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Three-dimensional localization of multiple acoustic sources in shallow ocean with non-Gaussian noise

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ABSTRACT

In this paper, a low-complexity algorithm SAGE-USL is presented for 3-dimensional (3-D) localization of multiple acoustic sources in a shallow ocean with non-Gaussian ambient noise, using a vertical and a horizontal linear array of sensors. In the proposed method, noise is modeled as a Gaussian mixture. Initial estimates of the unknown parameters (source coordinates, signal waveforms and noise parameters) are obtained by known/conventional methods, and a generalized expectation maximization algorithm is used to update the initial estimates iteratively. Simulation results indicate that convergence is reached in a small number of (≤ 10) iterations. Initialization requires one 2-D search and one 1-D search, and the iterative updates require a sequence of 1-D searches. Therefore the computational complexity of the SAGE-USL algorithm is lower than that of conventional techniques such as 3-D MUSIC by several orders of magnitude. We also derive the Cramér–Rao Bound (CRB) for 3-D localization of multiple sources in a range-independent ocean. Simulation results are presented to show that the root-mean-square localization errors of SAGE-USL are close to the corresponding CRBs and significantly lower than those of 3-D MUSIC.

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1. Introduction

Three-dimensional (3-D) localization of acoustic sources in shallow ocean is an interesting albeit challenging problem. Conventional methods of 3-D localization include several versions of the matched field processing (MFP) technique such as Bartlett, Capon, and MUSIC processors [1–3]. In the simplest and most robust version, viz., the Bartlett processor, an ambiguity function is computed by correlating the data vector measured by a horizontal linear array (HLA) with replicas of the signal vector on a 3-D grid over the search region. The resultant ambiguity function has a broad peak and a low peak-to-sidelobe ratio. Consequently, the Bartlett processor is susceptible to interference and has a low resolution. The Capon and MUSIC processors provide higher resolution. However, all these methods perform localization through a 3-D search which entails a high degree of computational complexity.

Also, an HLA does not provide good estimates of range and depth since the signal vector at an HLA is not very sensitive to variation of source range and depth. An alternative approach is to use a hybrid 2-D array composed of an HLA and a vertical linear array (VLA). The VLA data may be used to perform multiple-source range–depth estimation by any of the MFP methods [1–3] mentioned above. The HLA data may then be used in conjunction with the estimated range–depth of each source to estimate the bearing of that source through a 1-D search. This approach provides better range–depth estimates. The computational complexity is also reduced since the hybrid array requires one 2-D search for range–depth estimation and J 1-D searches for bearing estimation of J sources.

In recent years, some methods have been developed for bearing estimation of multiple sources in the ocean without prior knowledge of their ranges and depths [4–7]. These methods include subspace intersection method (SIM) [4,5], Rayleigh MUSIC (R-MUSIC) [6], and modified R-MUSIC (R-MUSIC-mdf) [7]. These methods exploit the fact that the N-dimensional signal vector at an array of N sensors belongs to an M-dimensional modal subspace if $N > M$, where M is the number of normal modes supported by the underwater acoustic channel. Thus it is now possible to localize J sources through one 2-D search and one 1-D search if a hybrid array is employed.

None of the above-mentioned localization methods make any assumption about the probability distribution of the additive noise. Hence, these methods can be employed with equal facility in

