Normal-mode matching localization in shallow water: Environmental and system effects

S. M. Jesus
SACLANT Undersea Research Centre, Viale San Bartolomeo 400, I-19026 La Spezia, Italy

(Received 2 March 1990; revised 8 January 1991; accepted 5 June 1991)

Matched-field processing is a passive range and depth source localization technique that has been extensively used in shallow-water environments. A vertical array of sensors is used to spatially sample the acoustic waveguide where the source signal embedded in additive ambient noise propagates. The array output is then matched with the signal replica field generated by a normal-mode model based on the environmental parameters that characterize the waveguide. Recent results obtained from real data show the feasibility of the technique and give evidence of its strong dependence both on the array aperture and on the knowledge of the environmental parameters used in the model. This paper describes a modified matched-field technique, called normal-mode matching, that is applied to real shallow-water data. Its performance is compared to that obtained by conventional matched-field processing using the same data set. Unlike conventional matched-field processing, the results indicate that unambiguous localizations can be obtained even for "short" arrays spanning only half of the water column.

PACS numbers: 43.30.Bp, 43.30.Wi

INTRODUCTION

Passive range and depth localization of an acoustic source in shallow water is a difficult, yet interesting problem that has received a great deal of attention in the last few years.[1–5] The simultaneous estimation of range and depth requires the use of numerical propagation models. The classical approach to this problem is to "match" the received acoustic data with the sound field predicted by the propagation model for a number of hypothetical range/depth source locations. This technique is called *matched-field processing*.

It is commonly accepted that the wave propagation and boundary interaction dominating shallow-water propagation can be well described by a normal-mode model. According to this model, the acoustic pressure measured at the receiver can be expressed as a linear combination of the natural modes (or normal modes) of vibration of the waveguide. The complex weights associated with the normal-mode depth functions of the waveguide, herein designated as normal-mode amplitudes, fully characterize the source-medium interaction and contain the source location information. Recently, techniques have been suggested that use the normal-mode amplitudes to extract the source location parameters, source depth,[6] and source range.[7] A unified framework allowing simultaneous estimation of source range and depth proposed by Yang[8] has been used in a very similar fashion by Wilson *et al.*[9] Modified versions of this technique have also been proposed recently by Smith *et al.*[5] and Shang.[10] This technique uses the linearity of the normal-mode propagation model to perform a change of variables from the cylindrical space coordinates to the normal-mode space coordinates. The idea pursued is to measure the degree of similarity between the estimated and the model-generated normal-mode amplitudes. The maximum of the similarity function will give an estimate of the range/depth source parameters. also called matched-mode processing. Yang[8] derived ran depth estimation patterns from simulated data and succe fully applied the method to experimental data obtained fr a long-range source signal propagation in the Arctic surf duct. In studies by Yang[8] and Wilson *et al.*,[9] the sound fi was unresolvable by the receiving array; i.e., there were m modes than sensors, but the array still spanned a large p tion of the sound channel. Other studies[5,10] emphasized range/depth estimator detection and resolution perf mances.

The present study examines the real data performa of the normal-mode matching technique in a shallow-wa environment. The results are compared to those obtained conventional matched-field processing in the same data s Particular emphasis is made on the array geometry, sou depth, source frequency and bottom characteristics.

I. THEORY

The ocean environment is modeled as a stratified wa guide with an arbitrary sound-speed profile in the verti Long-range sound transmission in such an environment be described by the discrete normal-mode model.[11] Gi the acoustic pressure predicted by a sufficiently accur propagation model, range/depth estimation of a submer source is an inverse problem. The impossibility of obtain a numerical or analytical inverse solution make us resor approximate solutions by forward modeling predicti Matched-field processing belongs to this category of forw modeling techniques. Matched-field processing can viewed as a two-dimensional (range and depth) generali beamformer; each "steering" vector is the model repl field formed by the point solution to the wave equation t describes the propagation between the source and the rec er for a given "look direction" in the range/depth space.

an "infinite" number of source range/depth combinations gives rise to an ambiguity surface. The coordinates of the maximum of this surface are the matched-field estimates of the actual range and depth source location. Normal-mode matching proceeds by direct inversion of the propagation model in order to estimate the normal-mode amplitudes. Forward modeling is then applied to estimate the source parameters by matching the estimated and the model predicted normal-mode amplitudes for a number of source range/depth combinations. Again, the range/depth coordinates of the maximum level of the ambiguity surface obtained gives the normal-mode matching estimate of the source location.

Normal-mode modeling

The solution of the wave equation for a narrow-band point source exciting a horizontally stratified, parallel waveguide is commonly expressed as a linear combination of the waveguide normal-mode depth functions. The normalized spatial dependence of the acoustic pressure measured at a vertical array of L sensors due to a unit power narrow-band source at location $\theta_T^t = (z_T, r_T)$, where superscript t stands for transpose and subscript T indicates the true source location, may be expressed as[11]

$$\mathbf{p}(\theta_T) = \mathbf{A}\mathbf{x}(\theta_T), \tag{1}$$

where $\mathbf{p}(\theta_T)$ is the L-dimensional vector of array output pressures, $\mathbf{A}$ is an $L \times M$ real matrix whose columns are the normal-mode depth functions expressed for all sensor depths $\{z_l; l = 1,...,L\}$,

