ENVIRONMENTAL INVERSION WITH AN AUTONOMOUS HYDROPHONE IN A WAVE ENERGY DEVICE DEPLOYMENT SITE

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Abstract: *This paper presents environmental inversion results of acoustic data in shallow water in Peniche (Portugal), collected in September 2013, during the Simple Underwater Renewable Generation of Electricity (SURGE) Project - a FP7 European collaborative demonstration project aiming at building a grid connected wave energy converter of type WaveRoller. A single autonomous hydrophone was moored at the position foreseen for the Waveroller deployment. Computer generated acoustic signals were transmitted over a 3 km oceanic transect with a step of 300 m. Incoherent transmission loss (TL) for 1/3 octave frequencies in the band from 318 to 1270 Hz is used in an acoustic inversion procedure for the estimation of geoacoustic parameters of a two-layer seafloor. The acoustic inversion is posed as an optimisation problem aiming at minimising the root mean square error (RMSE) between field TL and replica TL, using a genetic algorithm. This procedure is repeated a number of times in order obtain a posterior distributions for each unknown parameter, and the solution of the inversion is obtained by taking the maximum of the a posteriori distribution of each unknown parameter. The RMSE between the field TL and acoustic model TL obtained for the solution across the acoustic transect varies between 1.5 and 2.6 dB, depending on the frequency. As a procedure to validate the obtained model, the RMSE between field TL and model TL is calculated for an alternative frequency band (from 1600 to 8064~Hz), in order to check the amount of model mismatch for frequencies not entering the inversion procedure. In that case, the RMSE varies between 2.5 and 4.6~dB. This increment in the RMSE can be considered relatively small, allowing the obtained physical model to be considered meaningful, and therefore adequate for noise modelling purposes over an eventual impact area.*

Keywords: *acoustic inversion, acoustic modelling.*

1. INTRODUCTION

It is well established that the implementation of large-scale wave energy farms may have significant contributions in terms of introduction of underwater noise into the marine environment. The implementation of offshore renewable energy farms includes, in general, an acoustic monitoring plan which can be based both on *in situ* noise measurements and noise modelling studies. Noise propagation modelling offers the possibility to predict the soundscape over hypothesized scenarios with a *quasi* continuous spatial coverage, as to generate 2D noise maps at multiple depths.

A number of existing acoustic propagation models can provide the acoustic response of given environmental scenarios, provided that an accurate physical description of the propagation channel is available. The underlying physical model used in computational acoustic propagation models is typically made of a water column and one or multiple seafloor layers, and therefore the input may consist of parameters such as water depth, sound-speed profiles in the water column, and seafloor parameters such as sound velocity, density, attenuation, and thickness of one or multiple seafloor layers. Often, a complete and compatible description for a physical model with such a configuration is not available.

One option for assessing missing environmental data is by means of the so-called acoustic inversion [1]. An acoustic inversion is a procedure where physical properties are determined from experimental field data, by matching some acoustic observable with model replica data. Once a physical model has been determined and the noise source is accurately characterised, the user becomes able to predict the propagation of noise radiated away from the source. In the actual scope, this procedure is procedure can be seen as a field calibration.

This paper reports on acoustic inversion results obtained within the Project Simple Underwater Renewable Generation of Electricity (SURGE) in September 2013 in Peniche, off the West Coast of Portugal. Acoustic tones within the frequency-band 318 to 1270 Hz, transmitted over a 3 km transect, were received at a single hydrophone moored at the shallower end of the transect in order to estimated the acoustic transmission loss (TL). The data processing consists on the inversion for environmental parameters using a technique similar to classical Matched-Field Processing (MFP), using incoherent TL. The acoustic data inversion is posed as an optimisation problem, where solution search is carried out by means of a genetic algorithm (GA), and the final solution is determined by means of *a posteriori* probability distributions [2] generated from multiple runs of the GA.

The inversion results indicate that TL as a function of range can provide sufficient discrimination for inferring geometric and seafloor parameters, suggesting that this scheme can aid in overcoming missing environmental information relevant for noise propagation.

2. EXPERIMENTAL CONFIGURATION

2.1. Experimental configuration

The experimental configuration used for field calibration consisted of a transect with northwest direction departing from **P1**, with transmission positions **M02** through **M10** (see Figure 1). The mooring at **P1** contained an autonomous hydrophone, a digitalHyd SR-1 by MarSensing, and the acoustic source was a Lubell LL916C. Figure 2 depicts the experimental setup, with an autonomous hydrophone moored at 8 m depth, and an acoustic source tethered from the vessel down to 12 m depth. The acoustic transmissions were started at **M02** (about 450 m from **P1**) and finished at **M10** (about 3.05 km from **P1**).

