Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Assessment of the sea surface roughness effects on shallow water inversion of sea bottom properties

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PACS: 43.30.Hw, 43.30.Pc

ABSTRACT

The inversion of sea bottom properties and, in particular, the knowledge of the sound speed in the seabed is an essential piece of information for sonar performance prediction. In shallow water, both bottom and surface roughness (sea state) can be a factor of error for inversion procedures. The aim of this paper is to assess, in simple cases, the error on inversion procedures due to a limited knowledge of surface roughness and to a mismatch between actual values and the ones used for inversion. Simulations were performed using a conventional normal-mode model (ORCA). Under small roughness approximations, the surface scattering phenomenon was introduced using modal attenuation coefficients. For a given environment and geometry, the acoustic field was computed for fixed sea state and roughness (reference field) and the inversion was achieved for other sets of values. The sound speed in the sediment was recovered by a conventional inversion method based on the Bartlett operator. Several simulations were realized for a wide range of frequency (50-350 Hz) and various sea states (0-4). The estimation error depends on both the mismatch and the frequency as well as on the geometry. It can reach several tens of m/s.

INTRODUCTION

In shallow-water environment, sea and bottom roughness are important issues as they induce forward scattering and can therefore, strongly affect the propagation patterns. This phenomenon has been studied for years in order to introduce it into numerical models and to assess its effects, among others, on the acoustic propagation and the reverberation predictions.

The estimation of the sound speed in the sediment is essential information (in particular for sonar performance prediction). It can be accessed through inversion procedures. However, due to the complexity of the oceanic medium, the introduction of all actual environmental parameters in an inversion method may be quite impossible as access to ground truth may be of an important cost mainly in highly changing environments such as coastal areas. Some phenomena are consequently often neglected, depending on the "environment ignorance", the complexity of the phenomenon to take into account and the limitations of the models. This paper will concentrate on surface roughness but the same approach can be extended to other ocean characteristics, in particular bottom roughness: in a propagation experiment, the information on the surface is often defined in terms of sea state providing a roughness range (unless radar altimetry data are available to provide a roughness distribution). This lack of knowledge has motivated this study whose aim is to assess the effect of the sea surface roughness on the accuracy of the parameter recovered by an inversion method. For simplicity, we assumed a range-independent environment with an isotropic surface in space and only one geo-acoustic parameter (the sound speed in the sediment) to be recovered.

All the simulations were performed using the normal-mode based model ORCA. To take the sea surface roughness into account, the forward scattering phenomenon was introduced by means of modified attenuation coefficients. To assess the influence of the surface roughness on the inversion procedure, a "reference" field was calculated for a given set of environmental parameters. The sound speed in the seabed was then estimated by an inversion method (performed by means of the Bartlett operator), assuming other roughness. The effect of this mismatch between the "reference" values and the ones used in the inversion procedure was then investigated.

PROPAGATION AND FORWARD SCATTERING MODELING

To realize the simulations of the acoustic propagation, the normal-mode based model, ORCA, was used [1]. The normal-mode theory is not presented here (for more details see [2]) and just the main equation describing the acoustic pressure as a function of range and depth is recalled:

$$p(r, z_r) = i\sqrt{\frac{2\pi}{r}}\, e^{-i\pi/4}\, \frac{1}{\rho_s} \sum_n \frac{\psi_n(z_s)\psi_n(z_r)}{\sqrt{k_{rn}}}\, e^{ik_{rn}r} \qquad (1)$$

where:

- r si the range,
- z_s and z_r are respectively the source and receiver depths,
- ρ_s is the density at the source depth,
- n represents the number of modes,
- ψ_n is the normalized modal function of mode n,

- k_{rn} is the horizontal wavenumber associated to mode n.

