Three-dimensional multiple-source focalization in an uncertain ocean environment

Dag Tollefsen[a)]
Norwegian Defence Research Establishment (FFI), Box 115, 3191 Horten, Norway
dag.tollefsen@ffi.no

Stan E. Dosso
School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia V8W 3P6, Canada
sdosso@uvic.ca

Abstract: This letter develops a Bayesian focalization approach for three-dimensional localization of an unknown number of sources in shallow water with uncertain environmental properties. The algorithm minimizes the Bayesian information criterion using adaptive hybrid optimization for environmental parameters, Metropolis sampling for source bearing, and Gibbs sampling for source ranges and depths. Maximum-likelihood expressions are used for unknown complex source strengths and noise variance, which allows these parameters to be sampled implicitly. An efficient scheme for adding/deleting sources is used during the optimization. A synthetic example considers localizing a quiet source in the presence of multiple interferers using a horizontal line array.

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1. Introduction

Localization of multiple acoustic sources in the ocean, e.g., a weak submerged source in the presence of one or more strong interferers, is a challenging but important problem.[1–4] Matched-field processing[5] can be applied but requires knowledge of the acoustic environment and environmental model mismatch[6] can represent a limiting factor. To address mismatch, optimization over unknown environmental parameters to obtain the most probable source coordinates can be applied.[7] To simultaneously localize multiple sources in a known environment, Michalopoulou[4] developed an approach based on Gibbs sampling over unknown source locations, strengths, and variances. Dosso and Wilmut[8] and Dosso[9] developed a Bayesian focalization approach for simultaneous two-dimensional (2D) (range-depth) localization of an unknown number of sources in an unknown environment. Neilsen[3] localized multiple sources in three dimensions in known and (fixed) mismatched environments. Three-dimensional (3D) focalization of a single source in an uncertain environment was considered in Ref. 10.

This letter develops a Bayesian focalization approach to 3D localization of an unknown number of sources in an uncertain shallow-water environment with application to horizontal line array (HLA) data. The idea is to formulate a joint inversion over unknown source locations (range, depth, and bearing), complex source strengths (amplitude and phase at each frequency), and uncertain environmental properties. By also sampling over an unknown number of sources, the Bayesian information criterion (BIC) yields the number of sources consistent with data. The approach is applied to simulated data for a HLA in shallow water. This letter extends the approach in Ref. 8

[a)]Author to whom correspondence should be addressed.

from 2D to 3D focalization and to optimizing for an *a priori* unknown number of sources, and extends the 3D focalization approach of Ref. 10 to multiple sources.

2. Theory and algorithms

Consider complex acoustic data $\mathbf{d} = \{\mathbf{d}_f;\, f = 1,F\}$ at an N-sensor array and F frequencies. The acoustic field is assumed to be due to S sources at locations (range, depth, bearing) $\mathbf{x} = \{\mathbf{x}_s = (r_s,z_s,b_s);\ s = 1,S\}$. The data misfit is taken to be the negative log-likelihood function under the assumption of complex, circularly-symmetric Gaussian-distributed errors, with unknown source strengths $\mathbf{a} = \{[\mathbf{a}_f]_S\}$ (complex vectors with S elements) and unknown error variances ν_f. The data misfit function can then be written[8]

$$E(\mathbf{m};\mathbf{d}) = N\sum_{f=1}^{F} \log_e|(\mathbf{I} - \mathbf{D}_f(\mathbf{D}_f^{\dagger}\mathbf{D}_f)^{-1}\mathbf{D}_f^{\dagger})\mathbf{d}_f|^2, \tag{1}$$

where $\mathbf{D}_f$ is the $N \times S$ matrix defined by $[\mathbf{D}_f]_{hs} \equiv [\mathbf{d}_f(\mathbf{x}_s,\mathbf{e})]_h$ with $\mathbf{d}_f\,(\mathbf{x}_s,\mathbf{e})$ the modeled acoustic fields for a unit-amplitude, zero-phase source at location $\mathbf{x}_s$; $\mathbf{I}$ is the identity matrix and † represents conjugate transpose. The set of unknown model parameters is $\mathbf{m} = \{\mathbf{x},\mathbf{e},\mathbf{a},\nu\}$ with $\mathbf{e}$ representing N_E unknown environmental parameters. Evaluating Eq. (1) for explicit $\mathbf{x}$ and $\mathbf{e}$ applies the maximum-likelihood (ML) solutions for unknown source strengths and error variances, given by[8]

$$\hat{\mathbf{a}}_f = (\mathbf{D}_f^{\dagger}\mathbf{D}_f)^{-1}\mathbf{D}_f^{\dagger}\mathbf{d}_f \ \ ; \ \ \hat{\nu}_f = \frac{1}{N}\,|(\mathbf{I} - \mathbf{D}_f(\mathbf{D}_f^{\dagger}\mathbf{D}_f)^{-1}\mathbf{D}_f^{\dagger})\mathbf{d}_f|^2, \tag{2}$$

respectively, and the corresponding variability in these parameters is accounted for implicitly. This replaces explicit sampling over $\mathbf{a}$ and ν, and has proven to yield an efficient approach for multiple-source problems.[8]

