Improved active sonar tactical support by through-the-sensor estimation of acoustic seabed properties

Robbert van Vossen, Ellen Johanne Eidem, Sven Ivansson, Bruno Chalindar, Johnny Dybedal, Mathieu E. G. D. Colin, Frank P. A. Benders, Brodd Leif Andersson, Bénédicte Juhel, Xavier Cristol, Geir-Kyrre Olsen, Jörgen N. B. Pihl, Elling Tveit, Stéphane Jespers, Michael A. Ainslie

Abstract

Accurate environmental information is required for obtaining confident sonar performance predictions. This environmental information is, however, often unreliable or unavailable. To support anti-submarine warfare (ASW) operations, a through-the-sensor approach has been developed in which relevant acoustic seabed properties are derived from reverberation data, and a demonstrator system has been installed on a Royal Norwegian Navy frigate. It determines relevant acoustic seabed parameters from the reverberation data near real-time. This demonstrator system has been validated in several sea trials conducted off the coast of Bergen in Norway. The acoustic seabed parameters derived in these trials have a good correspondence with the available prior information. Furthermore, the results show that acoustic seabed parameters derived from reverberation data in previous trials can be used to improve reverberation prediction for subsequent trials, even when environmental conditions, i.e. sound-speed profiles, are different. Because the demonstrator makes information on acoustic seabed properties directly available for in-situ sonar performance prediction, it can be used as a tactical decision aid.

R. van Vossen, M.E.G.D. Colin, M.A. Ainslie, and F.P.A. Benders are with TNO, The Hague, The Netherlands, e-mail: robbert.vanvossen@tno.nl

E.J. Eidem and E. Tveit are with the Norwegian Defence Research Establishment (FFI), Horten, Norway

S. Ivansson, B.L. Andersson and J. Pihl are with FOI, Stockholm, Sweden

B. Juhel, X. Cristol and B. Chalindar are with Thales Underwater Systems, Sophia Antipolis, France

G.K. Olssen and J. Dybedal are with Kongsberg Defence Systems, Trondheim, Norway

S. Jespers is with DGA, Paris, France

Manuscript received November 17, 2012; revised Month DD, YYYY.

Index Terms

sonar, modeling, performance prediction, geo-acoustic inversion, anti-submarine warfare, tactical decision aid, reverberation

I. INTRODUCTION

Environmental conditions, including bathymetry, sound speed profiles, wind speed, and seabed morphology, have a critical influence on the performance of low-frequency active sonar (LFAS) systems deployed to support anti-submarine warfare (ASW) operations [1]. As a consequence, the performance of these sonar systems may show significant variations, and prediction tools are required to support their deployment [2]. This comprises not only planning prior to a mission, but also on-line adaptation of the deployment, such as changes in depth settings of the sonar system and advice on sonar pulse selection to optimize detection performances. The availability of on-line information on detection ranges is considered to be an essential support for the operator, and should result in more effective and efficient ASW operations. Sonar performance modeling is a key component enabling the sonar performance prediction, and is therefore an important tactical decision aid for operations with LFAS systems.

To be effective as a tactical decision aid, operational sonar performance predictions need to be reliable. Three conditions need to be satisfied:

1) Reliable sonar performance models need to be available.
2) Accurate information on the acoustic environment needs to be available.
3) Operational sonar performance models need to be efficient.

Requirements on reliability of sonar performance models have led to initiatives for the validation of reverberation models in the form of two Reverberation Modeling Workshops sponsored by the Office of Naval Research (ONR) held at the University of Texas at Austin in November 2006 and May 2008 [3]–[5], and for the Validation of Sonar Performance Assessment Tools workshop held in memory of David E. Weston at the University of Cambridge (UK) in April 2010 [6], henceforth referred to as the Weston Memorial workshop. The objective of these workshops was to define benchmark solutions for reverberation and sonar performance modeling to aid the validation of operational sonar performance models. Benchmark solutions for sonar performance in a Pekeris waveguide are presented by Ainslie et al. [7], [8].

The acoustic environment comprises the bathymetry, the sound speed field in the water column, the conditions at the sea-surface, and the geoacoustic parameters of the seabed. Because of their influence on the sonar performance, there have been substantial efforts in the context of Maritime Rapid Environmental Assessment (MREA) to measure these parameters and to understand this influence [1], [9]: these factors influence both the propagation of sound in the water column and the scattering at the sea-surface and the seabed. In conditions with an upwards refracting sound speed profile, sea-surface reverberation commonly has a significant influence on the sonar performance. The sea-surface reverberation is caused by rough-surface scattering and by scattering at wind-generated bubbles, and consequently strongly varies with wind speed [10]–[12]. In the case of downward refracting sound speed profiles, both reflection and scattering at the seabed are important processes. These influence both the sea-bottom reverberation and the echo level. Volume reverberation can be relevant in all conditions [13].

Information on bathymetry, wind speed, and sound speed profiles can be obtained by measurements, in contrast to acoustic seabed properties which are more difficult to determine. Information on the seabed properties stored in databases is often not accurate due to uneven data coverage and the data quality is commonly unknown [14]. Echo sounders provide useful information on acoustic seabed properties [15], [16]. It is, however, not straightforward to directly use this information provided by echo sounders to support LFAS operations. Echo sounders only provide information on seabed properties at close ranges representative of large grazing angles, whereas long-range LFAS predictions need information on the scattering and reflection at small grazing angles. In addition, it is difficult to obtain information representative for a large area with an echo sounder during a mission. Furthermore, echo sounder measurements are obtained at high frequencies and therefore have to be extrapolated to LFAS frequencies. Despite the difficulties echo sounders provide useful information on the acoustic seabed properties, mainly due to the absence of other sources of reliable information.

To support reliable LFAS performance prediction, the properties that determine the reflection coefficient and the scattering strength need to be considered. The sediment sound speed, attenuation, and density relevant for the reflection coefficient are usually not well constrained by direct measurements. Information on these quantities is often derived by using their correlation with grain size [17], [18]. This procedure is also used to extrapolate the echo sounder observations to LFAS frequencies [15].

For the scattering strength, the information is scarce. A compilation of measurements for seabed back-scattering strength [19] shows that there is no evidence for a relationship between grain size and scattering strength at LFAS frequencies, i.e. in the frequency regime where the grain size is much smaller than the wavelength. There are several mechanisms causing the scattering, including bathymetric slope, rough surfaces and subsurface structures [20]:

- roughness on grossly different length scales [21];

- buried shell fragments and gravel [22], [23];
- pockets of trapped gas [24];
- the existence of a sound speed gradient within the sediment layer [25].

Chotiros [19] indicated that variations in the back-scattering strength are significantly larger than 5 dB in the angle regime relevant to LFAS, even if the grain size is known.

An additional complexity is that it is hard to measure the scattering strength directly at small grazing angles relevant to LFAS, especially in shallow water with multipath propagation. For this reason, model-based approaches are commonly used to derive the scattering strength from reverberation data [26]–[37]. In the model-based approaches, reverberation measurements are compared to model predictions. By optimizing the match between the measured reverberation data and model predictions, inferences are made about the acoustic seabed properties such as the reflection loss and scattering strength.

Non-uniqueness is an issue in reverberation inversion [38], [39]. Since the objective of reverberation inversion is to improve the reliability of sonar performance prediction, it is especially important that reflection loss can be separated from seabed scattering strength. While scattering influences the reverberation level, the reflection changes both the reverberation and echo level. A trade-off between scattering strength and reflection loss thus directly results in uncertainty in sonar performance predictions.

Several procedures have been proposed to better constrain the acoustic seabed parameters. Additional information on seabed properties can be acquired by altering the vertical directivity of multi-ring transducers or triplet receiver arrays [38]. Furthermore, for dual-tow systems, short-range propagation data can be used to provide additional constraints on the seabed reflection coefficient, and can be inverted in combination with reverberation data to determine both the reflection and the scattering at the seabed [40], [41].

In this paper, reverberation inversion is applied to data acquired by an operational LFAS system installed on a Royal Norwegian Navy frigate, and inversion is considered in the 1-2 kHz frequency range. The estimates of the seabed parameters are obtained near real-time with a demonstrator system. Because of real-time requirements imposed on the inversion, the short-range propagation data are not included in the inversion. To ensure that both the reflection coefficient and scattering strength are resolved independently, a simple parameterization has been chosen for the seabed: it is assumed that the scattering strength satisfies Lambert's law, and the seabed is parameterized as a half-space, with sediment sound speed and sediment attenuation as parameters.

The main objective of the estimation of the acoustic seabed properties is their usage for improving the reliability of sonar performance predictions. This procedure is evaluated using data acquired in two trials conducted in June and October 2010 in the Northern North Sea off the coast of Bergen, Norway:

- The inversion results are compared to prior information, consisting of grab samples, gravity cores, and extensive single-beam echo sounder survey data [16], [42].
- The seabed properties derived from reverberation data acquired in June 2010 (referred to as Sea Trial 2) are then used to predict the reverberation measured in October 2010 (referred to as Sea Trial 4).

The outline of this paper is as follows. Section II discusses the sensitivity of reverberation and signal-to-background ratio to the relevant acoustic seabed parameters. The inversion approach is detailed in Section III, and the sea trials are described in Section IV. Section V discusses the inversion results obtained on data acquired in Sea Trial 2 (ST2), and includes the comparison with prior information obtained from gravity cores, grab samples, and extensive echo sounder surveys. In Section VI, ST2 data are compared to Sea Trial 4 (ST4) data, and Section VII presents results on the reverberation prediction of ST4 reverberation data. In Section VIII, the results are discussed, and the conclusions are given in Section IX.

II. Sensitivity of seabed reverberation and signal-to-background ratio to acoustic seabed properties

In this section, expressions for seabed reverberation and background level are derived for a monostatic source-receiver geometry. These are subsequently used to illustrate the sensitivity of sonar performance to acoustic seabed parameters. As a result of this sensitivity, it is required to reduce the uncertainty in these parameters to enhance the reliability of sonar performance predictions.

The derivation given here is based on [20] with minor modifications such that definitions are consistent with [43]. Reverberation generated by an omnidirectional transducer, denoted Q^{R}, can be expressed as:

$$Q^{\mathrm{R}}(t) = S_0 \int_0^{\pi/2} \mathrm{d}\theta_{\mathrm{in}} \int_0^{\pi/2} \mathrm{d}\theta_{\mathrm{out}}\ G_{\mathrm{Tx}}\left(r, \theta_{\mathrm{in}}\right) S\left(\theta_{\mathrm{in}}, \theta_{\mathrm{out}}\right) A\left(t\right) G_{\mathrm{Rx}}\left(r, \theta_{\mathrm{out}}\right), \tag{1}$$

where θ_{in} and θ_{out} denote the grazing angles corresponding to the incident and back-scattered waves at the seabed, respectively; $G_{\mathrm{Tx}}\left(r, \theta\right)$ is the propagation factor between transducer and seabed at position r for the ray incident at angle θ at the seabed at range r; $G_{\mathrm{Rx}}\left(r, \theta\right)$ denotes the propagation factor between the receiver and seabed at range r for the ray back-scatterd at angle θ at the seabed at range r, and S_0 is the source factor; The source level $\mathrm{SL} = 10 \log_{10} S_0$ dB re $\mu\mathrm{Pa}^2\mathrm{m}^2$.

The seabed scattering coefficient is denoted by $S\left(\theta_{\mathrm{in}}, \theta_{\mathrm{out}}\right)$. It is assumed that the scattering satisfies Lambert's law:

$$S\left(\theta_{\mathrm{in}}, \theta_{\mathrm{out}}\right) = \mu \sin\theta_{\mathrm{in}} \sin\theta_{\mathrm{out}}, \tag{2}$$

where μ is the Lambert parameter.

The area term contributing to the reverberation at time t is denoted by $A(t)$. Assuming that the scattered paths that contribute to reverberation at a given time t originate from a scattering annulus at a distance $r(t)$ from the source,

$$r(t) = \frac{c}{2}t \tag{3}$$

whose width δr is determined by the pulse duration T:

$$\delta r(t) = \frac{c}{2}T, \tag{4}$$

the area term is related to the time t, the sound speed c, and pulse duration T according to

$$A(t) \approx 2\pi r \delta r = \frac{\pi c^2 T}{2} t. \tag{5}$$

In equation 5, it is assumed that the grazing angles are small.

Equation 1 needs to be generalized to model in-beam reverberation recorded by operational LFAS systems. Both matched filtering and the source and receiver beam patterns need to be included. The effect of matched filtering can be incorporated by changing the pulse duration in equation 5. Instead of using the actual pulse duration of the transmit signal T, the range-resolution cell size can be used to include the matched filter, i.e. $T = 1/\mathrm{BW}$, where BW denotes the bandwidth of the received signal.

To incorporate the beam pattern, both horizontal and vertical beam patterns need to be considered. The vertical beampattern is important for multi-ring transducers and for triplet receiver arrays. The vertical source and receiver beampatterns can be incorporated in the propagation factors. The modified propagation factors are denoted by $G'_{\mathrm{Tx}}(r,\theta)$ and $G'_{\mathrm{Rx}}(r,\theta)$. Assuming horizontally isotropic reverberation, the horizontal triplet beam pattern can be incorporated by modifying the area term:

$$A^{\mathrm{BF}}(t) = \frac{A(t)}{2\pi} \int_0^{2\pi} \mathrm{d}\phi \; B(\phi|\phi^{\mathrm{s}}), \tag{6}$$

where $A^{\mathrm{BF}}(t)$ is the azimuthal beam pattern, and $B(\phi|\phi^{\mathrm{s}})$ is the beam pattern of the triplet array for the chosen steering angle ϕ^{s} [44], [45]. Thus, the reverberation obtained after beamforming and matched filtering can be expressed in a similar form as equation 1:

$$Q^{\mathrm{R_{out}}}(t) = S_0 \int_0^{\pi/2} \mathrm{d}\theta_{\mathrm{in}} \int_0^{\pi/2} \mathrm{d}\theta_{\mathrm{out}} \; G'_{\mathrm{Tx}}(r,\theta_{\mathrm{in}})\, S(\theta_{\mathrm{in}},\theta_{\mathrm{out}})\, A^{\mathrm{BF}}(t)\, G'_{\mathrm{Rx}}(r,\theta_{\mathrm{out}})\,. \tag{7}$$

The corresponding reverberation level RL is defined as:

$$\mathrm{RL} = 10\log_{10}\; Q^{\mathrm{R_{out}}} \;\mathrm{dB\ re}\ \mu\mathrm{Pa}^2. \tag{8}$$

In data-model comparisons, both reverberation and ambient noise contributions need to be considered. These are combined in the background level BL:

$$\mathrm{BL} = 10\log_{10}\left[Q^{\mathrm{R_{out}}}(t) + Q^{\mathrm{N_{out}}}\right] \ \text{dB re } \mu\mathrm{Pa}^2, \tag{9}$$

where $Q^{\mathrm{N_{out}}}$ is the mean-square pressures of the ambient noise after beamforming and matched filtering.

