HIGH RESOLUTION BEAMFORMING APPLIED TO A DIFAR SONOBUOY

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Introduction

An important sensor used in Naval acoustic operations is the directional frequency and recording (DIFAR) sonobuoy. The hydrophone component contains three sensors, making it possible to obtain directional acoustic information from a single device. A bender element, on the bottom of the hydrophone, measures the omni-directional component of acoustic pressure. The direction of the signal is obtained from two orthogonal sensors, combined in a separate cruciform-shaped wobbler assembly that measure the x and y components of acoustic pressure wavenumber. Each has a beam pattern consisting of two circles similar in shape to the well-known acoustic doublet.

Present DIFAR direction processing (Bscan) uses the arctangent of the co-spectra between the omni and two directional channels to estimate target bearing at only a single direction at each frequency. This technique may introduce errors when two sources such as a surface ship and an underwater target radiate energy simultaneously at the same frequency. The resulting bearing estimate will lie somewhere in between, usually closer to the stronger one, an effect known as *bearing bias* [1]. Debiasing algorithms can reduce these effects by removing non-signal components [2]. However, this method only addresses the bias that is introduced by relatively broadband interference masking discrete tonals. With two sources producing narrowband signals at the same frequency, bearing errors are still likely to occur [1].

An alternate approach is to apply beamforming algorithms to the Fourier transformed data in order to resolve energy received from multiple directions. The simplest is the conventional beamformer. It is very broad-banded and incapable of detecting point directional sources. Recently, high resolution, data adaptive techniques have been proposed that are particularly effective for small arrays of omni-directional sensors. The mathematical equivalent to the directional DIFAR buoy is the heave, pitch and roll buoy that has long been used by the oceanographic community to determine directional spectra of surface gravity waves ([5], [6] , [7]) and more recently [8] high frequency internal waves. The first of these is the maximum likelihood (ML) beamformer [3]. A spectral window is designed that favours transmission of point sources, while suppressing sidelobes. A generalization of the ML is the eigenvector (EIG) technique [4]. A noise matrix is defined and a spectral window, similar to that of the ML determined. Iterative improvements to the ML [5] and the EIG [6] have been proposed that further sharpen the directional resolution of these three-element point sensors.

The purpose of this presentation is to apply high resolution beamforming to DIFAR data and to assess its efficacy in resolving multiple direction point sources.

Theory

The DIFAR hydrophone provides three time series:

$$x_{ok}$$

$$x_{xk} = x_{ok}\sin\theta$$

$$x_{sk} = x_{ok}\cos\theta$$

where: x_{ok} is the time series from the omni-directional receiver, and x_{sk} and x_{ck} are the time series of the wave pattern travelling to the $+y$ and $+x$ directions respectively. Defining a look-of-direction vector as:

$$\beta^T = (1, \sin\theta, \cos\theta)$$

the conventional beamformer ($\hat{E}_{CB}$)is given by [9]:

$$\hat{E}_{CB} = \beta^T \hat{Q} \beta$$

where $\hat{Q}$ is the 3 x 3 cross-spectral matrix between the three channels. The ML beamformer ($\hat{E}_{ML}$) is given by:

$$\hat{E}_{ML} = [\beta^T \hat{Q}^{-1} \beta]^{-1}$$

To calculate the EIG beamformer, the cross-spectral matrix is partitioned into signal ($\hat{S}$)and noise ($\hat{N}$)components:

$$\hat{Q}_{ij} = \hat{S}_{ij} + \hat{N}_{ij} = \sum_{m=1}^{P} \lambda_m \phi_i^m \phi_j^m + \sum_{m=P+1}^{M} \lambda_m \phi_i^m \phi_j^m$$

where λ_μ is the eigenvalue and ϕ_m the eigenvector of the mth eigenmode of with $\lambda_1 > \lambda_2$ ...Thus the signal is defined as the portion of defined by the P largest eigenmodes and the noise by the M-P smallest eigenmodes. The EIG beamformer ($\hat{E}_{EV}$) is:

$$\hat{E}_{EV} = [\beta^T N^{-1} \beta]^{-1} = [\sum_{m=2}^{3} \frac{1}{\lambda_m} | \vec{\beta}^T \cdot \vec{\phi}^m |^2]^{-1}$$

An iterative improvement [5] has been proposed for any general beamformer. The estimate $\hat{E}^i$ at step i is:

$$\hat{E}^i = \hat{E}^{i-1} + \delta^i$$

$$\delta^i = \frac{|\mu|^{\xi+1} \hat{E}^{i-1}}{\mu\varphi}$$

$$\mu = 1.0 - \frac{\hat{T}^{i-1}}{\hat{E}^0}$$

$\hat{T}^{i-1}$ is the estimated beamformer calculated from the cross-spectral matrix determined from $\hat{E}^{i-1}$, ξ=1.0 and φ=5.0.

