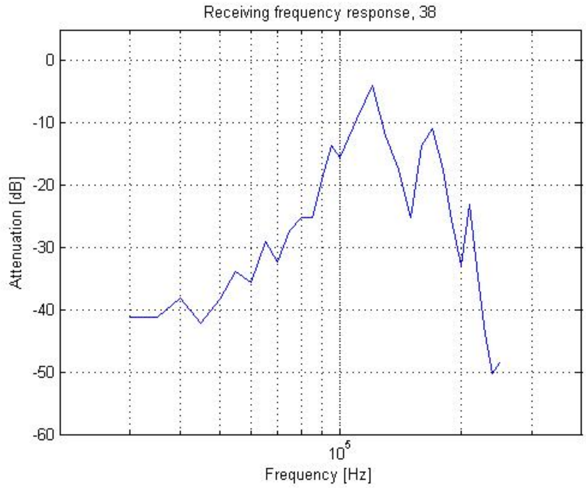


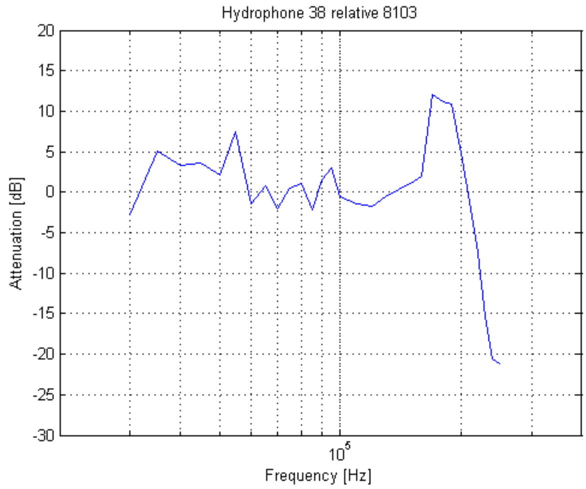
Hydrophone 37



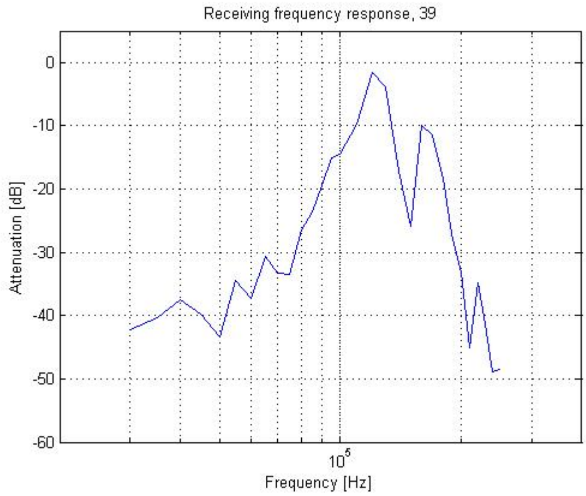


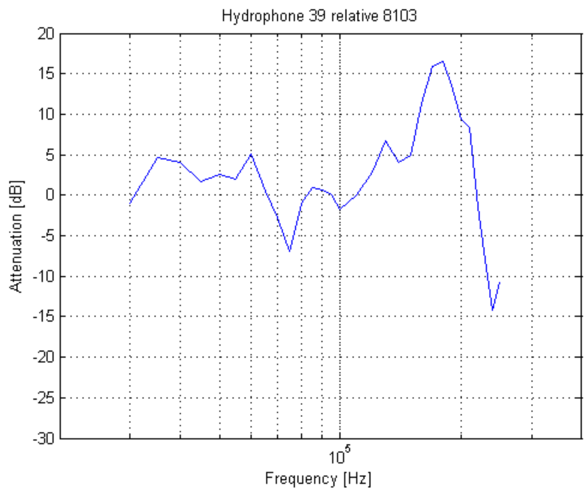
Hydrophone 38