$$\mathbf{A} = [\mathbf{a}_1, \mathbf{a}_2, ..., \mathbf{a}_M], \tag{2a}$$

where

$$\mathbf{a}_m^t = [a_m(z_1), a_m(z_2), ..., a_m(z_L)] \tag{2b}$$

and M is the number of modes supported by the waveguide. The M-dimensional complex vector $\mathbf{x}(\theta_T)$ is the normal-mode amplitude vector for the true source parameter location, θ_T, the mth element of which is defined by

$$x_m(\theta_T) = \left[a_m(z_T)/\sqrt{k_m}\right] e^{-\alpha_m r_T} e^{ik_m r_T}, \tag{3}$$

where α_m is the mth mode attenuation coefficient. The two sets $\{a_m(z); m = 1,...,M; 0 < z < H\}$ and $\{k_m; m = 1,...,M\}$ are the mode depth functions and the corresponding mode horizontal wave numbers characterizing the propagation channel of depth H. Note that these expressions have been obtained by normalizing out the range dependence, a phase shift and an arbitrary constant. The SACLANTCEN normal-mode model, SNAP,[12] is a computer program well-suited for calculating the acoustical pressure defined in (1). SNAP has been used in this study to calculate the mode depth functions, the corresponding horizontal wavenumbers and the mode attenuations.

Normal-mode amplitude estimation

Assuming that the acoustical pressure $\mathbf{p}(\theta_T)$ is corrupted by additive zero-mean Gaussian noise ϵ_p,

$$\mathbf{y}(\theta_T) = \mathbf{p}(\theta_T) + \epsilon_p, \tag{4}$$

$$\hat{\mathbf{x}}(\theta_T) = \left[\mathbf{A}^t \mathbf{R}_{\epsilon_p}^{-1} \mathbf{A}\right]^{-1} \mathbf{A}^t \mathbf{R}_{\epsilon_p}^{-1} \mathbf{y}(\theta_T), \tag{5}$$

where the noise and the acoustical pressure are assumed uncorrelated and $\mathbf{R}_{\epsilon_p} = E\{\epsilon_p \epsilon_p^H\}$ is the noise covariance matrix. In practice, the white noise assumption reduces (5) to $\hat{\mathbf{x}}(\theta_T) = [\mathbf{A}^t\mathbf{A}]^{-1}\mathbf{A}^t\mathbf{y}(\theta_T)$, which requires the inverse of $\mathbf{A}^t\mathbf{A}$, i.e., requires matrix $\mathbf{A}$ to be full rank. If $\mathbf{A}$ is a rank deficient matrix (our case), $r(\mathbf{A}) = k$ with $k < \min(L,M)$, then $\hat{\mathbf{x}}(\theta_T)$ is not unique and the optimal least-squares solution of (1) is

$$\hat{\mathbf{x}}(\theta_T) = \mathbf{A}^+ \mathbf{y}(\theta_T), \tag{6}$$

where $\mathbf{A}^+$ is the pseudo-inverse of $\mathbf{A}$. Equation (6) is also referred to as the minimum (Euclidean) length solution of (1).[13]

C. Source range/depth estimation

The approximate forward solution to the inverse problem is obtained as the range/depth coordinates for which the direct match between the measured and the model predicted quantities is maximum. For the normal-mode matching (NMM) technique, this is written as

$$RD_{\mathrm{NMM}}(\theta) = E\{|\hat{\mathbf{x}}^H(\theta_T)\mathbf{w}(\theta)|^2\}, \tag{7}$$

where $\mathbf{w}(\theta)$ is the model replica normal-mode amplitude vector at the source location θ. In the expression of $\mathbf{w}(\theta)$ given by (3), the compressional-wave attenuation coefficient $\exp(-\alpha_m r_T)$ has been dropped as suggested by Yang[8] and confirmed by our own tests in our shallow-water environment.

A similar expression is obtained for the conventional matched-field processor (MFP),

$$RD_{\mathrm{MFP}}(\theta) = E\{|\hat{\mathbf{y}}^H(\theta_T)\mathbf{p}(\theta)|^2\}, \tag{8}$$

where $\mathbf{y}$ and $\mathbf{p}$ have been defined above. If the sound field is correctly sampled, i.e., if the array is sufficiently dense to resolve even the higher-order modes and it spans the significant part of the sound channel, matrix $\mathbf{A}$ will be column orthonormal in which case, (7) and (8) will be equivalent. In that case, (7), or (8), will be the optimum receiver of a single point source in white noise. In practice, the spatial observation of the sound field is often restricted to some imperfectly, spatially sampled portion of the water column. This and the fact that in shallow water a large amount of energy is often lost by bottom-sound wave interaction result in a rank deficiency of matrix $\mathbf{A}$. Thus expression (6) must be used as the normal-mode amplitude estimator. By substituting (6) into (7) and using (1), this estimator gives the normal-mode matching processor response of the form

$$RD_{\mathrm{NMM}}(\theta) = E\{|\mathbf{x}^H(\theta_T)\mathbf{V}_k\mathbf{V}_k^t\mathbf{w}(\theta) + \epsilon_p^H[\mathbf{A}^+]^t\mathbf{w}(\theta)|^2\}, \tag{9}$$

where the decomposition $\mathbf{A} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^t$ has been used and where $\mathbf{V}_k$ is a $M \times k$ eigenvector matrix corresponding to the k largest singular values of $\mathbf{A}$. Reducing the number of normal modes improves the quality of the match, since the modes that have been rejected are those having the largest estimator variance [smallest eigenvalues of the covariance matrix of the maximum-likelihood estimator (5)]. The

by Yang[8] and solved in an subjective way by rejecting the smaller eigenvalues of an augmented version of matrix $\mathbf{A}'\mathbf{A}$. In this case, the k modes being selected are not necessarily the k lower-order modes but are the most energetic modes that are resolvable by the array. The way normal-mode matching adapts to the array configuration contrasts with conventional matched-field processing where the replica acoustic pressure is computed for all the scan source locations using all the modes, regardless of the array configuration. As we will see below, this difference will have a strong impact on the estimated range/depth ambiguity surface for many practical situations and in particular in shallow waters.