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all types of environmental noise. However, none of these methods has any claims to optimality in the statistical sense. It is known that the best statistical performance is provided by the maximum likelihood (ML) estimator which is asymptotically efficient and unbiased. Tabrikian and Messer [8] have investigated the problem of ML localization of a monochromatic source in a range-independent ocean in the presence of Gaussian noise using a hybrid array. However, it is known that ambient noise in the ocean is often non-Gaussian with a heavy-tailed probability density function (PDF) due to the impulsive nature of several noise sources such as shipping traffic, snapping shrimp, rain, etc. [9–11]. Extension of Tabrikian and Messer's approach to the problem of localization in non-Gaussian noise is a highly complex task. ML localization involves estimation of not only the $3J$ coordinates of J sources but also a large number of nuisance parameters associated with the signals and noise. Fessler and Hero [12] have proposed space-alternating generalized expectation–maximization (SAGE) algorithm to decrease the complexity of ML estimation. Kozick and Sadler [13] have applied the SAGE algorithm to the problem of estimating the directions of arrival (DOA) and signal waveform of plane waves in non-Gaussian noise represented by a Gaussian mixture model (GMM). Due to the universal approximation property of the GM distribution [14], any heavy-tailed noise PDF in the ocean can be modeled as a GM with a small number of components. In this paper we present an adaptation of the Kozick and Sadler algorithm [13] for 3-D localization of multiple acoustic sources in a range-independent ocean with non-Gaussian noise.

The localization algorithm proposed in this paper will be designated space-alternating generalized expectation–maximization for underwater source localization (SAGE-USL). The proposed algorithm uses data from a hybrid array consisting of an HLA and a VLA. The signals are modeled as complex exponentials with slowly varying amplitudes. Noise is modeled as a zero-mean Gaussian mixture (GM) since a wide class of non-Gaussian heavy-tailed noise distributions, including those encountered in the marine environment, can be well approximated by a GM distribution with a small number of components. The unknown parameters may be divided into two groups: (1) the desired parameters, consisting of the number of sources and their coordinates, and (2) the nuisance parameters, consisting of the signal envelopes and the parameters required to model the Gaussian mixture noise PDF. The algorithm involves initial estimation of all parameters using known methods, followed by an iterative procedure based on a modified version of the SAGE algorithm for updating the estimates sequentially. The noise parameters are initialized using a procedure similar to that of Kozick and Sadler [13]. The number of sources is estimated using the minimum description length (MDL) criterion [15]. Initial estimates of source ranges and depths are obtained from the VLA data using 2-D MUSIC algorithm [3], and initial bearing estimates are obtained from HLA data using the R-MUSIC-mdf algorithm [7]. A simple search-maximize-discard algorithm, described in Section 3 is used to determine the pairings of the range–depth and bearing estimates. The full hybrid array data and the estimated source locations are used to obtain initial estimates of the source envelopes. A modified version of the SAGE algorithm is then used to update the initial estimates. This paper is an extension of our earlier work [16] on localization of a single source in shallow ocean with non-Gaussian noise using a hybrid array.

In this paper, we have also derived expressions for Cramér–Rao bound (CRB) for 3-D localization of underwater acoustic sources in non-Gaussian noise with symmetric PDF. We have compared the root mean square localization errors of the proposed SAGE-USL algorithm and the classical 3-D MUSIC algorithm [3] with the CRB. Simulation results show that the performance of the proposed algorithm is significantly better than that of 3-D MUSIC.

The paper is organized as follows. The data model is presented in Section 2. Details of the proposed 3-D localization algorithm are presented in Section 3. Derivation of the CRB is presented in Section 4. The computational complexity of the proposed algorithm is analyzed in Section 5. Simulation results and conclusions are presented in Sections 6 and 7 respectively.

2. Data model

Consider a T-shaped array of N sensors receiving narrowband signals of center-frequency $(\omega/2\pi)$ from J far-field point sources in a deterministic and time-invariant shallow ocean. Let the array be composed of a uniform N_H-sensor HLA with inter-sensor spacing d_H located at depth z_H, and a uniform VLA of $N_V = N - N_H + 1$ sensors located at depths $z_{V_n} = z_{V_1} + (n-1)d_V$, $n = 1, \dots, N_V$. Let the array output at time t be denoted by the $N \times 1$ vector $\mathbf{y}(t)e^{-j\omega t}$. We consider K snapshots of $\mathbf{y}(t)$, which can be expressed as

$$\mathbf{y}(t) = \left[\mathbf{y}_H(t)^{\mathrm{T}}\, \mathbf{y}_V(t)^{\mathrm{T}}\right]^{\mathrm{T}}; \quad t = 1, \dots, K, \tag{1}$$