For sonar performance prediction, the interest is in the signal-to-background ratio SBR,

$$\mathrm{SBR} = \mathrm{S} - \mathrm{BL}, \tag{10}$$

where S denotes the signal level. It is determined by the source level, the propagation to the target, the target strength, and the propagation back to the receiver array.

The sensitivity to acoustic seabed parameters is illustrated using Problem A2.I of the Weston Memorial workshop [18], [46]. This problem concerns the SBR in a Pekeris waveguide with 100 m water depth and a sandy seabed with Lambert scattering. Full details on the problem and the analytical solution for the SBR is derived by Ainslie et al. [8].

Figure 1 shows the signal-to-background ratio (SBR) for three different values of the Lambert parameter, namely -32 dB, -27 dB, and -22 dB. As detailed in Harrison [47], the signal-to-background ratio tends to decrease with range at ranges smaller than a few km ($<$ 5 km). At intermediate ranges, there is a regime where the SBR is independent of range, i.e. the SBR is nearly constant in the range window between 5 and 25 km, and the sonar performance is reverberation limited. At longer ranges, the signal-to-background ratio further decreases. At these ranges, the performance is noise limited. In the reverberation-limited conditions, there is a large sensitivity to variations in the Lambert parameter. A change in the Lambert parameter results in an identical change in the SBR (equations 1 to 10) in reverberation limited conditions. Assuming a detection threshold of 12 dB, the detection range is determined by the intersection of the signal-to-background ratio curve and the detection threshold. This directly shows that a variation of $\pm$ 5 dB in the Lambert parameter has a significant effect on the detection range. For a Lambert parameter of -22 dB, the detection range would be 1.5 km, whereas for -32 dB, it is 37 km. The effect is large in this example because of the switch from noise-limited to reverberation-limited conditions. The influence of the reflection coefficient at the seabed is more complicated since this influences both the signal level and the reverberation. A first-order effect is that the reflection coefficient at the seabed controls the range at which the transition occurs from reverberation-limited conditions to noise-limited conditions.

The sensitivity to the seabed parameters will not always be as large as presented in this example. It depends on the environmental conditions such as the water depth and the sound speed profile. Because of

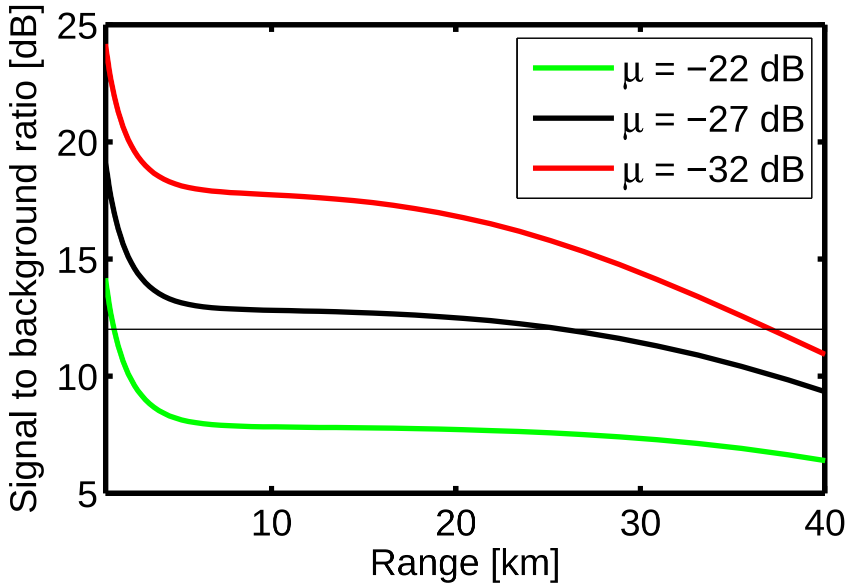

Fig. 1. Signal to total background ratio for Sonar Performance Modelling Workshop scenario A2.1 for different values of the Lambert parameter. The detection range is evaluated by assuming a detection threshold of 12 dB.

the sensitivity of sonar performance to environmental conditions, it is essential to make predictions based on accurate input, and a through-the-sensor reverberation inversion approach that determines acoustic seabed parameters is considered to be an important aid. The reverberation inversion procedure is explained in the following section.

III. Inversion Procedure

In the inversion, it is assumed that seabed reverberation dominates surface and volume reverberation. The background level in the port and starboard broadside beam is used to infer information on acoustic seabed properties. These properties are the Lambert parameter μ for the scattering at the seabed and the parameters determining the reflection coefficient or reflection loss at the seabed. The seabed is parameterized as a half-space, with sediment sound speed c_{sed}, sediment attenuation α_{sed}, and sediment density ρ_{sed} as parameters to be resolved [48]. The number of degrees of freedom are further reduced by assuming that the density is related to the sediment sound speed according to Bachman's formula [49]:

$$\rho(c_{\text{sed}}) = \left[-11.393 + 0.013778 \, \frac{c_{\text{sed}}}{1 \text{ m/s}} - 3.5162 \times 10^{-6} \frac{c_{\text{sed}}^2}{1 \text{ m}^2/\text{s}^2} \right] \times 10^3 \text{ kg/m}^3 \tag{11}$$

The remaining degrees of freedom are the Lambert parameter μ, the sediment sound speed c_{sed} and the sediment attenuation α_{sed}, respectively. The inversion is carried out in a range-independent mode.

To determine these parameters, the inversion procedure illustrated in Figure 2 is used. The procedure consists of the following steps:

- First, values for c_{sed}, α_{sed}, and ρ_{sed} are selected, and the reverberation level is modeled for the Port or Starboard beam.
- The measured and modeled reverberation data are smoothed by applying a moving average filter with 0.18 s length.
- The Lambert parameter is estimated in a time window between 1 and 2.2 s. It is determined by matching the average modeled reverberation level to the measured one.
- The modeled reverberation is updated by using the estimate for the Lambert parameter and the noise level NL is added to the modeled reverberation.
- The data fit is evaluated in the time window between 1 and 10 s. It is the mean difference expressed in decibels.
- Based on this data fit, new values for c_{sed} and α_{sed} are selected by using a genetic algorithm. In total, 5 iterations with a population size of 64 are used to satisfy near real-time constraints. By analysing the data fit, it has been verified that sufficient convergence is achieved with these settings. The average difference between the model prediction with the best data fit and the reverberation measurements is generally smaller than 1 dB in the time window between 1 and 10 s (e.g. Figure 3).

The sensitivity to the forward model is investigated by repeating the inversion for different forward models, namely ALMOST-REACT [50], LYBIN [51], [52], REV3D [53], [54], and TAMAR [55]. The analysis revealed that there are no significant differences in the inversion results obtained with the different forward models. This conclusion is supported by a comparison of the different forward models using ONR benchmark cases Problem XI and XII [3]–[5]. For incoherent solutions, differences between the models are smaller than 1-2 dB. For coherent solutions, differences are generally smaller than 3 dB, except for the caustic peaks [56]. In the remainder of this paper, results are presented that are obtained with REV3D. This model was chosen for the demonstrator system which was implemented on board the Royal Norwegian Navy (RNoN) frigate.

Before applying the inversion approach to measured reverberation data, tests have been conducted on synthetic data. For this purpose, the reverberation benchmark problems XI and XII [3]–[5] have been used. These tests confirmed that the Lambert parameter and the shallow-angle reflection coefficient at the seabed could be determined. However, sediment attenuation and sediment sound speed, that determine the angle-dependent reflection coefficient, cannot be fully resolved independently. This is illustrated in

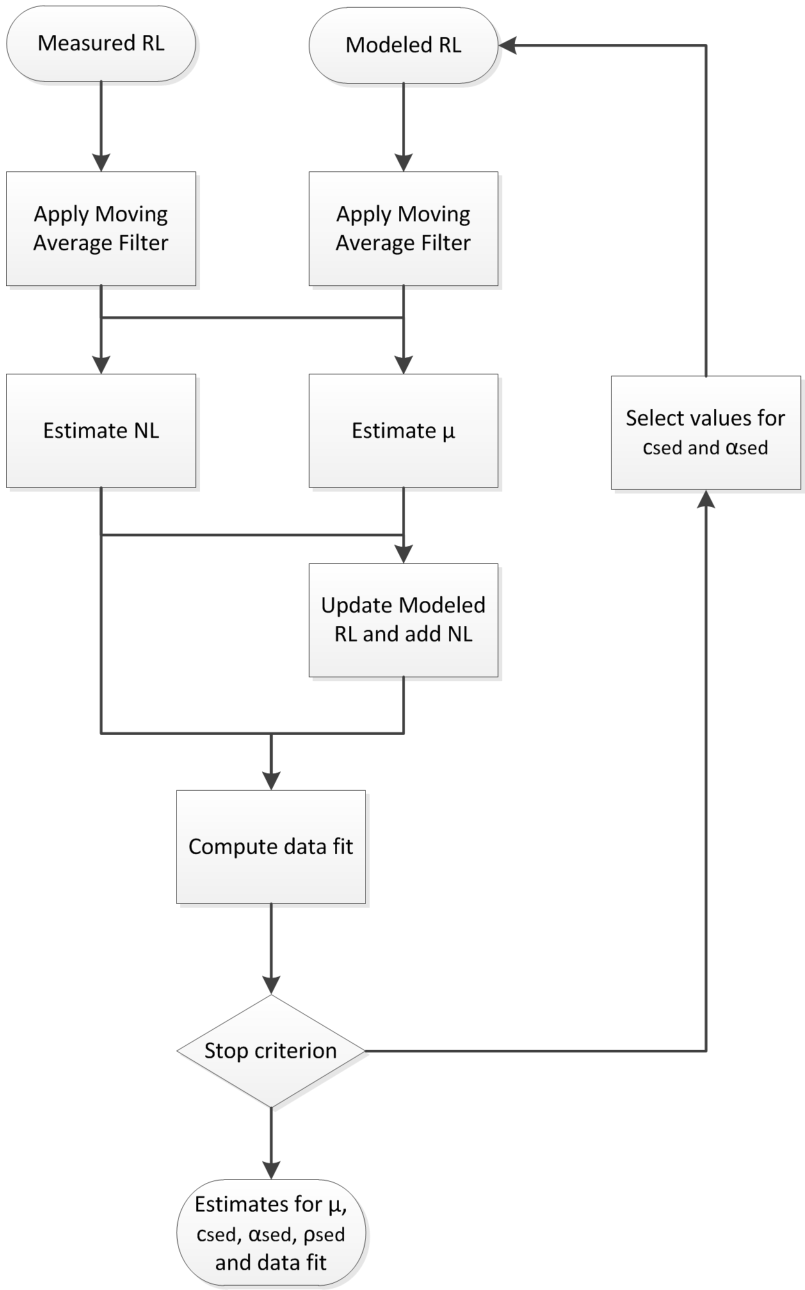

Fig. 2. Flow diagram for inversion procedure.

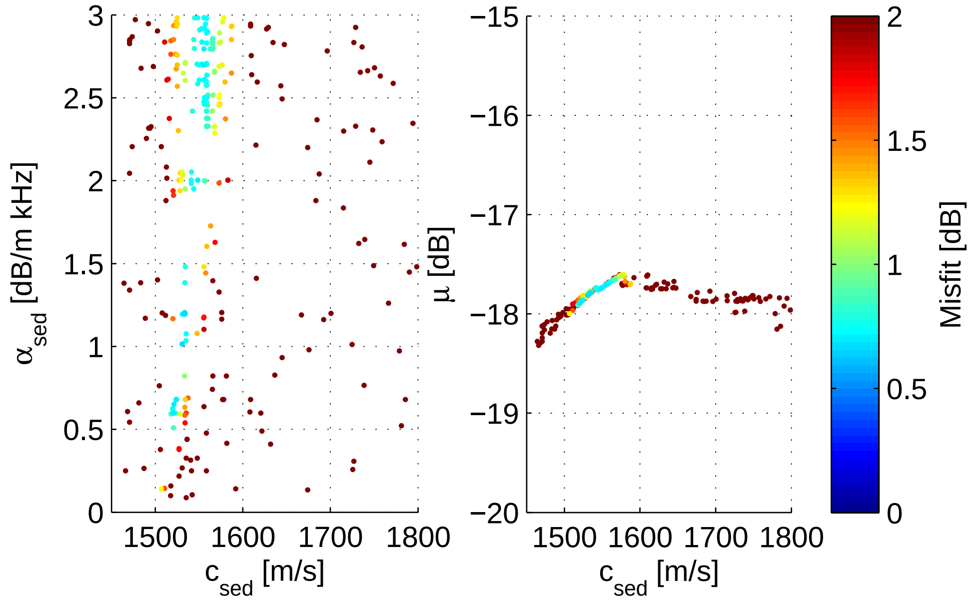

Fig. 3. Misfit corresponding to the samples of the genetic algorithm for sediment sound speed, sediment attenuation, and the Lambert parameter, applied to one ping of reverberation data (starboard) acquired at the start of ST2, day 2.

Figure 3. If one connects all results with a low misfit, i.e. the blue dots in Figure 3, it can be observed that the slope is resolved. This indicates that the ratio between sediment sound speed and sediment attenuation, and consequently the reflection coefficient at small grazing angles, is resolved.

Additional tests were conducted to study the influence of the half-space assumption in the inversion procedure [57]. Synthetic data were generated in a model with a layered seabed. The inversion results revealed that this does not influence the results for the Lambert parameter and that effective parameters are obtained for the sediment sound speed and the sediment attenuation. Specifically, at small grazing angles representative for LFAS, the reflection coefficients obtained by using a layered seabed [48] and a half-space, respectively, are very similar.

IV. Rumble-2 Sea Trials

A trial campaign consisting of four trials was organised to evaluate the demonstrator. In this paper, the focus is on Rumble-2 Sea Trial 2 (ST2) and Sea Trial 4 (ST4). Both trials were conducted in the Royal Norwegian Navy's exercise area in the Northern North Sea, off the coast of Bergen. The trial area is relatively flat with water depth between 260 and 320 m (Figure 4). These trials are of special interest since they were executed in different environmental conditions, i.e. with different sound speed profiles

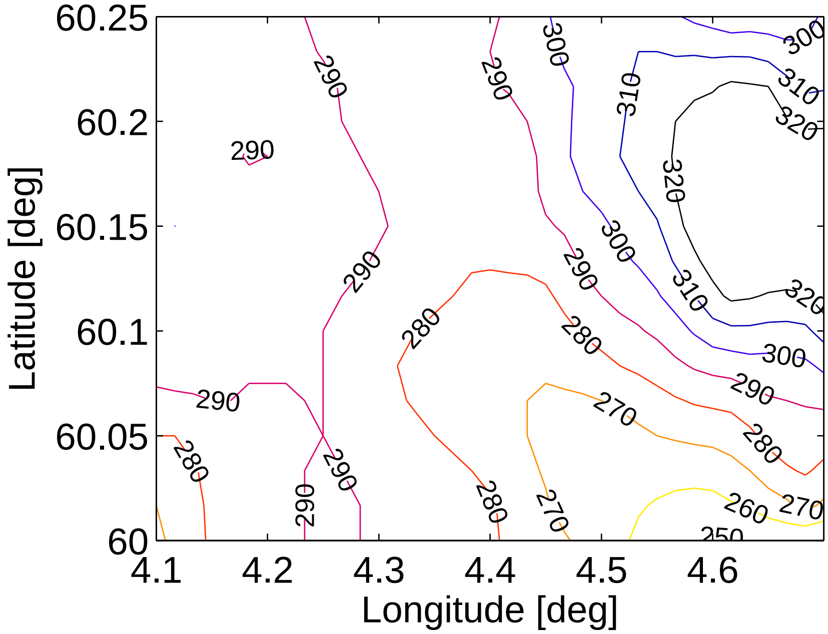

Fig. 4. Bathymetry in the trial area with depth contours in meters.

and surface conditions:

- ST2 was conducted in June 2010 in calm weather conditions (sea state 1-2). Sensitivity tests were carried out using the data acquired during the first day. In this paper, we consider data acquired during the second and third day, comprising approximately 1000 pings.
- ST4 took place at the end of October 2010 in rough weather conditions (sea state 5). Roughly 700 pings are analysed from this trial, acquired during 2 days.

