Rapid Environmental Assessment System: Concept, Geoacoustic Inversion and At-Sea Experiments

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Introduction

Maritime operations lead to an increasing focus on environmental effects in littoral areas and coastal zones. Shallow waters with water depths below 200 m, where amphibious operations are likely to take place and military systems will be deployed, have special characteristics. Typically, the water depth is rapidly changing and the physical parameters of the environment, including sea surface, water column, seafloor and sub-seafloor, exhibit a strong temporal and spatial variability. Seasonal, morning and afternoon effects in the water column may affect the sound velocity profile. Local variations in the bottom properties, such as the thickness, density, compression/shear sound speeds and attenuation of unconsolidated sediment layers and the sub-bottom are common. The environmental properties and therefore the frequency-dependent properties of the acoustic propagation medium are likely to vary from one area to the next, just a few tens, hundreds, or thousands of meters away. In these areas there is often intense human activity, with many man-made objects and noise sources in the water, or on the bottom.

Environmental parameters characterising the water column and the bottom, referred to as the set of *geoacoustic* parameters, will obviously affect the performance of military sensor systems in Anti-Submarine Warfare or Amphibious Operations. Predicting sonar performance during deployment is important, and adaptive sonar signal processing may yield significant improvements in situational awareness. This is not straightforward since the propagation characteristics are complex in a (very) shallow water acoustic waveguide where the interaction with the boundaries controls the propagation. Knowledge of the geoacoustic parameters is crucial to sensor deployment as part of a military operation. Obviously, in well-known operational areas there will be regular surveys and monitoring of the environment. A database, charting the temporal and spatial variability, will be made available; this is a standard task for hydrographic services around the world.

However, in the framework of the European Defence and Security Policy (EDSP) there is an increasing demand for rapid characterization of the environment in less-known and unknown shallow water areas. The word “rapid” implies that weeks to days ahead of an actual military operation one would like to do a brief survey of the relevant area. That should yield the environmental parameters that are passed on to the operational commanders who will then deploy their sensors and know what to expect from the sonar systems during the operation. The process of quick medium characterization is called *Rapid Environmental Assessment* (REA), as part of the process of *Battlefield Preparation* (BP). Preferably, this should be done as a covert operation, with a minimum set of equipment, without the need for having big ships or other military platforms in the area, and with a near real-time processing cycle for the data.

A number of REA system concepts have been considered. Many configurations are possible but the illustration in Fig. 1 shows one such approach. It shows a number of system components in the littoral zone; any ship, helicopter or aircraft might deploy the single sound source and the set of drifting acoustic-oceanographic buoys. These will acoustically monitor the environment for a given period and transmit their data via telemetry to a monitoring station (possibly relayed via aircraft or satellite). At the monitoring site the acoustic data is used and processed to yield the geoacoustic parameter set. In scientific terms this is called *geoacoustic inversion*; this technique will be discussed in more detail below.

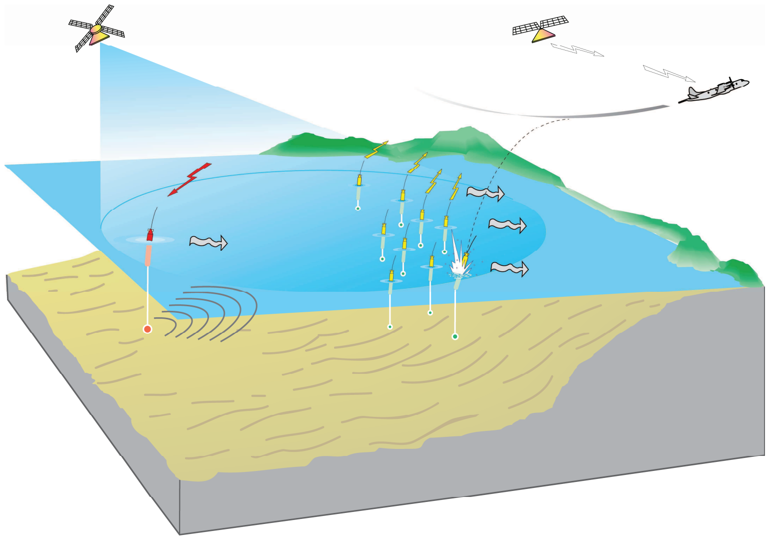

Figure 1. Shallow water Rapid Environmental Assessment (REA) system concept based on a single sound source (left), a set of drifting acoustic-oceanographic buoys (centre) and telemetry of data to a remote monitoring station such as a satellite or aircraft (top).

The system components shown in Fig. 1 are representative of specific system functions; there is a sound transmitter plus a number of receivers. Obviously, one may think of alternative realisations of these functions. The sound source might be a passing surface ship or even ambient noise in the littoral zone. The receiver hydrophones might be part of a horizontal towed array behind a ship, or of a moored vertical array. Instead of the drifting source and receivers one might deploy an Autonomous Underwater Vehicle (AUV) with sensor, navigation and communication sub-systems; in a distributed systems concept there might be a coordinated group of such vehicles. However, there is a definite advantage in limiting the set of system components. Therefore, the concept of a *sparse* set of receivers is highly relevant, and from a systems performance point of view the feasibility of REA with a sparse set of hydrophones will have to be investigated.

In 2002 the Royal Netherlands Naval College (RNLNC, now part of the Netherlands Defence Academy) started a research program on the topic of REA with a sparse set of acoustic-oceanographic sensors. The research focused on:

- the development of an effective and efficient geoacoustic inversion scheme with a novel approach;
- acquisition of experimental data at sea for validation of the REA geoacoustic inversion approach; and
- optimisation of the search strategy for geoacoustic parameter determination.

A first approach to the segmentation problem was presented in [13], using modern time-frequency methods, such as Gabor atoms to segment the downrange domain for a set of drifting receiver buoys. This limited investigation did not yield a convincing outcome; segmentation was most critical to algorithm tuning and tentative interpretation.

This paper discusses the principle of geoacoustic inversion. That will demonstrate the need for validation with experimental data. The RNLNC has been involved in two recent sea trials that will be described in brief. Results for the geoacoustic parameter characterization for typical examples will be shown and discussed. Finally, the paper presents conclusions, future recommendations and references for further reading. This NLARMS volume contains another paper about the REA research project (see contribution by Van Leijen).

Geoacoustic inversion and backpropagation techniques

The principle of geoacoustic inversion is shown in the diagram in Fig. 2 [1, 2]; in clockwise orientation the essential steps are shown. Remember that the goal is to obtain an estimate for the set of geoacoustic parameters shown in the lower part of the upper left plot: the sound velocity profile $c_1(z)$ in the water column (where z is the depth coordinate), the density d_2, sound speed c_2 and gradient g_2 and sound attenuation α_2 in the sediment layer, and the density d_3, sound speed c_3 and attenuation α_3 in the sub-bottom.