Determining the number of acoustic sources that contribute to the total acoustic field is an important issue in multiple-source localization. The approach applied here[9] is to evaluate the BIC, which can be written as:

$$\text{BIC} = 2E(\hat{\mathbf{m}};\mathbf{d},I) + M\log_e K, \tag{3}$$

where $\hat{\mathbf{m}}$ is the optimal model for model parameterization I (includes environment and sources), with $M = 2SF + F + 3S + N_E$ the total number of parameters, and $K = 2FN$ the number of data.

The focalization approach developed here is based on a series of perturbation cycles (iterations) over a decreasing control parameter (referred to as temperature): (1) Perturbing and accepting/rejecting environmental parameters via adaptive simplex simulated annealing (ASSA),[11] (2) perturbing and accepting/rejecting source bearings via the Metropolis criterion, (3) perturbing source ranges/depths via 2D Gibbs sampling, and (4) attempting a source insertion or a source deletion. Applying different sampling schemes for different types of parameters has been found to yield an efficient algorithm for the type of problem addressed here.[8,9,12]

ASSA, which combines the global search method of very fast simulated annealing with the local downhill simplex (DHS) method, is applied to optimize over environmental model parameters. DHS operations are followed by a random perturbation of all parameters, and the resulting model is conditionally accepted based on the Metropolis criterion (here applied to the BIC).

Source locations are sampled in two steps [(2) and (3) above]: Bearing is sampled by random perturbations drawn from a Cauchy distribution adaptively scaled based on a linearized estimate of the bearing variance multiplied by temperature; the resulting model is conditionally accepted based on the Metropolis criterion. Range/depth sampling is then carried out via 2D Gibbs sampling from conditional probability surfaces computed at a fixed grid of source ranges and depths.

Sampling of the number of sources is based on attempting either a source addition or a deletion (probability 0.5 for either). If a source insertion is attempted, the bearing of the new source is based on one-dimensional Gibbs sampling of the conditional distribution for bearing sampled from a coarse grid over the search interval and refined by a local derivative approximation; range and depth is then set by 2D Gibbs sampling. The new source is assigned ML values for source strength, and the insertion is accepted or rejected according to the Metropolis criterion. This procedure has been found to yield an efficient compromise between 3D Gibbs sampling (computationally expensive) and source insertion at a randomly chosen position (low probability of acceptance). If a source deletion is attempted, a source is selected uniformly at random among the existing sources. The locations and strengths of the remaining sources are reassigned: Source locations are sampled in two steps as outlined above, with ML values assigned for all source strengths. The new model is accepted or rejected according to the Metropolis criterion.

3. Example

The test case involves simulated acoustic data received at a 400-m long HLA on the seafloor in a 100-m deep acoustic waveguide. The array is comprised of 41 sensors spaced at 10-m intervals; this relatively sparse array (element spacing greater than one acoustic wavelength) was chosen to keep computational efforts reasonable. The scenario consists of two strong surface sources (denoted sources 1 and 2) at different bearings and one weak submerged source (source 3) at the same bearing as source 2. The source locations are $(r_1, z_1, b_1) = (4\,\mathrm{km}, 8\,\mathrm{m}, 6^\circ)$, $(r_2, z_2, b_2) = (8\,\mathrm{km}, 8\,\mathrm{m}, 30^\circ)$, and $(r_3, z_3, b_3) = (7\,\mathrm{km}, 50\,\mathrm{m}, 30^\circ)$, with corresponding signal-to-noise ratios (SNRs) at the array of 15, 8, and 0 dB at each of 9 frequencies uniformly spaced over 200 to 400 Hz. At each frequency, complex Gaussian errors were added to the synthetic data with variances and source amplitudes set to achieve the given SNRs (amplitudes $A_{sf} = |[\mathbf{a}_f]_s|$ are approximately 1.00, 0.78, and 0.28 for the three sources, respectively). Source phases were set independent of frequency to 45°, 90°, and −90° for the three sources, respectively.