During ST2, in total 18 sound speed profiles are measured, comprising 15 Expendable Bathy Thermograph (XBT) probes and 3 Expendable Sound Velocity (XSV) probes. A salinity of 35 psu is used to compute the sound speed profiles shown in Figure 5. The sound speed profile of ST2 has a channel with axis at 50 m depth. Below the channel, the profile is mildly downward refracting. The sound speed profiles for ST4 are derived from two XBT measurements and one Expendable Conductivity-Temperature Depth (XCTD) measurement. These profiles show more variability with location, presumably due to the presence of fresh water from the fjords. The depth of the thermocline varies in the range between 50 and 100 m. In comparison to ST2, the ST4 profiles are more strongly downward refracting. In ST2, the transducer and receiver array are positioned approximately at 115 m depth. In ST4, the depth is 90 m.

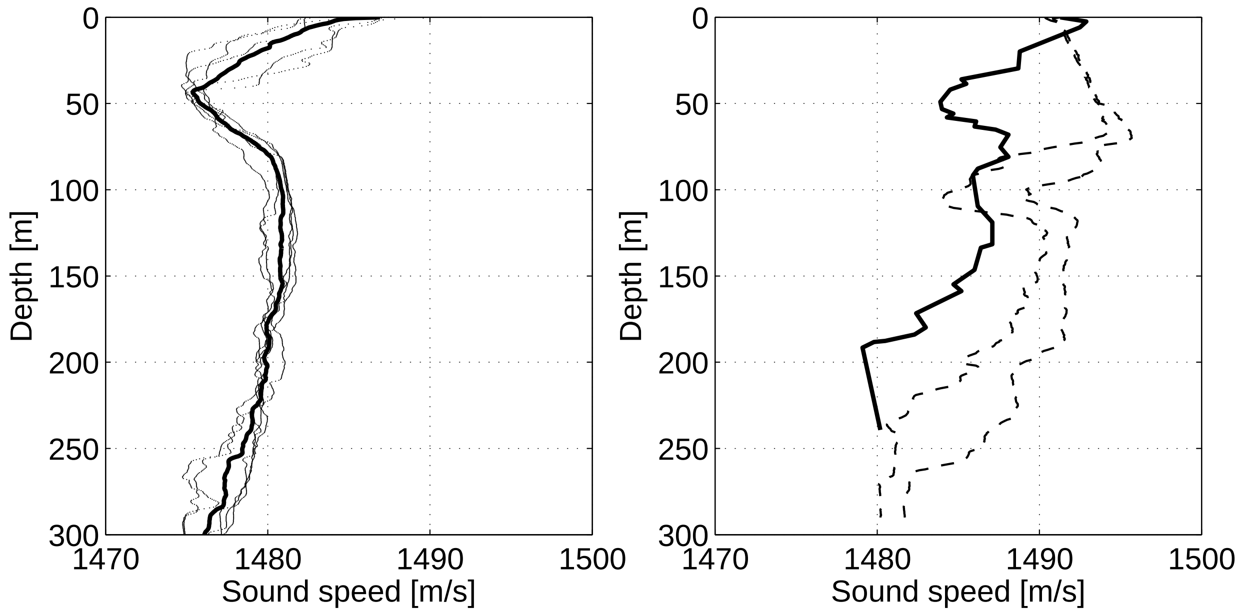

Fig. 5. Sound speed profiles measured during ST2 (left) and ST4 (right); The thick solid line indicates the average ST2 profile used for the reverberation inversion for ST2; For ST4, the thick solid line is the profile measured by the XCTD, and is used in the inversion of ST4 reverberation data. In ST2, the source and receiver depth is approximately 115 m, in ST4, it is roughly 90 m.

Information on the seabed properties in the trial area is available from gravity cores, grab samples, and extensive echo sounder single-beam back-scatter measurements. These measurements have been processed and interpreted to obtain a map indicating the classification of the seabed [16], [42]. The Folk classification system [58] was used to classify gravity cores and grab samples from the Bergen area with less than 2 % gravel. A modified version was used for bottom samples with more than 2 % gravel.

In the trial area, the most important seabed types can be divided into three classes (Figure 6):

- Mainly sand with a mixture of clay, silt and gravel,
- Mainly silt with some clay,
- Mainly clay with some silt and varying amounts minor sand. The bottom sample taken in this area contained 4 % sand.

The area with mainly sand is located in the south-eastern part of the area, and the western part of the area is mainly silt. The north-eastern part of the area is more complicated involving different seabed types, including mainly silt and mainly clay.

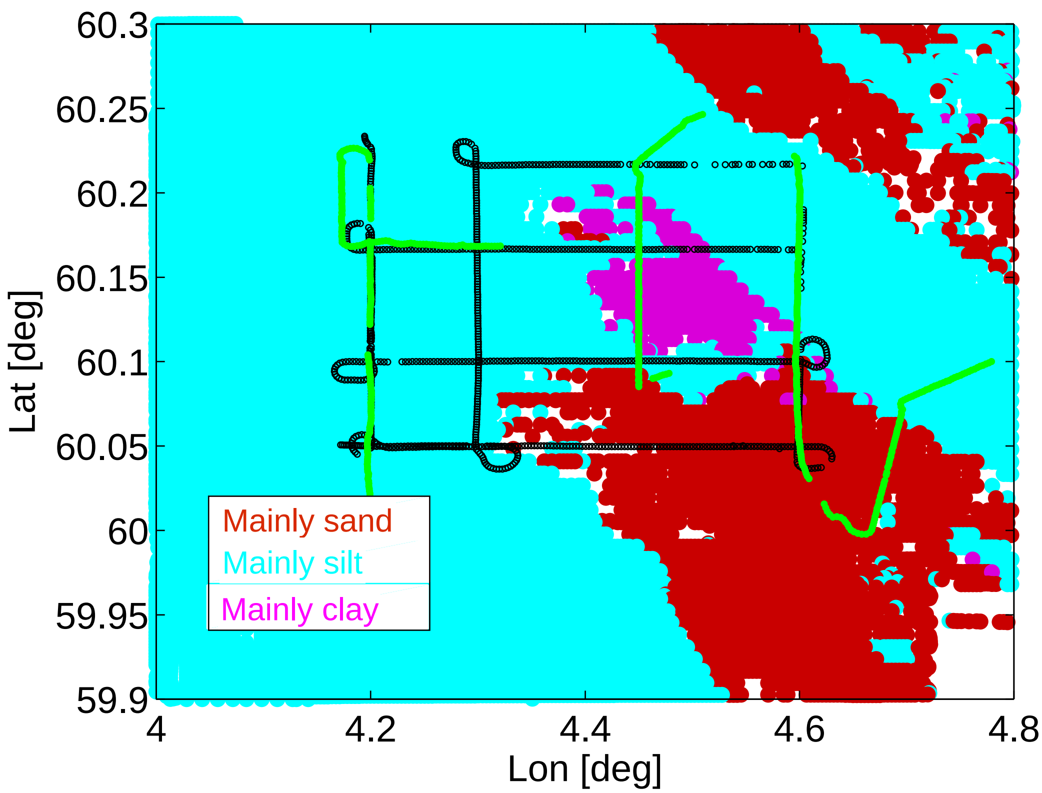

Fig. 6. Seabed types in the trial area. The red area denotes the area with mainly sand, the cyan area is mainly silt, and the purple area is mainly clay, respectively. The tracks sailed during ST2 and ST4 are indicated in black and green, respectively.

V. Results for Sea Trial 2: Comparison to Prior Information

In this section, the relation between the prior information and the estimates derived from low-frequency reverberation data is discussed. This is investigated for the Lambert parameter and the reflection coefficient at 7 degrees grazing angle (R7) using the reverberation measurements acquired in ST2. Due to nonuniqueness in the reverberation inversion, the sediment sound speed and attenuation cannot be resolved simultaneously [41]. The combination of these parameters is constrained, and gives the reflection coefficient at a fixed angle. The reflection coefficient at low grazing angles is most relevant for both long-range reverberation and propagation. Results are therefore presented for the reflection coefficient at 7 degrees. This is the grazing angle at the seabed at which rays propagate horizontally at the sea-surface. It corresponds to the largest skip distance in the ST2 sound speed profile.

The data set acquired in ST2 comprises approximately 1000 pings. For these data, the optimisation procedure that is used to determine the acoustic seabed properties yields a good match between modeled and measured reverberation data. The average misfit between the modeled and measured reverberation is generally smaller than 1 dB.

Figures 7 and 8 show sailed tracks and prior information on the seabed types. In addition, the corresponding reverberation data and inversion results for Lambert parameter and R7 are shown for the two legs that are selected. In Figure 7, the prior information indicates the presence of different seabed types at the southern and northern sides of the selected leg. The effect can be observed in the reverberation data. The reverberation decays more rapidly at the northern side where the seabed is composed of mainly silt, as opposed to the southern side, where the seabed is composed of mainly sand. One can observe that the 60 dB contour is at 14 s for the reverberation from the mainly sand area, and at 11 s for the mainly silt area. The different seabed properties are also retrieved in the inversion results. For the mainly sand area, R7 is generally larger than -2 dB, whereas for mainly silt, the maximum values of R7 are close to -2 dB. The inversion results show small differences in the results for the Lambert parameter. A trend is that the Lambert parameter values decrease from east to west, from coarser to finer sediments.

In Figure 8, results are presented for the southernmost east-west leg. Similar to the results shown in Figure 7, the Lambert parameter values decrease from east to west. For the southern side, the prior information, reverberation data, and inversion results for R7 clearly show a clear correlation. For the area with mainly sand, the reverberation decay rate is low, resulting in high values of the reflection coefficient, while lower values are obtained for the areas with mainly silt. The inversion results for R7 obtained for the northern side are higher than those obtained in Figure 7 due to the presence of mainly sand at short ranges.

The results presented so far indicate that there exists a correlation between the inversion results for R7 and the prior information. To further analyse this correlation, the inversion results corresponding to the regions with different seabed classification (Figure 6) are presented as distributions. The distributions of inversion results for the Lambert parameter and the reflection coefficient corresponding to the different seabed types are shown in Figures 9 and 10.

For reflection coefficient R7, there is a clear pattern: high values for the reflection coefficient correspond to the (hard) sandy seabed types, whereas lower values are retrieved for the softer seabed types. For silt, a relatively broad distribution is obtained. The angle 7 degrees may be close to the intromission angle in this case, resulting in a high sensitivity of R7 to small local variations in the sound speed of silt. For clay, the lowest values are obtained. The reverberation inversion results for R7 are thus consistent with the prior information.

There is also a pattern in the Lambert parameter inversion results: the Lambert parameter observed

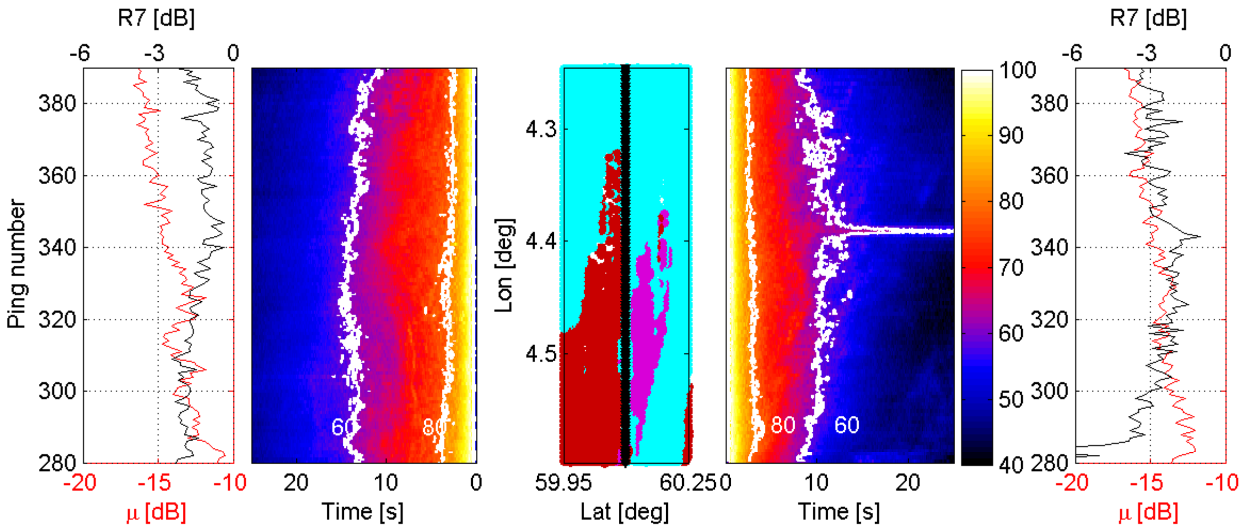

Fig. 7. Sea Trial 2: selected track at 60.10 degrees latitude (black symbols in center panel) and prior information on seabed conditions with areas with mainly sand (red), mainly silt (cyan), and mainly clay (purple), measured reverberation data for southern and northern sides, and inversion results for the Lambert parameter and the reflection coefficient at 7 degrees.