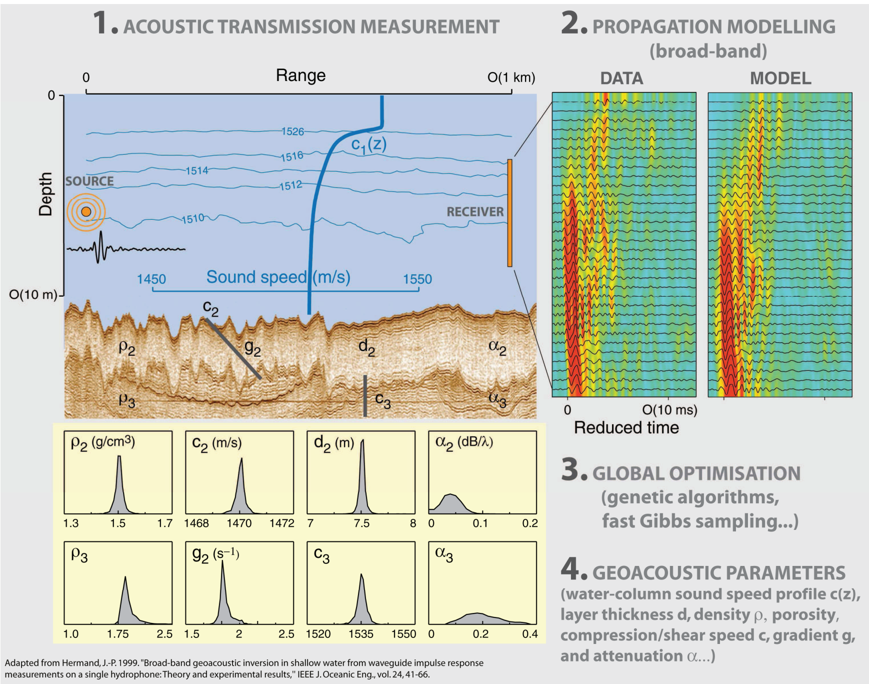

Figure 2. Principles of geoacoustic inversion using a broadband matched-filter approach. The essential steps that yield the set of geoacoustic parameters from the acoustic measurements are shown in clockwise sequence.

Step 1 involves the acoustic experiment: the sound propagation from the source to the receiver (the figure shows a vertical hydrophone array) in the shallow water acoustic waveguide is measured. In **Step 2** the measured data is compared with a receiver data replica field obtained with an acoustic propagation model. This propagation model requires an initial guess for the geoacoustic parameter set that represents the environment. The acoustic wave equation, either in the exact or some approximate form, will be solved at multiple frequencies. The *modelling over a broad range of frequencies* is an essential aspect of the current geoacoustic inversion approach, in combination with a sparse set of hydrophones. In **Step 3** the difference between the model and real data is used as input to a *backpropagation* scheme that will yield update information for the geoacoustic parameters. Scientifically, the search for the set of environmental parameters that will minimize the mismatch between the measured and the acoustic propagation model data corresponds to an *optimisation* problem.

Backpropagation, as shown in diagram in Fig. 3 [12], does the search by iteratively updating the set until the final solution is reached in **Step 4** (in this case a set of parameter value distributions in the lower left of Fig. 2). In the diagram the initial guess of the set of geoacoustic parameters is represented by the vector γ. With that initial estimate the *forward model* determines the acoustic propagation from the source ($r = 0$, where r is the range) to the receiver ($r = R$) for a given geometry; the resulting sound pressure field at the receiver hydrophone set is represented by $u(\gamma; R, z)$ (note the multiple frequency, broad-band approach).

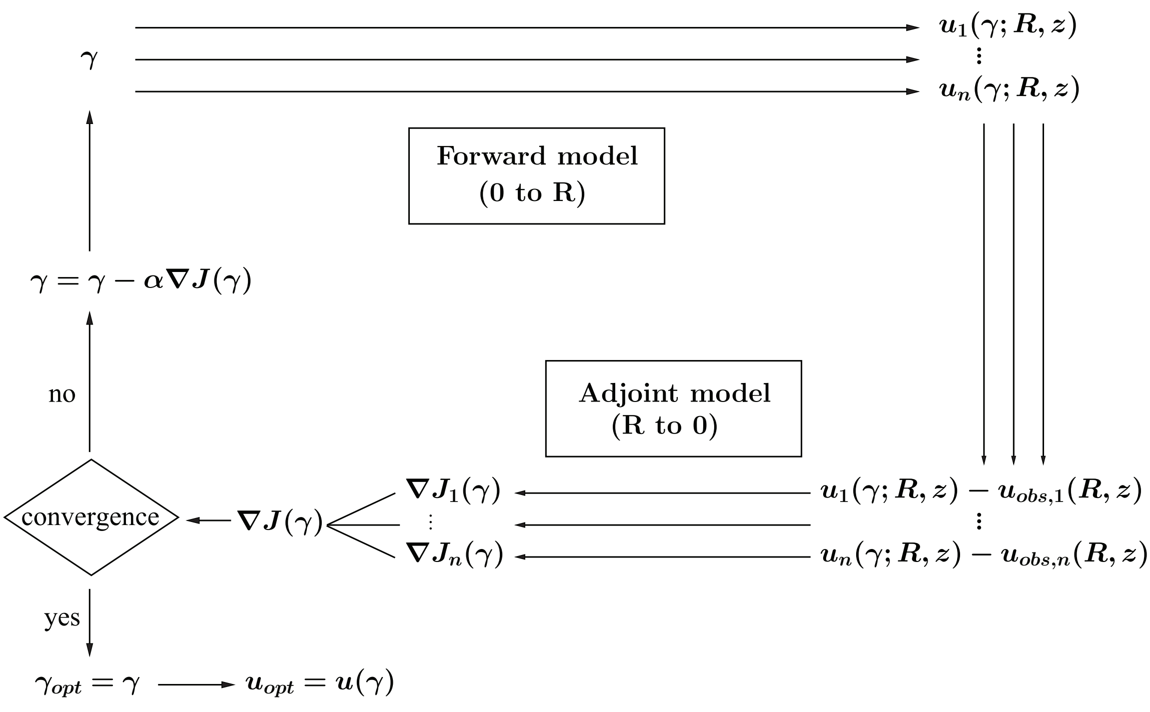

Figure 3. The backpropagation scheme for geoacoustic inversion. The gradient of the cost function J controls the search for the set of geoacoustic parameters γ that will minimize the difference between the model and measured data $u - u_{obs}$ at the receiver array. Shown in the figure is the broad-band, multiple frequency approach to both the forward and the backpropagating adjoint model [12].

