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AN ACOUSTIC INVERSION TECHNIQUE USING A SINGLE AUTONOMOUS HYDROPHONE: EXPERIMENTAL RESULTS

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Abstract
This paper presents environmental inversion results of acoustic data in very shallow water (less than 20 m) obtained in the scope of underwater noise monitoring activities. A single autonomous hydrophone was moored at a reference position within the working area. Acoustic transmissions were performed with a pair of acoustic projectors, from a small vessel. Three ocean transects were considered: the vessel departed from a position close to the moored receiver, accomplishing a set of transmission stations on a straight line, at distances of up to 4 km. For modelling purposes, emitter and receiver swapped roles, which resembles to what is usually called a synthetic array. The acoustic data was inverted for seafloor parameters, and source and receiver depths. The inversion procedure carried out herein is similar to Matched-Field Processing (MFP): the problem was posed as an optimisation problem where the replica field was obtained for candidate solutions. The objective function was the root mean square error (RMSE) between the observed transmission loss (TL) and that generated by forward modelling. The search of the solution was carried out with a genetic algorithm (GA), in an attempt to minimise that error. Empirical distributions were generated with candidate solutions of final GA generations, in order obtain a solution of the inverse problem as a maximum *a posteriori* estimate. The empirical distributions were in general compact and the RMSE achieved values below 1 dB. The results indicate that in underwater noise monitoring activities, using a single hydrophone for modelling purposes may be a viable option.

Keywords: autonomous hydrophone, underwater noise monitoring, environmental inversion.

1 Introduction

Examples of traditional sources of underwater noise are vessel traffic of various forms and sizes, active sonars, seismic exploration and drilling in oil and gas exploration, marine dredging and construction, and underwater blasting. It can be anticipated that activities related to the generation of renewable energies, such as offshore parks of wind or wave-energy, may become source of underwater noise with increasing relevance in terms of environmental impact. The main concern related with the introduction of increasing levels of underwater noise in the oceans and seas is the impact on cetaceans, pinnipeds, and fish. In order to stay aware of what is happening in regard to this type of environmental disturbance, noise monitoring programmes need to be included in Environmental Impact Assessments (EIA). One of the results of an EIA on underwater noise would be the definition of influence zones. An influence zone is an estimate of the radius within a certain acoustic effect is expected [1]. According to Richardson *et al.*, there are at least four influence zones: the *zone of audibility*; the *zone of responsiveness*;

the *zone of masking*; and the *zone of hearing loss, discomfort, or injury*. The definition of these zones depend both on the radiated SPL and spectral composition of the man-made noise, and on the animal's auditory system. At limit of audibility, also the level of environmental background noise will play a role.

Underwater noise monitoring usually requires a vessel or boat for the deployment of acoustic recording equipment at pre-defined positions or trajectories. This is often conducted with limited material and human resources, and usually only for a few days during daylight. In many problems the area subject to the impact may extend to several kilometres from the noise source. As the topography and other significant environmental properties may vary with azimuth and range, which poses a difficulty in terms of spatial coverage. The radiated noise may vary over time due to the changes in operation of the noise source. During the short duration of a sea trial one attempts to collect the maximum possible quantity of representative acoustic data providing maximum spatial coverage. Often (as for the estimation of the influence zones), the measurement of sound pressure level (SPL) takes place at positions with increasing range from the source until that noise becomes undetectable, and for various azimuths. This can be approximately obtained when the noise radiated by the source is stationary. If the noise radiated by the source is not stationary, then it is generally impossible to measure the SPL due to that source over space in a representative way.

This difficulty can be mitigated by including recordings over long periods at a fixed position, for example, at a position close to the noise source. A moored autonomous acoustic recorder can be used for noise recordings over longer periods without the presence of human resources. Such a concept has been proposed over the past decade in bioacoustic applications related to monitoring and tagging of marine mammals [2]. In man-made noise monitoring activities this concept opens the possibility for carrying out multiple simultaneous recordings at different selected positions in the area of impact at relatively low-cost. Otherwise only single recordings are carried out, since in most cases only one vessel is made available, and the teams of technicians are small. From this point of view, autonomous recorders are also interesting for acoustic modelling problems [3], which typically is an affair of large means (vessels and human resources).