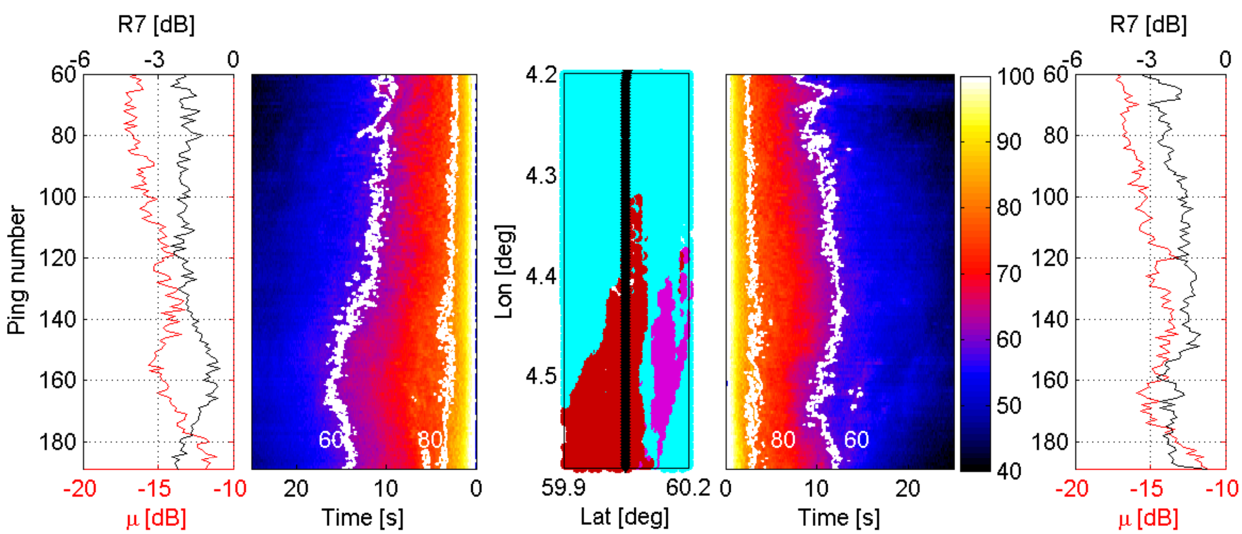

Fig. 8. Sea Trial 2: selected track at 60.05 degrees latitude (black symbols in center panel) and prior information on seabed conditions with areas with mainly sand (red), mainly silt (cyan), and mainly clay (purple), measured reverberation data for southern and northern sides, and inversion results for the Lambert parameter and the reflection coefficient at 7 degrees.

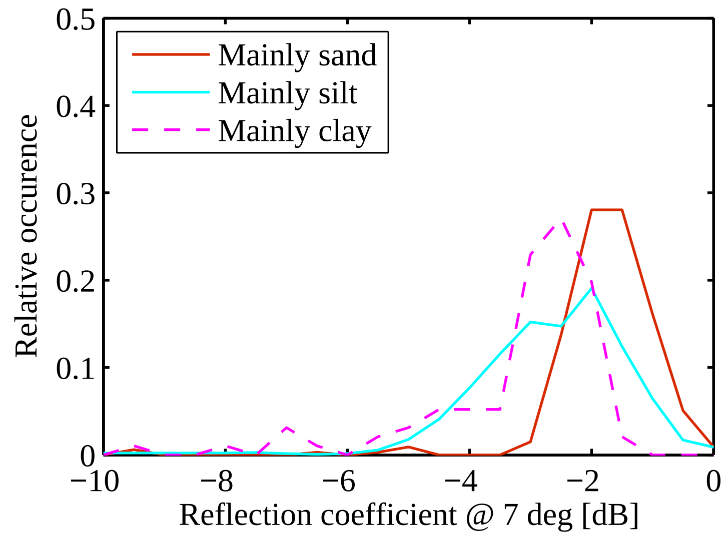

Fig. 9. Distributions of reverberation inversion results for the reflection coefficient at 7 degrees, R7, corresponding to the different seabed types in Figure 6.

for silt is 2-3 dB lower than the virtually coinciding values for the sand and clay. This indicates that there is no direct correlation between grain size, cf. Figure 6, and the scattering of sound at the seabed in the considered frequency range. This is also observed by Chotiros [19]. A possible explanation is that scattering at the seabed is caused by several mechanisms, including seabed roughness and heterogeneity in the seabed [20].

Interpolated maps of the inversion results for R7 and the Lambert parameter are shown in Figures 11 and 12. The map of R7 confirms the correlation with the prior information. The area with mainly sand in Figure 6 can be easily recognized in Figure 11. There is obviously not a perfect correlation between the prior information and the reverberation inversion results. The reason is that the prior information is mainly derived from single-beam echo sounder observations operated at 38 kHz, with higher frequencies and different incident angles than the reverberation data. A smoother map is obtained for the Lambert parameter, which is not correlated to the prior information on the seabed types.

VI. Results for Sea Trial 4: Comparison to Sea Trial 2

ST4 was conducted in different conditions compared to ST2, resulting in different sound speed profiles (Figure 5). In ST4, there is a larger sound-speed drop between sea-surface and seabed, and there is also a larger variability in the measured profiles. In Figures 13 and 14, prior information on the seabed,

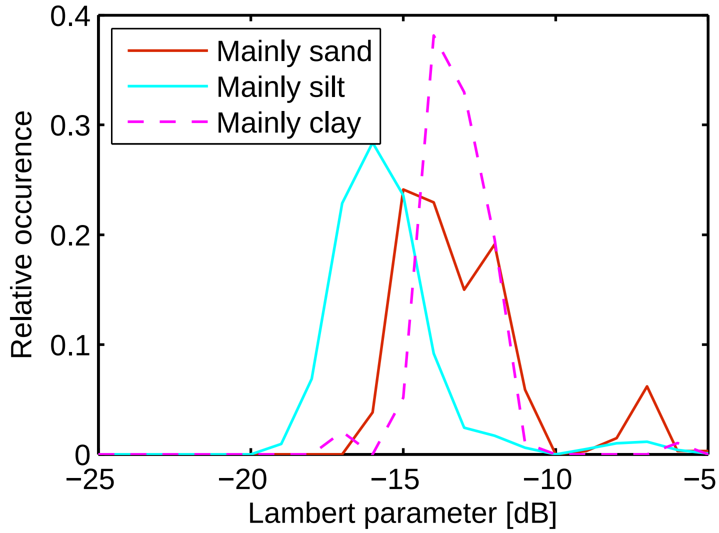

Fig. 10. Distributions of reverberation inversion results for the Lambert parameter corresponding to the different seabed types in Figure 6.

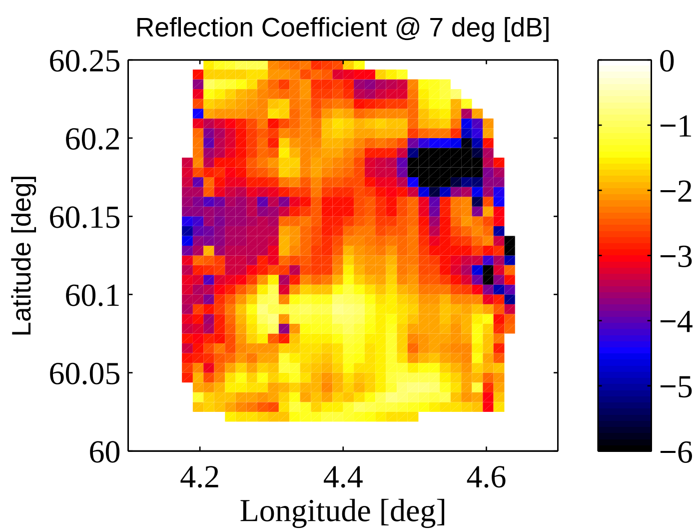

Fig. 11. Map of ST2 inversion results for R7, the reflection coefficient at 7 degrees. The color scale is in dB.

reverberation data, and inversion results are shown for ST2 and ST4 data for the same leg. Because of the larger sound speed drop in ST4, hence larger grazing angles and larger reflection loss at the seabed, the ST4 reverberation data show a larger decay rate compared to ST2. Note as well that both ST2 and ST4 data show significant differences between the eastern and western sides, and that the variability in the reverberation at the eastern side reflects changes in the seabed conditions from sand to silt. Despite

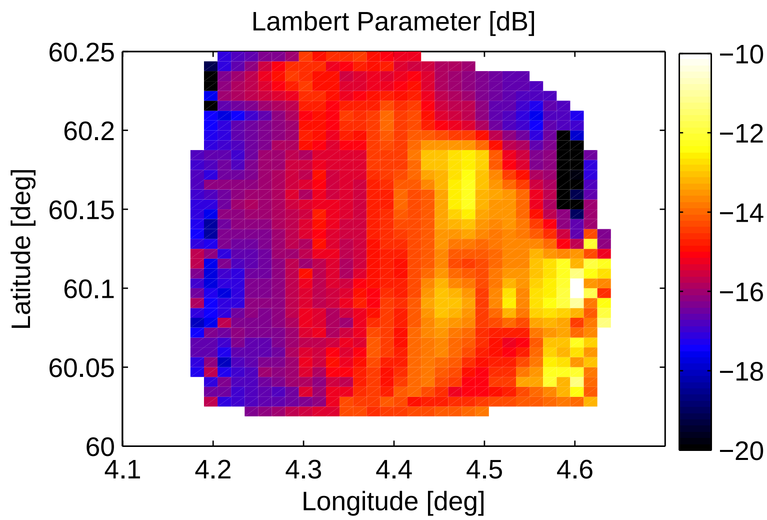

Fig. 12. Map of ST2 inversion results for the Lambert parameter. The color scale is in dB.

the differences in the ST2 and ST4 reverberation data, the inversion results for the Lambert parameter and R7 have similar magnitudes and show similar patterns. For the eastern side, the inversion results for R7 are consistent with the prior information for both ST2 and ST4, and R7 results for the western side are generally higher than for the eastern side. This is also consistent with the prior information, i.e. reflection coefficient for sand should indeed be larger than for silt.

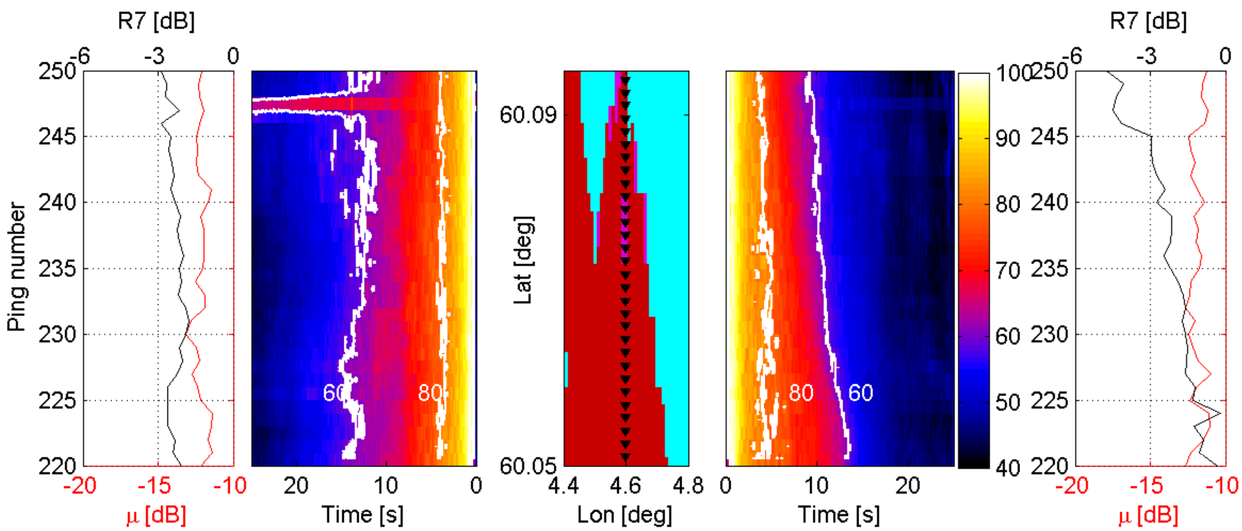

Fig. 13. Sea Trial 2: selected track (black symbols in centre figure) and prior information on seabed conditions with areas with mainly sand (red), mainly silt (cyan), and mainly clay (purple), measured reverberation data for western and eastern sides, and inversion results for the Lambert parameter and the reflection coefficient at 7 degrees. The selected track coincides with ST4 data shown in Figure 14.

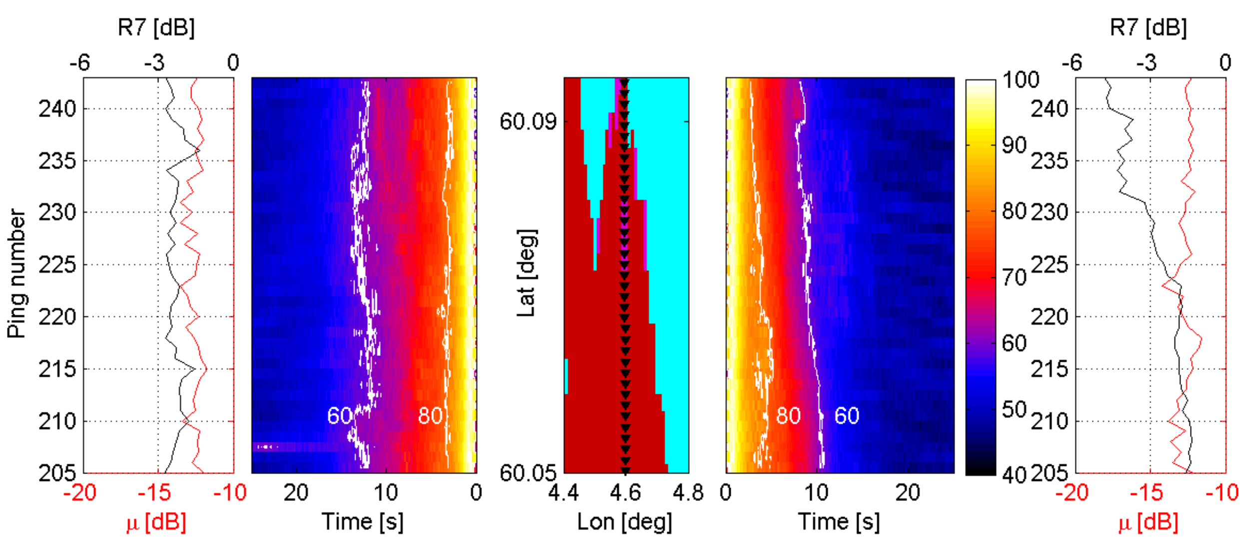

Fig. 14. Sea Trial 4: selected track (black symbols in centre figure) prior information on seabed conditions with areas with mainly sand (red), mainly silt (cyan), and mainly clay (purple), measured reverberation data for western and eastern sides, and inversion results for the Lambert parameter and the reflection coefficient at 7 degrees. The selected track coincides with ST2 data shown in Figure 13.

VII. Prediction of Sea Trial 4 Reverberation Measurements

The objective of the reverberation inversion is to improve the reliability of sonar performance predictions. As a step towards determining the added value for sonar performance prediction, it is investigated whether the real-time reverberation inversion results aid the prediction of reverberation. This test is of interest, since the ST4 reverberation is acquired in conditions with a different sound speed profile. ST2 was conducted in June 2010, and ST4 in October 2010. Furthermore, not all tracks sailed in ST4 coincide with tracks of ST2 (Figure 6). The track at 4.4° E longitude, for example, is perpendicular to the east-west tracks of ST2. For the assessment, the inversion results obtained in ST2 are used for the prediction of the ST4 reverberation. The ST4 reverberation measurements for the port and starboard beams are shown in Figure 15. These ST4 data comprise approximately 700 pings.