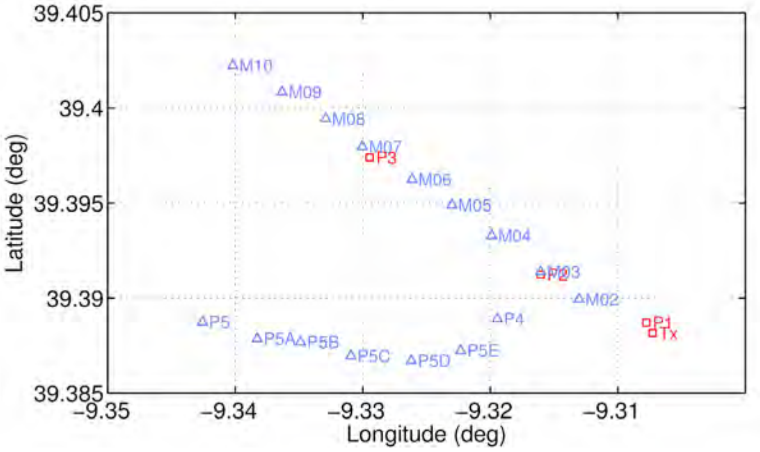

Figure 1: Experimental configuration followed for field calibration. Acoustic transmission stations are indicated with triangle, and hydrophone moorings are indicated by squares.

Figure 2 Experimental setup: mooring with an autonomous hydrophone and setup for source operation tethered *from boat.*

2.2. Acoustic signals

Field calibration is based on the transmission of a computer generated sequence, usually consisting on continuous waves, such as pure sinusoids, and LFMs. In the present case a mix of different signal types was transmitted, among them, 8 s sinusoids with 1/3 octave band centre frequencies from 126 to 10160 Hz. Figure 3 shows the tones' amplitudes estimated from a recording taken 1 m away from the source.

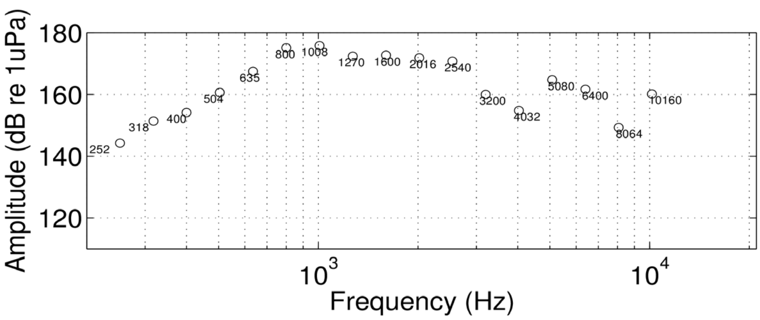

Figure 3: Amplitude estimates for pure sinusoidal tones recorded with a hydrophone 1 m away from the source. The numbers along the plot indicate the respective frequency in Hz.

3. EXPERIMENTAL CONFIGURATION

3.1. The baseline model

One of the most stringent issues for a model based inversion procedure is the choice of the underlying physical model. Often not all relevant physical properties are available. In the present case, part of the bathymetric data was readily available. The water depth of the most distant transmission positions were measured during the sea trial. Sound speed profiles were obtained *in situ* from a CTD device owned by WavEC. Figure 4 shows the baseline model reflecting the 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. The bathymetry of the transect is highly range-dependent in water depth, as it goes from 12 m at the source position down to 41 m at the last position of the transect. The sound-speed profile was measured at position **M10**, the deepest water depth of the transect, presenting a typical Summer profile for the Portuguese Coast.