I. REAL DATA RESULTS

Real data have been acquired in the area north of Elba Island off the west coast of Italy. This area is characterized by a water depth of 118 to 125 m above a sandy bottom formed by a 2.5-m-thick medium/hard sediment layer and a semi-infinite homogeneous subbottom (Fig. 1). The water sound-speed profile (see Fig. 1) is the typical September–October Mediterranean downward refracting profile with a high-temperature surface layer extending to 40-m depth. The environmental model described above and the corresponding bottom parameters have been established in Ref. 14. The receiving system was a free-drifting 62-m-long vertical array with 64 unequally spaced hydrophones (Table I) with the uppermost hydrophone situated at depth of about 40 m. The signal was simulated by an acoustic sound source emitting a continous wave tone at one of the following frequencies: 180, 332, or 740 Hz. The source was stationed at either 6 or 71 m, or was towed by an auxiliary ship at a depth of approximately 61 m. Ranges between the source and the receiving array varied from 5 to 27 km. The signals received at the array were transmitted via a high-density radio link to the ship. After sampling at a rate of 4000 Hz, all the 64 channels were fast Fourier transformed with a block size of 1024 samples. The interval between each time snapshot was approximately 1.5 s due to the time needed for processing. Three frequency bins, 4 Hz apart, in the neighborhood of the source frequency were saved for each time snapshot. An approximate array-averaged signal + noise-to-noise ratio was

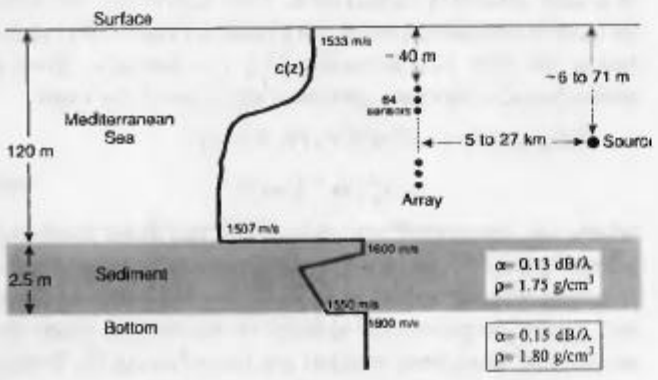


TABLE I. Vertical array configuration.

Hydrophone no. From	Hydrophone no. To	Spacing (m)
1	8	2
8	16	1
16	48	0.5
48	56	1
56	64	2

estimated by comparing the power received at the sou frequency to that received on a contiguous frequency b This value was of the order of 20 to 30 dB.

The real data set acquired in the area north of Elba c sists of more than 12 h during a 3-day period. From the th source frequencies (180, 332, 740 Hz) only 332 Hz g acceptable results. Occasionally accurate results could obtained at 740 Hz for the deep source locations (61 and m) and short ranges (< 10 km); in these cases the sou localization was very unstable (in time) and the sidel rejection (i.e., the difference, in dB, between the maxim and the highest sidelobe in the surface) was very low. At Hz, a 20-min period of relatively stable results was obtai at the end of a tow at 5-to 7-km range. Figure 2, extrac from that 20-min-period, shows two range/depth ambigu surfaces obtained from the match of the complete set of modes supported by the channel. Figure 2(a) (simula data) shows a sharp peak at the correct source location w a sidelobe rejection of 3.5 dB and a relatively small sidel