The environmental model, representative of the shallow continental shelf, consists of a water column of depth D and a seabed with a semi-infinite seabed with geoacoustic parameters sound speed (c_b), density (ρ_b), and attenuation (α_b). The water-column sound-speed profile is described by two parameters (c_1 and c_2) at depths of 0 and D m. Table 1 lists the true values for all environmental parameters together with the search bounds applied. (Relatively small search bounds were chosen for water column and seabed parameters due to the computational complexity of the problem.) The range-depth search grid defining the 2D conditional probability surfaces cover 1.2 to 10.0 km in range (grid spacing 50 m) and 2 to 98 m in depth (grid spacing 2 m). Search bounds for bearing were set from 0° to 180° re array endfire direction for each source. The number of sources is unknown but constrained to be 1 to 5.

The normal-mode numerical propagation model ORCA (Ref. 13) was used to compute synthetic data and replica acoustic pressure fields. The number of acoustic field computations required for each model $\mathbf{m}$ is $J \cdot N \cdot S$, where J is the number of range-depth grid points, and the factor S (number of sources) is due to variation in

Table 1. Environmental model parameters, true values, and search bounds.

Parameter and units	True value	Search bounds
c_b (m/s)	1580	[1570, 1590]
ρ_b (g/cm^3)	1.50	[1.36, 1.64]
α_b (dB/λ)	0.10	[0.02, 0.18]
c_1 (m/s)	1514	[1511, 1517]
c_2 (m/s)	1510	[1507, 1513]
D (m)	100	[98, 102]

grid to array element ranges (N elements) with bearing. For the given problem, $\sim 10^6$ field computations are required per frequency.

Figure 1 shows the focalization process in terms of the BIC, number of sources, and source coordinates for three sources, as a function of iteration. Only one realization of the simplex (the last accepted perturbation) is included at each iteration. The BIC decreases from between -6500 and -7400 over the simplex at start to a final value of -9526 after approximately 1700 iterations. The number of sources initially varies from 1 to 5, and then converges to the correct number of 3 for all simplex models. After initial oscillations over their entire search intervals, source range, depth, and bearing estimates converge to excellent estimates of the true values for all three sources; for the third (weak submerged) source convergence is slower than for the strong sources. The environmental parameters (not shown) converge after approximately 1100 iterations to near their true values. Water depth is offset by approximately 0.6 m and the two water sound speed values are offset by approximately -1 m/s from their true values. Seabed parameters converge to 1578.5 m/s, 1.49 g/cm^3, and 0.10 dB/λ for sound speed, density, and attenuation, respectively.

Figure 2 shows the estimated amplitudes, obtained from Eq. (2), for three sources at each of five (of nine) frequencies. Source amplitudes vary considerably over the first 1100 iterations, and then converge toward the true values for the strongest source (amplitudes A_{1f}), while A_{2f} and A_{3f} converge somewhat slower to near their true values. Source phases (not shown) converged to incorrect values in most cases. These observations of source amplitude and phase estimates are comparable to those obtained for a three-source test problem with a vertical line array.[8]