In order to study the influence of the sea surface roughness, the forward scattering phenomenon has to be included in the propagation model. A quite accurate modelling of this phenomenon can be realized thanks to scattering strength laws ([3], [4], [5]). However, for the sake of simplicity, we assumed that the roughness was small compared to the acoustic wavelength. In that case, the energy is scattered mainly in the specular direction and scattering effects can be simply associated to a loss of energy. Under this assumption, the modelling of forward scattering can be achieved by means of a modified reflection coefficient [2]:

$$R'(\theta) = R(\theta) e^{-0.5\Gamma^2} \quad (2)$$

where θ is the grazing angle, $R(\theta)$ is the reflection coefficient, Γ is the Rayleigh roughness parameter, given by:

$$\Gamma = 2k\sigma \sin\theta \quad (3)$$

with k, the acoustic wavenumber and σ the rms value of the surface roughness. As mentioned before, the use of the modified reflection coefficient requires that the surface is "reasonably smooth", i.e. the Rayleigh parameter is such that [4]:

$$\Gamma < \frac{\pi}{2} \Leftrightarrow \sigma \sin\theta < \frac{\lambda}{8} \quad (4)$$

where λ is the acoustic wavelength.

To introduce this coefficient (cf. Eq. 2) into normal-mode based models, modal attenuation coefficients were derived [6]. For the sea surface scattering, these coefficients, defined for each mode, are given by the following equation [7]:

$$\delta_{n,surface} = \frac{\sigma_{surface}^2 k_{zn}(0)}{k_{rn}} \left(\frac{d\psi_n(0)}{dz} \right)^2 \quad (5)$$

where:

- $\delta_{n,surface}$ is the modal attenuation coefficient defined for mode n,
- $\sigma_{surface}$ is the sea surface rms roughness,
- $k_{zn}(0)$ is the value of the vertical wavenumber associated to mode n on the surface,
- h is the water depth.

The additional loss due to the forward scattering phenomenon is then readily included in the propagation model by means of a complex horizontal wavenumber defined by:

$$K_{rn} = k_{rn} + i\delta_{n,surface} \quad (6)$$

If only the sea surface roughness is taken in to account (the water/sediment interface is assumed to be flat), the acoustic field is determined by:

$$p(r,z) = i\sqrt{\frac{2\pi}{r}} e^{-i\pi/4} \frac{1}{\rho_s} \times \sum_n \frac{\psi_n(z_s)\psi_n(z_r) e^{ik_{rn} r}}{\sqrt{k_{rn}}} e^{-\delta_{n,surface} r} \quad (7)$$

As the forward scattering is taken into account by means of these coefficients, the energy scattered from one mode to the others is neglected and the additional losses can be overestimated. However, such an assumption allows to roughly assessing the effects of roughness mismatch on the inversion procedure.

INVERSION METHOD

To achieve the inversion procedure, a "reference" acoustic field is first required. It is determined from Eq. 7, for a given set of environmental parameters:

- frequency: f,
- water depth: h,
- sound speed and density in the water, assumed to be range and depth independent: c_w=1500 m/s, ρ_w=1000 kg/m^3,
- sound speed, density and attenuation in the sediment: c_{ref}, ρ_b, β_b,
- sea surface roughness: σ_{ref} (corresponding to a sea state value: SS_{ref}).

The inversion was performed by means of the Bartlett operator, often used in matched-field techniques. This operator is a "resemblance" function that quantifies the similarities between the "reference" acoustic field and "tested" ones. The "tested" fields are calculated from Eq. 7, for different values of the sound speed in the seabed, considering the same set of environmental parameters except the value of the roughness, σ_t. The Bartlett operator is defined by the following relation ([8], [9]):

$$E = \frac{\left| \sum_{j=1}^{N_r} p_{j,ref}\, p_{j,t}^* \right|}{\sqrt{\sum_{j=1}^{N_r} \left| p_{j,ref} \right|^2 \left| p_{j,t} \right|^2}} \quad (8)$$

where:

- N_r is the number of range samples,
- p_{ref} and p_t are respectively the "reference" and "tested" acoustic fields,
- * denotes the complex conjugate.

This function is normalized and possesses values between 0 and 1 (1 means that the two fields are totally identical).

Therefore, for a set of input parameters, the maximum of this operator corresponds to the estimated value of the sound speed in the sediment (cf. Figure 1).

The accuracy of the result depends on the mismatch between the "reference" parameters and the "tested" ones (used for achieving the inversion) as well as on the increment used for the inversion (intrinsic error).