The mismatch between the model and measured field at the receiver $u_i - u_{obs,i}$ is then backpropagated from the receiver to the source using the *adjoint model* (see the next section), yielding a gradient of the cost function $J(\gamma)$. The cost function weighs the quadratic difference between the model and measured field on the receiver array over the multiple frequencies. It may contain additional *regularisation* terms to control the character of the solution. The cost function gradient is used to update the set of environmental parameters (note the term $\alpha\nabla J(\gamma)$ in the figure, with α a tuning parameter) and an *iterative optimisation scheme* is obtained, as shown by the clockwise loop in the figure, until after a number of iterations the final estimate γ_{opt} is reached.

The adjoint method of optimal control for REA

This section discusses the elements and techniques in the geoacoustic inversion scheme, and summarizes the salient features of the PhD thesis work of Meyer [12], as part of the RNLNC REA research project. Consider the separate blocks from the diagram shown in Fig. 3:

- The forward model is a parabolic-type approximation to the acoustic wave equation. The Wide-Angle Parabolic Equation (WAPE) generates the replica model of the receiver data for the range-independent shallow water acoustic waveguide. It is demonstrated to give a sufficiently accurate propagation pattern, when compared with a more complex and computationally demanding full-field coupled normal model, such as Kraken-C [14]. The multiple frequency approach involves 7 different source frequencies between 200 Hz and 800 Hz.
- The sound speed profile in the water column is represented in varying detail, depending on the type of inversion. In ocean acoustic tomography the sound speed profile is determined, and one type of representation used in this research is through Empirical Orthogonal Functions. In geoacoustic inversion the range-independent interface between the water column and the bottom is represented by a non-local boundary condition [11], which means that at a certain position the solution is affected by the boundary parameter values further upstream and downstream.
- The gradient of the cost function is determined by backpropagating the residual sound field, i.e., the mismatch between the measurements and the replica, from the receiver to the source. Backpropagation is based on an adjoint model approach, an optimal control method [7, 10] used in various fields such as meteorology, geophysics, fluid dynamics, but also in missile guidance performance evaluation. Application of the adjoint method to underwater acoustics is fairly recent. In this research a semi-automatic adjoint generation [5] via a modular graph approach [15] for the WAPE has been used.
- The gradient approach for updating the estimates of the set of geoacoustic parameters has been compared with other search techniques. Iterated Local Search and population-based meta-heuristic techniques, such as Genetic Algorithms and Ant Colony Optimisation [8] were evaluated for the same shallow water scenarios.

A meta-heuristic can be seen as a general algorithmic framework which can be applied to different optimisation problems with relatively few modifications to make them adapted to a specific problem. The classical, meta-heuristic *global search* algorithms, typically used for inverse problems in oceans acoustics, iteratively update the model by introducing random variations of the control parameters (the elements in the vector γ) and in doing so can move uphill in the cost function to escape from local minima. However, for complex environments and models or for large (possibly correlated) control parameters sets they require a huge number of modelling runs and are relatively inefficient especially moving downhill, e.g., near convergence and for correlated parameters.

The adjoint approach is a complement or alternative to the traditional inversion methods in the sense that it provides a mechanism of optimisation that is directly based on and controlled by the underlying physics of a shallow water waveguide, provides gradient information (i.e., produces corrections to the respective model inputs that caused the mismatch between the observations and model predictions). It belongs to the category of *local* methods since it is gradient-based and significantly reduces the number of modelling runs.

In the thesis various realistic shallow water scenarios were considered, demonstrating the feasibility of the approach. These scenarios were either based on the geometry and conditions during the 1994 Yellow Shark (YS'94) sea trial, for which detailed ground truth is available, or on recent experimental data from the MREA/BP'07 trial (see the next section). A performance analysis is presented, when balancing the number of hydrophones of the vertical receiver array against the broad-band, multiple-tone approach. Convergence of the solution is considered, i.e., does the final iterative solution for the sound speed profile or the geoacoustic parameter set approach the ground truth, and in how many iteration steps was this solution achieved? Also, in many cases a clear hierarchy was found where some parameters (depending on the scenario) converged before others. Also, in one scenario, the shallow water time-variability of the sound speed profile over 48 hours was studied, demonstrating the tracking potential of this inversion approach.

Since validation with experimental data has always been an important component in the RNLNC REA research program, two recent sea trials will be described briefly.

The sea trials

The RNLNC was involved in two recent sea trials: Saba'06 (RNLN only) and MREA/BP'07 (multi-national initiative). Both were organized in close cooperation with the Netherlands Hydrographic Office (NHO), and were carried out with participation of a highly modern ship from the Hydrographic Service of the Royal Netherlands Navy, HNLMS *Snellius*, shown in Fig. 4.

The Hydrographic Survey Vessel (HSV) is equipped with an impressive sensor and systems suite: a hull-mounted Search Light Sonar (FURUNO CSH5), a towed high resolution high speed Side-Scan Sonar (KLEIN 5500, 455 kHz), GPS navigation (Thales Aquarius 02, dGPS, EGNOS/WAAS, LRK), a towed magnetometer (Marine Magnetics SeaSPY), a moving vessel Sound Velocity Profiler (BOT - MV P100, SV, T&P), a Single Beam Echosounder (Kongsberg Simrad EA 600, 38, 12, 200 kHz), a Multibeam Echosounder (Kongsberg Simrad EM 3000D, 300 kHz), a Navigational Echosounder (Kongsberg Simrad EN 250, 38 kHz), a single sweep system (Seatools Ultra Short Baseline System Sonardyne), and miscellaneous datalogging and processing equipment (QINSy and ISIS Sonar SSS). The following sections will provide an overview of the experimental set-up.

Figure 4. HNLMS Snellius, hydrographic survey vessel (length: 82 m*, beam: 13.1* m*, draught: 4* m*, displacement: 1875* tons*, speed: 12* kts*, built: 2003, propulsion: diesel-electric 1250* kW*, crew: 18)*

