FREQUENCY- AND SIGNAL TYPE DEPENDENCE OF THE PERFORMANCE OF BROAD-BAND GEOACOUSTIC INVERSION IN A SHALLOW WATER ENVIRONMENT WITH SOFT SEDIMENTS

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Abstract: Geoacoustic inversion techniques are an attractive means for estimating physical properties of underwater environments. These techniques aim, at least partly, at a substitution of the costly methods of probing the seabottom by grab samples or cores. However, geoacoustic inversion comes at the price of high computational efforts. Especially, in cases in which large numbers of parameters need to be inverted for, finding the best fit between the measurements and a predicted model requires hundreds of iterations. Efficient global optimization tools exist that help reducing these efforts. One of these methods is the differential evolution method, which is employed in this paper. Beside the time needed for the optimization, another issue is the computational effort needed for establishing the forward model. It highly depends on the number and magnitude of frequencies employed. In general, high frequency calculations are more computational intensive. It is therefore investigated, for a given soft-layer bottom model, which frequencies are beneficial for the estimation of seabottom parameters and which frequencies only increase the computational time. Employed are frequencies in the bands of 300–800Hz (low-frequency) and 800–1600Hz (mid-frequency) for creating broad-band signals. Both, signals composed of tones at discrete frequencies (multi-tones) and frequency modulated waveforms (chirps) are compared. These signals are observed at a 4-element vertical line array. The measurements were performed during the Maritime Rapid Environmental Assessment / Blue Planet (MREA/BP'07) experiments [Le Gac & Hermand, 2007], which were carried out in the Mediterranean Sea in 2007, to address novel concepts of characterizing the continental shelf environment. The data originate from a shallow-water location, west of Italy and south-east of Elba Island, which is known to be composed of very fine grained sediments and an underlying silty clay bottom.

1. INTRODUCTION

The knowledge of physical properties of the underwater environment is essential for many disciplines, ranging from coastal engineering to shallow-water naval operations. Since direct measurement involves a range of time- and cost-intensive techniques, inverting environmental features from acoustic measurements has become highly attractive.

Measuring set-ups that are currently used, such as sparse drifting arrays [1-3], allow for fast applications at sea, where they can cover large areas without the need of a dedicated ship to sail. Typically, a larger frequency range is employed to compensate for the lack in spatial information these sparse systems have to deal with [4]. For this purpose, multi-frequency geoacoustic inversion methods are available [3-6]. They can be divided into spatially and frequency coherent approaches. Here, both types are applied to a range independent shallow water scenario with soft sediments. The aim is to investigate the effect of reducing the numbers of frequencies or restricting the frequency range, in order to reduce the computational costs. Both, a lower frequency range and a lower number of frequencies are computationally favourable. On the other hand, higher frequencies might resolve different environmental parameters, and a too small number of frequencies might result in inaccurate or incorrect parameter value estimates. Both choices are application related and might differ for sediment classification purposes and precise sonar performance tests.

For the current analysis, active acoustic data obtained by a sparse drifting hydrophone array are considered. They are taken at a site in the Mediterranean Sea, west of Italy and south-east of Elba, which is well-known from a set of experiments, such as the Yellow Shark experiments [4, 6]. The present data originate from the Maritime Rapid Environmental Assessment / Blue Planet (MREA/BP'07) experiment, carried out in spring 2007. These data are matched with a standard normal mode propagation model, resembling the acoustic field, by applying the efficient differential evolution method.

This paper is organized as follows. First, a brief description of the MREA/BP'07 sea trial and the dataset is given in section 2. In section 3, the geoacoustic inversion process is described in theory, before results, obtained at a single location, are compared for different signal types and frequency bands in section 4. Finally, the results are summarized and are embedded in the context of the research project in section 5.