The actual experimental work is part of noise level modelling in the scope of an EIA within the ocean volume adjacent to a future inland large-scale aquaculture plant owned by ACUINOVA S.A. at Praia de Mira, Portugal. It consists of 1728 fish pools, which will be supplied with ocean water pumped in from a shaft connected with two underwater tunnels with extremities approximately 2.5 km away from the beach. The waters are then returned to sea through two other underwater tunnels with extremities approximately 1 km away from the beach. The underwater noise monitoring programme aims at monitoring the noise that may be produced by the intake and returns at the tunnels' extremities. At full capacity, a total of two intake and two return tunnels will be working, eventually radiating noise caused by collapsing bubbles or other related phenomena. In the worst case of simultaneous operation, there would be four noise sources contributing for the total noise over the area. The environmental scenario is very shallow water with water depths at the tunnels' extremities ranging from 13 to 16 m. This is rather complex in terms of monitoring and problem study, as it is unknown at what times what is being pumped through each tunnel, and which is the flow rate. This requires complementary procedures that go beyond noise recordings at single positions over the study area.

This paper addresses the feasibility of using transmission loss (TL) data observed with a single autonomous hydrophone to determine environmental properties influencing acoustic propagation [4]. TL at multiple frequencies is used for its robustness against experimental and environmental uncertainty, and its low sensitivity to random fluctuations that occur due to rough surface or bottom. The receiver is moored at a fixed position and repeated transmissions of multi-tones from stations with increasing range over a straight line are carried out for TL observation, which forms a horizontal synthetic array [5]. Until the data respecting to each synthetic array is ready several hours elapsed. It is obvious that coherent array processing methods can not be employed, which is the main reason for using TL as the observable for acoustic data inversion.

The inversion of the acoustic data was carried out using a technique similar to classical Matched-Field Processing (MFP). Classical MFP mostly use vertical or horizontal receiver arrays with significant apertures, with a sufficient level of synchronisation to allow coherent array processing. Coherent array processing also requires observation windows short enough to assure a certain degree of environmental stationarity. Here, instead, only incoherent TL data is used. For data processing, the receiver/emitter roles were swapped to form the synthetic array data: it was assumed that the emitter was stationary at the receiver's position, and that the receiver was repeatedly deployed at the emitter's position, which exploits the reciprocity of the acoustic propagation. The inversion results achieved herein indicate that TL observed with a single receiver can produce sufficient environmental discrimination, provided that a sufficient number of acoustic transmission stations are made available.

2 The experiment

The acoustic experiment took place from 23 to 25 of September, 2008, off the Portuguese West Coast near Praia de Mira in a working box centred at coordinates 40.43N, 8.84W with approximate dimensions 9 km$\times$5 km. The maritime conditions were in general favourable with wave height less than 1 m, absence of wind and strong fog.

2.1 Experimental configuration

The experimental configuration consisted of a mooring with an autonomous hydrophone attached at a position coincident with the future water intakes, and a small boat that navigated the acoustic source away from the mooring over pre-defined ocean transects. Figure 1 shows a scheme of the receiver mooring and the boat navigating the acoustic source. The mooring consists of a surface float for recovery and a subsurface float that maintains the mooring cable vertical. The ballast of 15 kg is made of lead weights used in diver belts. The autonomous hydrophone was attached between the subsurface float and the ballast at 7 m depth. The boat was 10 m long with a cabin where computer and acoustic equipment was operated and kept dry. The acoustic source, deployed at 5 m depth, consists of two independent acoustic projectors light enough to be deployed and recovered by hand at each transmission station.