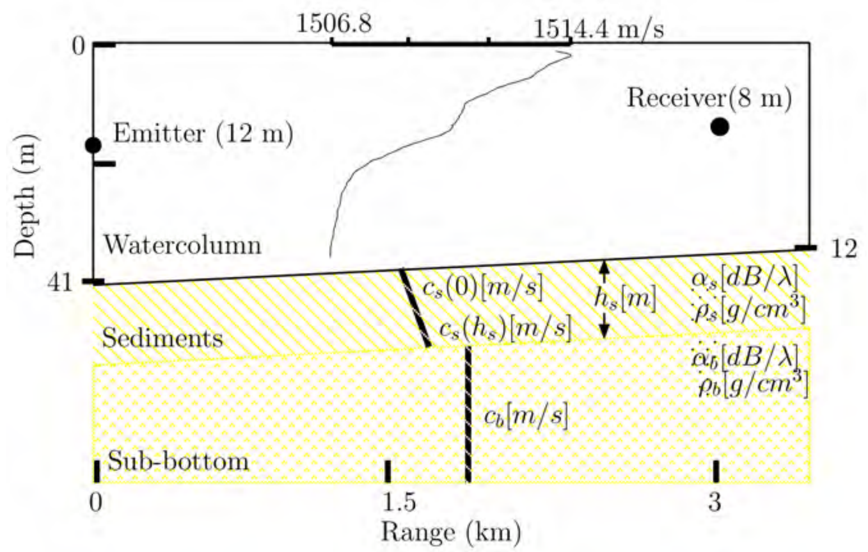

Figure 4: Baseline model for acoustic propagation modelling.

The water temperature at the surface was approximately 17 degrees Celsius, and 13 degrees Celsius at the bottom. The seafloor layers are parameterised with compressional speeds, densities, and attenuations. The compressional speed in the sediment is linear with depth. In this study the seafloor densities are defined as a function of compressional speed according to the following dependency [3]:

$$\begin{aligned}\rho(c) &= 14.8c - 21014 \ \text{ if } c \leq 1.53 \\ \rho(c) &= 1.135c - 0.190 \ \text{ if } c > 1.53,\end{aligned} \qquad (1)$$

where c is a compressional speed in the sediment or sub-bottom layer in km/s. This allows for melding two free parameters into a single parameter of sound speed 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. The baseline model shown in Figure 4 also shows emitter/receiver geometry. Note that these appear swapped, since for acoustic model computations, it is more convenient to provide one acoustic source and multiple receivers.

3.2. The objective function

The acoustic transmissions were designed having in mind an acoustic characterisation of the environmental medium in terms of transmission loss (TL) experienced by a continuous wave of a single frequency when it travels across the medium between emitter and receiver. In this case incoherent TL is considered, i.e., only absolute amplitudes at emitter and receiver are taken into account. The estimator for the TL is given as

$$\hat{T}L_{inc}\left(f_k, r_n\right) = \frac{\left|\hat{X}_{inc}\left(f_k, r_n\right)\right|}{\left|\hat{S}_{inc}\left(f_k\right)\right|} \tag{2}$$

where f_k is the k^{th} tonal frequency, and r_n is the source-receiver range at the n^{th} transmission position over a given transect. $\left|\hat{X}\left(f_k, r_n\right)\right|$ is the estimated amplitude of the received sinusoid transmitted from position n of the transect, and $\left|\hat{S}\left(f_k\right)\right|$ is the estimated amplitude of the received sinusoid, both at frequency f_k. For a given transect, the TL is estimated for each source/receiver range with $n = 1,\ldots,N,$ over frequencies f_k, with $k = 1,\ldots,K.$ The objective function used for acoustic data inversion is based on the TL observed over the set of transmission stations considered for the ocean transect and a set of frequencies. For this study the following error function was adopted:

$$E(\underline{\theta}) = \sqrt{\frac{1}{KN_p}\sum\sum\left[TL_{dB}\left(f_k, r_p, \underline{\theta}\right) - \hat{t}l_{dB}\left(f_k, r_p\right)\right]^2} \tag{3}$$

where $TL_{dB}\left(f_k, r_p, \underline{\theta}\right)$ represents the TL observed between the emitter and a receiver at range r_p and frequency f_k, while $\hat{t}l_{dB}\left(f_k, r_p, \underline{\theta}\right)$ 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 cope with the solution ambiguity inherent to a large number of free parameters.

3.3. 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 $\hat{t}l_{dB}\left(f_k, r_p\right)$ in eq. (3).

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 multiple receivers were placed across the transect. Candidate acoustic models will be computed with the KRAKEN normal-modes computer code [4]. Replica TL is matched with the observed TL using eq. (3). For each inversion 10 independent GA populations were started. The GA was set to 40 generations of 70 individuals. 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 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}. Since the GA is a stochastic search method, for each data set multiple independent searches are carried out.

The third step aims at obtaining a final estimate by merging candidate solutions of the last generation of each population into marginal empirical probability density functions (PDF) 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 called maximum *a posteriori* (MAP) solution (in a Bayesian framework) [2].