2. THE MREA/BP'07 TRIAL

With the aim of addressing novel concepts of rapidly characterizing the underwater environment, the MREA/BP'07 sea trial was performed in the spring of 2007. This trial is documented in [1, 7]. The trial area is located in the Mediterranean Sea, west of Italy, and south-east of Elba Island, as documented in Fig. 1.
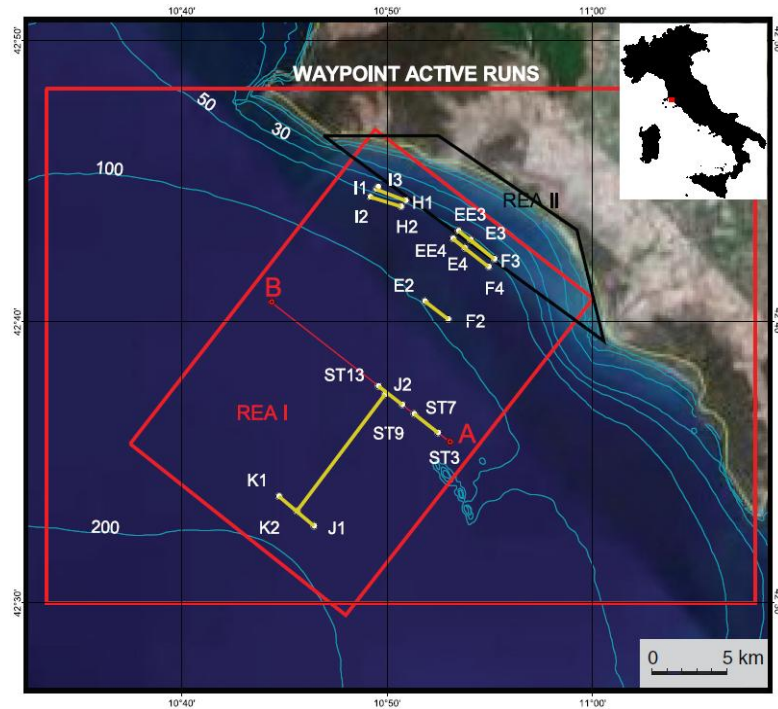
Fig.1: Overview of the active geoacoustic inversion runs (yellow lines) in the MREA/BP'07 area. For the inversion considered in this paper, the source is stationary at position ST3 and the receiving VLA started its drifting towards the source at position ST7.

From a hydrographical survey that was carried out simultaneously, water depths in this region are known to range from 5 m to 120 m over an area of several kilometers. Local variations are rather small, which slopes below 1°. Seismic measurements during the same experiment revealed a stratified structure of the seabottom, consisting of a sediment layer of 5-50m depth that covers the subbottom. Former experiments, such as the Yellow Shark experiments in 1994 [4, 6], provide information about the local sediment composition. Fine grained materials, mainly clay composites, can be found throughout the entire area.

For the current research on the performance of geoacoustic inversion, we focus on a single active acoustic run, located in an area with almost constant environmental conditions, allowing us to choose a range independent environmental model. The locations of all active acoustic runs performed during the MREA/BP'07 are shown in Fig. 1. Considered is a measurement configuration that includes a stationary source, located at position ST3, and a drifting receiver array, launched at position ST7. Both positions are approximately 1.8 km apart. Water depths at these locations are about 110 m and a rather small 7-m sediment layer, consisting of clay, is covering a silty-clay bottom. This is documented by core samples, described in the appendix of [6].

The receiving unit is a vertical line array (VLA), composed of four 5-m spaced hydrophones, with the shallowest one placed at 20 m depth. This VLA was drifting towards the NATO's *NRV Leonardo*, which was carrying a low- (300-800 Hz) and mid-frequency (800-1600 Hz) source at approximately 90 m depth. These sources sent predefined sequences of acoustic signals, including signals composed of tones at discrete frequencies (multi-tones) and frequency modulated waveforms (chirps) in both bands. The multi-tones consist of 32 frequencies, of which 20 in the low-frequency range and 12 in the mid-frequency range. The chirps are sampled at 1-Hz steps. However, in order to increase the computational performance, 2-, 10-, and 20-Hz steps are investigated.

3. THE INVERSION METHOD AND PROPAGATION MODEL

Geoacoustic inversion is based on finding an optimal match between the measured and the modeled acoustic field, resulting in a parameter combination that is descriptive for the environment. Often, large numbers of parameters are needed to describe both the source-receiver geometry and the environmental features that influence the sound propagation. Here, both the source-receiver geometry and the environment are inverted simultaneously. For the description of the environment a range independent 3-layer model is employed, consisting of the water column and a stratified sediment layer on top of a subbottom. Environmental parameters considered are the sound speed, attenuation, and density of the sediment and subbottom as well as the water depth and sediment thickness. Since most relations between these parameters and the acoustic field are non-linear, the search space is likely to contain local optima. Inverting for these parameters, therefore, requires an efficient global optimization approach. For this reason, the differential evolution (DE) method is applied as described in [8], in order to find the best match between the model and measurements in an iterative process.

For the MREA/BP'07 experiment, an optimal setting of DE has been chosen according to synthetic inversion results [9]. It involves 12800 forward calculations of the acoustic field, which were found to be necessary for convergence.