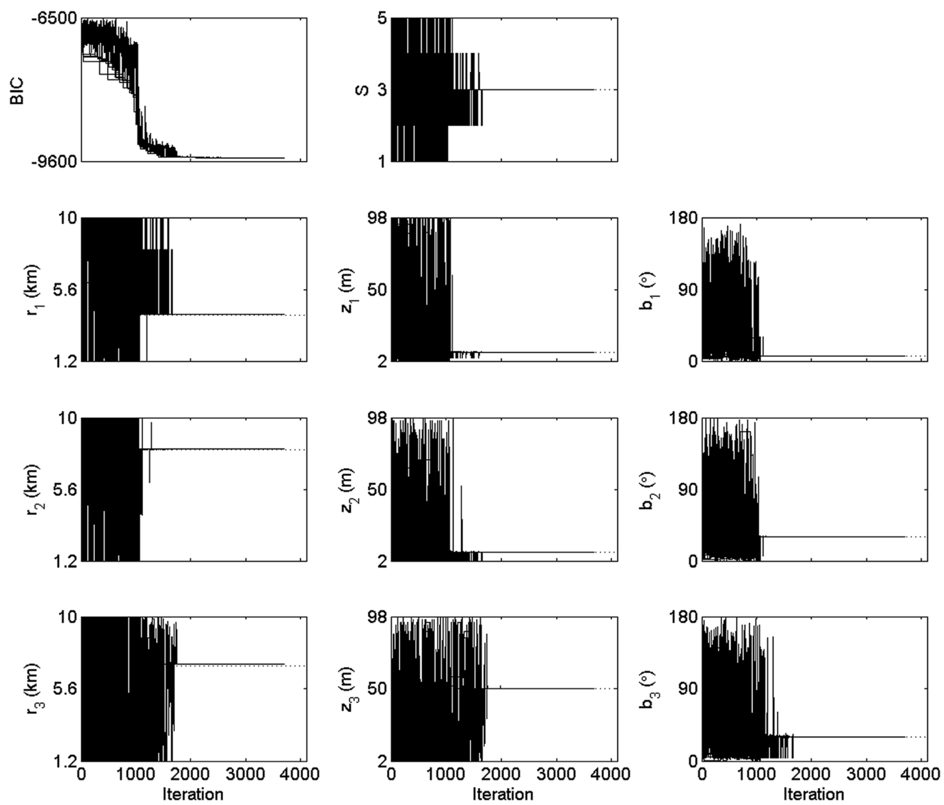

Fig. 1. Focalization process for the BIC, number of sources S, source ranges (r_1 to r_3), depths (z_1 to z_3), and bearings (b_1 to b_3). Dotted lines indicate true parameter values. All parameters are plotted over their search bounds.

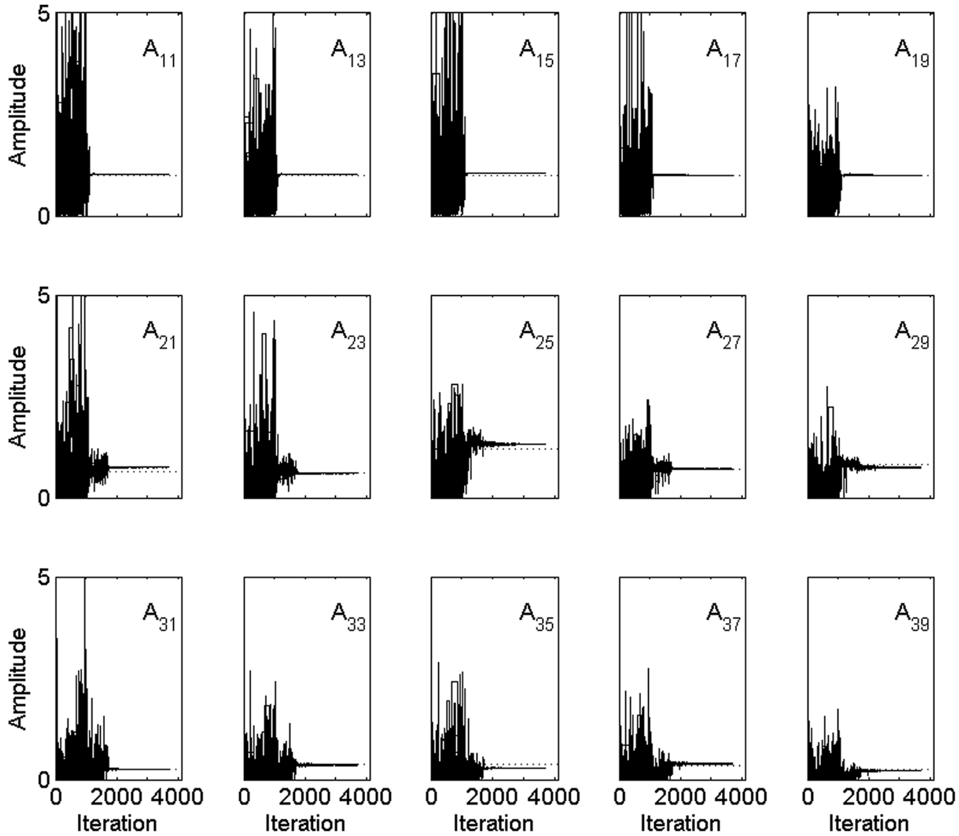

Fig. 2. Focalization process for source amplitudes, A_{sf}, where indices s and f indicate source and frequency number, respectively. Dotted lines indicate true values.

4. Summary

This letter developed and applied a focalization approach for 3D localization of an unknown number of sources in shallow water with uncertain environmental properties using a HLA. The algorithm minimizes the BIC using adaptive hybrid optimization for environmental parameters, Metropolis sampling for source bearing, and 2D Gibbs sampling for source range and depth. For unknown complex source strength and noise variances, maximum-likelihood expressions are used that allow these parameters to be sampled implicitly. An efficient scheme for adding and deleting sources is used during the optimization. The presented example demonstrated the ability of the approach for localizing a quiet source in the presence of multiple interferers in a shallow-water environment with uncertain environmental parameters. Results were presented for sources near the array endfire direction; some degradation of results (in terms of localization errors of one or more sources) may be expected for sources that approach the array broadside. The approach developed in this letter was applied to a range-independent environment; a recent paper[14] successfully applied focalization (and tracking) of a single source to real data in a weakly range-dependent environment modeled as range independent.

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