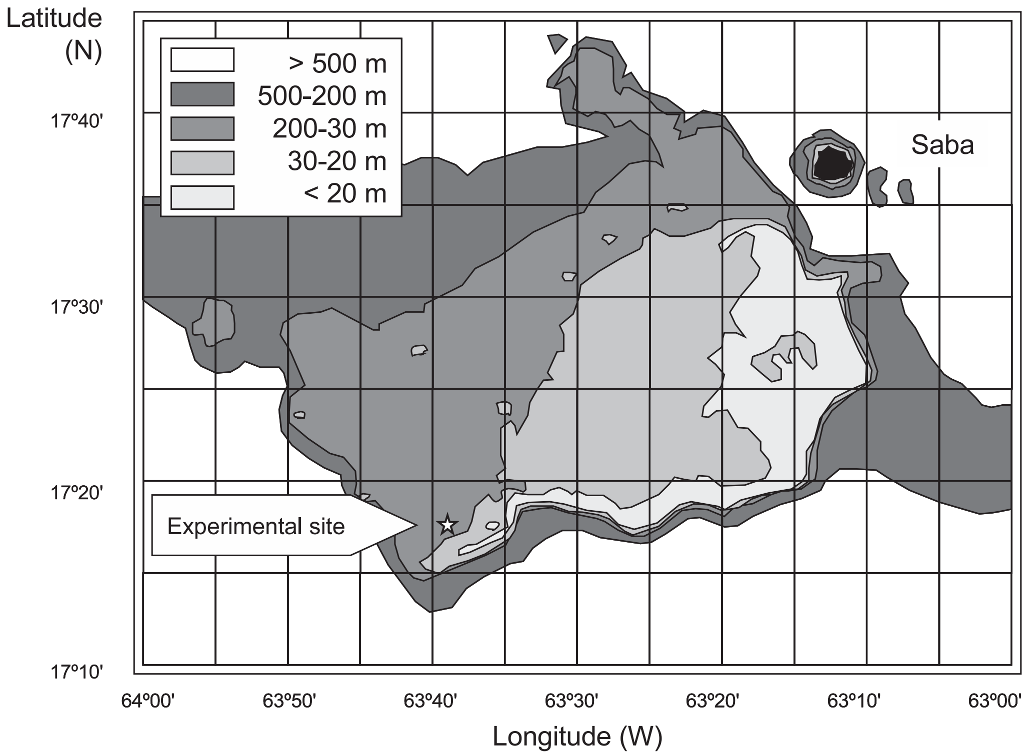

Figure 5. The geographic location of the island of Saba (top right) and the position of the Saba bank (light grey areas to the southwest of the island).

Saba'06

During the spring of the year 2006, hydrographic survey vessel HNLMS *Snellius* ran an extensive bathymetric survey on the Saba bank, a large submerged atoll located in the north-eastern Caribbean, see Fig. 5. The survey provided an excellent opportunity for a number of small-scale geoacoustic experiments in a shallow water environment. 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 aim of the Saba bank environmental experiments was to use a sparse setup with as few as four or five receivers. This approach reduces the large quantities of data that are recorded with dense arrays. It therefore significantly reduces the time that is needed to pre-process the data and start an inversion process that will yield the geoacoustic properties of the seafloor and sub-seafloor.

The environmental impact was kept to a minimum by exploiting the hydrographic ship as a sound source of opportunity. It was moving away from a light, sparse vertical array deployed from a rubber boat at anchor. During the morning of April 24, HNLMS *Snellius* sailed along the array in a cooperative mode on a pre-defined track with a constant speed and bearing, yielding systematic logging of accurate DGPS positions that allows for a proper reconstruction of the experimental geometry. Five tones from the diesel generator (115.5, 209.4, 269.1, 329.1 and 706.8 Hz) were selected for the geoacoustic inversion.

The acoustic array receiver data were recorded on board a small rubber boat on a digital multi-channel recorder. The pressure and temperature in the water column were measured from the rubber boat using a thermistor string and later combined with salinity data to obtain sound velocity profiles. Collected data was transferred to commercial laptop computers and processed on board of the HSV. The experiment demonstrated that a small scale REA campaign can be launched and that the geoacoustic inversion process can be completed within a 24-hour timeframe.

MREA/BP'07

The purpose of the MREA/BP'07 sea trial, in April-May 2007, south of Elba Island in the Mediterranean Sea, was a multi-disciplinary experimental effort that aimed at addressing the Battlespace Preparation (BP) concept [6]. The focus was on the establishment of an integrated 4D (3-dimensional space and time) Recognized Environmental Picture (REP) of a shallow water environment in support of two types of maritime operations: Anti-Submarine Warfare (ASW) and Amphibious Operations. For this purpose, several standard and advanced techniques of environmental characterisation covering the fields of underwater acoustics, physical oceanography and geophysics have been combined within a coherent scheme of data acquisition, processing and assimilation. Details are given in the MREA/BP'07 Sea Trial cruise and data reports [3, 4].

The BP'07 sea trial was part of a broader, multi-national Maritime REA (MREA) initiative that NATO Undersea Research Centre (NURC) coordinated in the Ligurian Sea in 2007, see Fig. 6. The experiment has benefited from the oceanographical and bathymetric surveys that have been conducted by the Italian Navy (Instituto Idrografico della Marina) during and after the BP'07 time frame. In addition, external efforts, mainly in oceanographic modeling and satellite remote sensing techniques with NRL Stennis Space Center (NRLSSC), SHOM, GHER, ULB/LOCEAN/LAMFA, MIT/Univ. Harvard, INGV, ARPA and Meteo France have contributed to the BP'07 experiments.