The fitness of a parameter value combination is characterized by an energy function. Several energy functions are suggested in literature [10, 11]. Most associate a better fit with lower energy. Their major difference is whether they treat the data coherent in the spatial or frequency domain. For multi-tones, which do not contain frequency coherent information, generally, a standard Bartlett processor [5] is chosen, such as here. For frequency modulated waveforms the relative magnitudes and phase, in general, are known. Therefore, frequency coherent processing is applied to the chirp signals, according to [11].

The model chosen for calculating the acoustic field per frequency f is a standard normal modes model. Normal modes solve the wave equation through eigenvalue decomposition. The computational complexity of the eigenvalue decomposition, in general, is cubic with the number of eigenvalues [12]. This number of eigenvalues is directly related to the number of normal modes N_m, or eigenvectors. In turn, N_m is related to the frequency and the environmental conditions, as described in [13].

$$N_M = \frac{2(H_W + H_S)f \ln\left[\sqrt{1 - \frac{\bar{c}}{c_b}} + 1\right]}{\bar{c} \ln 2} + \frac{1}{2} \tag{1}$$

Here, H_W and H_S are the water depth and sediment thickness, respectively. Further, $\bar{c}$ is the sound speed averaged over the water column and sediment layer, and c_b is the sound speed of the sub bottom. Since a range independent environment is assumed, variations in N_M will be dominated by frequency changes. For the frequency ranges considered, the number of modes ranges between 9 and 26 for the low-frequencies and can reach up to 114 for the mid-frequencies.

4. RESULTS

In the scope of the MREA project, it is investigated to what extent the efficiency of the geoacoustic inversion can be increased within the accuracy limits of its applications, by either reducing the number of frequencies accounted for or by employing low frequencies only. Both, chirps and multi-tones in the two frequency bands of 300-800 Hz and 800-1600 Hz are considered for this analysis. The inverted parameters, which are introduced in Sec. 3 and are presented in the following, have been averaged over approximately 50 m (3 sequences of signals), in order to reduce variations that occur due to the limited number of observations (4 hydrophones) and imperfectness in the environmental model. Since, per signal type, different numbers of signals are available in a single sequence, the amount of data involved in the averaging process varies. In total, averaging incorporates 3 multi-tones, 6 low-frequency chirps, or 9 mid-frequency chirps.

For studying the effect of reducing the number of frequencies, we first investigate the low-frequency chirp signals, since they employ the lowest number of normal modes (see Eq. 1). These signals in the band of 300-800 Hz are selected at 2 Hz, 10 Hz, and 20 Hz intervals, thus accounting for 250, 50 and 25 frequencies for establishing the acoustic field, respectively. The estimated environmental parameters are presented in Fig. 2.
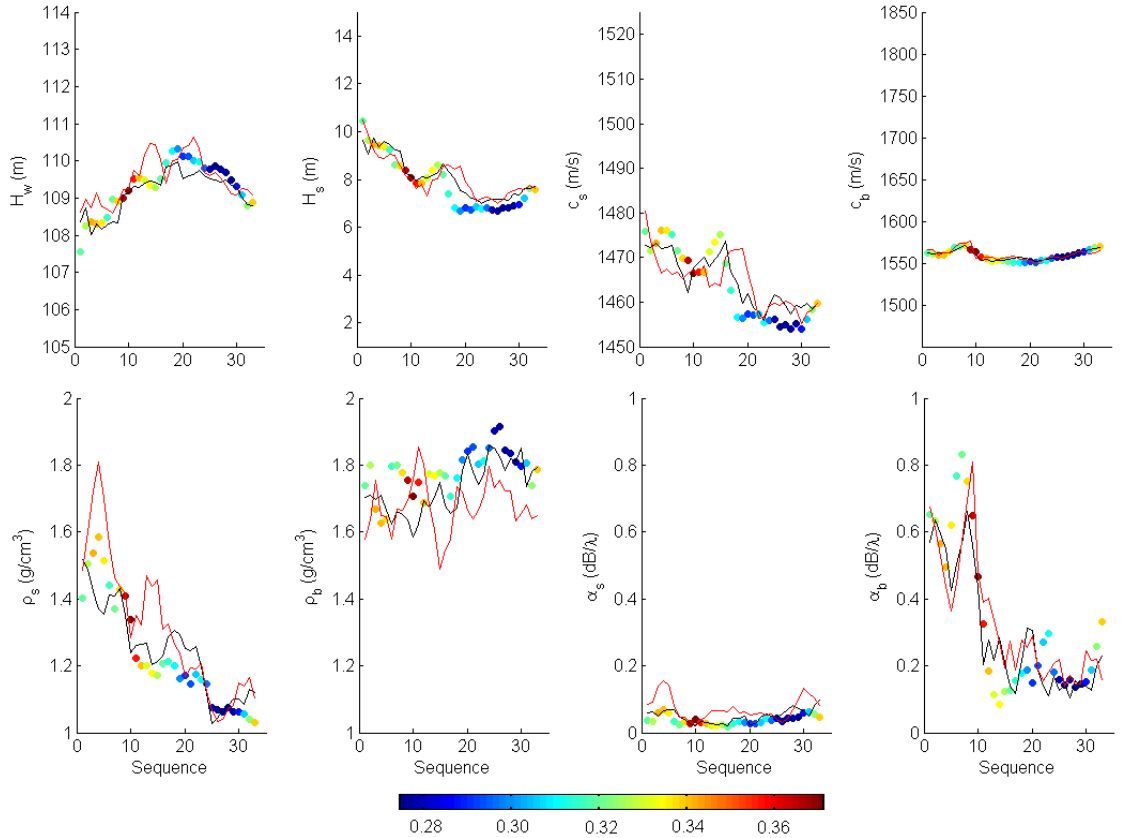
Fig.2: Averaged environmental parameters (from left to right and top to bottom: water depth, sediment thickness, sound speed of the sediment and subbottom, density of the sediment and subbottom, and attenuation of the sediment and subbottom) between locations ST3 and ST7 estimated by geoacoustic inversion of the 300-800 Hz chirp signals, sampled at 2 Hz (dots), 10 Hz (black line), and 20 Hz (red line).