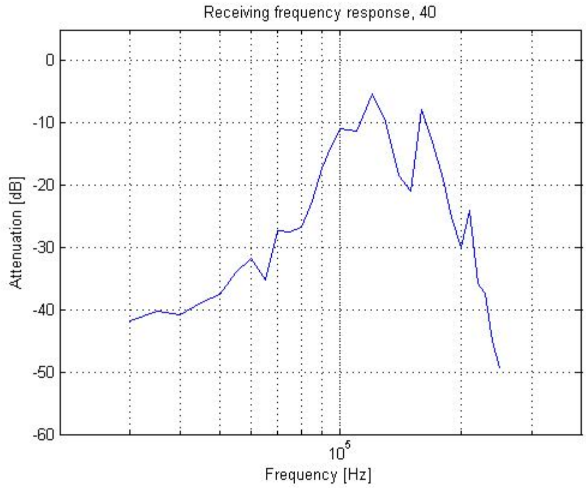
Hydrophone 39

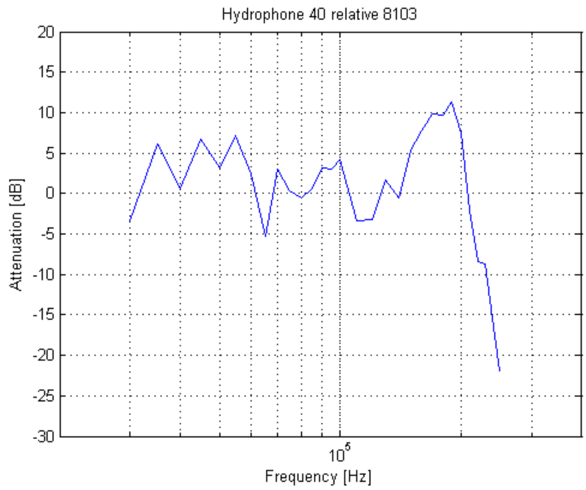




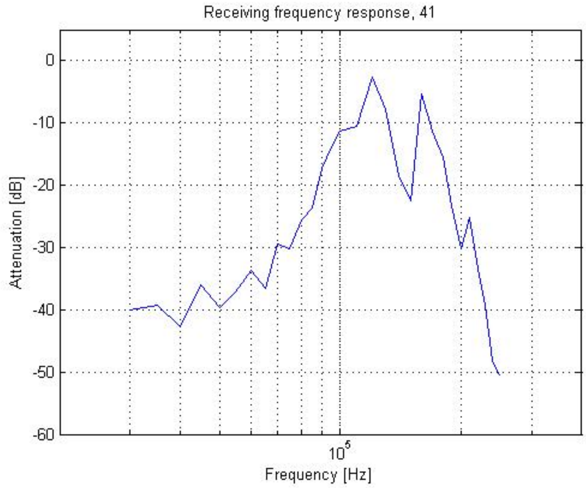
Unusually low at 210 kHz. One of the hydrophones sent to Brüel & Kjær.

