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Geoacoustic inversion in the north-eastern Caribbean using a hydrographic survey vessel as a sound source of opportunity

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ABSTRACT

During the spring of 2006, hydrographic survey vessel HNLMS “Snellius” ran an extensive multibeam and sidescan survey of the Saba bank, a large submerged atoll located in the north-eastern Caribbean. The survey provided an excellent opportunity for a number of small-scale geoacoustic inversion experiments in a shallow water environment which attracts many divers for its unique tropical ecosystem and rich marine wildlife. The feasibility of a rapid deployment of ocean-acoustic sensors and equipment was demonstrated for the purpose of an environmental assessment of the area southwest of the small volcanic island of Saba. The environmental impact was kept to a minimum by exploiting the hydrographic ship as a sound source of opportunity that was moving along the survey lines and passing by a sparse vertical line array that was deployed from a rubber boat at anchor. Several low-frequency narrowband tones were identified for the inversion process that provided an accurate account of the experimental geometry in terms of moving source and receiving array positions, and detailed geoacoustic properties of the sea floor and sub-seafloor.

1. Introduction

Human activities in coastal environments have led to an expanding exploration of the underwater medium and a rising diversity of man-made noise in the ocean. This work studies the potential of exploiting such noise sources by using a ship as sound source of opportunity to assess geoacoustic properties of the sea bottom. Unlike scientific experiments with a horizontal receiver array (Koch and Knobles, 2005) or a vertical line array at a fixed distance (Chapman et al., 2006), the trials reported here aim to explore receptions with a sparse vertical line array over an increasing range interval.

The source of opportunity approach has two advantages. First of all, in a fragile ecosystem like the Saba bank in the north-eastern Caribbean, extensive use of sonar systems to sense the environment may not only disturb human divers and marine mammals, but high-power and sustained transmissions may even have a damaging effect on their hearing sensitivities (Richardson et al., 2005; National Research Council, 2005). Secondly, there is a case for environmental assessment other than using sonar transmissions, like when examining recordings from previous measurement campaigns. Other examples are interference of other sensor systems or military oceanography with constraints on the exposure of platforms. The main objective of the experiments on the Saba bank was to obtain an accurate acoustic description of the water column and sea bottom. Such a rapid environmental assessment (REA) enables accurate predictions of both active and passive sonar performance and further enhances acoustic sensing capabilities.

Within the framework of its Rapid Environmental Assessment research programme, the Netherlands Defence Academy (NLDA) aims to demonstrate the feasibility of a rapid deployment of ocean-acoustic sensors and supporting equipment followed by a swift inversion process to obtain a detailed acoustic characterization of a shallow water environment, which could be a model of the acoustic propagation medium (Hermand et al., 2006). Following an optimization approach of metaheuristic search strategies, the inversion is to result in an accurate account of the environment and an uncertainty assessment of the describing geoacoustic parameters.

The Netherlands Hydrographic Office (NLHO) maintains a survey policy (NL-HO, 2006) that states a periodical survey in the Caribbean to maintain adequate nautical charting near the Netherlands Antilles. Since the 1996 survey by HNLMS “Tydeman”, there had been no extensive Caribbean hydrographical activities of the NLHO and therefore in the spring of 2006, HNLMS “Snellius” sailed out to survey the waters of St. Maarten, Saba, St. Eustatius, the Saba bank, Curacao, Aruba and Bonaire. A joint team of NLDA and Université libre de Bruxelles (U.L.B.) boarded HNLMS “Snellius” for environmental experiments on the Saba bank using various sound sources, receivers and additional hydrographic equipment (Hermand et al., 2007). The experiments resulted in a

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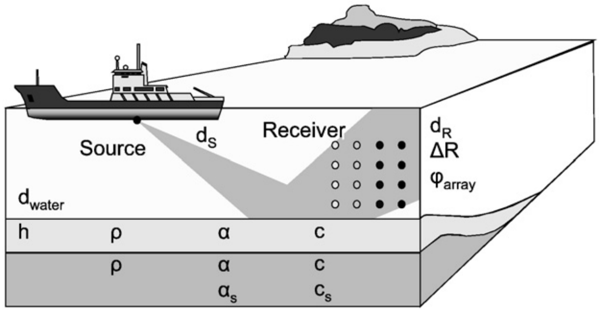

Fig. 1. Illustration of the general set up (not to scale) of the inversion experiment. Included are the geometric and geoacoustic parameters subject to inversion.

geoacoustic assessment of the sediment and subbottom; in addition the standard hydrographic survey of the interior and the edges of the bank provided some degree of environmental ground truth.