3.4. Inversion results

The inversion was carried out considering frequencies 318, 400, 504, 635, 800, 1008, 1270 Hz for matching replica TL with observed TL using eq. (3). The number of receiver positions is 9, i.e., positions M02 to M10. The search consisted in matching the TL predicted with the acoustic was against the TL estimated from the acoustic data collected in the real environment for each pair range/frequency. The search was performed by a global optimisation scheme which is stochactic, resulting in a different solution for each search. Therefore the final result is obtained as a statistical observation. Figure 5 shows the empirical marginal distributions for each parameter based on 12 runs of the optimisation procedure. The geometric parameters (left column) present compact *a posteriori* distributions, with a maximum for source depth at 10.4 m, and approximately 5 m for receiver depth.

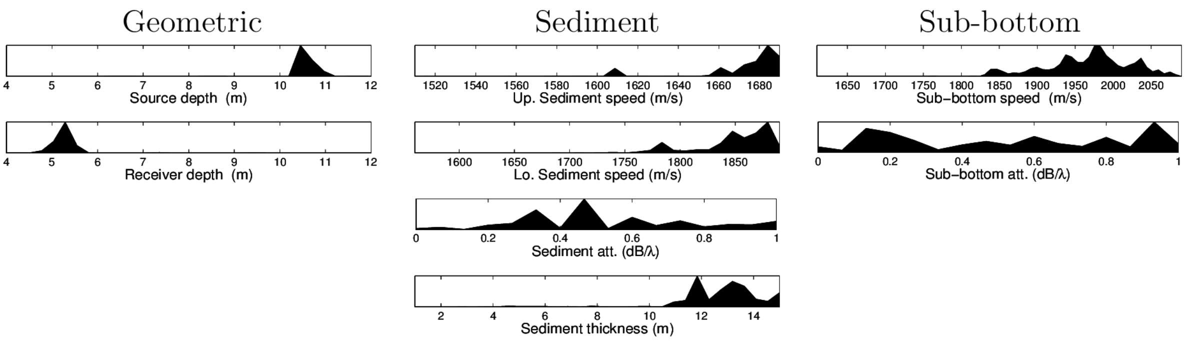

Figure 5 Empirical probability functions for eight parameters.

In the middle column are shown the distributions for sediment. In general, these distributions are compact, presenting reduced ambiguity. The upper speed in sediment has the MAP at 1683 m/s. This is in line with typical sound speeds in sandy seafloors (1650 m/s). The wave attenuation has MAP at 0.45 dB/λ, also in line with table values for sand. The distributions for sub-bottom show more spreading than those for sediment, which is expected due to the low sensitivity of the field to deeper layers. Nonetheless, there is single peak for sub-bottom speed, and some ambiguity for sub-bottom attenuation. The set of parameters obtained by means of the inversion procedure is now seen as a physical model that could be used in a noise modelling procedure within that area. In order to have an idea of the accuracy of the

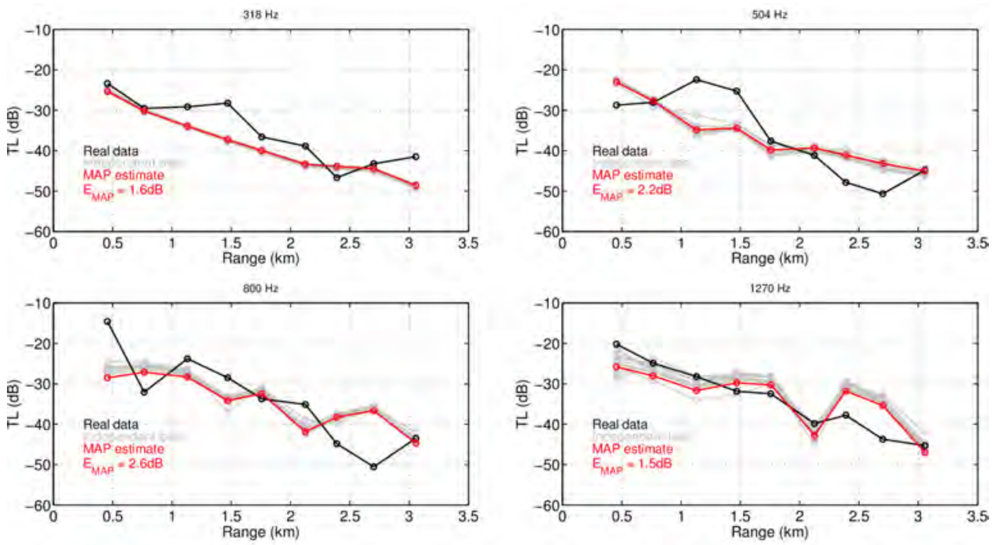

Figure 6: Comparison of observed transmission loss with modeled TL: observed TL (black); best model of each independent GA population (gray); maximum a posteriori model (red).