Figure 2(a) shows the navigation carried out during transmissions, and 2(b) shows the emitter/receiver range throughout days 23 to 25. During the sea trial acoustic transmissions over three ocean transects were performed: on September 23, the mooring was deployed at a coordinate coincident with the South water intake tunnel extremity (marked as C2), an the source was navigated to West, at a maximum range of approximately 3 km from the mooring; then a new set of transmissions to South relative the mooring was started at the same day and completed during the next day afternoon with a maximum range of approximately 3.7 km; finally during the morning of September 25, the mooring with the autonomous hydrophone was deployed at a coordinate coincident with the North water intake tunnel extremity (marked with C1),

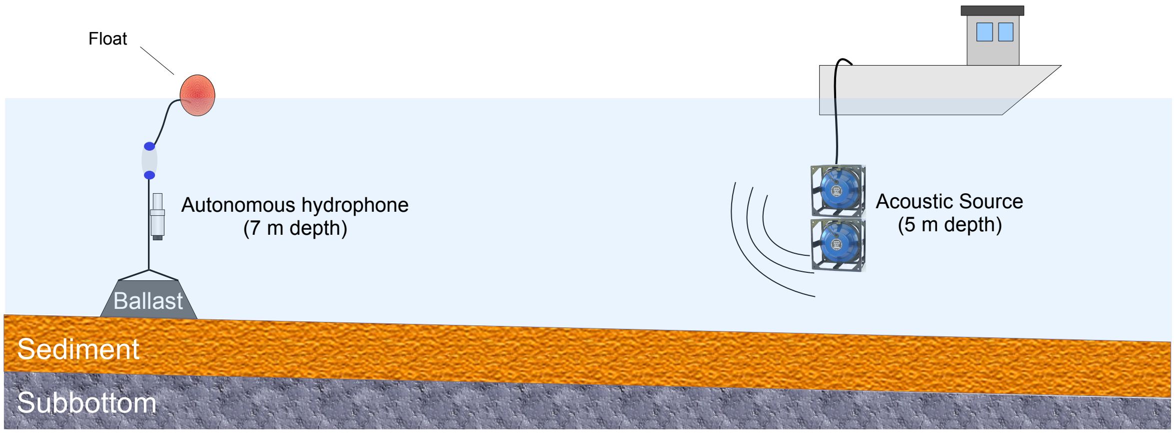

Figure 1: Experimental setup: acoustic reception mooring with an attached acoustic receiver and boat with acoustic source.