For the prediction of the ST4 reverberation, the sound-speed profiles measured during ST4 are used, together with the acoustic seabed properties derived in ST2. The predicted reverberation is then compared to the measured ST4 reverberation. The result is shown in Figure 16. The median difference between predicted and measured reverberation is 2.7 dB.

To determine the benefit of the real-time reverberation inversion, the prediction procedure is repeated without using the ST2 reverberation inversion results. For the prediction, the prior information shown in Figure 6 is used. The corresponding acoustic material properties (Table I) are based on the values listed in Ainslie [20] for the sediment sound speed, sediment attenuation, and sediment density. For the Lambert parameter, -27 dB is used for medium silt and coarse clay [59]. A higher value for the Lambert parameter, -21 dB, is used for the medium sand. This higher value is chosen because the prior information on this area derived from grab samples indicates the presence of gravel in the medium sand area [16].

The comparison between these predictions and the measured reverberation in Figure 17 shows that the discrepancy is larger. The median difference between predicted and measured reverberation is 6.0 dB. Thus, even if accurate information is available on the grain size, it is difficult to accurately predict the reverberation. The differences are not only caused by differences in the Lambert parameter. The comparison of R7 obtained in the reverberation inversion (e.g. Figure 9) to R7 that corresponds to grain sizes listed in Table I shows that the reverberation inversion yields 1-2 dB lower values for R7 for the sand and silt regions. We suspect that this difference has the following explanation: the sediment sound speed and attenuation in Table I are representative for a given grain size. They are, however, not necessarily representative for a layered seabed. Thus, when R7 is computed using a half-space assumption, the listed

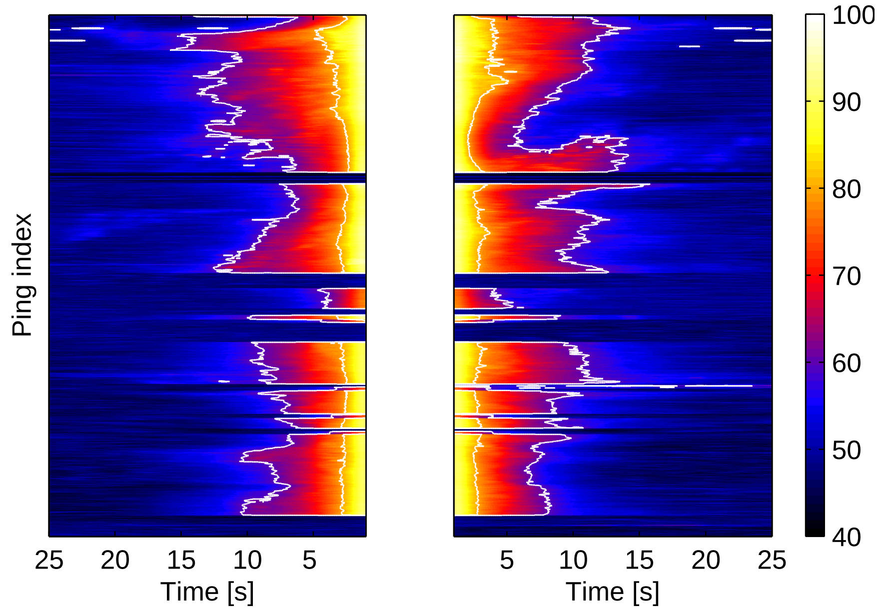

Fig. 15. Waterfall images of ST4 reverberation measurements in the port (left) and starboard (right) beams for the tracks shown in Figure 6, values in dB. Contours are drawn for reverberation levels of 60 and 80 dB.

TABLE I

SEABED TYPES AND CORRESPONDING ACOUSTIC SEABED PROPERTIES USED FOR THE REVERBERATION PREDICTION OF ST4 DATA. THE SYMBOL ϕ REFERS TO THE REPRESENTATIVE GRAIN SIZE, AND c AND ρ DENOTE THE SOUND SPEED AND DENSITY OF THE SEA WATER JUST ABOVE THE SEABED.

Area in map in Figure 6	Seabed type	ϕ	μ [dB]	c_{sed}/c	α_{sed} [dB/λ]	ρ_{sed}/ρ	R7 [dB]
Red	Medium sand	2	-21	1.1752	0.87	2.014	-0.50
Cyan	Medium silt	6	-27	1.0352	0.21	1.555	-0.87
Purple	Coarse clay	9	-27	0.9877	0.08	1.353	-16

values might not be optimum. On the other hand, the parameters obtained in the reverberation inversion are effective parameters for a layered seabed. As a consequence, these cannot be directly related to tabulated material properties for different grain sizes.

VIII. DISCUSSION

The objective of the reverberation inversion is to improve the reliability of sonar performance predictions by using in-situ observations. To be effective as a tactical decision aid, additional checks are required to verify assumptions, for example that seabed reverberation dominates surface and volume

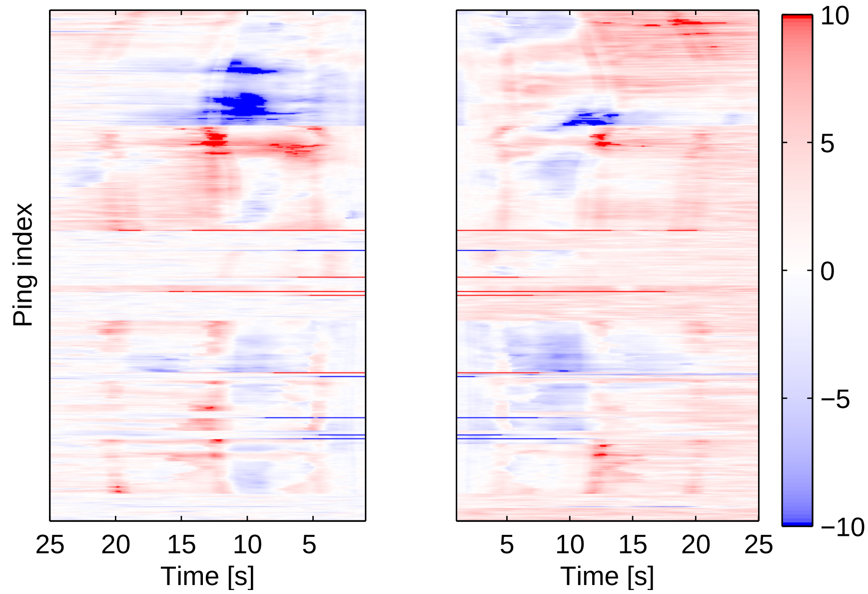

Fig. 16. Waterfall images of the difference between measured reverberation (Figure 15) and predicted ST4 reverberation for the port and starboard beams (in dBs). The predictions are made using the acoustic seabed properties obtained by the reverberation inversion of ST2 reverberation data (cf. Figures 11 and 12).

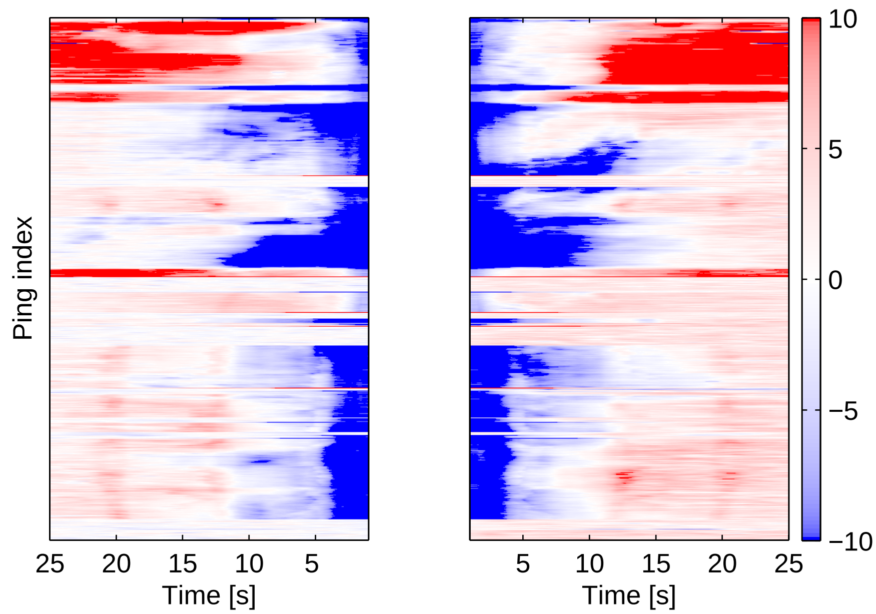

Fig. 17. Waterfall images of the difference between measured reverberation (Figure 15) and predicted ST4 reverberation for the port and starboard beams (in dBs). The predictions are made using the acoustic seabed properties derived from the prior information (see Table I).

reverberation. Otherwise, the use of results obtained from the reverberation inversion may not lead to more effective and efficient ASW operations. We investigated this in more detail for ST2 and ST4. One of the differences between ST2 and ST4 is namely the high sea-state (5) in ST4. Despite this high sea state, bottom reverberation appears to be dominant in ST4 reverberation data. Changes in bottom conditions can be clearly observed in the reverberation data (Figures 13 and 14) and the ST4 reverberation data also shows significant port/starboard differences (Figure 16). Furthermore, ST2 and ST4 inversion results for the seabed parameters show similar trends, and ST2 inversion results for the seabed parameters could be used to predict the ST4 reverberation measurements. It is not well understood why surface reverberation and coherence loss in the sea-surface reflection coefficient have little impact at sea state 5. A possible explanations could be the depth of the transducer and receiver array, roughly 90 m depth, in combination with a downward refracting sound speed profile (Figure 5).

Concerning the inversion results, both the results for the Lambert parameter and the reflection coefficient are of interest, and these may have implications for sonar performance predictions. Commonly, the value of -27 dB is used as reference value for the Lambert parameter. This value is originally stated in a paper published by MacKenzie [59] (Urick [60] attributes the value of -28 dB to MacKenzie [59]). The Lambert parameter values obtained in this study are in line with more recent compilations of back-scattering strength measured at low grazing angles, cf. Gauss et al. [61], Chotiros [19] and Jackson and Richardson [62]. Based on the analysis presented in Section II, it is evident that differences of the order of 8 dB could significantly influence sonar performance predictions. As a result of the significant variability of the back-scattering strength reported in the literature, it is difficult to make confident predictions with tabulated values for the back-scattering strength. A through-the-sensor approach as presented in this paper appears to be a good solution for obtaining reliable information on the scattering strength at the seabed. It should be noted, though, that in a through-the-sensor approach, the calibration of both the sensors and signal processing chain needs to be known.

For the reflection coefficient, there is a clear correlation with the grain size. It is observed that higher values for the reflection coefficient at 7 degrees (R7) are obtained for larger grain sizes. However, we also observe that the values for R7 are 1-2 dB smaller compared to R7 values that are derived from tabulated values of sediment sound speed and attenuation corresponding to medium sand and medium silt [17], [18], as specified in the prior information on the survey area. This suggests that the use of these parameters, in combination with a half-space assumption, could lead to incorrect estimates of propagation loss and reverberation. As an alternative to the half-space assumption, reverberation inversion with a layered seabed and regression relations on grain size for the sediment parameters has been considered [63], [64]. This approach can also benefit from short-range propagation inversion that is applicable in the case of dual-tow LFAS systems [41].

IX. Conclusions

A demonstrator system that estimates relevant acoustic seabed properties using a through-the-sensor approach has been installed on a Royal Norwegian Navy frigate, with the objective of improving the reliability of sonar performance predictions. The performance of this demonstrator system has been evaluated by using data acquired in two sea trials. The trials are conducted in the same area during a different period of the year, i.e. with different sound speed profiles, and are therefore ideally suited to investigate the robustness of developed methodology. Furthermore, prior information on the seabed properties, derived from gravity cores, grab samples, and extensive echo sound surveys, is available.

The comparison between prior information and inversion results for the reflection coefficient at small grazing angles shows a positive correlation. The estimated reflection coefficient increases with grain size derived from grab samples, gravity cores, and extensive single-beam echo sounder surveys. However, it is also observed that the values for the reflection coefficient at 7 degrees (R7) are 1-2 dB smaller compared to values derived from Hamilton-Bachman grain size acoustic seabed properties regression relations. This suggests that the reflection coefficient is overestimated when these material properties are used in combination with a half-space assumption. As a consequence, this could lead to incorrect estimates of the propagation loss and reverberation level. It is also observed that values obtained for the Lambert parameter are significantly higher than those that are generally used as reference values modeling studies. Furthermore, the results also show variability in the Lambert parameter for different seabed types. There is, however, no evidence for a correlation between grain size and scattering strength in the considered frequency range.

While the decay rate is different due to different sound speed profiles, consistent inversion results are obtained on reverberation data acquired in both sea trials. Furthermore, we demonstrated that the inversion results derived in Sea Trial 2 (ST2) could be used to predict the Sea Trial 4 (ST4) reverberation data. When the prior information on the seabed properties in the trial area is used for the ST4 predictions, the median error between the predicted and measured reverberation is 6.0 dB. With the aid of the ST2 inversion results, the median error in the reverberation prediction was reduced to 2.7 dB.

For demonstrating the improvement in sonar performance predictions, both reverberation level and echo level should preferably be considered. With the data available, the echo level could not be assessed. The reverberation prediction results are considered to be important since reverberation depends on both the reflection and the scattering at the seabed. The capability to predict reverberation for a different sound speed profile suggests that parameters that determine both the reflection coefficient at low grazing angles and the scattering strength are robustly retrieved.

ACKNOWLEDGMENT

This work was performed within the EDA (European Defence Agency) project Rumble-2 realized within the scope of the contract B-0122-ESM3-GC 'RUMBLE-2'. The authors acknowledge the Royal Norwegian Navy for hosting and supporting the Rumble-2 sea trials and for making the data available. The Swedish, French, Norwegian, and The Netherlands' Ministries of Defence are acknowledged for the financial support. The architects of the Rumble-1 project, Alain Plaisant and Dick Simons, are acknowledged as well. We further acknowledge the reviewers for their constructive comments which clearly helped us to improve the manuscript.

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Robbert van Vossen is Senior Research Scientist in the Acoustics and Sonar Department of The Netherlands Organisation for Applied Scientific Research (TNO). His research focuses on signal processing, modeling, and inversion techniques for anti-submarine warfare and naval mine-counter measures applications. He received his MSc degree in geophysics from Utrecht University in 2000, and his PhD in seismology (cum laude) in 2005.

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Ellen Johanne Eidem was born in Norway in 1964. She received the MSc degree in physics and mathematics from the Norwegian University of Science and Technology, Trondheim, Norway, in 1990. She has since been with the Norwegian Defence Research Establishment (FFI), Horten, Norway, where she currently works as a Senior Researcher. Her work includes seabed classification, sonar performance analysis, low-frequency matched field processing, and research efforts within magnetic mine countermeasures.

