The sound of sediments: acoustic sensing in uncertain environments
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Chapter 5

Geoacoustic Inversion with Self Noise of an Autonomous Underwater Vehicle

Abstract

This work reports on an experiment from the Maritime Rapid Environmental Assessment sea trials in 2007, where autonomous underwater vehicles were deployed for environmental assessment. Even though these underwater vehicles are very quiet platforms, this work investigates the potential of vehicle self noise for geoacoustic inversion purposes. It is shown that sound speed in marine sediments has been found by a short range inversion from vehicle self noise that was recorded with a sparse vertical receiver array. With the demonstrated inversion method, large areas can be segmented into range-independent patches that can each be characterized by separate inversions.

5.1 Introduction

Various military and civilian activities at sea have a connection with marine sediments. For Anti-Submarine Warfare (ASW) and Mine Counter Measures (MCM), the sonar performance is strongly affected by the acoustic properties of the sea bottom. The sediment type influences the underwater visibility for divers and also indicates the likelihood of burial of mines, pipes and other objects. From a civilian point of view, the continental shelf is being surveyed for petrol, gas, minerals and other natural resources. A worldwide network of pipes and cables supports the

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internet and the transport of natural resources and information. These networks on the sea floor require inspection, maintenance and repair.

All this human activity depends on adequate sensing of the underwater domain. Today’s marine survey deals with high resolution bathymetry from multi beam echo sounders, and extensive acoustic imaging that is provided by side scan sonar. Autonomous underwater vehicles (AUVs) are programmed to do the job and carry these sensors to remote environments. AUVs are true underwater robots that can access locations where human divers cannot go, because of dangerous underwater currents or great depths.

As a first step to assess what is in the seabottom, this work studies the potential of autonomous underwater vehicles to measure acoustic properties of the seabed. The method to do so is geoacoustic inversion. This technique aims to find parameters such as density and sound speed, by analysis of bottom reflected sound. Instead of using sonar transmissions, shipping sounds can be used as sound sources of opportunity [76]. In this case, the sound source is the machinery noise of the underwater vehicle itself. Recordings of a REMUS AUV were made during the Maritime Rapid Environmental Assessment sea trials of 2007 (MREA07). It was anticipated that the weak source level of an AUV might limit its potential for geoacoustic inversion. But as it turned out, low frequencies from a REMUS signature can still be strong enough to find the sound speed of marine sediment.

5.2 Inversion with AUV self noise

Scientific experiments with geoacoustic inversion traditionally depend on a controlled source geometry and a vertical or horizontal receiver array [126]. Experiments with controlled sound sources have been carried out for broad band and narrow band transmissions while the reception is usually done with a vertical array [48]. In an attempt to exploit sound sources of uncontrolled nature a variety of low and mid-frequency (0.1 kHz – 6 kHz) sources of opportunity has been investigated such as ambient noise [46], different kinds of sea life [28, 124], aircraft propellers [18], shipping [104, 64, 21] and even land vehicles [29]. This current experimental work demonstrates how acoustic properties of the seabed are inverted from AUV self noise. During the MREA07 sea trials, two REMUS AUVs [84, 6] have been observed to radiate several low frequency tones in a broad band of 0.8 kHz - 1.4 kHz while the vehicles were deployed to run bathymetrical surveys in a shallow water area. Underwater sound was received with a sparse vertical array from a small boat at anchor.

The method described here does not rely on high power sonar transmissions and has a limited environmental impact. Like other sound source of opportunity concepts, the use of AUVs has potential for military applications, such as discreet
5.3 Concept of inversion with self noise

Self noise of ships has been used before for inversion purposes [104, 64, 21]. In these cases receptions were made with many hydrophones, such as 32 or more, mostly configured in a horizontal array and at a long distance from the noise source. Previous work on geoacoustic inversion with ship noise [76] investigated the use of narrowband tones and short range receptions. The movement of the ship was used to collect a series of independent observations. Acoustic data were recorded with a sparse vertical array of four hydrophones that spanned the water column. The result was a local range-independent environmental model. The current work follows the same approach, by receiving noise of an underwater vehicle at short range and on a light sparse array in a vertical configuration.

5.3.1 Error function

Acoustic inversion methods are meant to derive a geometric or environmental model from observed underwater sound. In an iterative process, numerous replica models are constructed and evaluated. Inversion is a search for the best model and therefore the acoustic impact of replica models needs to be compared with the observed data.

