Calibration of sensors for acoustic detection of neutrinos

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Abstract. Calibration of sensors is an important task for the acoustic detection of neutrinos. Different approaches have been tried and used (calibrated hydrophones, resistors, powerful lasers, light bulbs explosion, etc.) We propose some methods for calibration that can be used in both the lab and the telescope (“in situ”). In this paper, different studies following these methods and their results are reported. First, we describe the reciprocity calibration method for acoustic sensors. Since it is a simple method and calibrated hydrophones are not needed, this technique is accessible for any lab. Moreover, the technique could be used to calibrate the sensors of a neutrino telescope just by using themselves (reciprocally). A comparison of this technique using different kind of signals (MLS, TSP, tone bursts, white noise), and in different propagation conditions is presented. The limitations of the technique are shown, as well as some possibilities to overcome them. The second aspect treated is the obtaining of neutrino-like signals for calibration. Probably, the most convenient way to do it would be to generate these signals from transducers directly. Since transducers do not usually have a flat frequency response, distortion is produced, and neutrino-like signals could be difficult to achieve. We present some equalization techniques to offset this effect. In this sense, the use of inverse filter based in Mourjopoulos theory seems to be quite convenient.

1. Introduction
Although acoustic detection of neutrinos has been proposed long time ago [1], it is just recently when science community show an increasing interest, and a major effort has been made for achieving this objective. Some experiments and test facilities have been appeared in water [2,3,4,5,6] and in ice [7]. It is also worthwhile to mention the efforts made in simulations [8] and in R&D for acoustic telescopes [9,10]. Calibration of acoustic sensors of the telescope, both in the lab and “in situ”, is also a clue aspect on this task, and different approaches have been proposed [2,11,12]. In this paper, two studies related to calibration are presented: calibration of the sensitivity of acoustic sensors using the reciprocity method, and generation of neutrino-like signals using transducers.

2. Calibration of the sensitivity of acoustic sensors using the reciprocity method
One of the more common methods for calibration of the sensitivity of acoustic transducers is the reciprocity technique. A detailed description of the method is usually present in basic books of acoustics and transduction; see for example [13,14], and it is not included here. The procedure is quite simple and allows to calibrate hydrophones with non-calibrated ones. No sophisticated acoustic equipment is needed, which could be very convenient for the application in particle physics labs. However, it usually requires free field configuration, which is not always an easy configuration for
this kind of labs. In this work we study the use of different calibration signals and configurations in order to overcome the limitations mentioned. On the other hand, the reciprocity technique could, under certain circumstances, be also used to calibrate the sensors of neutrino telescopes just by using themselves reciprocally.

Using three non-calibrated hydrophones (designated by letters \(a\), \(b\), \(c\)), the sensitivity of transducer \(c\) can be obtained in just three steps involving four measurements: \(V_b\), \(V_c\), \(V_c'\) and \(I_b\) (voltages and current in the transducers \(b\) and \(c\)) with the expression

\[
S = \left( J \left[ \frac{V_c}{V_c'} \right] \frac{I_b}{I_b} \right)^{1/2}
\]

where \(J\) is the reciprocity parameter, which depends on the acoustic propagation conditions. The expression of this parameter is given in [15] for different cases. Thus, \(J=2d/(r f)\) for the spherical free field case, \(J=2A/(r c)\) for a tube assuming plane waves and \(J=2\pi V/(r c^2)\), for a coupler, which consists in a small volume and assumes that the pressure is the same at any point, where \(d\) is the distance between the transducers, \(r\) is the density of the medium, \(f\) is the frequency, \(A\) is the area of the tube, \(c\) the speed of the wave, and \(V\) is the volume of the coupler. Notice the different frequency dependence of \(J\) for every configuration.

Our studies have been done using Airmar Tech. P319 transducers \(a\) and \(b\), and a Reson TC4034 hydrophone as transducer \(c\).

2.1. Studies using different kind of signals

The use of different kind of signals implemented in Cool Edit and Aurora [16] (MLS, sine sweep, tone bursts and white noise) has been studied for reciprocity calibration of the sensitivity of acoustic sensors in a 1.10x0.85x0.80 m\(^3\) tank. In figure 1, the results of the calibration of the sensitivity of transducer \(c\) for different signals are presented, and compared to the reference calibration provided from the manufacturer. Despite the limitations of the configuration, that is, the reflections in the small tank, the results are in a rough agreement with the reference calibration. However, it is also true that this technique must be refined before being able to use it for precise calibration of transducers. Another interesting aspect is that there are observable differences depending on the signal used. This can be explained in terms that the effects of the limitations in the method, such as the reflections in the walls, are sensitive to the signal used.

\[
\text{Figure 1. Results of the calibration of the sensitivity of transducer } c \text{ for different signals}
\]

2.2. Studies using different propagation conditions

Additional to the tank study, in which we assumed a spherical free field wave, we have studied two more cases. The first one is a cylindrical 170 cm-length tube with a diameter of 8 cm, in which plane...
waves are assumed. The second configuration is a coupler consisting on a small 25 cm-length tube and a diameter of 8 cm with methacrylate walls. The results of the calibration of the sensitivity of transducer $c$ in these two configurations are presented in figure 2 and compared to the reference calibration for both, using MLS and sine sweep signals. Again, a rough estimation of the sensitivity of the transducer is achieved, and the results are even more dependent of the signal used. According to the results, the coupler with MLS signal choice seems to be very promising, moreover, considering the limitations of the coupler used, which was a self-made prototype not optimised in materials nor in geometry. Therefore, this method could be proposed as a standard rough calibration of hydrophones in small labs working in collaboration for the development of an acoustic neutrino telescope in water. In addition, it has even more advantages for calibration of hydrophones for ice because of the small volume needed.