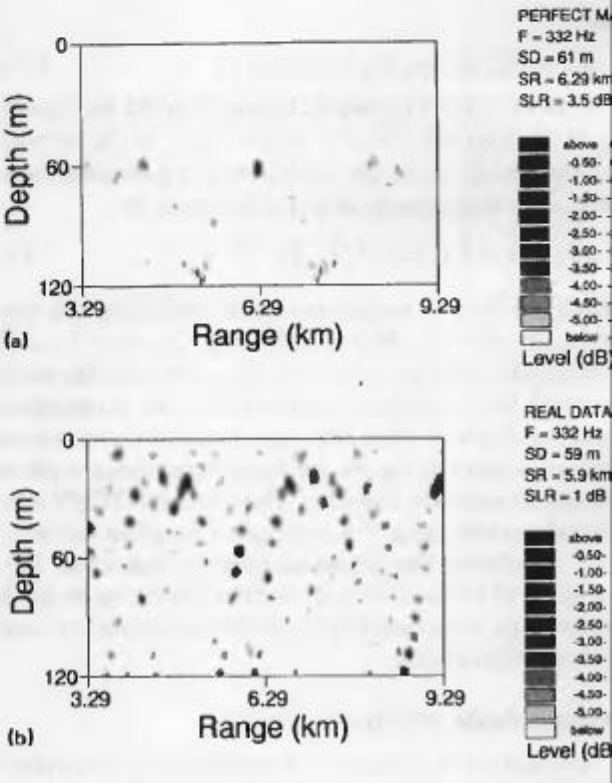
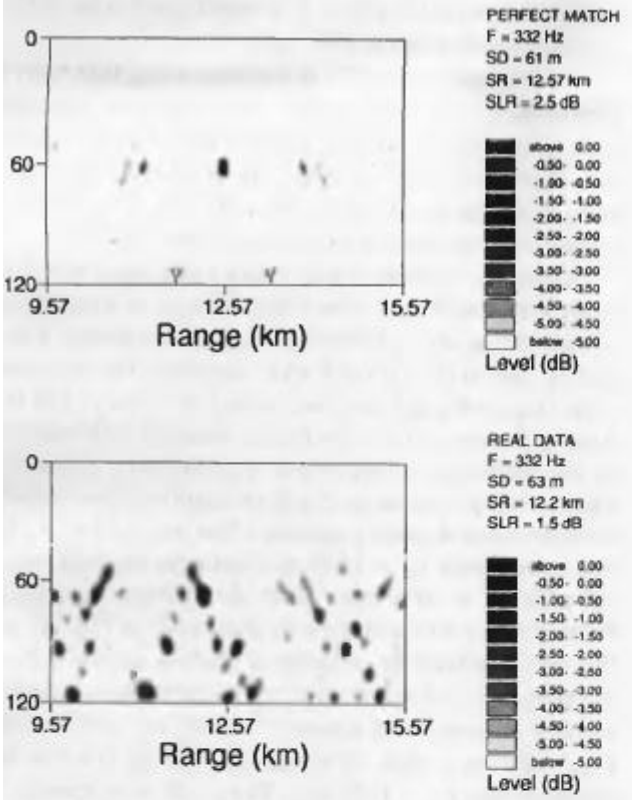


FIG. 2. Range/depth ambiguity surfaces in the scenario of Fig. 1. Exp



G. 3. Range/depth ambiguity surfaces in the scenario of Fig. 1. Expected rce depth/range is 61 m/12.57 km: perfect match with simulated data and real data (b) where estimated source depth/range is 63 m/12.2 km.

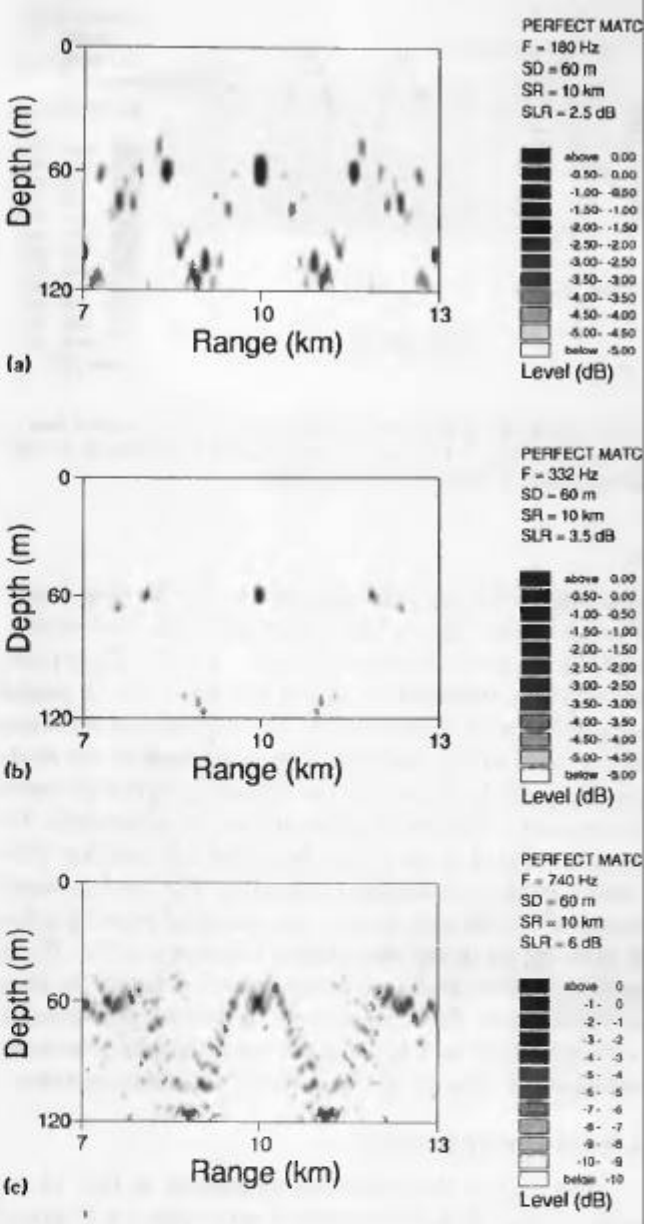


FIG. 4. Range/depth ambiguity surfaces obtained from simulated data i the scenario of Fig. 1. Source depth/range is 60 m/10 km: at (a) 180 Hz (b) 332 Hz, and (c) 740 Hz.

verage concentrated below the thermocline (depth >40 . This is in contrast with the real-data range/depth ambiity surface [Fig. 2(b)], which shows a large number of elobes (even above the thermocline) with levels up to 1 below the maximum. The maximum is obtained for a irce located at 59-m depth and 5.9-km range. This is very se to the expected values (61 m and 6.29 km).