As already mentioned, during an *in situ* experiment, the usually accessible parameter is the sea state that defines a range of roughness. We have therefore investigated three different cases, depending on both the sea state and roughness mismatch:

- *no mismatch at all*: SS_t=SS_{ref} and σ_t=σ_{ref}. This case was performed to estimate the intrinsic error of the inversion procedure,
- *no mismatch on sea state*: the sea state is correct defining a range of roughness ([σ_{min} - σ_{max}], see Table 1): SS_t=SS_{ref} and σ_{min}<σ_t<σ_{max} ,
- *sea state and roughness mismatch*: error of +/-1 on the sea state estimation

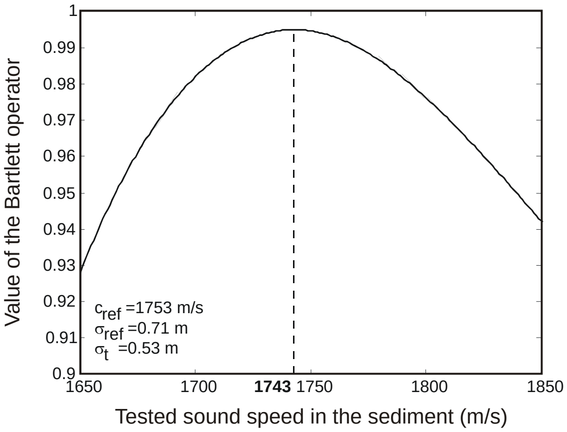

Figure 1. Value of the Bartlett operator as a function of the "tested" value of the sound speed in the sediment.
Input parameters: f=250 Hz, h=100 m,
c_{ref}=1753 m/s, σ_{ref}=0.71 m, σ_t=0.53 m.
The maximum value of the operator corresponds to the estimated value of the sound speed: 1743 m/s.

Table 1. Roughness range as defined by sea state

Sea state	*rms roughness (m)*		*mean rms roughness (m)*
	σ_{min}	σ_{max}	
0	0	0	0
1	0	0.14	0.07
2	0.14	0.35	0.25
3	0.35	0.71	0.53
4	0.71	1.41	1.06
5	1.41	2.12	1.76
6	2.12	2.83	2.47

EFFECT OF A MISMATCH ROUGHNESS ON THE ESTIMATION OF THE SOUND SPEED IN THE SEDIMENT

For illustration, we have simulated the case of an inversion procedure using a single hydrophone and broadband ship noise as source ([10], [11]), which can be modelled considering a single fixed source and a range of positions for the receiver. The influence of roughness mismatch was investigated on a wide range of frequencies.

For all the simulations, the following input parameters were used:

- frequency range: from 50 to 350 Hz with a frequency step of 5 Hz (i.e. 61 values),
- maximum propagation range: R=5 km,
- range step: Δr=5 m,
- source and receiver depths: z_s=1 m and z_r=7 m,
- range and depth independent sound speed and density in the water: c_w=1500 m/s and ρ_w=1000 kg/m^3,
- a half-space fluid sediment bottom characterized by constant values of the sound speed, density and attenuation: c_{ref}=1753 m/s, ρ_b=1900 kg/m^3 and β_b=0.8 dB/λ,

The acoustic fields used to perform the inversion were computed for different values of the sound speed in the sediment, ranging from 1550 m/s to 2100 m/s with a step of 1 m/s. Two sets of results are presented in this paper.

The first one concerns the *inversion error as a function of the roughness mismatch*. This error is not expected to be proportional to the input mismatch for the following reasons:

- the modal attenuation coefficients are proportional to the square of rms roughness (Eq. 5),
- the acoustic field is proportional to the cosine of modal attenuation coefficients (exponential term in Eq. 7),
- the value of the Bartlett operator represents a normalized mean square error (cf. Eq. 8).

The simulations were performed for a "reference" roughness σ_{ref}=0.53 m (i.e. SS_t=3) and six different roughness mismatches (difference between the "tested" value and the "reference" one):

- *Case A:* σ_t=0.53 (SS_t=3), $\Delta\sigma$=0, f_{max}=500 Hz,
- *Case B:* σ_t=0 (SS_t=0), $\Delta\sigma$=-0.53, $f_{max}=\infty$
- Case C: σ_t=0.25 (SS_t=2), $\Delta\sigma$=-0.28, f_{max}=1070 Hz,
- *Case D:* σ_t=0.35 (SS_t=3), $\Delta\sigma$=-0.18, f_{max}=760 Hz,
- *Case E:* σ_t=0.71 (SS_t=3), $\Delta\sigma$=0.18, f_{max}=370 Hz,
- *Case F:* σ_t=1.06 (SS_t=4), $\Delta\sigma$=0.53, f_{max}=250 Hz,

The maximum frequencies, f_{max}, associated to each value of the roughness are defined in order to fulfil the condition on the Rayleigh parameter (cf. Eq. 4). These frequencies are determined from Eq. 4, with θ the critical angle calculated for the worst case, i.e. maximum "tested" value of the sound speed in the sediment (2100 m/s).