The work reported here focuses on geoacoustic inversion with the hydrographic ship acting as a sound source of opportunity; observations were made with a sparse vertical array deployed from a small rubber boat at anchor. With the ship sailing away from the receiver array, various time independent measurements of sound pressure in the water column correspond to incoherent observations over range. Spectral analysis of the uncontrolled sound source identified several low-frequency narrowband tones in a broad frequency band that are exploitable for inversion by the creation of replica fields with a propagation model. Geoacoustic inversion techniques were applied to derive physical properties of the ocean bottom by comparison of the spatial and temporal structure of observed and replica sound pressure fields.

2. Material and methods

Early experiments of geoacoustic inversion (Hermand and Gerstoft, 1996) relied on a controlled sound source and dense vertical array of typically 32 or more hydrophones. The aim of the Saba bank environmental assessment experiments was to use a sparse receiver setup with as few hydrophones as in (Hermand, 1999) but relying on sources of opportunity and easily deployable vertical line arrays, i.e., hand deployed from a rubber boat or any launch available on hydrographic vessels. This capability of fast deployment allows sampling of a wide geographical area through “range-independent” acoustic inversions within regions for which environmental properties are expected, from standard hydrographical data and geological ground truth, to be sufficiently homogeneous in the horizontal to apply these methods. The use of sparse sensors reduces the large quantities of data that are recorded with arrays and therefore significantly reduces the time that is needed to pre-process the data and start a geoacoustic inversion process.

During the morning of 24 April 2006, HNLMS “Snellius” passed the sparse vertical array in a cooperative mode on a pre-defined track with a constant speed and bearing. The main difference with a non-cooperative mode is the systematic logging of accurate DGPS positions that allows for a proper reconstruction of the experimental geometry. The acoustic data was received on a sparse array and recorded on board a small rubber boat on a digital multi-channel recorder. The sparse array of 5 m spacing was set up to sample the lower half of the water column, roughly from 15 m to 30 m. The general illustration of the experiment (not to scale) is given in Fig. 1.

Next to the underwater sounds, the pressure and temperature in the water column was measured from the rubber boat using a thermistor string and later combined with salinity data to obtain sound speed profiles. All deployed equipment had been flown in earlier to Saba Island with the NLDA-ULB team. Following the