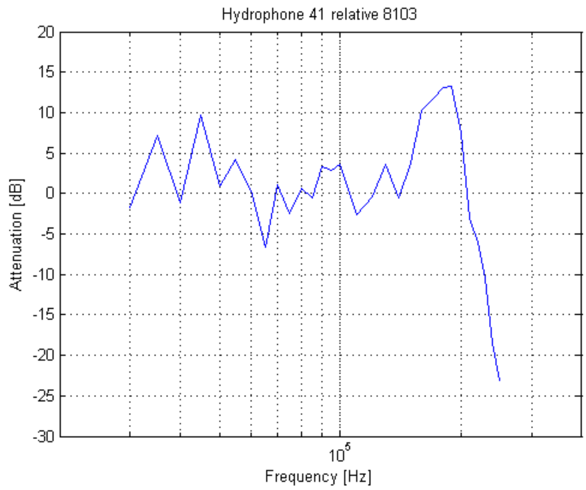
Hydrophone 40





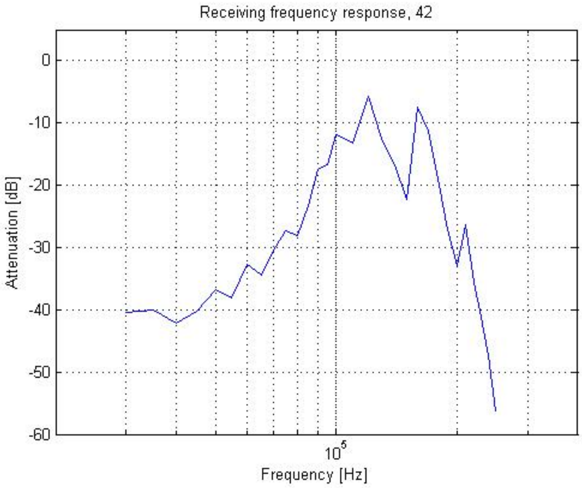
Hydrophone 41

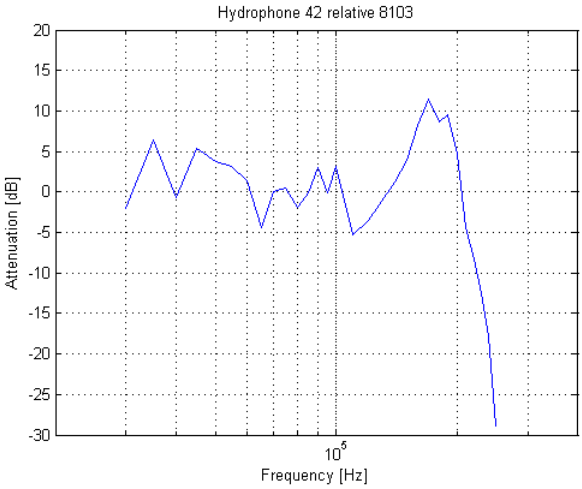




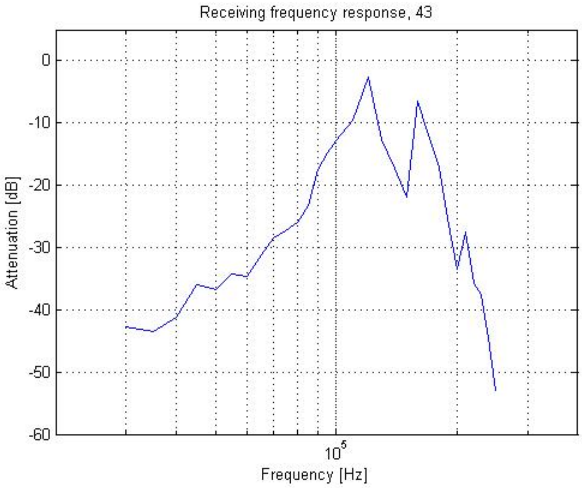
Unusually jittery.