The error on the estimated sound speed in the sediment as a function of the roughness mismatch (Cases A to F), for a given frequency f=250 Hz, is plotted on Figure 2.

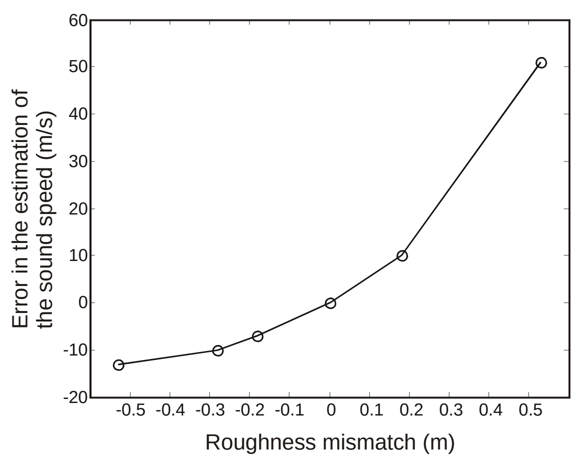

Figure 2. Error on the inverted sound speed in the sediment as a function of the roughness mismatch.
σ_{ref}=0.53 m (i.e. SS_{ref}=3) f= 250 Hz.

Figure 2 shows that the inversion error increases with the roughness mismatch in a non linear way (rather expected result). It also shows an unexpected result: the same mismatch in absolute value does not induce comparable inversion errors:

- $\Delta\sigma$= - 0.53 m (Case B) corresponds to -13 m/s,
- $\Delta\sigma$= 0.53 m (Case F) corresponds to 51 m/s.

Case A corresponds to the intrinsic error of the inversion procedure. It was found to be constant with frequency (<1 m/s). The choice of the sound speed step for inversion (1 m/s for Figure 2) may affect the results: a coarser step leads to a higher inversion error but does not change the general conclusions.

Only one example is presented here, however it is important to note that the inversion error does not depend only on the roughness mismatch but also on the value of the "reference" roughness (see Figure 3).

The effects of both the roughness mismatch and the acoustic frequency were then investigated. Assuming that the "reference" sea state is $SS_{ref}=3$, three different cases were considered:

- *Case 1: no sea state mismatch:* $SS_t=3$, the "reference" roughness ranges from σ_{ref}=0.35 m and σ_{ref}=0.71 m and the "tested" roughness is σ_t=0.53 m (equivalent to $\Delta\sigma=\pm0.18$ m),
- *Case 2: sea state mismatch:* $SS_t=4$, to determine the maximum error associated to this case, the "reference" roughness is σ_{ref}=0.35 m and the "tested" roughness is σ_t=1.06 m (equivalent to $\Delta\sigma$=0.71 m),
- *Case 3: sea state mismatch:* $SS_t=2$, to determine the maximum error associated to this case, the "reference" roughness is σ_{ref}=0.71 m and the "tested" roughness is σ_t=0.25 m (equivalent to $\Delta\sigma$=-0.46 m),

The obtained results are split in two parts:

- no mismatch on the sea state (Case 1): Figure 3,
- sea state mismatch (Cases 2 to 3): Figure 4.