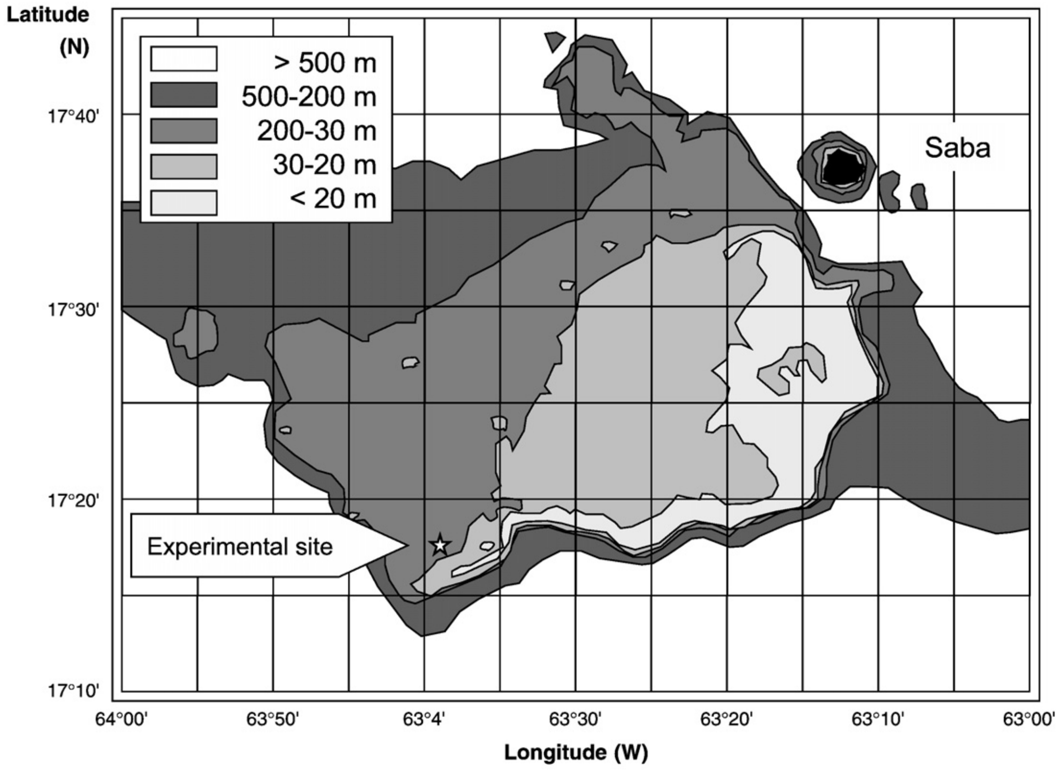

Fig. 2. Map of Saba Island and a general bathymetry of the Saba bank. A star at position 17°17′48″N 63°38′30″W indicates where the inversion experiments took place.

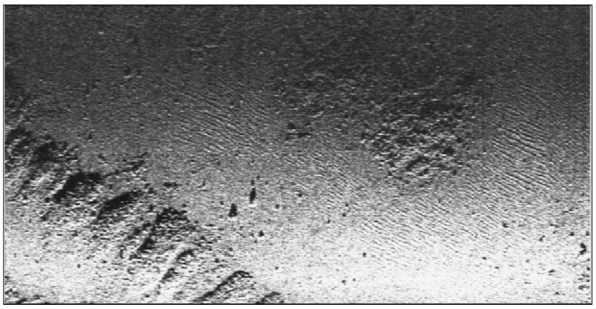

Fig. 3. Numerous outcrops, boulders and sand waves are visible on HNLMS "Snellius" sidescan sonar that operates at 445 kHz. The image covers an area of approximately 80 m by 40 m.

successive runs, the collected data was transferred to commercial laptop computers and processed on board the mother ship. The experiments demonstrated that a mini REA campaign can be launched in parallel to and without interfering with a standard hydrographic survey and that effective geoacoustic inversion results can be obtained, all within a 24-h timeframe.

3. The Saba bank

The Saba bank lies southwest of Saba, a volcanic island in the north-eastern Caribbean. Fig. 2 shows the shallow-water submarine bank that covers approximately 2200 km^2 and the flat top which is found at some 20 m–40 m below sea level. The bank shows all characteristics of an atoll (van der Land, 1977) and houses a unique tropical ecosystem with actively growing coral reefs and a rich marine wildlife (Dilrosun, 2000). Human activity on the bank mainly concerns scuba diving and local fishery; wooden lobster traps are found widely on the shallow bank. The southern part of the Saba bank, where most of the geoacoustic experiments took place, is considered to be part of a Cretaceous platform of carbonate nature (Warner, 1989; Church and Allison, 2005).

During a previous hydrographical survey in 1972, it was found (van der Land, 1977) that the area is covered by a rather thin sediment layer of carbonate sand, probably less than 20 cm thick. Numerous calcareous outcrops and boulders have been reported and are confirmed by the hydrographical survey of 2006 as can be seen in Fig. 3. The ripples in the 445 kHz sidescan sonar image are roughly spaced by half a meter and confirm the presence of a sandy sediment layer.

4. Low frequency measurements and inversion

The experiment that is considered here was carried out during the morning of 24 April 2006, between 9:40 and 10:05 h, local time, at position 17°17′48″N 63°38′30″W as indicated in Fig. 2. The obtained sound speed profile at this position was nearly constant with depth values between 1542.3 m/s and 1542.5 m/s.

In order to find exploitable tones for the inversion, fast Fourier transforms were used to make spectral decompositions of the ship noise as recorded on the hydrophones and pictured in Fig. 4 for the phone at a depth of 25 m. The spectrograms uncover some interesting features. The hyperbolic shapes, which are known as the Lloyd Mirror curves or in–out effect, are the result of multi-path propagation due to extensive surface and bottom interaction: a promising attribute for geoacoustic inversion. As the phones are separated in depth, each spectrogram displays a slightly different pattern with a unique combination of spacing and curvature that further depends on the depth, range and speed of the moving sound source. Another result of the ship passing by is a Doppler-shift that is best noticed and measured on the stable tone at 706 Hz. Combined with basic passive acoustic techniques (Lurton, 2002; Urban, 2002), ship speed and also ship to receiver ranges can be determined so that the geometry for a non-cooperative ship can be reconstructed. In the inversion that follows the more accurate DGPS logging is used, and the average DGPS speed of 7.8 knots reveals a minor difference with the calculated Doppler speed of 7.6 knots. (Accuracy of acoustically-derived ship speed is limited by the width of the tone spectral bands with respect to the FFT bin width.)