The observed signatures from ships that are used here are narrowband tones. For simultaneous receptions on $N_S$ hydrophones, the received signature components of a ship can be obtained using Fourier transformation as $D_f$, with $f$ the acoustic frequency (in Hz). Likewise, tones can be modeled in the frequency domain as a vector $\mathbf{w}_f$ with entries for the $N_S$ hydrophone depths. Replica data $\mathbf{w}_f$ are calculated with a propagation code and a model vector $\mathbf{m}$ that holds geoacoustic parameters such as sediment density and sound speed. A common method to match observed data $D_f$ with the replica vector $\mathbf{w}_f(\mathbf{m})$, is to use a normalized Bartlett processor of the form [126, 9]

$$B_f(\mathbf{m}) = \frac{\left[ \mathbf{w}_f^H(\mathbf{m}) \overline{\mathbf{R}}_f \mathbf{w}_f(\mathbf{m}) \right]}{\left[ \text{tr} \left[ \overline{\mathbf{R}}_f \right] \| \mathbf{w}_f(\mathbf{m}) \|^2 \right]}, \quad (5.1)$$
where $\dagger$ denotes the conjugate transpose operator, $m$ is the model vector to be optimized and $\hat{R}_f$ are the cross-spectral density matrices defined as
\[
\hat{R}_f = D_f D_f^\dagger.
\] (5.2)

By definition $0 \leq B_f(m) \leq 1$ and a perfect match between observed data and replica data is found when $B_f(m) \equiv 1$. Geometric and geoacoustic parameters can be estimated by maximizing Eq. 5.1. To minimize the mismatch over $N_F$ frequencies, an error function can take form
\[
E(m) = \frac{1}{N_F} \sum_{f=1}^{N_F} [1 - B_f(m)]
\] (5.3)
or more general for receptions at $N_R$ ranges
\[
E(m) = \frac{1}{N_F N_R} \sum_{f=1}^{N_F} \sum_{r=1}^{N_R} [1 - B_{f,r}(m)]
\] (5.4)

### 5.3.2 Movement of the sound source

For fixed source-receiver geometries, observations $D_f$ are usually obtained from Fourier transformed receptions, where the integration time $\tau_B$ is reciprocal to the bandwidth $B$ of the transmitted signal. For a moving sound source of the size of an AUV it is favorable to keep the distance travelled small in comparison with wavelength. For a maximum ships displacement of $\lambda/4$, the integration time $\tau_v$ can be chosen to depend on ships speed $v$ as
\[
\tau_v = \frac{c}{4v f}
\] (5.5)
with $v$ and $c$ in m/s and $f$ in Hz. Typical ship noise contains low frequency narrowband components with $f < 2$ kHz. For $v = 9.7$ m/s (5 kn, or knots\(^2\)) and $c = 1500$ m/s it follows that $B < 52$ Hz. The smallest integration time can been chosen as
\[
\tau = \min(\tau_B, \tau_v).
\] (5.6)

The movement of the ship is further used to collect a series of independent observations. Based on the principle of reciprocity of source and receiver [58], and the assumption of a range-independent environment, the source can be modeled at a fixed position while the receptions are taken to vary in distance to the source. As a result, the observations at $N_R$ different source-receiver ranges can be regarded as incoherent observations from a 2D-array with a horizontal aperture of $N_R$ groups of vertical hydrophone arrays.

\(^2\)The knot is a maritime unit for speed equal to one nautical mile per hour or 0.514 m/s.
5.4 AUV experiments

Autonomous vehicles are cooperative platforms that run programmed tracks and submerge to desired depths. Deployment is mainly limited by bad weather or water conditions, like swell or high sea states and the presence of fishing nets. Most AUVs are well equipped to sample the water column. Normal operation of a REMUS AUV results in temperature and salinity data of the water column and a bathymetric chart of the surveyed area. Both types of data are input to the inversion process. In this chapter self noise is received at a fixed position but autonomous vehicles are also capable of towing their own receiving sensors [53, 54].

5.5 Observations

On the morning of April 29th, 2007, two REMUS AUVs were deployed in a shallow water area nearby the medieval sea village of Castiglione della Pescaia, Italy. The experimental geometry and historical bathymetry [5] are shown in Fig. 5.1. Both vehicles ran along the tracks in an area of 0.1 km by 2 km that was selected to overlay and be in line with the 33 m depth contour line. Markers indicate positions of the sparse vertical line array (SVLA), CTD sampling of Fig. 5.2, seismic bottom profile of Fig. 5.3 and the side scan sonar (SSS) image of Fig. 5.4. Experiments were conducted in very calm waters, sea state 2 or less, and under a partial cover of clouds. In the water column, the ambient noise was highly fluctuating due to the presence of many coastal vessels, mainly recreational boats. Before and during the experiments no fishing activities had been observed.