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Sven Ivansson is with the Swedish Defence Research Agency, where he has worked with seismics, seismology, and underwater acoustics since thirty years. He got a licentiate degree in applied geophysics from Luleå University of Technology in 1987 and a Ph.D. degree in technical acoustics from the Royal Institute of Technology in Stockholm in 1994. He has published papers on seismic tomography, theoretical and computational aspects on seismo-acoustic wave-fields in laterally homogeneous media, and phononic crystal slabs with application to anechoic coatings. Dr. Ivansson is a member of the Acoustical Society of America.

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Bruno Chalindar

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Johnny Dybedal

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Mathieu E. G. D. Colin received the MSc in 2001 from Ecole Nationale Superieure des Ingnieurs des Etudes et Techniques de l'Armement (ENSIETA) in Brest, France. He has worked since then in the Sonar department of the Netherlands Organisation for Applied Scientific Research (TNO) on sonar related topics such as active and passive sonar processing and performance modelling. He recently obtained the Ph.D. degree from the Faculty of Aerospace Engineering of the Delft University of Technology on the topic of towed array signal processing.

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Frank P. A. Benders

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Brodd Leif Andersson received the BSc in Mathematics at the University of Uppsala, Sweden, in 1986. He has been at the Swedish Defence Research Agency (FOI) since 1985. His research interests are wave propagation in underwater and atmospheric acoustics, and inversion of environmental parameters.

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Bénédicte Juhel

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Xavier Cristol

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Geir-Kyrre Olsen

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Jörgen N. B. Pihl received a BSc degree in Physics at the Department of Physics, University of Uppsala in 1969, where he also obtained his PhD in atomic physics in 1976. Since then he has been working at the Swedish Defence Research Agency (FOI). During the first ten years he developed instrumentation and methods for geotomography, applied to mineral exploration and nuclear waste disposal. Since 1986 he has been active in the area of underwater research, mainly underwater acoustics, and has lead many projects concerning new sonar technology, such as Synthetic Aperture Sonar and Multistatic Sonar. Dr. Pihl is also often engaged as a sonar expert by the Royal Swedish Navy and the Swedish Defense Materiel Administration (FMV).

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Elling Tveit

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Stéphane Jespers graduated Civilian Engineer (MSc) in Electrical Engineering (Telecommunications and Hyperfrequencies) from Université Catholique de Louvain (B) in 1979 where he conducted statistical atmospheric impact studies on radio and TV signals at 12 and 35 GHz using radiometers and the European OTS satellite. In 1983, he joined SACLANTCEN (IT) to develop submarine target strength measurement techniques in support of the Low Frequency Source Adjunct to the Towed Array Sonar project 20. In 1990, he joined DCN/Le Brusc to experiment an LF Sonar Intercept demonstrator designed for French SSNs and SSBNs. He specialized also in various Array Processing techniques applied to towed arrays and Synthetic Aperture Sonar (SAS). In 2000, he became Head of Department at NURC (IT), leading the Undersea Reconnaissance, Surveillance and Networks thrust area. In 2007, he joined the French Defence Procurement Agency DGA, where he is now Group Leader in Undersea Warfare. Stéphane Jespers is the chairman of the new NATO UWW-CG Underwater warfare capability group and a member of the SFA (Société Française d'Acoustique). He is a reviewer of IET articles on sonar and has chaired sonar sessions at UDT Europe and ECUA.

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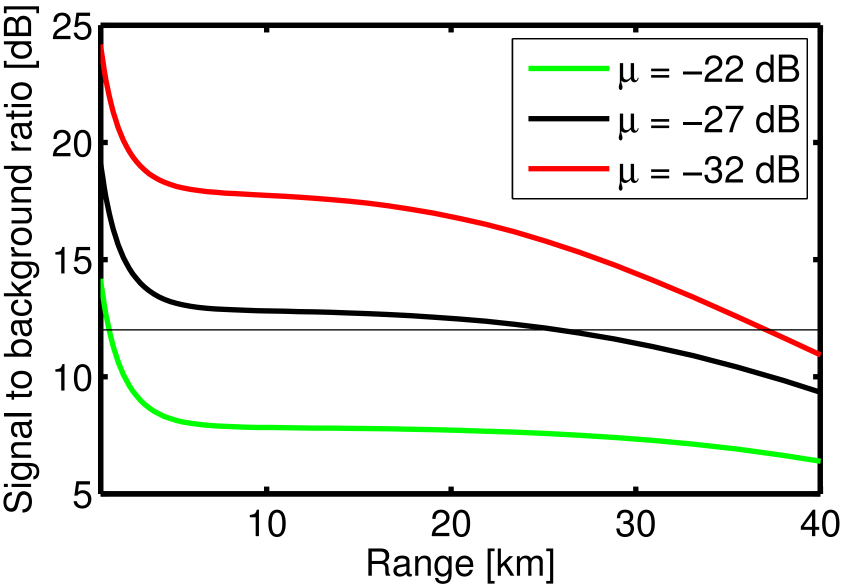
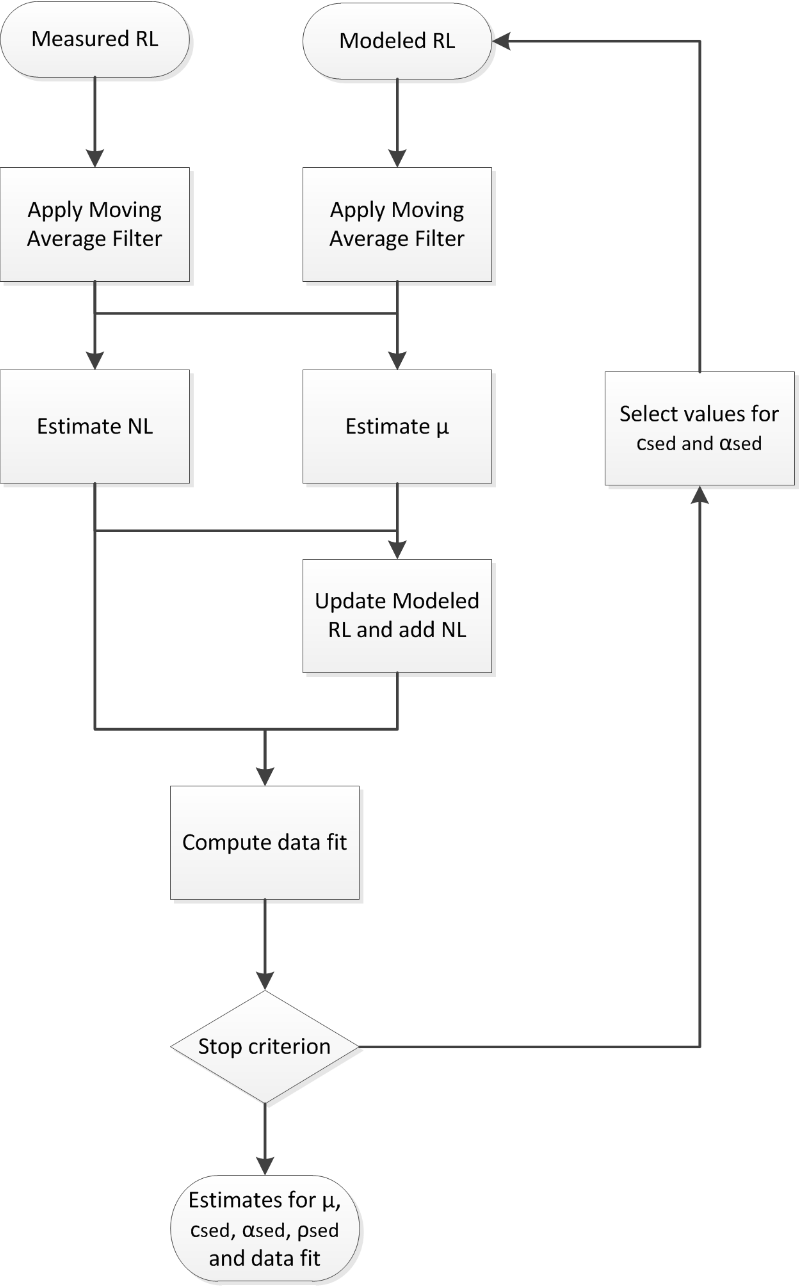
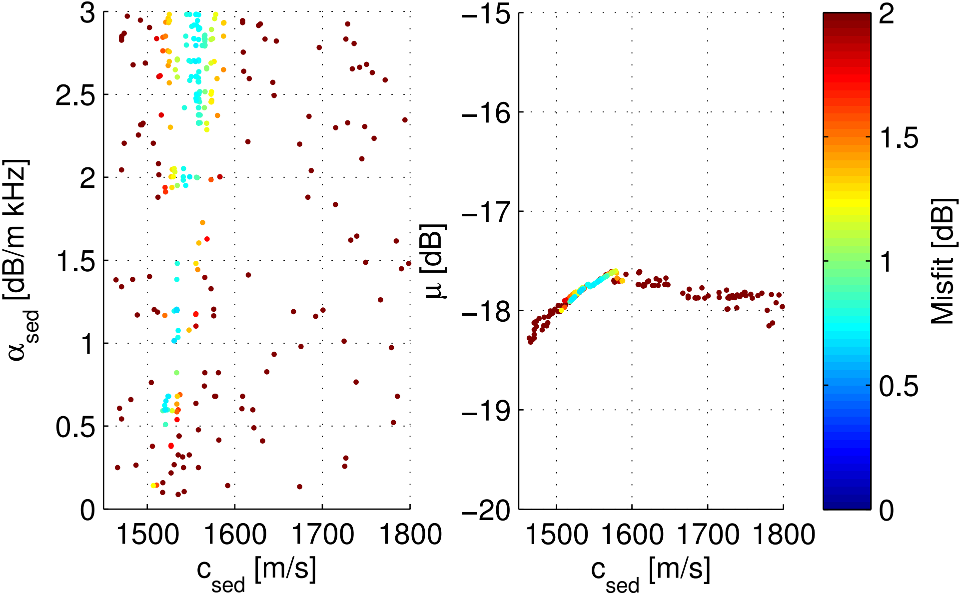
Michael A. Ainslie, author of Principles of Sonar Performance Modeling (Springer, Berlin) received the BSc degree in physics from Imperial College, London, U.K., in 1981, the MSc degree in Mathematics from the University of Cambridge, Cambridge, U.K., in 2011, and the PhD degree in ocean acoustics from the Institute of Sound and Vibration Research (ISVR), University of Southampton, Southampton, U.K., in 1992. He holds the position of Visiting Professor at ISVRs Centre for Ultrasonics and Underwater Acoustics and his research interests include sonar performance modelling and the impact of sound on aquatic life. Dr. Ainslie was awarded the 1998 A. B. Wood medal by the U.K. Institute of Acoustics for his contributions to seabed acoustics and sonar performance modeling. He is a Fellow of the Institute of Acoustics and of the Acoustical Society of America.

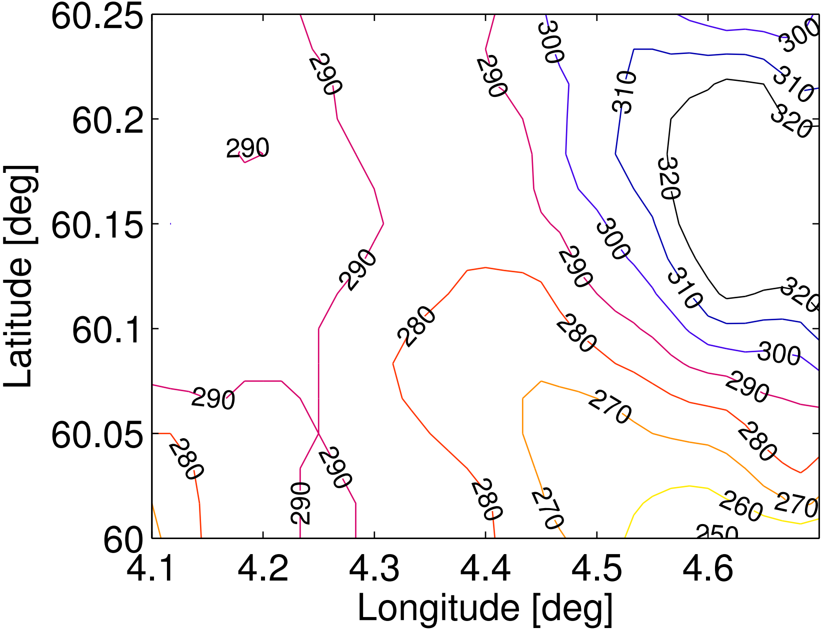


μ = −22 dB
μ = −27 dB
μ = −32 dB
Signal to background ratio [dB]
25
20
15
10
5
10
20
30
40
Range [km]

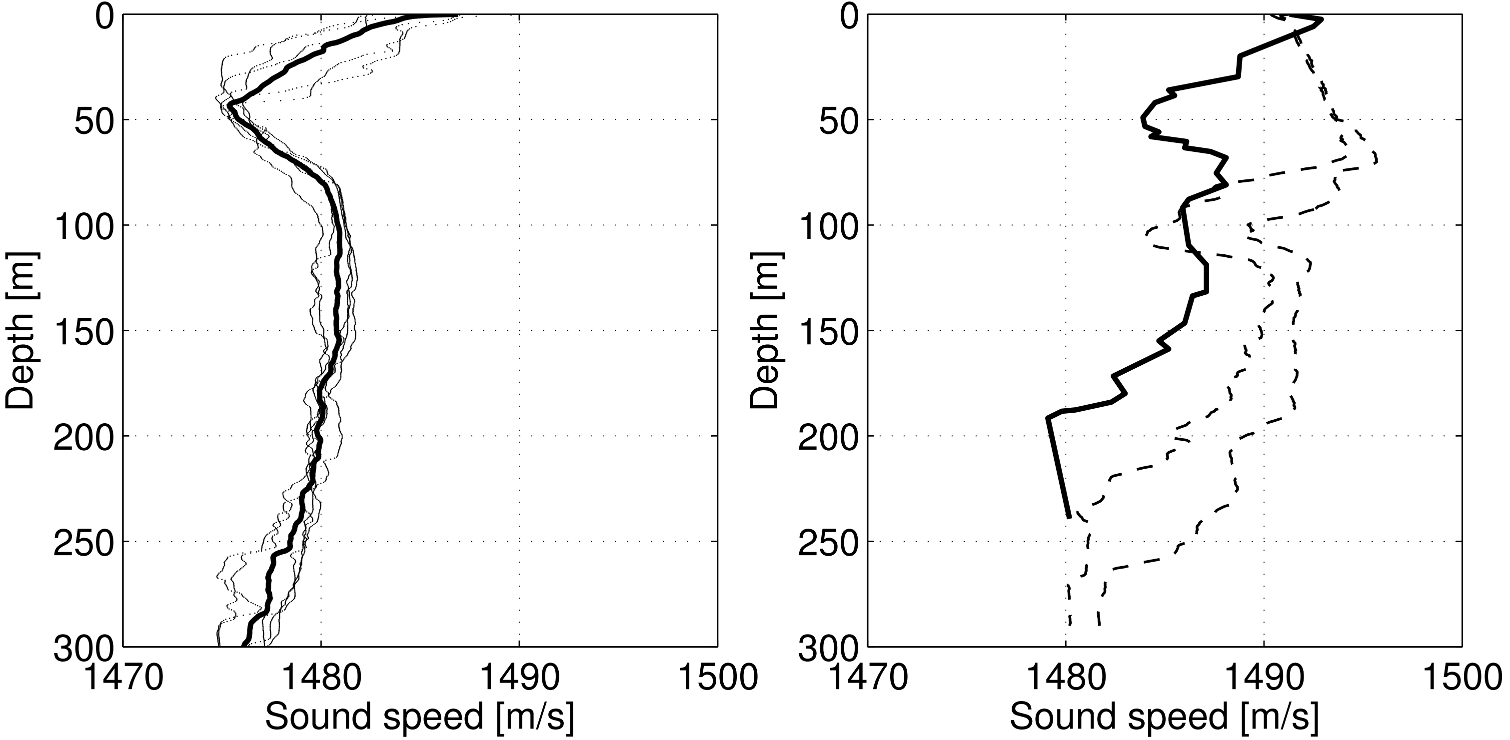

Measured RL
Modeled RL
Apply Moving Average Filter
Apply Moving Average Filter
Estimate NL
Estimate μ
Select values for csed and αsed
Update Modeled RL and add NL
Compute data fit
Stop criterion
Estimates for μ, csed, αsed, ρsed and data fit