For the inversion process several tones have been identified that are strong and stable. A strong tone is still resolvable when a short integration time is used such as the reciprocal of the estimated spectral bandwidth of the tone. Unstable lines have an irregular shift in frequency and therefore hop between the frequency bins. For this reason the very strong line at 225 Hz and its overtones have not been selected; these tones radiate from the gearbox and are very unstable due to ship pitch and movement through the waves. Five stable tones from the diesel generator have been selected for inversion; these are received at 115.5 Hz, 209.4 Hz, 269.1 Hz, 329.1 Hz and 706.8 Hz. The lines originate from the same source and are therefore assumed to radiate from the same location. The actual depth and exact position of the acoustic centre of the machinery sound that radiates from the hull are unknown; the offset of these parameters from the DGPS position are optimized as a first step in the inversion scheme while array hydrostatic pressure data and DGPS data from HNLMS "Snellius" and the rubber boat are taken as *a priori* information.

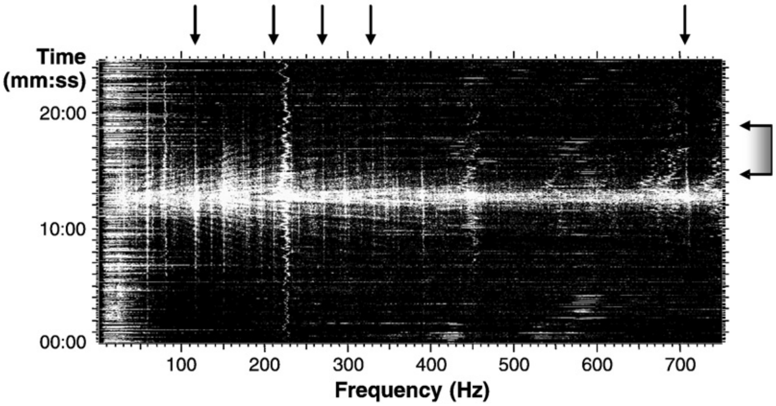

Fig. 4. Spectrogram from the hydrophone at a depth of 25 m and showing 25 min of data with the passing by of HNLMS "Snellius". The closest point of approach is at 12:30 min after commencing the run at 09:40 LT.

Table 1
Model A with search intervals for geometric and acoustic parameters describes a halfspace environmental model of the Saba bank.

Parameter (unit)	Min		Max	Inversion result
Geometry:				
Source depth (m)	1	..	5	3.55
Range correction (m)	−20	..	0	−10.8
Array tilt[a] (m)	−2	..	0	−1.0
Receiver depth correction (m)	−2	..	0	−0.83
Water depth (m)	34	..	36	34.8
Bottom:				
Sound speed (m/s)	2000	..	2250	2115
Shear sound speed (m/s)	500	..	700	625
Density (g/cm^3)	2	..	3	2.65
Attenuation (dB/λ)	0	..	5	–

[a] Horizontal offset between top and bottom phone.

With the ship sailing away from the receiver array, the observed sound pressure fields relate to a variety of grazing angles and distances between source and receiver array. The inversion will be based on ship noise recorded between minute 14:40 and 18:50. The selected time interval corresponds to receptions at ranges between 300 m and 1500 m, and has been divided in $N_R = 103$ samples. As a result, the selected range interval covers various changes in the characteristic pattern of multipath interference as can be seen in Fig. 4. The in–out effect suggests strong bottom reflections that form an important condition for geoacoustic inversion.

4.1. Geoacoustic inversion setup

The inversion process has been divided in two stages. The first stage involves a simple environmental model A to obtain an accurate geometry of the experiment and the acoustic parameters of the subbottom. The second stage of the inversion process exploits these results and aims to complement with a geoacoustic description of the sediment layer and to establish a full environmental model B.

4.1.1. Model A: geometry and subbottom

The first stage inversion aims to resolve the essential geometrical parameters of the experiment next to the acoustic properties of the subbottom. Acoustic energy radiates from an unknown depth and location relative to the ship located DGPS receiver antenna. The ship sails away at some distance from the sparse receiver array and therefore the range correction is regarded as a constant offset to the DGPS-derived positioning. Hydrophones that span the lower part of the water column are spaced by 5 m. The array is expected to cover a depth interval from 14.33 m to 29.33 m, in addition the inversion takes into account a small correction on the depth and also for tilt of the array due to current, the rubber boat being on anchor. The simple environmental model A describes a half space environment whereby the initial neglect of the sediment layer is justified by the low-frequency nature of the 5 selected tones (all below 750 Hz) with respect to the assumption (van der Land, 1977) of limited sediment layers thickness (<λ/10). An overview of all geometric and geoacoustic parameters for inversion is given in Table 1. The listed search intervals are based on *a priori* knowledge like a source depth that depends on keel depth and propeller size, and also a few tryout inversions have been run that are not further reported here.