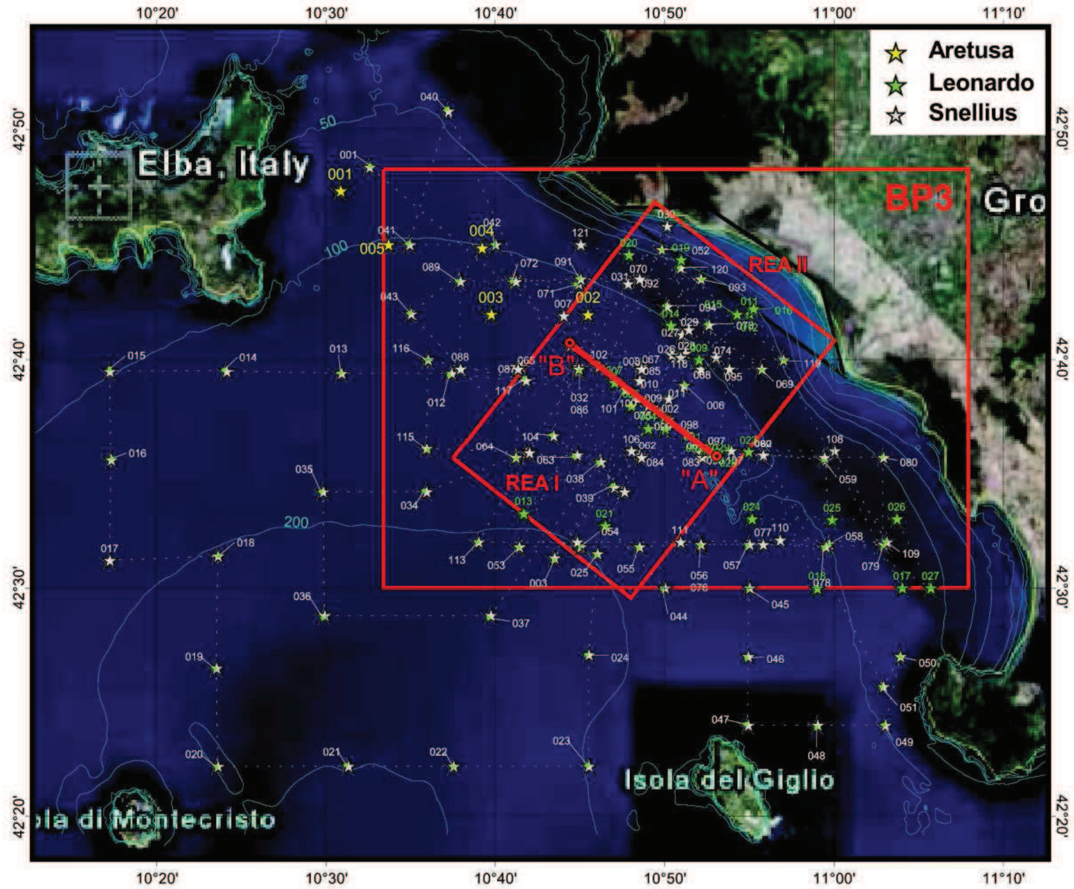

Figure 6. Geographic location of the MREA/BP'07 sea trial. The boxes REA I and REA II are the two main experimental areas. The transect A-B where part of the MREA/BP'07 geoacoustic inversion runs were carried out is the same as for the Yellow Shark '94 experiment. CTD locations are indicated (see [4] for details).

The following vessels were involved: NRV *Leonardo* (NATO), HNLMS *Snellius* (NL) and ITS *Galatea* and *Aretusa* (IT). In addition to these assets, the Marine Mammal Mitigation policy was applied during the acoustic experiments with the support of the Centro di Richerche sui Cetacei (CE.TU.S.) and its RV *Krill*.
Here is an overview of the type of measurements and models used during the trial:

- Seabed characterisation. This included a number of systems on board HNLMS Snellius: GPS, yielding National Marine Electronics Association (NMEA) position strings in the WGS84 ellipsoid and GMT, bathymetry with a Kongsberg Maritime EM3000-D multibeam echo sounder, seismic survey with Uniboom broadband geophysical source from NURC and an EdgeTech X-Star full spectrum digital sub-bottom profiler from TNO (Netherlands Organisation for Applied Scientific

Research), side-scan sonar imagery (Klein 5500), seabed classification with the bi-frequency (12 kHz and 36 kHz) Kongsberg Maritime single beam echo sounder (SBES) EA 600, superficial sediment samplings with a Hamon grabber.

- Estimation of geoacoustic properties. These included both active and passive runs. During the active runs NRV Leonardo deployed a sound source emitting LF (300–800 Hz, ping duration 3 s or 5.8 s) and MF (800–1600 Hz, duration: 1 s or 5.8 s) chirp and multi-tone signals. Data were recorded with a rubber boat or on two drifting buoys with sparse vertical line arrays deployed from HNLMS Snellius, at typical distances of 1–2 km. On the passive runs NRV Leonardo acted as a sound source of coincidence, with typical CPA's of 100-300 m. On two days RNLN AUV REMUS was used for a passive run.
- Water column properties. These were both measured and modelled.
    - ❖ For the in situ measurements, two types of Conductivity, Temperature, and Depth (CTD) sensors were used, with the second providing fluorimetry, sea water clarity and equipped with a rosette for water sampling. HNLMS Snellius deployed a Moving Vessel Profiler (MVP) free falling temperature sensor. In addition, NRV Leonardo deployed two thermistor strings. A Datawell directional waverider was deployed approximately in the middle of transect AB. Remote sensing data was also provided: NRLSSC, together with NURC, delivered AVHRR data from the NOAA12, NOAA14, NOAA15, NOAA18 satellites. The full period of the experiment was covered by those data. SST and cloud analysis were made available on the GEOS server.
    - ❖ The modelling efforts during the sea trial involved three main objectives: net-centric oceanographical forecasts linked to adaptive sampling strategies and super-ensemble predictions by NRLSSC and NURC at two resolutions (2 and 0.6 km grid size), real-time oceanographical forecasts onboard HNLMS Snellius by TNO (a 2-way nested high resolution HOPS model in the areas BP1, resolution 0.6 km, and BP3, resolution 0.3 km), and wave forecasts by NRLSSC/NURC. In order to support those efforts, global models and/or forcing fields were made available by MREA'07 partners: ALADIN wind forcing by SHOM, MFS/OPA oceanographical forecasts (~ 7 km resolution) by INGV.

Both trials have yielded enormous quantities of high-quality experimental data. At sea preliminary, short term data processing was performed, demonstrating the REA concept and providing the operational command with a 4D REP.

Results and discussion

The following sections will present a number of examples of water column and geoacoustic inversion.

Two adjoint-based inversion examples with synthetic and YS'94 data

The first example presents the sound pressure field for the WAPE model with NLBC in a shallow water environment (see Fig. 7). The synthetic true field is calculated for an isospeed water column with $c = 1520$ m/s, water depth $H = 135$ m, on a 512×512 grid area, over a hard reflecting bottom (sand, $c_b = 1600$ m/s, $\alpha_b = 0.5$ db/λ and $\rho_b = 1.8$ g/cm^3).

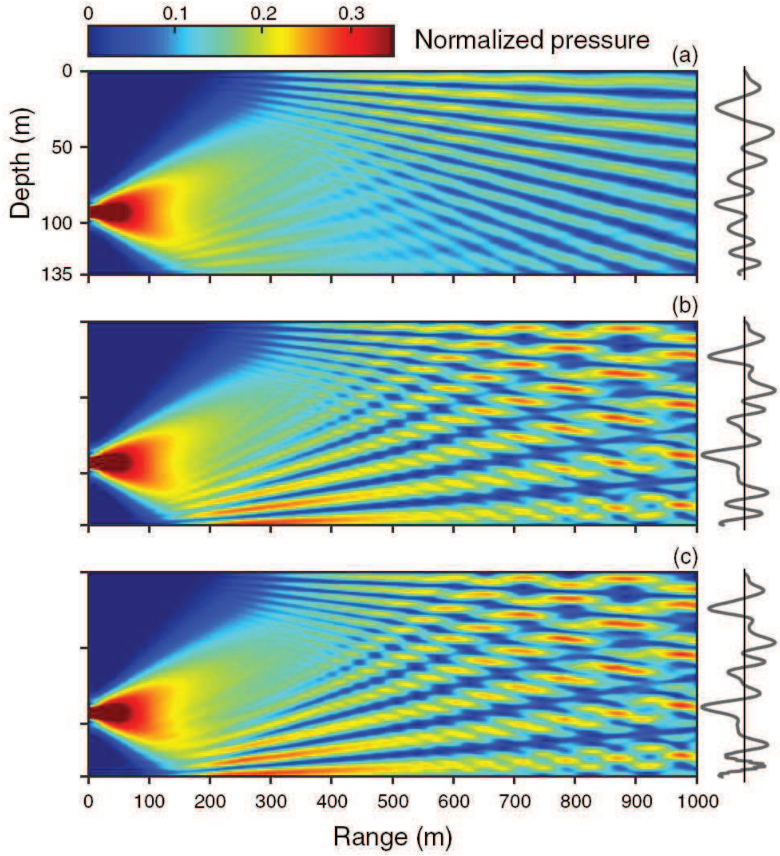

Figure 7. Acoustic pressure field, obtained with the WAPE and optimal NLBC control. Source is positioned left at 93 m *depth, with source frequency f = 500* Hz. *Vertical receiver array (512 elements, equispaced over the water column) is positioned at range 1000* m. *Left: initial guess (a), true value for synthetic data (b), and (c) inverted acoustic pressure field after 16 iterations. Right: imaginary part of the complex acoustic pressure field at range R = 1000* m *[12].*

Observe how, with a very limited number of iterations (initial guess for the bottom properties: clay, $c_b = 1505$ m/s) many detailed features in the propagating field are resolved. Integrated errors over the receiver array have been determined (not shown here).