5.5.1 Water column and SVP

Part of the MREA07 sea trials was an extensive sampling of the water column by measuring conductivity, temperature and depth (CTD) for the purpose of oceanographic modeling and forecasting. As such and with the deployment of the AUVs and two small motor boats, a CTD measurement was taken in the middle of the designated area. The sound velocity profile in Fig. 5.2 is obtained according to the method of Medwin [86], see appendix B. The profile reveals a strong negative gradient below depths of 10 m.

5.5.2 Bottom: bathymetry and seismic profiling

An area with a water depth of $\approx 33$ m was selected for the initial experiments and the AUVs were programmed to run at 3 m above the seabed and in straight lines.
Figure 5.1: Left: Geometry for the experiments on April 29th 2007, south east of the Island of Elba. Depth contour lines are in meters; the first AUV track is based on the 33 m depth contour line. Right: The Very Shallow Water (VSW) team deploys of a REMUS vehicle from a small boat.
parallel with the bottom contour lines. Depths along the first leg are confirmed with ADCP data and found to be between 32 m and 33 m.

The area selection was also based on a seismic survey that was run on April 24th with an EdgeTech X-Star sub-bottom profiling system, provided and operated by TNO. The bottom profile in Fig. 5.3 is for a segment perpendicular to the AUV lines. At a water depth of 33 m possible layers of sediment are observed at 8 m and 10 m in the seabed (dark lines), and at 18 m (changes in texture).
Chapter 5. Geoacoustic inversion with an autonomous underwater vehicle

During the self noise inversion experiments the REMUS vehicles operated their 900 kHz side scan sonars (SSS). The acoustic image in Fig. 5.4 shows a school of small fish and their shadows on the sea floor. Fishery with trawling nets has left sharp traces on the bottom which is an indication that the sediment is composed of clay, silt or sand and certainly not fluid-sediment or hard rock.

5.5.3 Receiving sensors

Acoustic recordings of the AUVs were made from a small boat and with a sparse vertical receiver array. The light array consisted of four hydrophones that were spaced by 5 m and designed to span the water column from 15 m down to 30 m. Acoustic data were recorded with a digital multi-channel recorder. The recording position was at the deeper side of the 33 m contour line, at 42°44.888′N, 010°49.655′E.

5.6 Self noise of REMUS AUVs

Literature on REMUS noise tests is limited. For an operating depth of 8 m Holmes [53] reports a maximum noise level in 1/3 octave band levels of 130 dB re 1µPa at 1 m for a centre frequency of 1 kHz while the major noise components are essentially omni-directional and observed to vary less than 3 dB with bearing. RPM dependent noise was observed at 14.6 m behind the vehicle and found mainly in a frequency band between 700 Hz and 1700 Hz. A comparison of the REMUS with particular military vessels would require classified information, but an unclassified
5.6. Self noise of REMUS AUVs

The observed signature of the first REMUS AUV in survey mode is limited to a single tone that steps through the frequency bins. Figure 5.5 pictures the tone for both survey speeds. When the AUV increases its speed with 0.5 kn, the stepping tone appears to increase roughly proportional (within a 16% margin). It is further observed that the frequency changes every second in a regular pattern that is repeated over every 15 seconds. Considering that the frequency is proportional to the speed of the vehicle, the frequency modulation is explained by a feedback loop with a delay of the AUV’s internal velocity system. With a feedback every second the vehicle over and under compensates the desired speed every 15 seconds. It was further noticed that during another experiment the Ocean Explorer AUV displayed a very similar survey signature.
5.6.2 Acoustic signature at maximum speed

The second REMUS was programmed for maximum speed and passed the array with a closest point of approach (CPA) of about 15 m. From spectrogram analysis a number of narrow band tones were observed between 0.8 kHz and 1.8 kHz, as shown in Fig. 5.6. The harmonic distribution of the tones around a carrier frequency (at 1.1 kHz) is typical for a resonating source. As the REMUS is direct driven by a brushless motor, the most likely source of the resonance is the ball bearing between the propeller shaft and the vehicle\(^3\). It is further noticed that during the experiment the Doppler-corrected shaft revolutions diminished by 2%. This decrease is probably due to the consumption of energy from the battery.

5.7 Results

For inversion the eight strongest tones have been selected from the runs at maximum speed. The selected harmonics are overtones 32, 34-38, 40 and 48 of a 27.3 Hz fundamental frequency and cover a broad frequency band between 850 Hz and 1350 Hz. Sound pressure was observed while the AUV was closing in on the receiver array. A time interval of 20 seconds was subdivided into 20 separate cuts and with an integration time one second each. The observations cover an estimated range

\(^3\)Conclusion based on personal communication with Hydroid and passive sonar experts from the Royal Netherlands Navy.
interval of 58 m to 105 m. This estimation is based on slant ranges between the AUV and the upper phone, and calculated with basic Doppler-arithmetic [82].