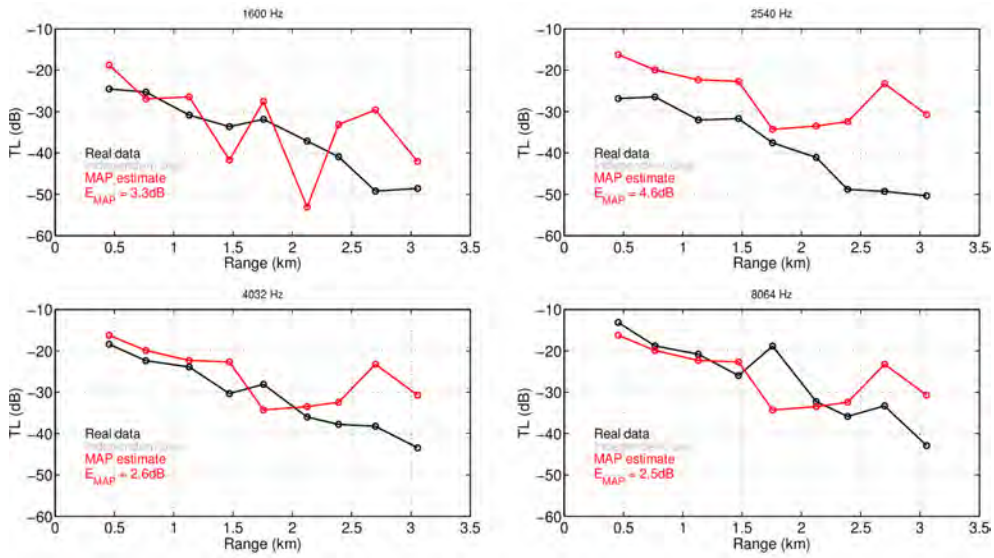

Figure 7: Comparison of observed transmission loss with modelled TL for frequencies not used in the inversion procedure: observed TL (black); maximum a posteriori model (red).

model, replica TL generated by the computational model, over range, can be compared with *in situ* measured TL. Figure 6 shows the TL data for frequencies 318, 504, 800, and 1270 Hz 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 between the two curves is indicated. The RMSE varies between 1.5 dB for 1270 Hz and 2.6 dB for 800 Hz. The modelled TL can track relatively well the real data TL, in particular for the highest frequency. Figure 7 shows another validation test, where frequencies up to 8 kHz are included, in order to check the validity of the estimated parameters for a frequency range outside the frequency range used in the inversion procedure. The RMSE estimates increase slightly for frequencies 1600 and 2540 Hz, up to 4.6 dB, but remain bounded to 2.6 dB for frequencies 4032 and 8064 Hz, i.e., a similar amount of error as frequencies up to 1270 Hz.

4. CONCLUSIONS

Acoustic inversion results based on a single hydrophone were obtained for seafloor parameters of a three-layer model. The acoustic inversion procedure was based on the transmission loss measured across a 3 km transect for 7 frequencies in the band 318 to 1270 Hz. Seafloor parameters and source and receiver depths were included in the search space, and the optimisation was carried out by means of a genetic algorithm. Source and receiver depths were estimated with realistic results, were source depth 10.4 m (true value approximately 12 m), and receiver depth was estimated 5 m (true value approximately 8 m). Concerning the seafloor parameters, sound speed in sediment and sub-bottom provided the most compact *a posteriori* distributions, with credible peak values.
A validation step based on the comparison of measured TL with replica TL at frequencies not used in the inversion procedure, in the band 1600 to 8064 Hz, was carried out. While the RMSE for inversion data was in the range from 1.5 to 2.6 dB, for the higher frequencies this indicator ranged from 2.5 dB (at 8054 Hz) to 4.3 dB (at 2540 Hz).

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] D. F. Gingras and P. Gerstoft. Inversion for geometric parameters in shallow water: Experimental results. *J. Acoust. Soc. Am.*, 97: pp. 3589–3598, 1995.

[2] P. Gerstoft and C. F. Mecklenbrauker. Ocean acoustic inversion with estimation of a posteriori probability distributions. *J. Acoust. Soc. Am.*, 104(2):808–819, 1998.

[3] E. L. Hamilton. Sound velocity–density relations in sea-floor sediments and rocks. *J. Acoust. Soc. Am.*, 63(2):366–377, 1978.

[4] M. P. Porter. The KRAKEN normal mode program. *Technical Report SM-245*, SACLANT Undersea Research Centre, La Spezia, Italy, 1991.