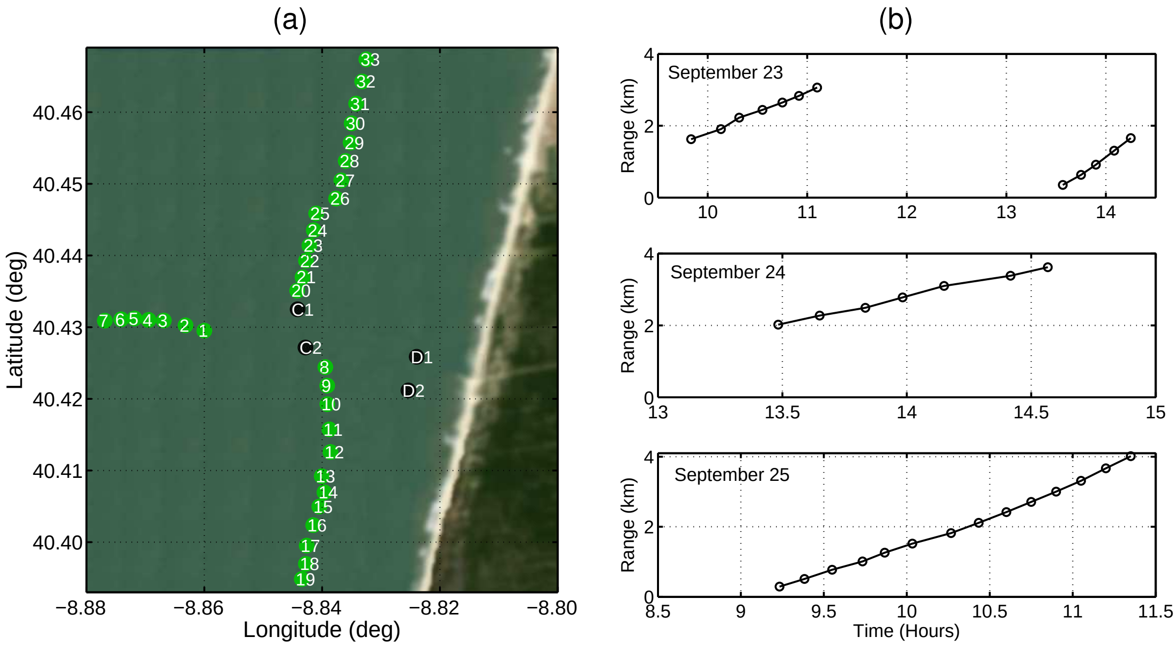

Figure 2: Experimental configuration of the acoustic experiment: (a) the numbered green dots indicate acoustic transmission sequence; the black dots marked with D1 and D2 represent water returns and the black dots marked with C1 and C2 represent water intakes. (b) Curves indicating range between the acoustic emitter and receiver throughout days 23 to 25.

and a new set of transmissions to North was started with a maximum emitter/receiver range of 4 km.

2.2 Acoustic equipment

The acoustic equipment consisted of the emission system operated from the boat, and an autonomous self-registering hydrophone attached to the mooring.

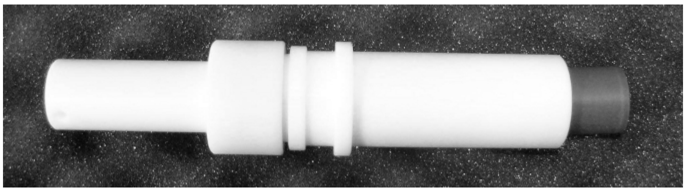

Figure 3: The autonomous hydrophone that was moored for acoustic data recording.

The emission system consisted of a mini-portable computer with a stereo soundcard. The sound card output was connected to a stereo car amplifier. This choice allowed using simultaneously two acoustic projectors, each emitting a time-series. The idea of using two projectors was to allow the simultaneous transmission of two tones at maximum possible sound pressure level. These acoustic projectors, manufactured by Lubell Labs (Ohio, USA), have transmit voltage response (TVR) of 152 dB *re* 1μPa / 1 V at 1 kHz. At maximum input voltage of 20 V rms the projected sound pressure level can attain values close to 180 dB.

The reception of acoustic signals was carried by means of an autonomous hydrophone designed by MarSensing Lda. for acoustic monitoring activities (see Figure 3). This compact device has a band-pass of 1 to 25000 Hz, with a sampling frequency of 50781 samples per second. The transducer has a sensitivity of -193 dB *re* 1 V / 1μPa, and the amplification chain consists of a pre-amplifier with a nominal gain of 31$\times$ followed by a programmable gain amplifier (PGA) that allows for programming gains of 1$\times$, 2$\times$, 4$\times$, . . . , 64$\times$. With the PGA set to 1, this hydrophone allows to record signals with a maximum rms pressure level of approximately 167 dB *re* 1μPa, and 130 dB *re* 1μPa with the PGA set to 64. This autonomous recorder allows for scheduled acquisition with up to 99 time entries and diverse acquisition trigger modes. The data is stored on an MMC card in 16-bit WAV format, with file lengths programmed by the user. At the time of this experiment it used 1 GByte cards, that could store 2h50m of data in continuous acquisition mode (meanwhile, it has been upgraded to 2 GByte). The power supply is a 3.7 V lithium battery of type 18650.

3 Experimental results

3.1 Signal characteristics

The transmitted acoustic signal consisted of tones in a frequency band from 200 to 11000 Hz. The sequence started with a 2-second LFM with a 500 to 4500 Hz band used for automatic detection of remaining sequence. Each channel transmitted 37 10 s tones, with the left channel transmitting frequencies 200, 250, 500, . . . , 5750, 6000, 6400, . . . , 10400, 10800 Hz, and the right channel transmitting frequencies 200, 375, 625, . . . , 5875, 6125, 6600, 7000, . . . , 10600, 11000 Hz. Figure 4 shows an amplitude estimate of the transmitted frequencies obtained 1 m away from the acoustic source. The amplitudes vary between 136 and 165 dB over the whole spectrum, with a slight decay of the maximum values in the upper half of the band. The strong variability over the frequency range reflects both the variability in the TVR of the transducers and the variability in the input rms voltage. During signal reproduction the input voltage was measured in the interval from 1.86 to 16.8 V *rms*, which represents a variation range of approximately 19 dB. An additional issue contributing for this variability is power leakage occuring due to generation of several harmonics for each tone. Nonetheless, in the present work, for the purpose of acoustic inversions only frequencies in the band 250 to 1500 Hz were used, where most frequencies attain relatively high amplitudes, which allows for high signal-to-noise ratio.