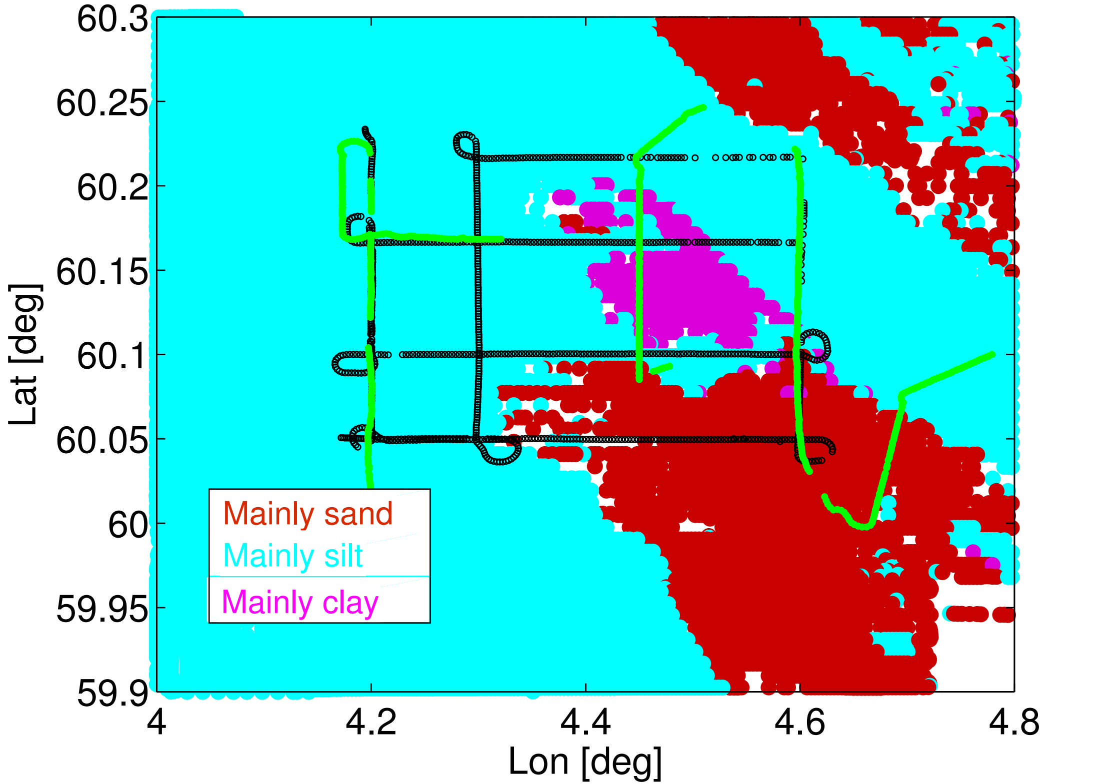


3
2.5
2
1.5
1
0.5
0
1500
1600
1700
1800
α_{sed} [dB/m kHz]
c_{sed} [m/s]
−15
−16
−17
−18
−19
−20
μ [dB]
c_{sed} [m/s]
2
1.5
1
0.5
0
Misfit [dB]

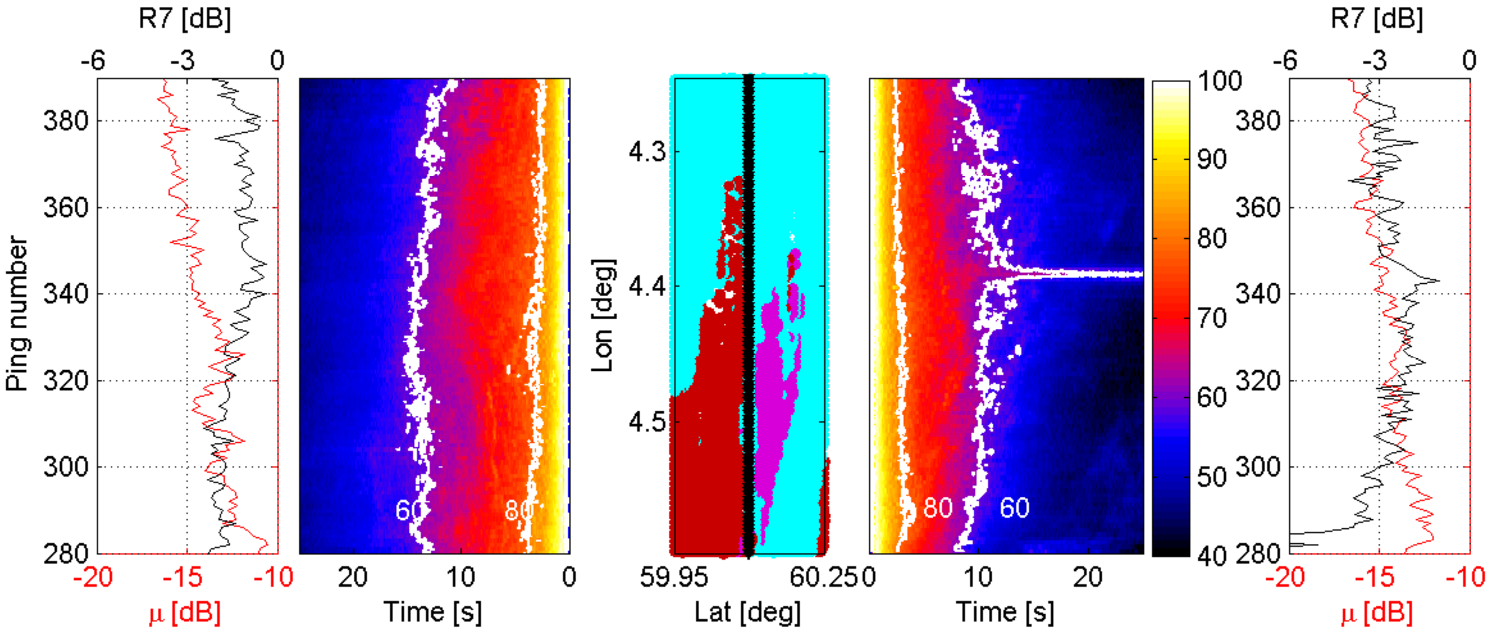


60.25
60.2
60.15
60.1
60.05
60
Latitude [deg]
4.1
4.2
4.3
4.4
4.5
4.6
Longitude [deg]
250
260
270
280
290
300
310
320

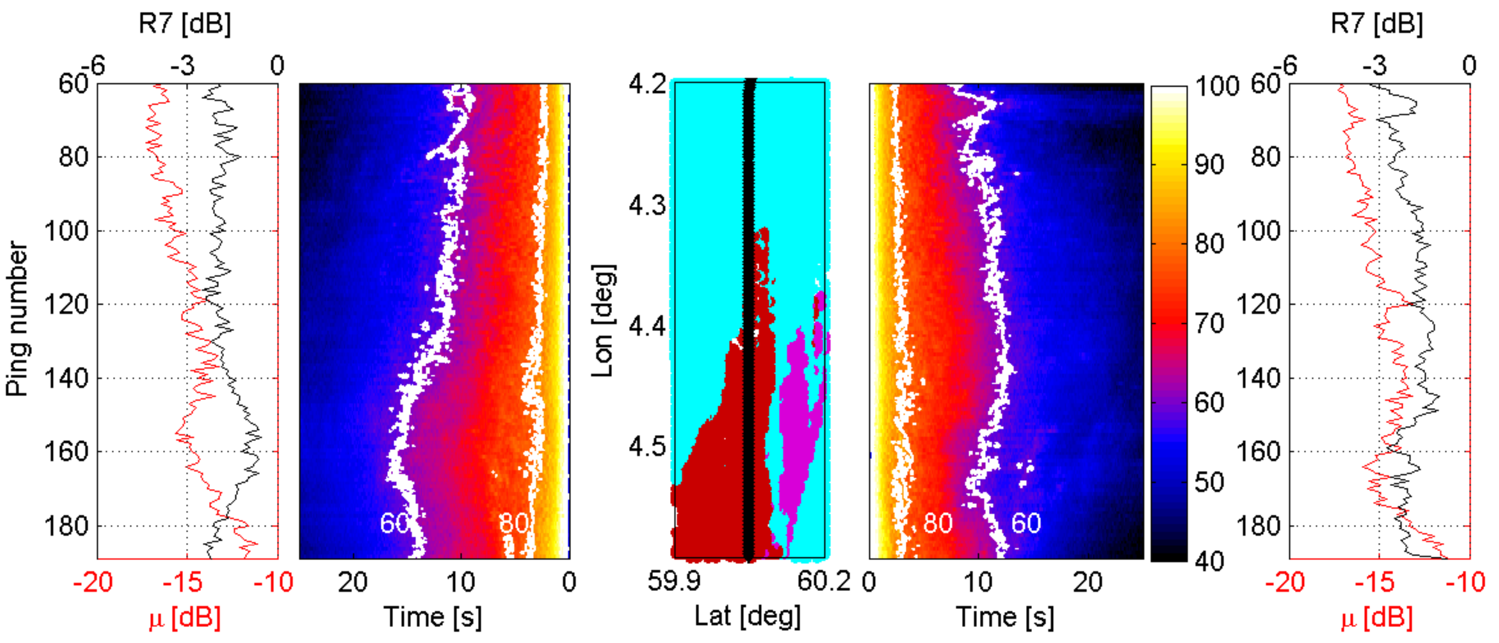

0
50
100
150
200
250
300
Depth [m]
1470
1480
1490
1500
Sound speed [m/s]
0
50
100
150
200
250
300
Depth [m]
1470
1480
1490
1500
Sound speed [m/s]



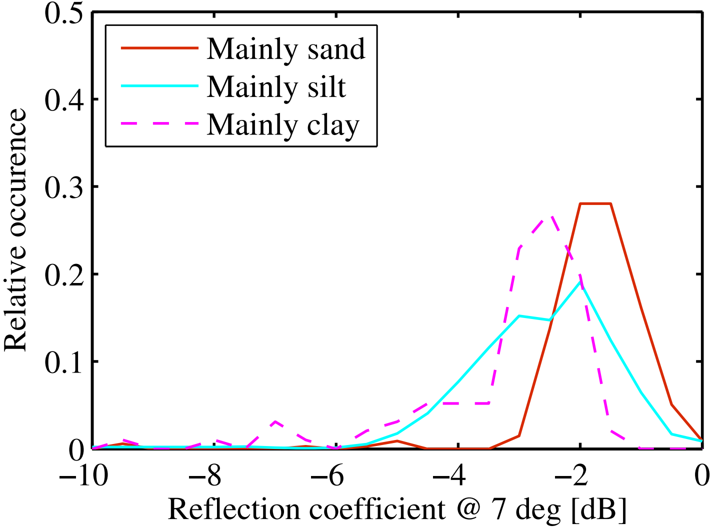
Mainly sand
Mainly silt
Mainly clay
Lat [deg]
Lon [deg]
60.3
60.25
60.2
60.15
60.1
60.05
60
59.95
59.9
4
4.2
4.4
4.6
4.8



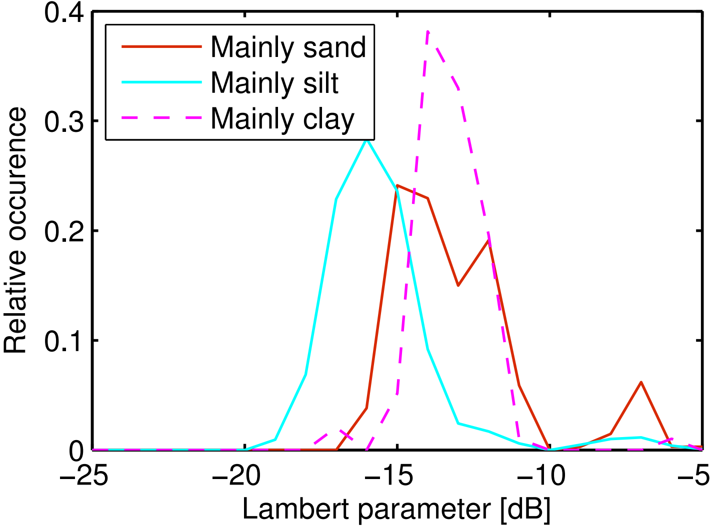
R7 [dB]
-6
-3
0
380
360
340
320
300
280
Ping number
-20
-15
-10
μ [dB]
20
10
0
Time [s]
60
80
4.3
4.4
4.5
Lon [deg]
59.95
60.25
Lat [deg]
100
90
80
70
60
50
40



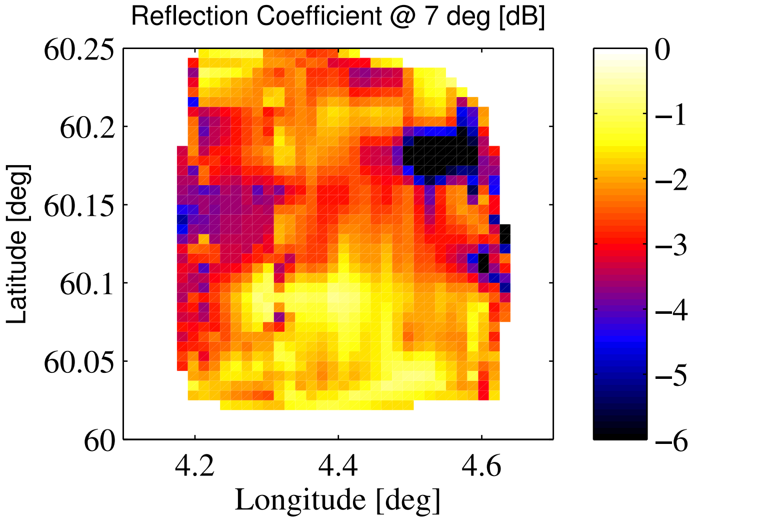
R7 [dB]
-6
-3
0
60
80
100
120
140
160
180
Ping number
-20
-15
-10
μ [dB]
20
10
0
Time [s]
60
80
4.2
4.3
4.4
4.5
Lon [deg]
59.9
60.2
Lat [deg]
0
10
20
Time [s]
80
60
100
90
80
70
60
50
40
R7 [dB]
-6
-3
0
60
80
100
120
140
160
180
-20
-15
-10
μ [dB]