Most parts of the other runs were made at longer ranges, m 10–25 km. Figure 3 shows one occasional result obned at a range of 12.5 km and for a source depth of 61 m. e range/depth surface of Fig. 3(a) (simulated data) is ilar to that of Fig. 2(a), however, it shows some higher elobes up to 2.5 dB below the maximum, due to the longer ge of propagation. Figure 3(b) (real data) shows a prely located source with a sidelobe rejection of 1.5 dB and a y small range-depth estimation error of 3% both in depth l in range. Note here, however, that in contrast to the ult of Fig. 2(b), no significant sidelobes appear above the rmocline, considerably reducing the surface ambiguity. is reduction is due to the fact that only a reduced number modes have been used for the range/depth match: 8 des out of the 17 supported by the channel.

DISCUSSION

The real data performance of the normal-mode matchprocessor will be discussed on the basis of simulated data ults obtained in the same source-medium-receiver condi-

environment and receiver mismatch tests. Comparison i made with the performance and robustness of the matched field processor in the same conditions.

Before starting the discussion of each particular envi ronment or system parameter, let us look at the expecte performance of the normal-mode matching processor in th real source-medium-receiver conditions free of both nois and mismatch. For this test, two source depths were select ed: a shallow source at 6 m and a deep source at 60 m. A mean range of 10 km was chosen for this test. The result obtained for the three source frequencies are shown in Fig. 4 At 180 Hz only nine modes exist, which results in a sma sidelobe rejection of 1 dB for the shallow source (not shown and 2.5 dB for the deep source [Fig. 4(a)]. At 332 Hz [Fig

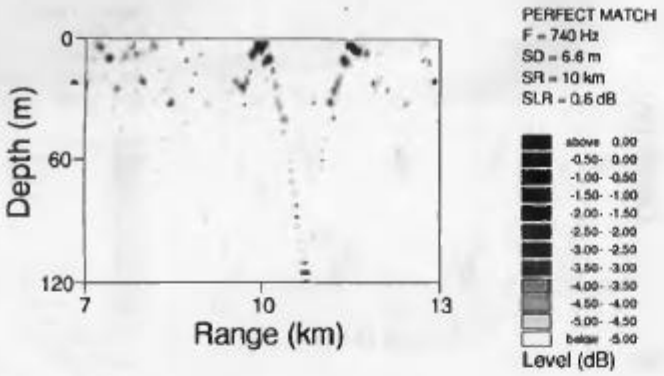


FIG. 5. Range/depth ambiguity surfaces obtained from simulated data in the scenario of Fig. 1. True source depth/range of 6 m/10 km at 740 Hz. Estimated source depth/range is 6.6 m/10 km.

increased to 3.5 and 6 dB respectively, for the deep source position (60 m). Severe localization problems were encountered for the shallow source at 740 Hz (Fig. 5). These problems can be explained by noting that from the 38 modes supported by the channel at 740 Hz only the first 30 modes can be resolved by the array (estimated rank of the mode depth matrix **A**). However, the remaining eight high-order modes carry a non-negligible amount of information for sources situated in the surface layer and it is therefore difficult to obtain a reasonable localization. For the 6-m depth source at 332 Hz (not shown), the estimated source depth is in error by 0.6 m and the sidelobe rejection is of 3.5 dB. In general, the best results were obtained at 332 Hz for the deep source location. The assessment of the relative performance of the normal-mode matching and matched-field processors using the real data set of Fig. 2 follow in the next sections.

A. Environmental effects

The bottom characteristics established in Ref. 14 assume a 2.5-m-thick fluid sediment with density 1.75 g/cm^3 and compressional-wave attenuation of 0.13 dB/λ. The sound speed in the sediment varies from 1530 to 1600 m/s. The subbottom has a slightly higher density (1.8 g/cm^3) and an attenuation of 0.15 dB/λ. The sound speed in the su tom is assumed equal to 1600 m/s.

In previous studies,[4,15] it was mentioned that bo normal-mode matching and the matched-field proc were relatively insensitive to mismatches on bottom p ties. This conclusion was based on simulated tests w array of sensors spanning the total 120-m water colum a sound source emitting a continuous wave at 740 Hz

Using the scenario of Fig. 1, and a frequency of 33 it has been found that even small changes in some b parameters could significantly degrade the result. T mainly due to the reduced array aperture, the down refracting profile and the lower source frequency (332 Among the several tests, the results obtained with misr on the subbottom sound speed is particularly intere Figure 6 shows the range/depth ambiguity surface obt from the normal-mode matching of the true field with tom sound speed $C_b = 1800$ m/s and a replica field ge ted with $C_b = 1600$ m/s. Note the striking resemb between this result and the real data result of Fig. 2(this case, the sidelobe coverage at shallow depths is d the bottom sound speed mismatch which results in a number of unresolved modes: 17 modes are assumed $C_b = 1600$ m/s while 29 modes do exist on the true obtained with $C_b = 1800$ m/s. The result of processin real data record of Fig. 2(b) with $C_b = 1700$ m/s is sho Fig. 7. The sound source is unambiguously located w sidelobe rejection greater than 1 dB at 56-m depth an km range. The overall aspect of the range/depth surfa tained in this case is much closer to that expected fro perfect match case [Fig. 2(a)]. Changes in other env mental parameters such as water depth and bottom ment attenuation, showed no improvement.