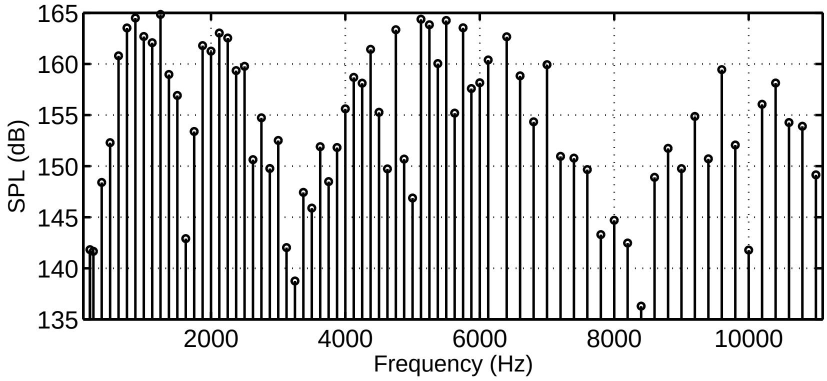

Figure 4: Spectral amplitudes of transmitted tones at 1 m away from the source.

3.2 The baseline model

One of the most stringent questions issues for a model based inversion procedure is the choice of underlying physical model. Often not all relevant physical properties are available. In the present case water depth was measured *in situ* with the boat's SONAR while it navigated across the area. Water temperature data for soundspeed estimation was measured with a self-recording thermistor sensor. Figure 5 shows the baseline model reflecting knowledge on bathymetry, water temperature, and emitter/receiver geometry. This is a three-layer model consisting of a watercolumn, a sediment layer and an infinite half-space. For the North and South transects, the bathymetry is approximately range-independent, while for the West transect the water depth varies from 16 to 30 m. The sound-speed profile is approximately isovelocity given the reduced waterdepth. The seafloor layers are parametrised with compressional speeds, densities, and attenuations. The compressional speed in the sediment is linear with depth. In this study the density is defined as a function of compressional speed according to the following dependency [6]:

$$\begin{cases} \rho(c) = 14.8c - 21.014 \text{ if } c \leq 1.53 \\ \rho(c) = 1.135c - 0.190 \text{ if } c > 1.53, \end{cases} \tag{1}$$

where c is compressional speed in the sediment or sub-bottom layer in km/s. This allows for melding two free parameters into one free parameter c, with increased influence to the acoustic propagation, and a dependent parameter $\rho(c)$. Additionally, that knowledge can contribute to increase the solution constraint and to eliminate non-physical solutions from the search space.

3.3 The objective function

The objective function used for acoustic data inversion is based on the TL observed over the set of transmission stations considered for each ocean transect and a set of frequencies. For this study the following error function was adopted:

$$E(\underline{\theta}) = \sqrt{\frac{1}{KN_p}\sum_{k=1}^{K}\sum_{p=1}^{N_p}[\mathrm{TL}_{\mathrm{dB}}(f_k, r_p, \underline{\theta}) - \hat{\mathrm{tl}}_{\mathrm{dB}}(f_k, r_p)]^2}, \tag{2}$$