Here, the averaged results of the 2-Hz sampling are considered as reference. They are plotted as colored dots, with the color indicating the energy of the best fit. Results of the inversions with 10- and 20-Hz sampling are given as black and red lines, respectively. It can be seen that the results are comparable for all three sampling rates and for most of the estimated parameters. However, less sensitive parameters, such as densities, benefit from a larger number of frequencies. Still, inaccuracies in the results obtained from the 10- and 20-Hz sampled signals lie within a single standard deviation (not shown) of the 2-Hz sampled estimates, which is assumed to be sufficient for sediment classification purposes. For other applications that require more accurate results, fast inversions based on 20-Hz sampling can provide limits for the search range, which in turn can reduce the computational time of the inversions when applied to a larger amount of frequencies.

The following comparison of the low-frequency results to mid-frequency results is meant to provide information on the additional value of the mid-frequency inversions. The 800-1600 Hz mid-frequency chirps have been sampled at 10-Hz intervals, thus employing 80 frequencies. The results, which have also been averaged over three sequences, thus approximately 50 m, are presented by the black lines in Fig. 3. Again, the results of the inverted 2-Hz sampled low-frequency chirps (colored dots, taken from Fig.2) are given as reference.
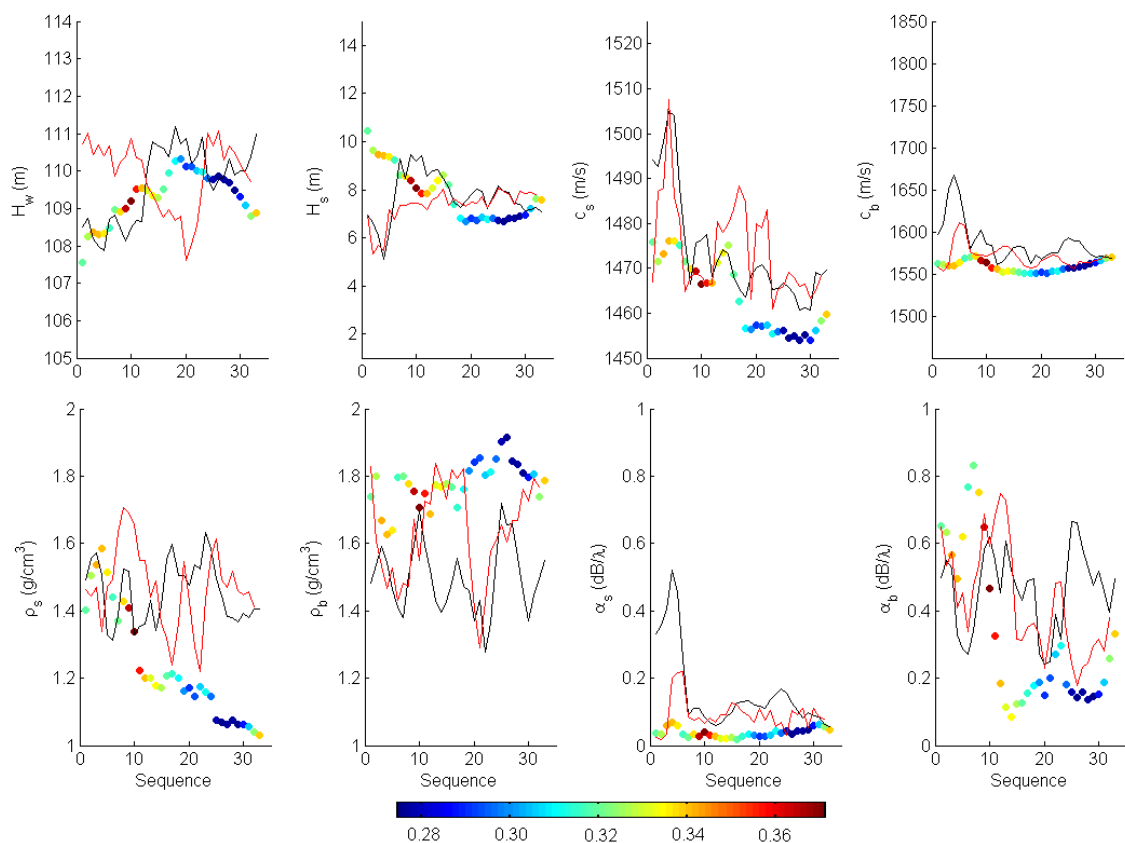
Fig.3: Comparison between averaged geoacoustic inversion results from low-frequency chirps, sampled at 2 Hz (dots) to those obtained from either mid-frequency chirps, sampled at 10 Hz (black line) or 32-frequency multi-tones (red line). The results are averaged over approximately 50 m.