B. System effects

In Fig. 2(a) and (b), the source location is pre pinpointed. This high resolution indicates that a rela high number of accurately estimated modes were use ing the match process. However, Fig. 2(b) exhibits a number of high-level sidelobes at shallow depths tha absent in the perfect match case of Fig. 2(a). These

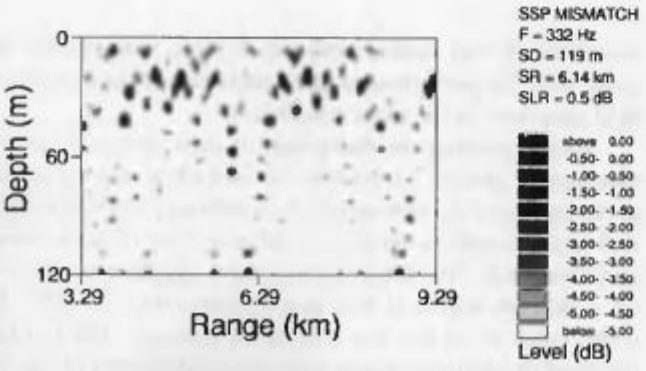


FIG. 6. Range/depth ambiguity surfaces obtained from simulated data in the scenario of Fig. 1 with subbottom sound speed mismatch: true 1800

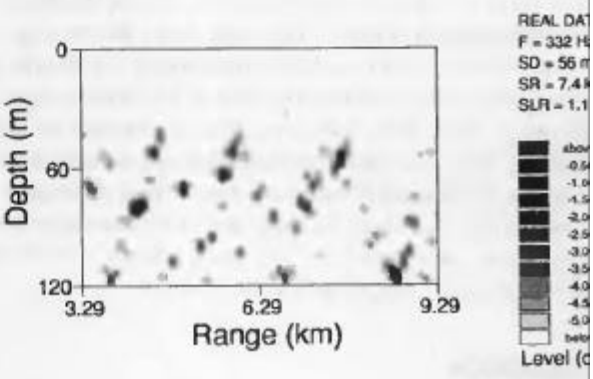
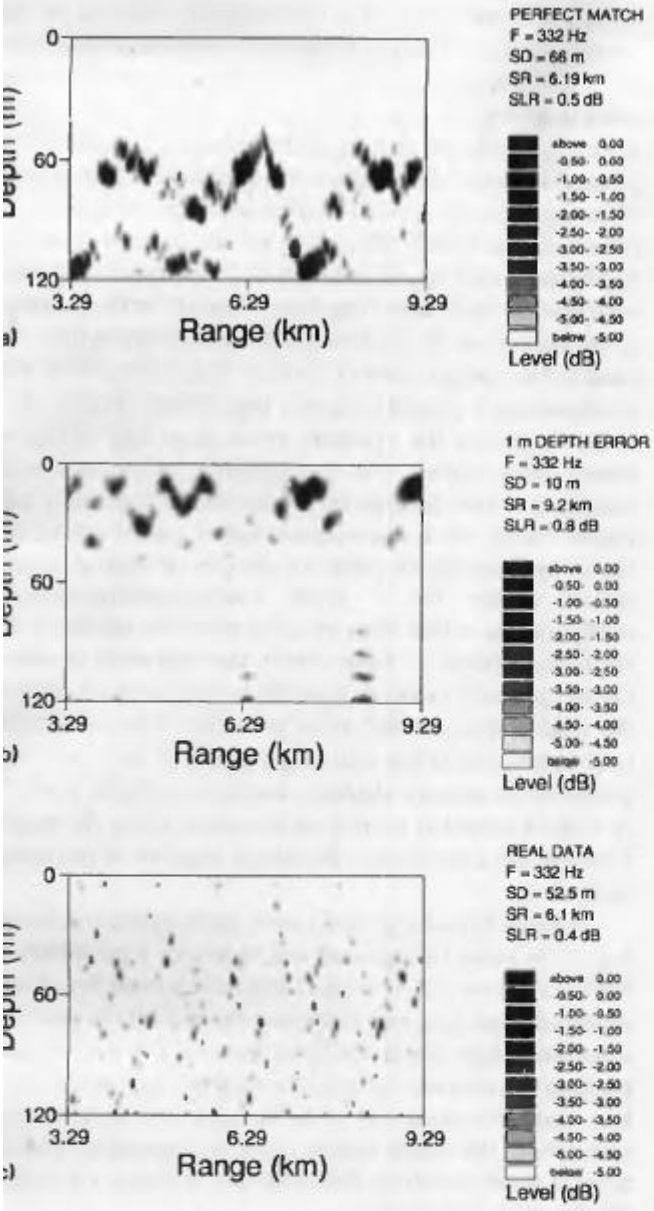


FIG. 7. Range/depth ambiguity surface obtained with real data of Fi and in the scenario of Fig. 1 with bottom sound speed of 1700 m/s, ins