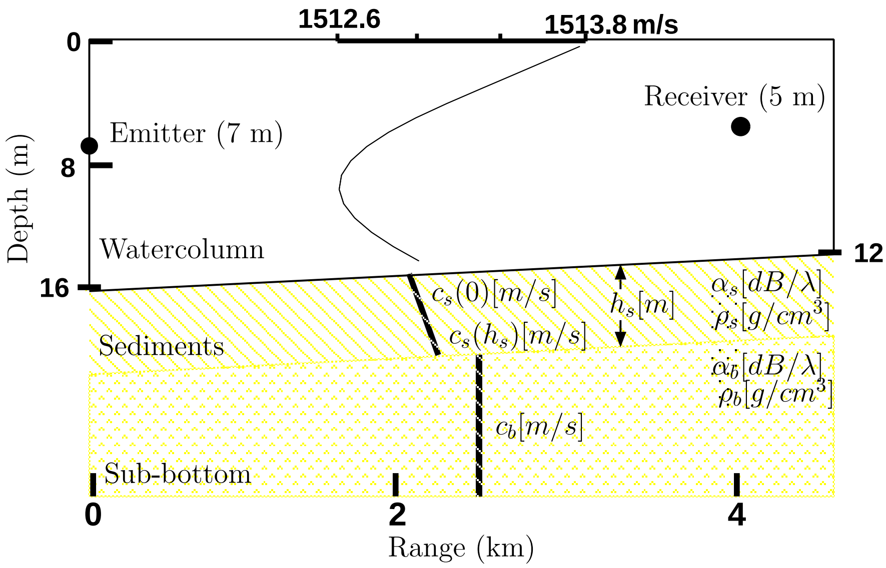

Figure 5: Baseline model for the experimental area. Bathymetry an temperature were measured in September 2008.

where $\hat{\text{tl}}_{\text{dB}}(f_k, r_p)$ represents the TL observed between the emitter and a receiver at range r_p and frequency f_k, while $\text{TL}_{\text{dB}}(f_k, r_p, \underline{\theta})$ represents the replica TL for a candidate parameter vector $\underline{\theta}$. This objective function is the root mean square error (RMSE) between the two quantities described above over distance and frequency. The idea is to match the observable both over space and frequency, as an attempt to exploit the diversity available over these domains, in order to reduce the solution ambiguity inherent to the large number of free parameters left.

3.4 Data processing

The acoustic inversion is roughly divided into three steps: first the transmission loss is estimated using the acoustic field received for each transmission station and the spectral amplitudes of the emitted signal. This step generates $\hat{\text{tl}}_{\text{dB}}(f_k, r_p)$ in eq. (2). Then, acoustic inversion for seafloor and geometric parameters is carried out by optimisation. The optimisation is carried out with a genetic algorithm (GA). Since the GA is a global random search method, for each data set the multiple independent searches are carried out. Finally, the solution is obtained by maximising empirical marginal probability density functions (PDF) of the search parameters, whose data is generated by taking candidate solutions of the final GA generations [7].

The first step is ordinary spectral estimation of the emitted signal $S(f)$ and received signal $X(f)$. The TL is estimated as the absolute value of the ratio between $X(f)$ and $S(f)$ for each transmission station.

The second step is the main step of the inversion procedure. The search parameters are divided into sediment layer parameters (upper and lower compressional speeds, wave attenuation, and sediment thickness), sub-bottom parameters (compressional speed, wave attenuation), and geometric parameters (source and receiver depths). Note that source and receiver swap roles, where inversion will proceed as if the acoustic source was deployed at a fixed position and the receiver was navigated across each transect. Candidate acoustic models will be computed with the KRAKEN normal-modes computer code [8]. Replica TL is matched with the observed TL using eq. (2). For each inversion 10 independent GA populations were started.

The GA was set to 40 generations of 70 individuals. The the mutation probability was set to 0.008, in order to cause 30% of the population to be mutated at each generation, provided that each individual is is coded into a bit chain of 39 bits. The crossover probability was 0.8. The size of the search space is approximately 5.5×10^{11}.
The third step aims at obtaining a final estimate by merging candidate solutions of the last generation of each population into marginal empirical PDFs of each parameter. These empirical functions are obtained by summing the fit of the final candidates over each parameter search interval. The empirical distribution will depend on the distribution of the candidates and their fits. These empirical distributions can provide a statistical analysis on the solution convergence, as one can calculate the mean value and the variability over the search interval, or maximise the distribution in order to obtain the model estimate. This model estimate has been call maximum *a posteriori* (MAP) solution (in a Bayesian framework).