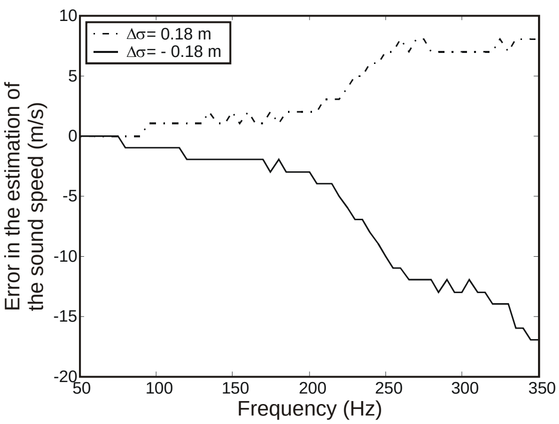

Figure 3. Error in the inversed sound speed in the sediment as a function of frequency: no sea state mismatch. SS_{ref}=3 (i.e. σ_{ref}=0.35 m and σ_{ref}=0.71 m) and SS_t=3 (i.e. σ_t=0.53 m).

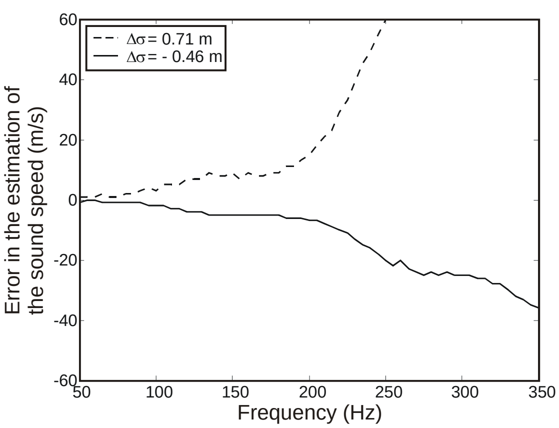

Figure 4. Error in the estimated sound speed in the sediment as a function of the frequency: sea state mismatch. SS_{ref}=3 (σ_{ref}=0.35 m), SS_t=4 (i.e. σ_t=1.06 m), SS_{ref}=3 (σ_{ref}=0.71 m), SS_t=2 (i.e. σ_t=0.25 m).

Figures 3 and 4 clearly show, for each mismatch, the influence of the frequency on the inversion: depending on the roughness mismatch, a difference of 50 Hz can induce a variation of few m/s or ten of m/s. This variation is not intrinsic to the inversion method: as mentioned previously, when there is no mismatch (Case A), the sound speed in the sediment is accurately estimated.

The "step aspect" of the error, in Figure 3, may be attributed to both the finite step of the inversion procedure and the modal aspect of the field (mode existence for a discrete number of frequencies).

The inversion error, for sea state mismatch (Figure 4) is important and can exceed 50 m/s in the high frequency end of the spectrum. However, the results obtained for Case 1 (Figure 3) tend to prove that even when the sea state is estimated properly, the inversion error can exceed 10m/s.

CONCLUSION

Many other simulations have been achieved under the same approximations (range invariant, Rayleigh criterion) with different configurations: water column depth and sound velocity in the sediment. They led to the same order of magnitude for the inversion error.

The simulations achieved allowed to evaluate the influence of a sea surface roughness mismatch on the inversion of the sound speed in the sediment. The same approach can be applied to bottom roughness ignorance. For a given roughness mismatch, it is expected to have a lower error induced as the reflection coefficient at the bottom interface is lower than at the surface. Nevertheless, the evaluation of bottom roughness is more difficult to achieve (it often uses acoustic devices at higher frequency) and the mismatch value is expected to be much higher.

The inversion error will also be affected by other mismatches: water column, spatial variability of both roughness and velocity profiles....

It is difficult to know the required accuracy on the sound velocity in the sediment as it highly depends on the application and on the scenarios used. Nevertheless it is expected that all the inversion errors induced by various mismatch will cumulate and may lead to inversion error higher than 100 m/s in the studied frequency range.

This error does not depend either on the direct modelling or on the inversion procedures but is due to mismatches between the environment parameters used by these procedures and the actual ones, for a realistic "ignorance of the environment".

For application requiring, for a comparable range of frequency, a metric accuracy on the sound velocity in the sediment, the statistical properties of the sonar environment have to be estimated in a highly accurate mode (in both time and space). In this case, one has to evaluate if a direct measurement of the sound velocity is not preferable depending on the operational conditions.

ACKNOWLEDGMENTS

This work has been partly performed at ENSIETA (Ecole Nationale Supérieure des Ingénieurs des Etudes et Techniques d'Armement). The authors would like to thank Dr. Cédric Gervaise for his comments and the ENSIETA for its support.

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