IG. 8. Range/depth ambiguity surfaces obtained in the scenario of Fig. 1 ith simulated data and true source depth/range of 61 m/6.29 km: with onventional matched-field processing (a), estimated source depth/range 6 m/6.19 km; 1-m array depth mismatch and normal-mode matching (b), timated source depth/range 10 m/9.2 km. (c) shows the range/depth mbiguity surface obtained with conventional matched-field processing on ie real data set of Fig. 2(b) and in scenario of Fig. 1. Expected source epth/range is 61 m/6.29 km, estimated 52.5 m/6.1 km.

obes, found almost continuously during that 20-min run, re responsible for a number of losses of source localizations nd may be due to sensor position errors which induce mode stimation inaccuracies. The higher-order modes and those ith the lowest signal-to-noise ratio are the most sensitive to iese errors. The relatively short range (5–7 km) implies iat these modes still carry a non-negligible quantity of ource location information needed for the range/depth lo- alization process. This is apparently not the case shown in ig. 3. The longer range (12 km) attenuates the higher-or- depth match, enhancing the source localization by reduci the sidelobes at shallow depths [Fig. 3(b)].

Tests done with the real data record [Fig. 2(b)] whe the array has been raised by 1 or 2 m with respect to t assumed array depth of 40 m, and/or tilted by a few degre showed that the sidelobe structure above the thermocli could be, in some cases, enhanced. In these cases, the sou location was lost or ambiguous with a very low sidelobe jection. This raises the question: How sensitive are matche field techniques to errors on the sensor location? From sy thetic data studies,[15,16] it was deduced that bo normal-mode matching and the matched-field processo have equivalent sensitivity to sensor position mismatch. T sensitivity is claimed to be of the order of one wavelength accuracy in sensor depth and about 0.5 deg of tilt, for array spanning the total water column. In our case, whe the array spans only half the water column, one may expec higher sensitivity. This is illustrated by first showing wi simulated data [Fig. 8(a)], the range/depth ambiguity su face obtained by matched-field processing in the sa source/receiver environment used for Fig. 2. The source estimated roughly at the correct location (66-m depth, 6.1 km range) with, however, a large ambiguity (sidelobe rej tion 0.5 dB; localization accuracy $\pm$ 11 m in depth, $\pm$ 0 km in range). If the replica field is generated for an arr raised by 1 m, the result using normal-mode matching is loss of the source location [Fig. 8(b)] while with t matched-field processor the result is still poor but very clo to that obtained in the perfect match case of Fig. 8(a). other words with short arrays, a conventional matched fie is more robust than normal-mode matching to sensor dep mismatch. This result can be easily understood by noti that the main difference between the two processors co cerns the number of modes that can effectively be resolved a given situation. The influence of sensor depth errors mode estimation is higher for the highest-order modes. In short-array configuration, this penalizes normal-mo matching when compared to conventional matched fie This is confirmed by looking at the matched-field result o tained from the real data record of Fig. 2, shown in Fig. 8(c This range/depth ambiguity surface is consistent with th of Fig. 2(b) (sidelobes at shallow depths) with, however poorer localization (sidelobe rejection of 0.4 dB and sour location estimate 52.5-m depth, 6.1-km range). The effect an horizontal sensor displacement degrades in the sa manner for both processors. To some extent, the uncertain of sensor position can be taken into account on both proce sors by introducing the appropriate correction factors f range and depth.

A few other remarks can be made when comparing no mal-mode matching results presented here and those o tained with conventional matched-field on the same re data set.[4] In general, the localizations obtained with conve tional matched-field are poorly defined, i.e., small resoluti both in depth and range as well as poor sidelobe rejectio typically 0.3 dB, compared to 1 or 1.5 dB with normal-mo matching. However, with a conventional matched field sor results have been shown for the highest frequency (738 H

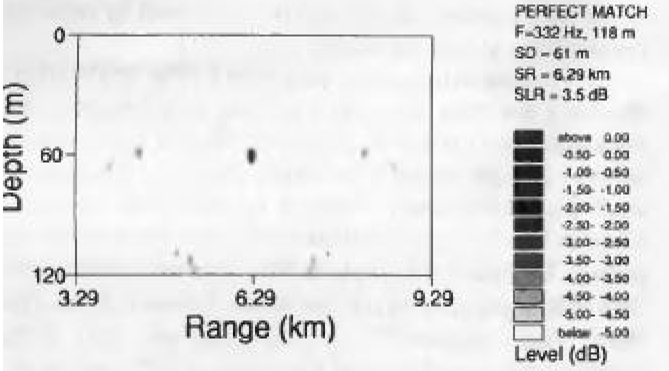


FIG. 9. Range/depth ambiguity surface obtained from simulated data on nvironmental conditions of Fig. 1 but with a 118-m-long array. True ource location 61 m/6.29 km. This result was obtained either by normal-node matching or conventional matched-field processing.

occasional and poor results could be obtained with normal-node matching under similar conditions. This performance of the conventional matched-field processor is certainly due to its robustness to errors in the sensor location a particularly important concern both for shallow sources (in our particular environment) and for high frequencies. The main limitation of a conventional matched field is the small number of modes that can be resolved. This number depends essentially on the configuration of the receiving system, i.e., the effective aperture of the array relative to the acoustic channel in which the source energy propagates. To illustrate this point, we deviate from the receiving array structure of the real data study in order to simulate a 118-m array that spans the total water column (60 hydrophones at 2-m spacing). Figure 9 shows that the result is, as expected, identical for both processors and shows approximately the same performance as that obtained with normal-mode matching in the 62-m-long array case [Fig. 2(a)]. This result shows that the normal-mode matching, unlike the conventional matched field, takes into account the effective aperture and geometry of the array in the range/depth match process and adapts to it [see Eq. (9) and related remarks]. This feature is particularly important in shallow-water environments where the sound wave strongly interacts with the bottom, and therefore leaks a large amount of energy.