3.5 Inversion results

The inversion was carried out considering frequencies 250, 500, 750, 1000, 1250, 1500 Hz for matching replica TL with observed TL using eq. (2). The number of receiver positions is 14 for the North transect, 7 for West transect, and 12 for the South transect. Figure 6 shows the TL data for some frequencies in comparison with the replica TL computed for the best model of each independent population, and the replica TL computed for the MAP estimate. Also the RMSE calculated for each frequency is indicated. Except for the 250 Hz frequency, the error is always below 1.5 dB for all the remaining frequencies in the three transects. For the West transect the error attains values as low as 0.4 dB, and is in general lower than in the other case. This does not necessarily mean that the inversion result is of best quality, since this case has less transmission stations than the other. In general, the error between the observed TL and the MAP TL tends to decrease for frequencies above 500 Hz. This may be due to an improved SNR as the the frequency increases, due to increasing signal strength and noise power decay.

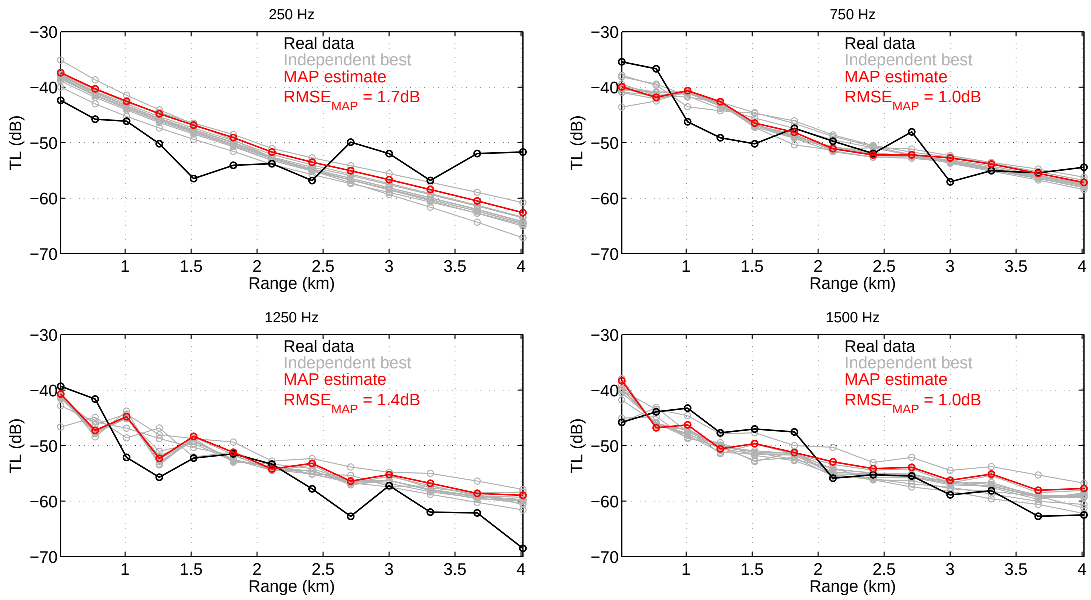

Figure 6: Comparison of observed transmission loss with modeled TL: observed TL (black); best model of each independent GA population (gray); maximum *a posteriori* model (red).

Figure 7 shows the empirical marginal distributions for each parameter of each inversion. It becomes clear that upper and lower compressional speeds in the sediment are highly influent parameters, since their distributions are the most compact, specially for the North and South transects. Their is a very consistent agreement for these parameters over the three inversions. For the remaining parameters, the North transect shows the most compact distributions, whereas even sediment attenuation has a very compact distribution, with a value in agreement with that of the South transect. Note that also the probability distribution for the source depth is close to the baseline source depth (7 m), and receiver depth has the probability between 4 and 5 m for North transect and the distribution peak for 5.5 m (baseline receiver depth is 5 m). In general, the inversion results of the different transects appear to be quite satisfactory, although the West transect has slightly more uncertainty. It appears that the degree of uncertainty agrees with the number of transmission stations available for each transect. The final comment is to call the reader's attention that three inversions using independent acoustic data, have produced similar empirical distributions, and to a certain extent coincident maximum *a posteriori* estimates were obtained.