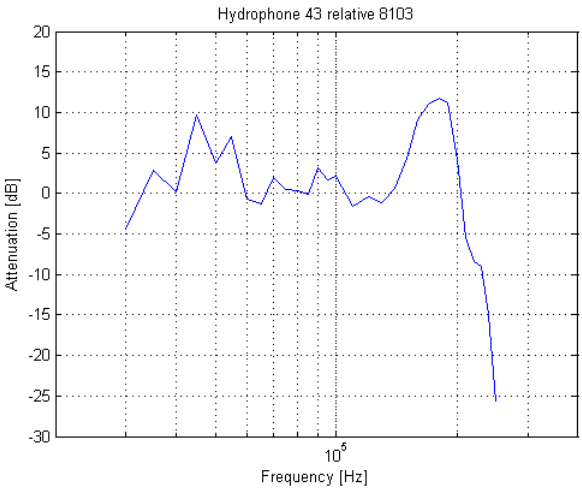
Hydrophone 42



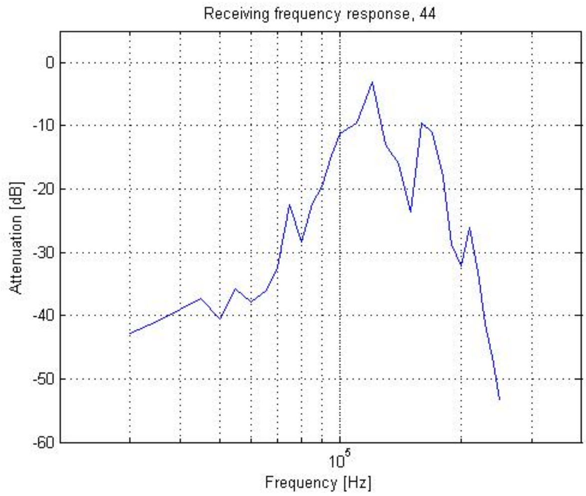


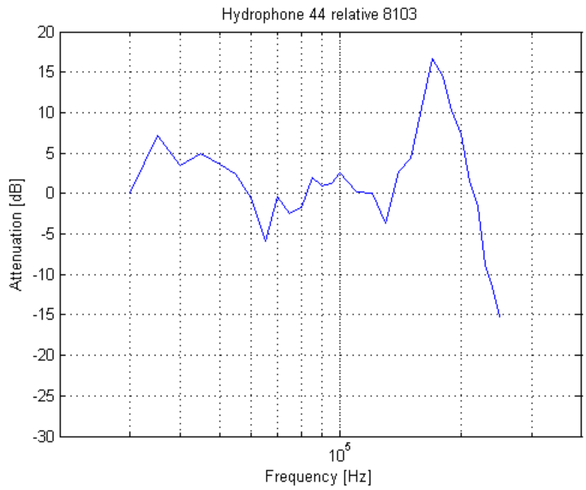
Hydrophone 43





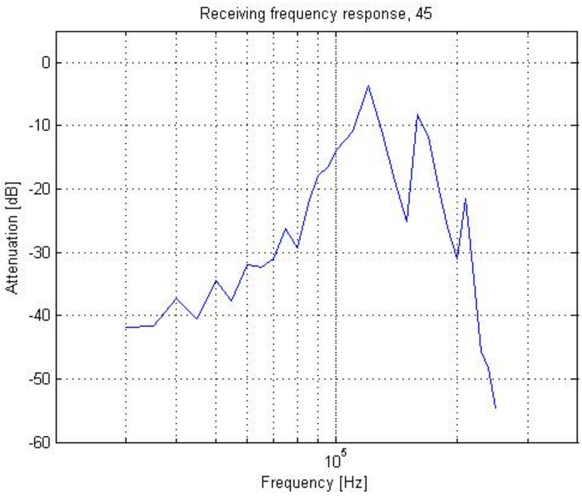
Hydrophone 44

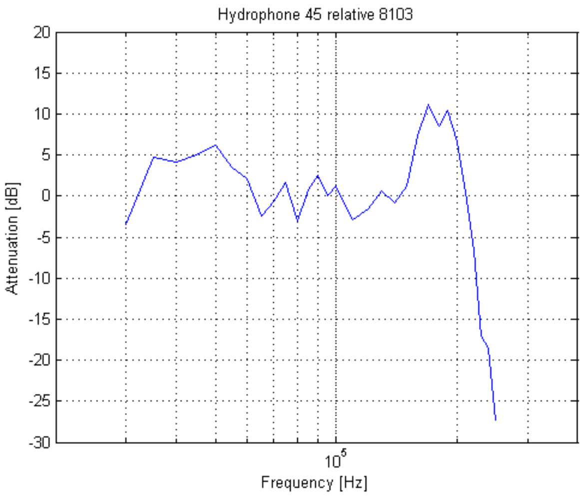




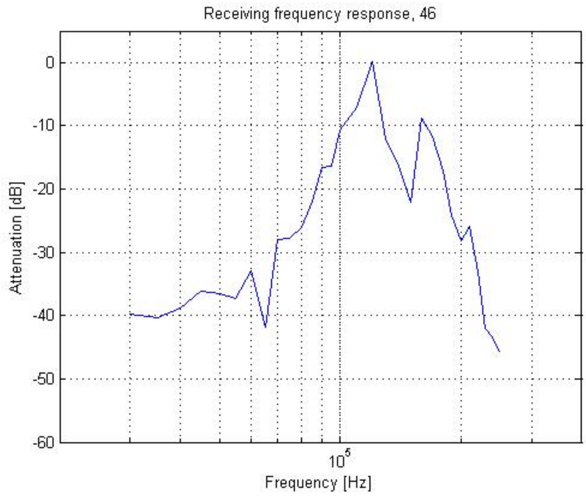
Strong resonance at 170 kHz. One of the hydrophones sent to Brüel & Kjær.