Clearly, deviations between the low- and mid-frequency results are observed in all parameters. Causes for these deviations can be manifold and have to be further investigated. We assume this behavior to be due to the possible malfunctioning of the mid-frequency source. Especially, density estimates of the sediment (ρ_s) and subbottom (ρ_b), which in general should be higher for the subbottom, give rise to the assumption of erroneous mid-frequency signals. Also the sparseness of the sampling might influence the results. However, averaging applied to the mid-frequency signals involves more signals than the averaging applied to the low-frequency signals.

A further comparison with the multi-tone inversions (Fig. 3, red lines), which contain both low- and mid-frequency information, confirms deviations in the inversion results, when employing mid-frequency signals. Here, however, deviations might also be due to differences in processing strategies, either frequency or spatial coherent, and due to the different amount of signals included in the averaging process, which are twice as much for the low-frequency chirps.

From these results an additional value of the mid-frequency inversions can neither be confirmed nor rejected.

5. CONCLUSION

Geoacoustic inversions have been carried out for signals in the low- (300-800 Hz) and mid-frequency range (800-1600 Hz) at different sampling rates. In general, accounting for more frequencies increases the accuracy of the inversions. The required accuracy, however, depends on the application. The following conclusions are based on the aim of mapping sediment classes. For the low-frequency chirps it is found that the number of frequencies could at least be reduced by a factor of 10, compared to the original sampling of 1 Hz. Still, this sampling rate corresponds to 50 times 12800 forward calculations of the acoustic field during the optimization process, with each employing 9 to 26 normal modes.

For some parameter estimates, such as the sediment thickness and sound speed in the subbottom, even a reduction to 25 low-frequencies is feasible. Other parameters, however, benefit from additional frequencies taken into account. In applications that require an increased accuracy, accounting for these 25 frequencies only might be a suitable setting for preliminary inversions. From this, a number of parameters can be fixed and search ranges for the remaining parameters can be reduced, before being included in a more accurate second inversion step, only inverting for those parameters that require a higher frequency resolution.

Inversions of both the mid-frequency chirps and the multi-tones, which cover the entire frequency range, show deviant behavior for all inverted parameters. Since both inversions involve signals from the mid-frequency source, it is hypothesized that this behavior is related to a possible unknown directivity of the source. This has to be further investigated. Conclusions regarding a possible additional value of mid-frequency inversions is, therefore, not possible at this stage.

Frequency incoherent inversions of multi-tone signals, in general, would be preferable in terms of computational time. However, disagreement that is observed in the inversion results obtained from the chirps and the multi-tones might also be caused by the use of different energy functions; the multi-tones are processed spatially coherent, whereas the chirps are processed frequency coherent and account for source characteristics.

6. ACKNOWLEDGEMENTS

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