The initial aim of the inversion was to find a full set of geometric and geoacoustic parameters, as specified in Table 5.1. The geoacoustic parameters describe a range-independent environmental model. Replica data were obtained from KrakenC, a range-independent normal mode propagation model [105]. The metaheuristic inversion scheme Differential Evolution [121] was selected for being the most efficient method to compare replica data with the observed data [77] (see chapter 7). The method-specific parameters are a population size of 50, a total of 40 iterations, differential factor of 0.6 and cross-over rate of 0.8. Altogether, this inversion evaluated $8 \times 50 \times 40 = 16000$ calls to the KrakenC propagation code.

The convergence of the geometric parameters is shown in Fig. 5.7. The geoacoustic parameters did not all converge to an unambiguous solution; the subbottom parameters did not respond at all. The convergence of the sound speed is pictured in Fig. 5.8. The solutions for sediment sound speed and layer thickness and attenuation (diagrams are not displayed) are obtained where $\Phi$ has a minimum. The obtained parameters are listed in Table 5.1.

### Table 5.1: Parameters for geoacoustic inversion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Interval</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source depth</td>
<td>m</td>
<td>0 – 33</td>
<td>30</td>
</tr>
<tr>
<td>Range correction</td>
<td>m</td>
<td>-50 – +50</td>
<td>-22</td>
</tr>
<tr>
<td>Array tilt (offset)</td>
<td>m</td>
<td>-2 – +2</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Sediment:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sound speed (compr.)</td>
<td>m/s</td>
<td>1450 – 1650</td>
<td>1520</td>
</tr>
<tr>
<td>Sound speed gradient</td>
<td>s$^{-1}$</td>
<td>0 – 15</td>
<td>–</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>m</td>
<td>0 – 40</td>
<td>18.5</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm$^3$</td>
<td>1.5 – 2.0</td>
<td>–</td>
</tr>
<tr>
<td>Attenuation</td>
<td>dB/λ</td>
<td>0.0 – 0.5</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Subbottom:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sound speed (compr.)</td>
<td>m/s</td>
<td>1500 – 1900</td>
<td>no response</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm$^3$</td>
<td>1.5 – 2.5</td>
<td>no response</td>
</tr>
<tr>
<td>Attenuation</td>
<td>dB/λ</td>
<td>0.0 – 0.5</td>
<td>no response</td>
</tr>
</tbody>
</table>

5.8 Discussion

It has been shown that even a small autonomous underwater vehicle such as the REMUS radiates observable underwater sound and can be located with matched
field processing. AUVs are typically used to scan the sea floor with side scan sonar and other sensors. In addition to bathymetry and acoustic imaging, the method described here provides the sound speed of the top layer. As such, the contribution of inversion with self noise is a further characterization of marine sediments.

The sound speed of the sediment is found to be 1520 m/s, which classifies the material as silty clay [58]. Repeated inversions resulted in sediment sound speeds within a margin of ±5 m/s of 1520 m/s, which is within 5% of the used interval of 1450 m/s to 1650 m/s. The sediment classification is supported by a local grab sample\(^4\), which was shown in Fig. 5.8. Next to attenuation, a sediment layer thickness has been found of 18.5 m, which is confirmed by the seismic profiling of Fig 5.3 that shows a change in texture around 18 m.

In the reported experiment, a full geoacoustic model has not been found. The experiment took place on a weekend day when the ambient noise was highly fluctuating due to much activity of recreational boats. Simulations with synthetic data

\(^4\)As of yet, the grab samples have not been analyzed for acoustic properties.
(not further documented here) confirmed that with an increase of ambient noise, the subbottom parameters are the first to become undetectable with the objective function that is used. This is not remarkable as weak subbottom reflected signals have to compete with ambient noise, direct path receptions, and sound reflected from the sediment and the water surface. The signal to noise ratio can increase in various ways, like with lower ambient noise during the week or night time, or by adaptive beam forming of separate vector sensors in an array. It is therefore concluded that self noise of an AUV can be exploited to characterize the sediment and eventually to obtain a full geoacoustic model.

5.9 Conclusions

Autonomous underwater vehicles are flexible and capable assets for remote sensing of the underwater environment. It has been demonstrated that the self noise of an AUV has been used to measure sediment properties such as the sound speed with geoacoustic inversion methods. This result complements the bathymetry and acoustic imagery from a regular AUV survey, and the geoacoustic inversion provides a further characterization of marine sediments. The resulting environmental model means a vast improvement in the accuracy of predicted sonar performance in shallow water.