IV. CONCLUSION AND PERSPECTIVES

The performance of the normal-mode matching source localization method has been analyzed through a real data study. The two main issues for performance characterization are the sidelobe behavior of the range/depth ambiguity surface and the robustness of the method to environmental and source/receiver parameters mismatch. The dependence of the method on the precise knowledge of the receiving system geometry has also been studied. A comparison has been made with results obtained by the conventional matched field in the same conditions.

The results obtained with real data confirm the ability of normal-mode matching to handle short vertical arrays. Compared with the real data results obtained by matched

sulting in some cases in a unambiguous estimate of source position. However, a relatively high sensitivity to s sor position and/or noise has been noticed, leading in so cases to ambiguous and/or inaccurate source location e mates. It is believed that normal-mode matching is less pendent than the conventional matched field on the num of modes that significantly contribute to the acoustic fi therefore, it is weakly affected by known changes in the vironmental and source parameters;[15] the results obtai with normal-mode matching mainly depend on the accur of the normal-mode amplitude estimates which, in turn, pend on the configuration of the receiving system. When t configuration is precisely known, the method adapts to i order to achieve the optimum result according to the sumed data model. The performance of normal-m matching mainly depends on the number of accurately e mated modes. As a consequence, better results can be tained by selecting an optimum number of accurately e mated modes for a given source–medium–recei configuration, rather than by using all of the modes in matching process. To some extent, the suggestion of sel ing an optimum number of modes is reinforced by some the results obtained with real data where detections co only be obtained when matching a subset of the modes s ported by the acoustic channel. Another possibility would to make a weighted normal-mode match where the wei function was a monotonic decreasing function of increas mode order.

A better knowledge of the array position and the mod ing of the noise background will represent a possibility further improve the robustness and detection ability of n mal-mode matching and therefore, its reliability in practi situations where the model describes well the real physi propagation characteristics of the medium. In practical sh low-water situations, due to the strong bottom-sound w interaction, the sound field is often undersampled mak normal-mode matching the technique of choice for ran depth source localization.

ACKNOWLEDGMENTS

Thanks are due to Dr. R. D. Hollett, who was respon ble for the at-sea data collection, and to S. Bongi, who dev oped all the plotting software used in this paper.

[1] H. P. Bucker, "Use of calculated sound fields and matched-field detec to locate sound sources in shallow water," J. Acoust. Soc. Am. 59, 3 373 (1976).

[2] R. Klemm, "Range and depth estimation by line arrays in shallow wat Signal Process. 3, 333–344 (1981).

[3] E. J. Sullivan, "Passive localization using propagation mod SACLANTCEN SR-117 [AD A189404], La Spezia, Italy, SACLA Undersea Research Centre (1987).

[4] R. M. Hamson and R. M. Heitmeyer, "Environmental and system ef on source localization in shallow water by the matched-field processin a vertical array," J. Acoust. Soc. Am. 86, 1950–1959 (1989).

[5] G. B. Smith, C. Feuillade, D. R. DelBalzo, and C. L. Byrne, "A nonli matched-field processor for detection and localization of a quiet sour a noisy shallow-water environment," J. Acoust. Soc. Am. 85, 1158–1 (1989).

[6] E. C. Shang, "Source depth estimation in waveguides," J. Acoust.

ng in waveguides by using mode filter," J. Acoust. Soc. Am. 78, 172–175 1985).
I. C. Yang, "A method of range and depth estimation by modal decompo-ition," J. Acoust. Soc. Am. 82, 1736–1745 (1987).
G. R. Wilson, R. A. Koch, and P. J. Vidmar, "Matched mode localiza-ion," J. Acoust. Soc. Am. 84, 310–320 (1988).
E. C. Shang, "An efficient high-resolution method of source localization processing in mode space," J. Acoust. Soc. Am. 86, 1960–1964 (1989).
I. Tolstoy and C. S. Clay, *Ocean Acoustics* (McGraw-Hill, New York, 1966).
F. B. Jensen and M. C. Ferla, "SNAP: The SACLANTCEN normal-node acoustic propagation model," SACLANTCEN SM-121 [AD A067256], La Spezia, Italy, SACLANT Undersea Research Centre (1979).
G. Strang, *Linear Algebra and its Applications* (Academic, New York, 1976).
[14] F. B. Jensen, "Comparison of transmission loss data for different shall water areas with theoretical results provided by a three-fluid norm mode propagation model," SACLANTCEN CP-14 [AD A004805], Spezia, Italy, SACLANT Undersea Research Centre (1974).
[15] S. M. Jesus, "Source localization in shallow water by normal mo matching: synthetic and real data analysis," SACLANTCEN SR-1 [AD B140556], La Spezia, Italy, SACLANT Undersea Research Cen (1989).
[16] R. M. Hamson and R. M. Heitmeyer, "An analytical study of the effect environmental and system parameters on source localization in shall water by matched field processing of a vertical array," SACLANTCE SR-140 [AD B134955], La Spezia, Italy, SACLANT UnderSea R search Centre (1988).