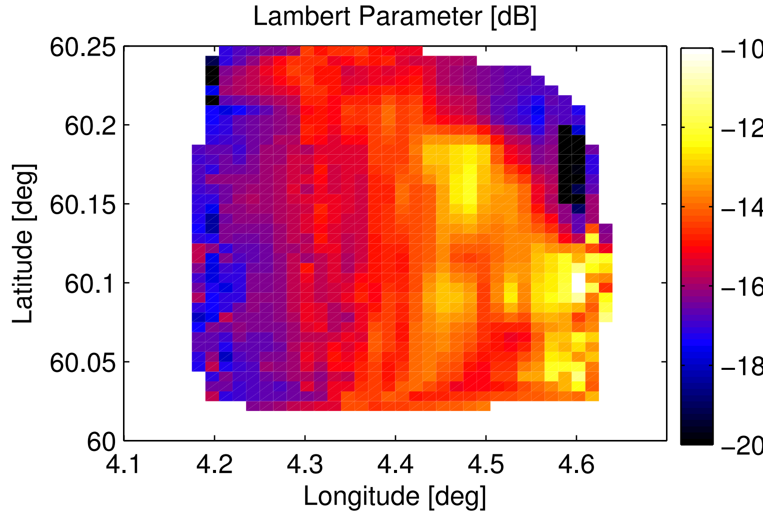


Mainly sand
Mainly silt
Mainly clay
Relative occurence
Reflection coefficient @ 7 deg [dB]
0.5
0.4
0.3
0.2
0.1
0
−10
−8
−6
−4
−2
0

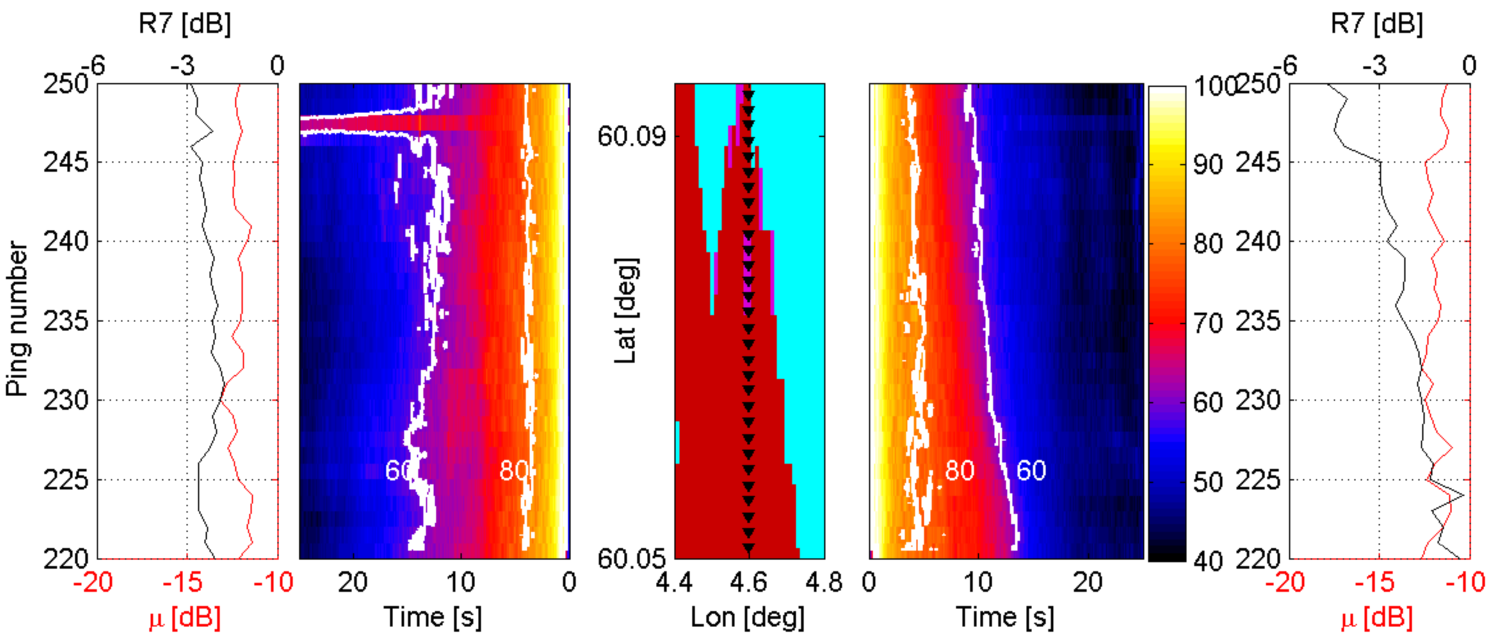


Mainly sand
Mainly silt
Mainly clay
Relative occurence
0.4
0.3
0.2
0.1
0
−25
−20
−15
−10
−5
Lambert parameter [dB]

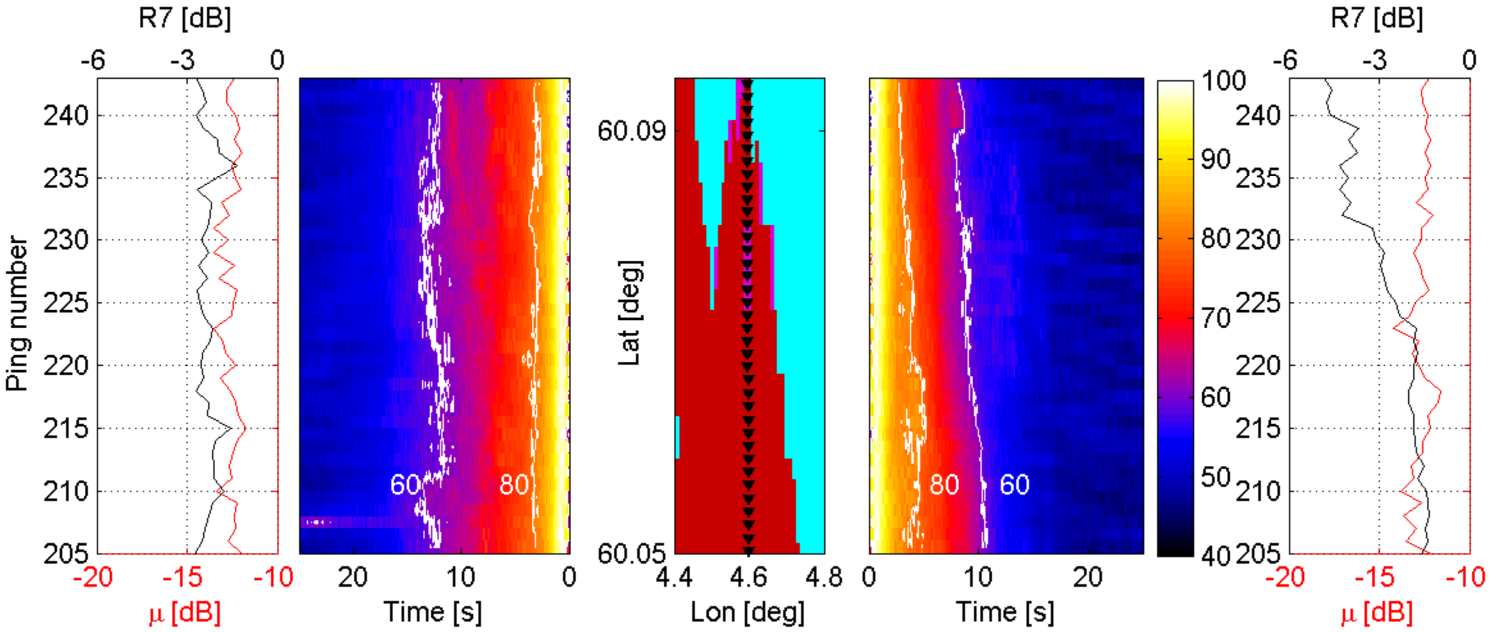

Reflection Coefficient @ 7 deg [dB]
60.25
60.2
60.15
60.1
60.05
60
Latitude [deg]
4.2
4.4
4.6
Longitude [deg]
0
−1
−2
−3
−4
−5
−6



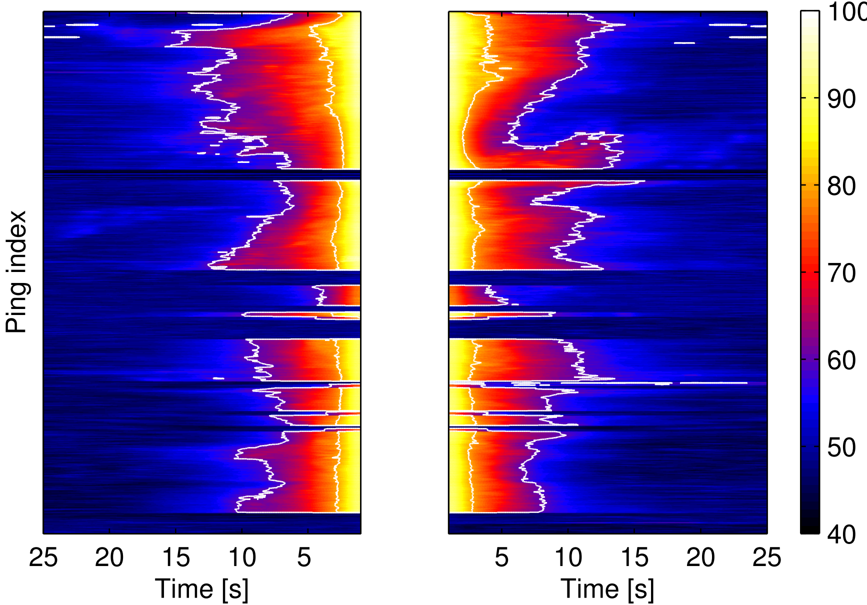
Lambert Parameter [dB]
60.25
60.2
60.15
60.1
60.05
60
Latitude [deg]
4.1
4.2
4.3
4.4
4.5
4.6
Longitude [deg]
−10
−12
−14
−16
−18
−20



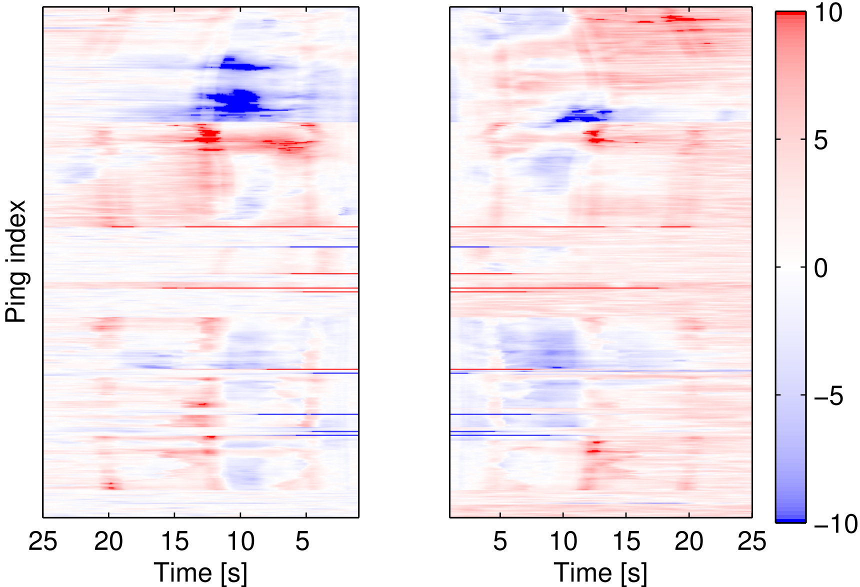
R7 [dB]
-6
-3
0
Ping number
250
245
240
235
230
225
220
-20
-15
-10
μ [dB]
Time [s]
20
10
0
60
80
Lat [deg]
60.09
60.05
4.4
4.6
4.8
Lon [deg]
100
90
80
70
60
50
40



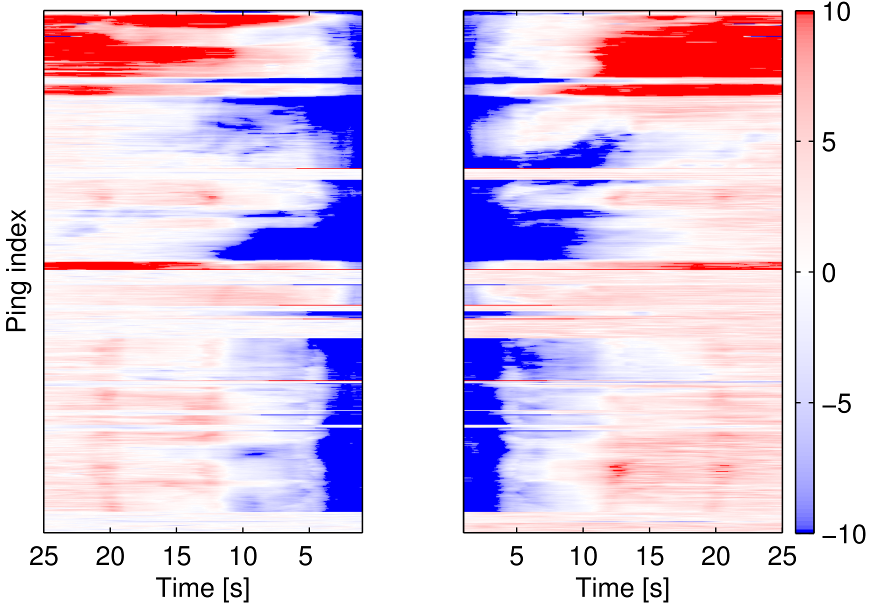
R7 [dB]
-6
-3
0
Ping number
240
235
230
225
220
215
210
205
-20
-15
-10
μ [dB]
60
80
20
10
0
Time [s]
60.09
60.05
Lat [deg]
4.4
4.6
4.8
Lon [deg]
80
60
0
10
20
Time [s]
100
90
80
70
60
50
40
R7 [dB]
-6
-3
0
240
235
230
225
220
215
210
205
-20
-15
-10
μ [dB]



Ping index
25
20
15
10
5
Time [s]
5
10
15
20
25
Time [s]
100
90
80
70
60
50
40



Ping index
25
20
15
10
5
Time [s]
5
10
15
20
25
Time [s]
10
5
0
−5
−10


Ping index
25
20
15
10
5
Time [s]
5
10
15
20
25
Time [s]
10
5
0
−5
−10