$$\mathbf{y}_H(t) = \mathbf{P}_H(\mathbf{x})\mathbf{s}(t) + \mathbf{w}_H(t), \qquad \mathbf{y}_V(t) = \mathbf{P}_V(\mathbf{x})\mathbf{s}(t) + \mathbf{w}_V(t), \tag{2}$$

where $\mathbf{y}_H(t) = [y_{H,1}(t) \dots y_{H,N_H}(t)]^{\mathrm{T}}$ and $\mathbf{y}_V(t) = [y_{V,1}(t) \dots y_{V,N_V}(t)]^{\mathrm{T}}$ are the received data vectors at the HLA and VLA respectively, $\mathbf{w}_H(t) = [w_{H,1}(t) \dots w_{H,N_H}(t)]^{\mathrm{T}}$ and $\mathbf{w}_V(t) = [w_{V,1}(t) \dots w_{V,N_V}(t)]^{\mathrm{T}}$ are the corresponding additive noise vectors, and superscript T denotes matrix transpose. The vector $\mathbf{s}(t)$ is defined as $\mathbf{s}(t) = [s_1(t) \dots s_J(t)]^{\mathrm{T}}$, where $s_j(t)$ is the slowly varying complex amplitude of the jth source signal at time t. We assume a "conditional model" [17] for the signals, wherein the signal envelopes $\{s_j(t);\ t = 1, \dots, K\}$, for $j = 1, \dots, J$, are modeled as unknown nonrandom functions. The vector $\mathbf{x} = [\mathbf{x}_1 \dots \mathbf{x}_J]$ is a row vector of the source positions where $\mathbf{x}_j = [r_j, z_j, \theta_j]$ denotes the jth source position in terms of range r_j, depth z_j, and bearing θ_j. The range r_j is measured with reference to the VLA and the bearing θ_j is measured with reference to the endfire direction of the HLA. It is assumed that any change in the source position over the set of K snapshots is negligible. The matrices

$$\mathbf{P}_H(\mathbf{x}) = \left[\mathbf{p}_H(\mathbf{x}_1) \dots \mathbf{p}_H(\mathbf{x}_J)\right], \qquad \mathbf{P}_V(\mathbf{x}) = \left[\mathbf{p}_V(\mathbf{x}_1) \dots \mathbf{p}_V(\mathbf{x}_J)\right] \tag{3}$$

are the steering matrices of the HLA and the VLA, and $\mathbf{p}_H(\mathbf{x}_j)$ and $\mathbf{p}_V(\mathbf{x}_j)$ are the steering vectors denoting the response of these arrays to a source of unit strength located at the position $\mathbf{x}_j$.

We shall model the ocean as a range-independent waveguide in which the sound speed, density, and water column depth are range-independent, i.e. a water column of depth h, sound speed c and density ρ lies over a sea bed of sound speed c_b and density ρ_b. Absorption in the ocean bottom is taken into account by assuming the sound speed c_b to be a complex-valued function. According to the normal mode theory of sound propagation in a waveguide [18], the acoustic pressure due to a point source in the far-field region can be expressed as the sum of a discrete set of normal modes. Under the far-field approximation, the signal vector at the HLA due to the jth source can be expressed as [18]

$$\mathbf{p}_H(\mathbf{x}_j) = \mathbf{A}(\theta_j)\mathbf{b}(r_j, z_j); \quad j = 1, \dots, J, \tag{4}$$

where $\mathbf{b}(r_j, z_j) = [b_{1j} \dots b_{Mj}]^{\mathrm{T}}$ is the mode amplitude vector whose elements are

$$b_{mj} = \Psi(z_H)\Psi(z_j)\frac{e^{(ik_m - \alpha_m)r_j}}{\sqrt{k_m r_j}}; \quad m = 1, \dots, M, \tag{5}$$

and $\mathbf{A}(\theta_j)$ is an $N_H \times M$ matrix expressed as

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