Table 2
Model B with parameters and search intervals describes a thin sediment layer covering the subbottom of the Saba bank.

Parameter (unit)	Min		Max	Inversion result
Geometry:				
Water depth (m)	32	..	35	34.6
Sediment layer:				
Layer thickness (m)	0	..	2.5	0.15
Sound speed (m/s)	1480	..	1900	1590
Density (g/cm^3)	1	..	1.8	–
Attenuation (dB/λ)	0	..	5	–

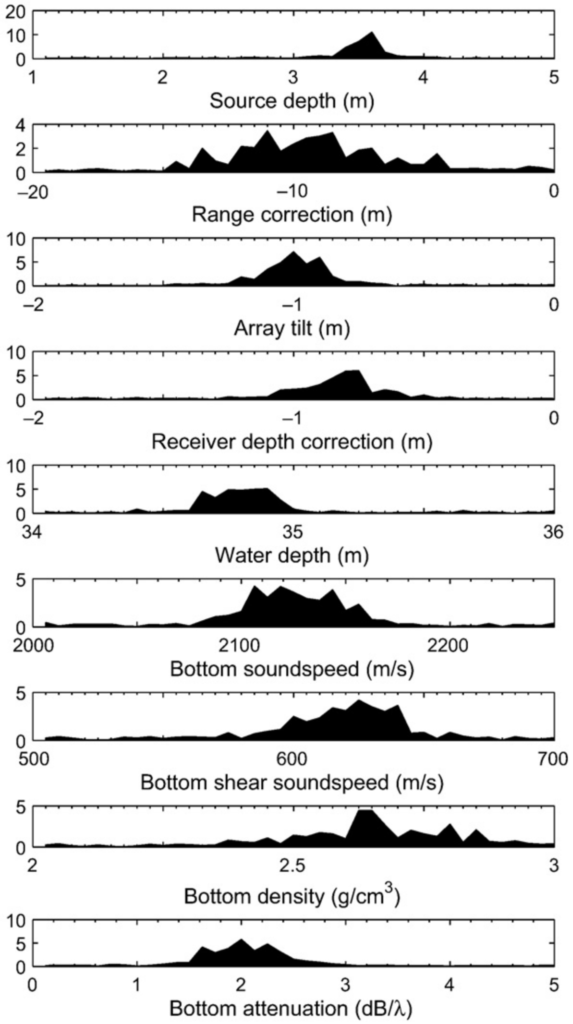

Fig. 5. Posterior probability density distributions based on 20 runs with a genetic algorithm on environmental model A.

4.1.2. Model B: sediment layer

The second stage aims to complement with the geoacoustic inversion of the sediment layer. Environmental model B and the inversion parameters with search intervals are specified in Table 2.

4.2. Objective function

The objective function matches observed data with replica data from the KrakenC propagation model. With an uncontrolled sound source and data received at different positions and time, a suitable objective function should carefully be selected. Sound pressure levels of the identified tones are not known and may vary over time. The adapted objective function Φ for model vector m is therefore chosen as the incoherent sum of the Bartlett power for each combination of frequency (Hermand and Gerstoft, 1996) and range

$$\Phi(m) = \frac{1}{N_f N_R} \sum_{i=1}^{N_f} \sum_{j=1}^{N_R} \left[\frac{trR(\omega_{i,j}) - \omega^*(m,\omega_{i,j})R(\omega_{i,j})\omega(m,\omega_{i,j})}{\omega(m,\omega_{i,j})\omega^*(m,\omega_{i,j})} \right]. \quad (1)$$

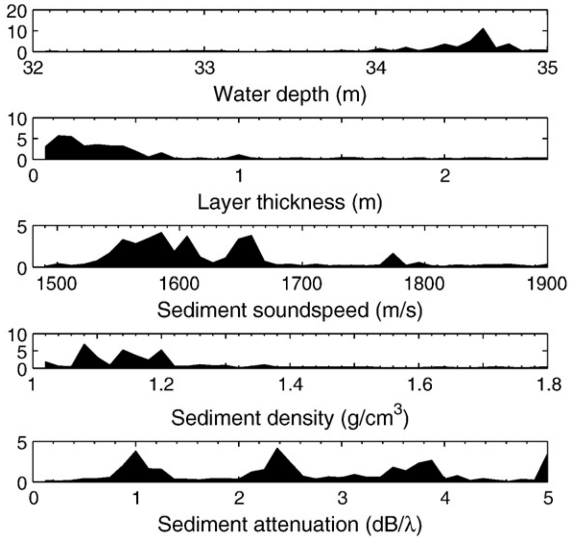

Fig. 6. Posterior probability density distributions based on 20 runs with a genetic algorithm on environmental model B.