The second example demonstrates a combined water column and geoacoustic inversion, using YS'94 shallow water (depth 113.1 m) experimental data and a multi-frequency approach (7 source frequencies: 200, 250, 315, 400, 500, 630 and 800 Hz). Measurements were done with a vertical receiver array (32 hydrophones, with 2 m spacing between 37.2 and 99.2 m depths) at $R = 1.5$ km from the source. The result in Fig. 8 shows the quality of the estimation process (compare the final estimated values with the ground truth), and illustrates the parameter hierarchy: the compression speeds in bottom, sediment layer and water column start to converge before the attenuation and density

Both examples demonstrate the capability of the adjoint-based inversion approach. It can both resolve propagation phenomena in the water column and do an efficient combined search for a set of environmental parameters, as was demonstrated in the second example.

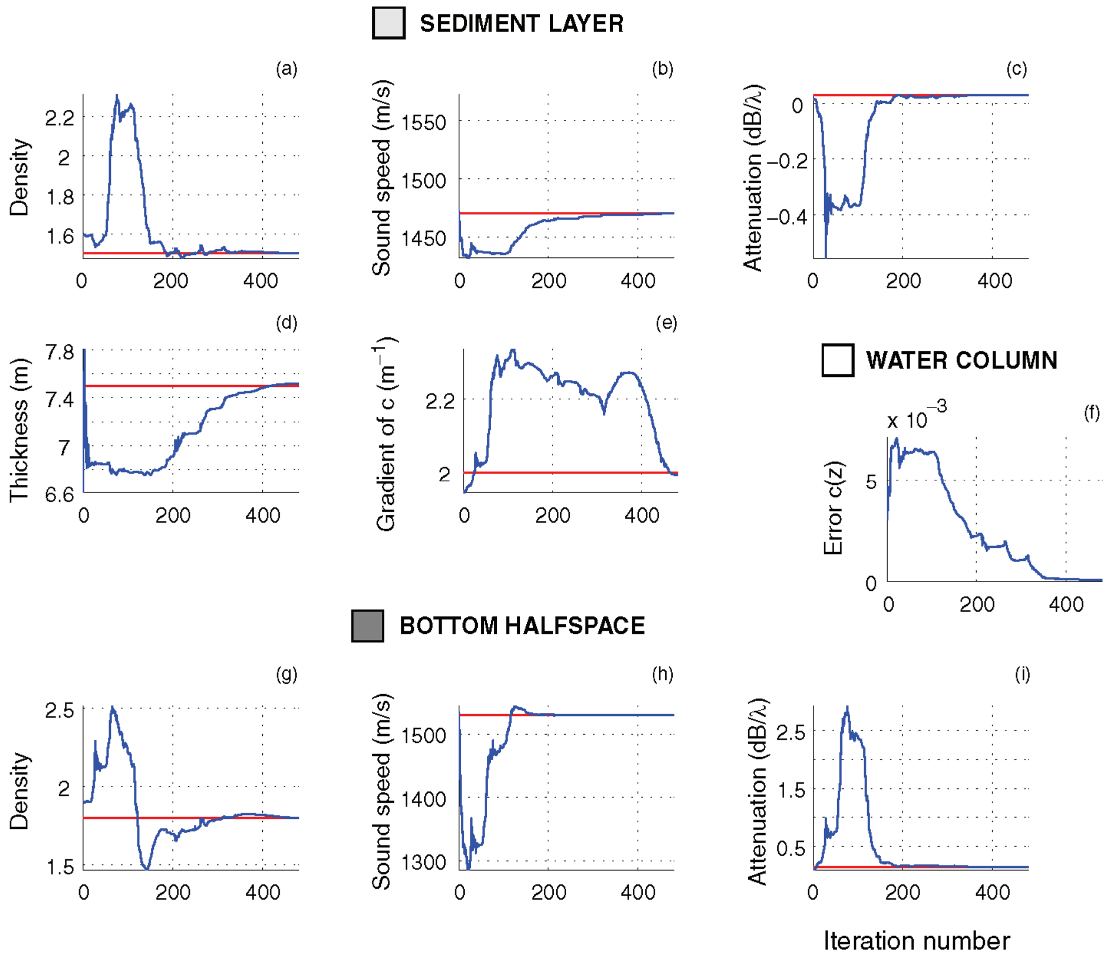

Figure 8. Results of geoacoustic inversion combined with simultaneous correction for an uncertain sound speed profile for the 32-element vertical receiver array and 7 source frequencies. Evolution of the estimated geoacoustic parameters vs. iteration number is shown (3 upper plus 2 centre left plots for the sediment layer, 3 lower plots for the bottom halfspace), together with the depth-integrated error of the water column sound speed profile (centre, right plot). Ground truth for the geoacoustic parameters is shown as red lines.

Geoacoustic inversion with Saba'06 experimental data

In [9] the search process, as part of the geoacoustic inversion, is based on a genetic algorithm. The hydrographic survey vessel acted as the sound source of opportunity and 5 tones from the ship generator noise on the receiver hydrophones (4 hours of recording on April 24, 2006) were used for the inversion of both the experimental geometry and the geoacoustic parameters in the halfspace bottom. Replica data at the receiver were obtained with the Kraken-C acoustic propagation model.

The result is shown in Fig. 9 as a set of posterior probability density distributions. The genetic algorithm settings were: per parameter 40 individuals per generation, crossover rate 0.1, mutation rate 0.1, and 2000 cells per forward run. The results indicate that the experimental geometry is estimated reasonably well, with some error on receiver array position and tilt (position verification with DGPS measurements of the set-up). The estimated values of the halfspace bottom parameters are less representative of the ground truth (a sandy sediment layer over calcareous rock sub-bottom); therefore a second environmental model was used for a more refined geoacoustic inversion run (results not shown here).