![Figure 2. Results of the calibration of the sensitivity of transducer $c$ using the tube and the coupler configurations using MLS signals (left) or sine sweep (right)](image)

3. Generation of neutrino-like signals using transducers

Generation of neutrino-like signals is necessary to calibrate acoustic sensors for neutrino detection, as well as for the calibration of the acoustic neutrino telescope itself. Probably, the easiest and most convenient way to generate these signals is from transducers directly. However, since powerful transducers do not usually have a flat frequency response, distortion is produced, and it could be difficult to achieve. In this section we present some equalization techniques to offset this effect.

This study has been done in a 1.10x0.85x0.80 m$^3$ tank using the Airmar Tech. P319 transducer as emitter and the Reson TC4034 hydrophone as receiver. This hydrophone has a flat frequency response below 100 kHz, whereas the emitter has a resonance at 50 kHz with a quality factor $Q=28$. Both transducers are controlled by a computer with a HDSP9632 soundcard working at 192 kHz sampling frequency. Cool Edit and Aurora software are used for the data acquisition and analysis.

The neutrino-like signal used for generation is the pressure pulse due to a $1.2 \times 10^{31}$ GeV shower in sea water at a distance of 1 km with a zero degree angle with respect to the plane transverse, according to simulations of the ACORNE collaboration [3].

3.1. Without equalisation

Certainly, the first attempt to generate neutrino-like signals from transducers is to feed it with an electric signal of the same shape. The results of this rough attempt are presented in figure 3, where the neutrino-like signal labelled as reference, which is used for feeding the emitter, is compared to what is directly observed in the receiver. It is clear that the received signal is highly distorted compared to the emission signal. There is a kind of inertia, in which the 50 kHz resonance has a notorious effect.
3.2. Equalisation

After the first attempt, a question arises: if feeding with the original signal, this is not received. Could we feed with another signal in order to obtain the original signal in the receiver position? This is an inverse problem. To solve it, the first step is to know the transfer function of the system. Using a MLS signal, which is quite convenient due to their properties [16,12], we could obtain the impulse response, and therefore the transfer function. Afterwards, we could apply two equalisation techniques implemented in the Aurora software. Flatten spectrum is the name of the first technique that creates an inverse filter inverting only the minimum phase component of it, that is the magnitude of the transfer function is inverted. The second technique, named inverse filter, inverts mixed-phase impulse response following the Mourjopoulos least-squares technique [17]. Finally, once the filter is obtained, the original signal is convolved with the filter in order to obtain the signal that should be used for feeding the transducer. In figure 4 different steps of these procedures are presented. On top, the impulse response is shown: a) extended spectrum, b) zoom at the peak. c) and d) show the filters obtained using the inverse and flatten spectrum techniques respectively. Finally, e) and f) show the feeding signals obtained in both techniques.

The final result of the method is shown in figure 5, which shows the received signals applying both techniques in comparison with the neutrino-like signal reference. The flatten spectrum technique improves a little with respect to the case of non equalisation. However, it is still far from being good. Much better results are observed in the inverse filter based in the Morjopoulos technique, which reproduces the neutrino-like signal shape with large accuracy.

Figure 3. Received signal by feeding directly with the neutrino-like signal (reference).
Figure 4. a) Impulse response of the system, extended spectrum, b) zoom at the peak of the impulse response. c) and d) show the filters obtained using the inverse and flatten spectrum techniques, respectively. e) and f) show the feeding signals obtained in these techniques.

Figure 5. Received signals applying inverse filter and flatten spectrum techniques in comparison with the neutrino-like signal reference.
3.3. Convolution with MLS plus Inverse filter

Finally, we would like to propose a technique for the calibration with neutrino-like signals using transducers: instead of using the original neutrino-like signal for feeding, our proposal is to use this signal convolved with a MLS signal and apply the inverse filter. The emitted and received signals are, therefore, long signals, which only recover into neutrino-like signals after MLS deconvolution. This technique of calibration could have a series of advantages in a telescope: better signal to noise ratio, because of the large average in which the MLS results. Therefore, less amplification would be needed, or in other point of view, it could be used for larger distances. On the other hand, it would be possible to calibrate at the same time as measuring because the signal appears only after deconvolution with the MLS with the only effect of a little increase of the noise, but normally negligible. Moreover, in some cases the same sensors for detection could be used also for calibration, generating this kind of signals.

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