The matrices R correlate data from the four receiver depths for each frequency $\omega_{i,j}$ out of the $N_f = 5$ tones and $N_R = 103$ range samples. Like other objective functions for standard matched field processing and geoacoustic inversion with ship noise, Φ is non-coherent in frequency as in Koch and Knobles (2005) but coherent in depth as Chapman et al. (2006) reported for inversion with a vertical array at fixed range. For a horizontal array coherent summation over range would be favourable (Koch and Knobles, 2005). However, the synthetic aperture considered here is constructed from distinct time intervals; combined with the uncontrolled nature of ship sound and dieselgenerator noise, Φ is based on non-coherent summation over range.

5. Results and discussion

For the optimization part, a genetic algorithm was configured with 40 individuals per generation, mutation rate of 0.1, crossover rate of 1.0, and a total of 2000 forward calls for each run. Fig. 5 shows the posterior distributions based on 20 parallel runs for model A and central values are listed as inversion results in Table 1.

First, the geometry of the experiment has been obtained. It appears that the array was 83 cm higher in the water column than expected. The array was further tilted with a horizontal displacement of about 1 m between the upper and lower hydrophone; this corresponds to an angle of 3.8° with the vertical. The five tones are found to radiate from an acoustic centre 3.55 m below the waterline and 10.8 m from the DGPS referenced position. The broad distribution of the range correction parameter suggests that the ship radiates from a larger surface.

A second result for model A is that the subbottom of calcareous rock has a density of 2.65 g/cm^3. In comparison with other heavy subbottom types, such as basalt, the obtained sound speeds of $c_p = 2115$ m/s and $c_s = 625$ m/s are quite low. The subbottom attenuation has a very weak response to the objective function because of the non-coherent summation over range. Furthermore, sediment density and attenuation affect the amplitude of signals of interest, whereas absolute source levels and vertical beam patterns of the radiated tones are typically not known for sources of opportunity. The suggested $\alpha = 2$ dB/λ in Fig. 5 needs further validation and is therefore not listed in Table 1.

The results of model A that are listed in Table 1 were taken as input for model B, the genetic algorithm was configured with settings identical to model A. Fig. 6 shows the distributions for model B and the resulting central values are listed in Table 2.

The presence of a thin and comparatively slow sand layer over the fast subbottom is well detected and the respective sound speeds and layer thickness are well determined. Inversions with model B resulted in an apparent sediment layer of some 15 cm thickness, which is in accordance with the initial assumption of maximal 20 cm. Contrary to the assumed homogeneous stratified sediment layer, the actual sediment displays wave patterns and comprises outcrops and boulders. The irregular character gives an explanation for the spread in layer thickness in Fig. 6 and the appearance of a local optimum of 1660 m/s for sediment sound speed next to the predominant distribution around 1590 m/s. Notice that both sound speeds match with the sandy nature (Hamilton and Bachman, 1982) of the grab samples that were taken from the hydrographic ship. The obtained values of density and attenuation are obviously not reliable as is mostly clearly pointed out by the broad distribution of sediment attenuation.

In summary the broad frequency range of the ship tonals and the increasing distance between source and receiver array both contribute to obtain a well-behaved *a posteriori* distribution for most of the determinant parameters.

6. Summary and conclusions

With the inversion of the experimental geometry and geoacoustic properties of the sea bottom at the southern part of the Saba bank, it has been demonstrated that ship noise can be used as a sound source of opportunity for rapid environmental assessment. The uncontrolled sound source was recorded on a sparse vertical line array that was deployed from a rubber boat together with other supporting hydrographic sensors. The result of the geoacoustic inversion process is both an accurate description and an uncertainty assessment of a range-independent environmental model of a sandy sediment layer over a subbottom of calcareous rock. With passive sensing and further processing of received sound sources that are already present the environmental impact was kept to a minimum.

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