Geoacoustic inversion with MREA/BP'07 data

The next example, taken from the cruise report, serves as another demonstration of the passive geoacoustic inversion capability of the the REA concept. NRV *Leonardo* acted as a source of opportunity; sound in the frequency range 0–2 kHz was recorded over a 10 minute period and used as the basis for geoacoustic inversion. Nine parameters were initially guessed with limited a priori knowledge (estimation intervals divided into 40 samples). The final estimated parameter set is shown in the lower half of Fig. 10, and the most significant parameters are well-estimated. The values closely match those obtained 10 years ago under well-controlled conditions using a broadband controlled source, a small number (2–4) of hydrophones and model-based matched filter processing (time reversal).

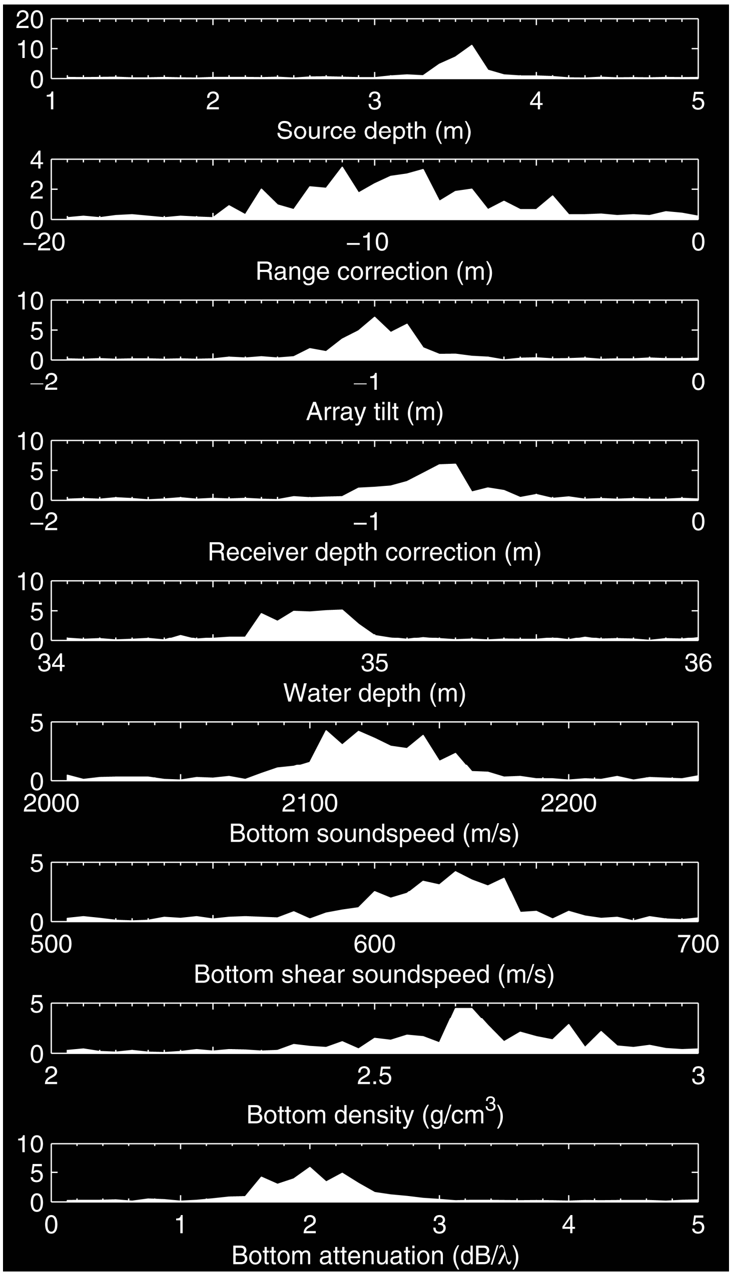

Figure 9. Posterior probability density distributions of the experimental geometry and the geoacoustic parameters during the Saba'06 sea trial. Estimates are based on 20 runs with a genetic algorithm.

The final example, taken from [12], demonstrates the tracking capability, monitoring the range average sound speed changes over a 48 hour period during the MREA/BP'07 trial. The sound speed profile (SSP) is modelled using a set of three Empirical Orthogonal Functions (EOFs) that account for 99% of the sound speed variability in the water column. The inversion process based on the acoustic measurements yields the evolution of the three weighting coefficients μ_1, μ_2 and μ_3 for the EOFs. These are compared with a detailed prediction, calculated with the NRL Naval Coastal Ocean Model (NCOM) that uses a limited set of SSP measurements. The results are shown in Fig. 11, where the upper plot shows the 48 hours NCOM prediction, and in the lower there is the evolution of the weighting coefficients that represent the SSP. Note the afternoon effect (left plot, at time intervals 10–20 and 36–46 hrs), and the excellent agreement between the prediction and the inversion results when both are reconstructed with 3 EOFs.