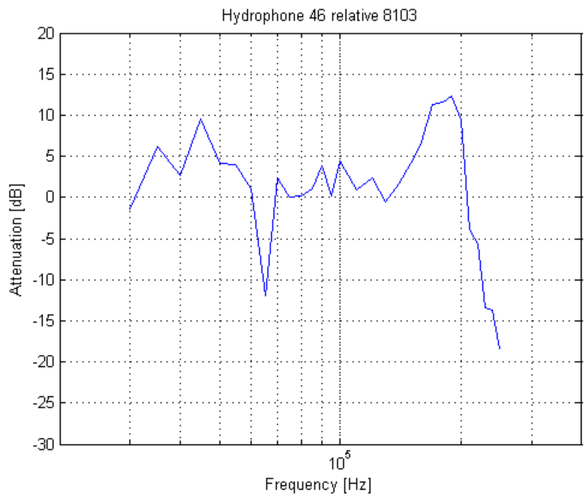
Hydrophone 45





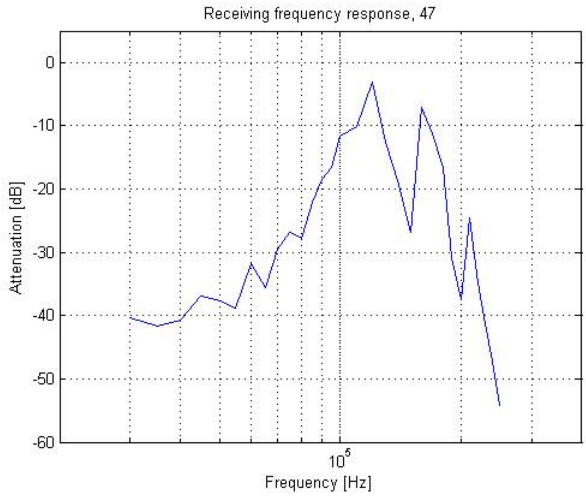
Hydrophone 46

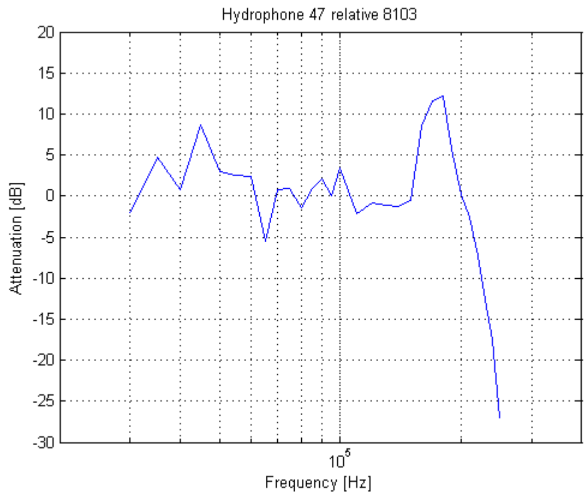




Big drop at 65 kHz.

Hydrophone 47





Appendix B

Appendix B will contains the table of configuration for our measurements.

The record length was changed from 750 samples to 550 samples at 130 kHz to lessen the data.

Frequency	Cycles	Trigger Level	Vertical Range	Voltage
30	9	0.05	2.0	10
35	12			
40	13			
45	16			
50	18			
55	19			
60	20			
65	22	0.25		
70	24			
75	26			
80	28	0.5	3.0	
85				
90	30	1.0	4.0	
95	32			
100	34			6
110	36			
120	40			3
130	30	0.5		4
140	34			6
150	38			10
160				6
170	40			
180		0.3	2.0	10
190	50			
200	24			
210				
220		0.2		
230				
240				
250	56			