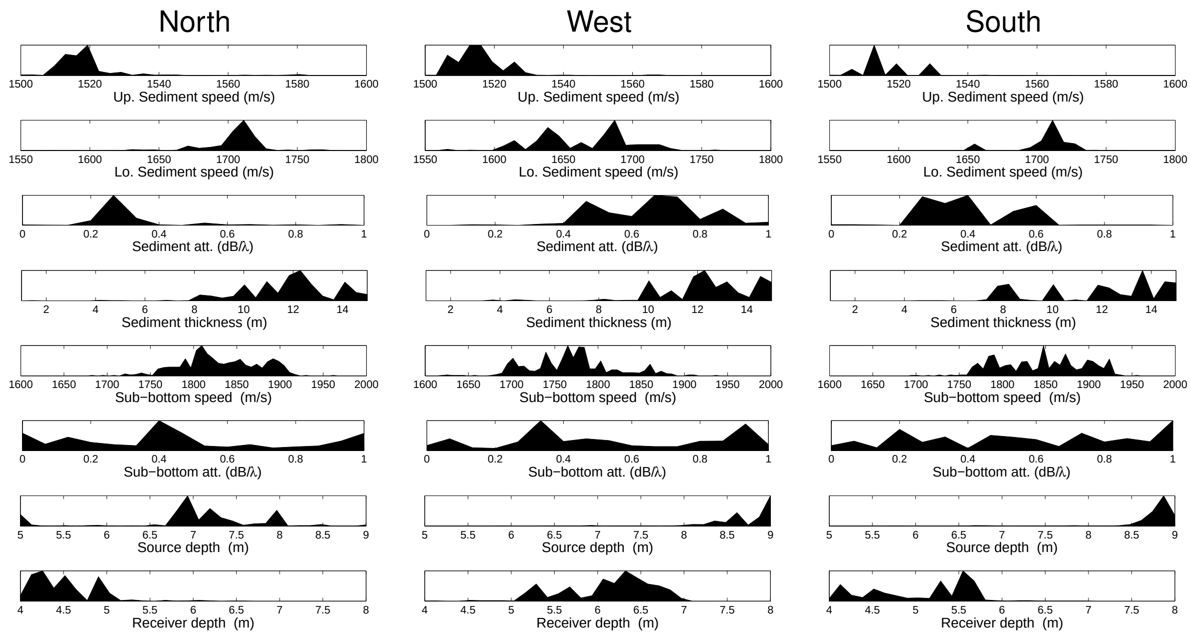

Figure 7: Empirical probabilty functions for the eight parameters and each transect.

4 Conclusions

This paper presented an attempt to take a well established acoustic inversion technique, that has been mostly demonstrated in the context of environmental inversion for seafloor and watercolumn properties using vertical arrays of hydrophones where large means are available, to the context of underwater noise monitoring activities where small vessels are used and small teams of two or three person are employed. In the present case, only a single autonomous acoustic receiver is available, acoustic transmissions are performed over multiple stations with increasing range over a straight line. For acoustic inversions, receiver and emitter swap roles, as if a long horizontal array was used for acoustic reception.

The inversion was performed for seafloor parameters, and emitter and receiver depths, using a genetic algorithm for the search. This procedure was carried out for three ocean transects started in the area of the industrial facility under study. The inversion results, based on TL as the observable, have shown an exceptional agreement, specially in the case of the North and South transects where respectively 14 and 12 transmissions stations were considered. The West transect appears to have a slightly higher parameter uncertainty in comparison to the other, possibly due to the reduced number of transmission stations (only 7). These results demonstrate that the TL is an observable that allows sufficient discrimination for reasonably inferring geoacoustic and geometric parameters.

These results indicate that meaningful environmental inversions for acoustic propagation modelling can be achieved with minimal acoustic equipment. Such a procedure enables the experimenter to complement *in situ* acoustic observations of man-made noise with acoustic modelling of the sound pressure level across the adjacent area for acoustic propagation studies and noise mapping.

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