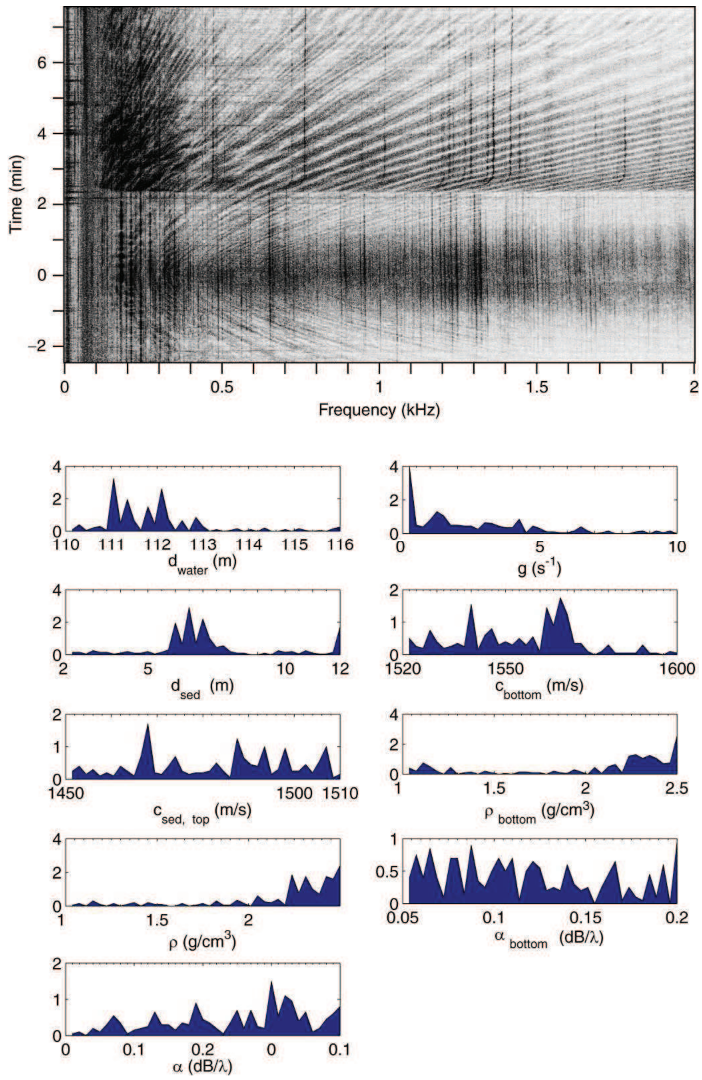

Figure 10. Preliminary results of passive geoacoustic inversion at station ST07 along the AB transect using NRV Leonardo as a sound source of opportunity. Top: spectrogram of Leonardo self-noise over a 10 minute period in the frequency range 0-2 kHz. *Frequencies, ranges and depths selected for the inversion are respectively [226.2, 452.6, 486.1, 582.9, 698.5, 948.5, 1163.4, 1239.3]* Hz; *[0.689, 0.706, 0.723, 0.740, 0.758, 0.775, 0.792, 0.809, 0.827]* km; *[19.04, 24.01, 28.98, 33.95]* m. *Bottom: a posteriori distribution of the estimated geoacoustic parameters: water depth, sediment layer thickness, compression speed, density, attenuation, speed gradient, bottom compression speed, density, attenuation [4].*

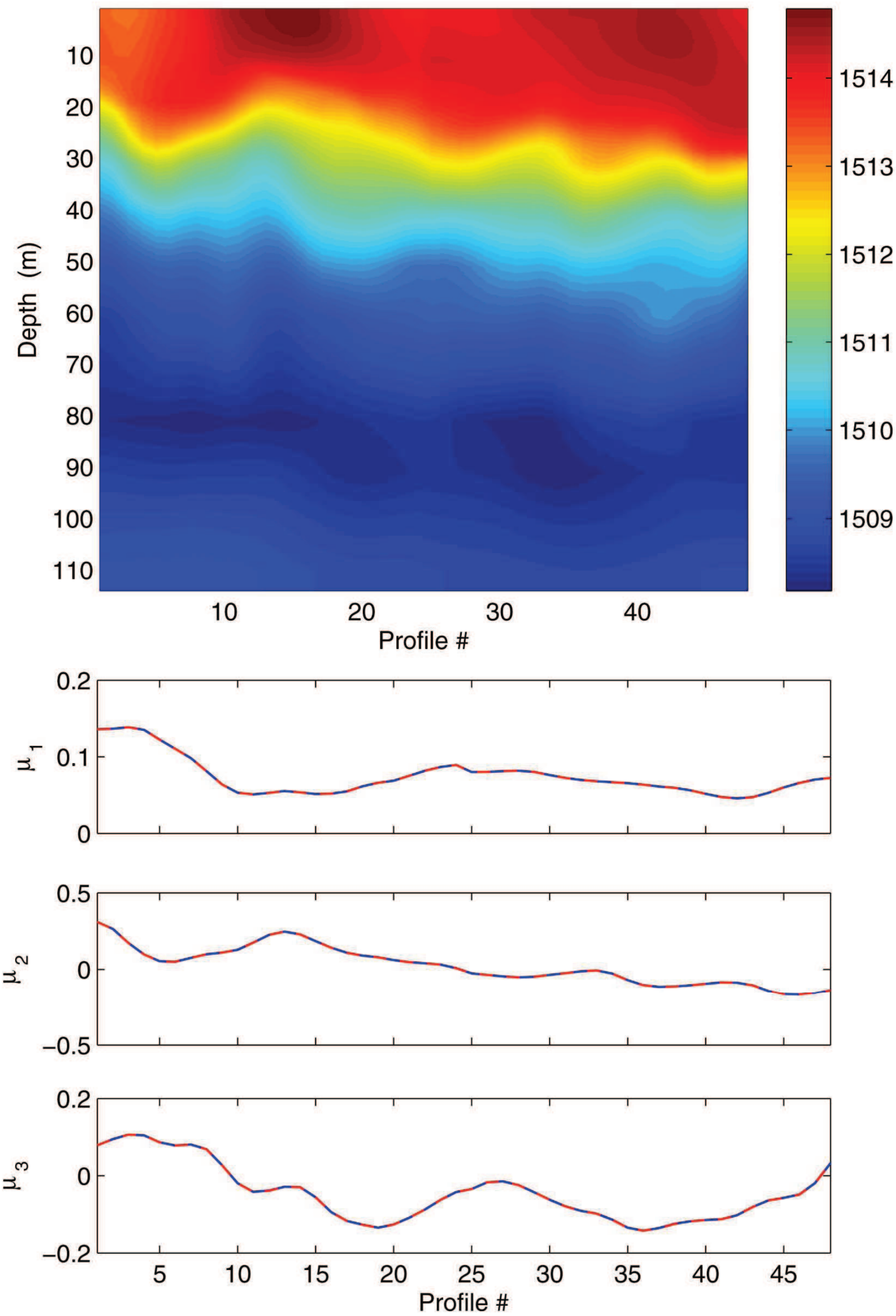

Figure 11. Temporal variability of the range-average sound speed profiles over a 2-day period (1 hr intervals starting on April 28, 2007 at 00:00h) along the MREA/BP'07 transect. Top: the NCOM predictions. Bottom: the evolution of the 3 EOF weighting functions (red dashed lines show the inversion results, blue lines the reconstructions based on the NCOM predictions). Note the afternoon effect in the upper plot and the excellent agreement in the lower plot.

Conclusions

This paper gives an overview of a 6-year RNLNC research effort into the subject of REA in shallow water areas. The research focused on demonstrating a REA concept, based on a sparse set of receivers, the use of both a controlled sound source and sources of opportunity (such as passing surface ships), and a number of optimisation schemes, based on global search and adjoint modelling. This scheme yields water column and bottom properties in an iterative process (for ocean acoustic tomography and geoacoustic inversion, respectively), with a parameter search based on the underlying physics of the acoustic waveguide for minimized computational load (the adjoint-based approach). The REA concept investigated in this work is suitable for covert operations.

In order to validate the REA inversion approach the RNLNC has participated in two recent sea trials, Saba'06 and MREA/BP'07. Onboard near real-time processing demonstrated the capability of this concept. Both trials have resulted in high-quality and well-documented data sets. The MREA/BP'07 trial was designed for Battlefield Preparation and demonstrated that a combination of in situ measurements, remote sensing and modelling could provide the operational commander with a Recognized Environmental Picture in support of Anti-Submarine Warfare or Amphibious Operations.

A discussion on segmentation should follow the acoustic patch concept put forward in the MREA/BP'07 cruise report: after the hydrographic survey with a ship or an AUV range-independent geoacoustic inversion will be done for patches of the operational area. Separating the full spatial domain into smaller patches requires further research.

Already, the research team has produced a respectable amount of scientific output: journal and conference papers including invited papers and a PhD thesis. A basis for further research in an international context has been created, that could be pursued in the near future.

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