Simulations

The data adaptive algorithms were tested for *np* simulated beams travelling towards directions θ_n at angular spreads of σ_n and isotropic noise level E_N defined by:

$$E = \sum_{n=1}^{np} P_n \exp\left(-\frac{(\theta - \theta_n)^2}{2\sigma_n^2}\right) + E_N$$

The simulations demonstrated that: a. none of the beamforming algorithms could detect a signal emanating from three directions simultaneously; b. E_{CB} could not separate a signal emanating from two directions; c. the data adaptive methods could distinguish two peaks separated by an angular spread of 120^0; d. the iterative improvement used with E_{EV} could resolve peaks to 90^0 separation but tended to over-resolve sharp peaks in high signal-to-noise situations.

Field Data

The high-resolution beamforming methods were applied to field data collected in an open ocean situation. Three ships were present. Contact 1, north of the study site, was traveling from west to east at over 20 kts, contact 2, south of the study site, was moving at over 15 kts in a southwest direction, and contact 3, the deployment vessel, was travelling to the southeast.

Several acoustic tonals were detected. At 25 Hz (fig 1), for example, a strong source at 340^0 (contact 1) and a weaker one at 195^0 (contact 2) were found by all the techniques except the E_{CB}. At 42.5 Hz (fig 2) contact 2 was correctly identified by E_{ML} and E_{IML} along with a weak indication of contact 1 to the North. E_{EV} indicated a contact at bearing 110, matching contact 3, with a smaller hump for contact 2. E_{IEV} separated those two contacts, resulting in a strong bearing for contact 3, and a weaker one for contact 2. These last two methods could not discern contact 1, and although they detected contact 3, the relative strengths seem to be in error. The ability to provide accurate directional information from broadband noise was also a desired feature for target detection and localization. The frequency spectrum between 150 and 250 Hz contained no tonals and was used to compare the performance of the techniques. The Bscan showed a concentration of dots along bearing 180^0 and 340^0 with a wide bearing variation between estimates. The high-resolution beamforming techniques indicated two distinct contacts corresponding to contact 1 to the North and contact 2 to the South. The direction estimates showed considerably less variation between frequency bins than the Bscan.

Summary

High-resolution beamforming techniques have been successfully applied to DIFAR data to provided accurate directional information. Although the current processing techniques are adequate for most situations, the presence of multiple contacts, or strong directional noise, may hinder target detection, and localization. Simulations and experimental results from field data showed that E_{ML} provided the best overall results in terms of accuracy, peak-to-trough visibility and processing time, for a range of parameters. E_{IML} improved the peak-to-trough difference at the expense of processing time, but in most cases, the weaker contact was

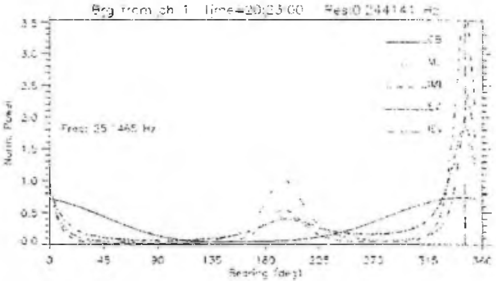

Fig. 1. Direction estimates at 25 Hz. Vertical line is the Bscan.

already visible with E_{ML}, making the gain minimal. It was also found that E_{EV} may produce spurious peaks, or create double peaks, in isolated cases. E_{EV} is otherwise accurate, with E_{IEV} providing marginal improvement.

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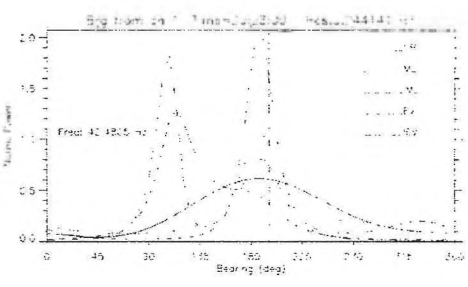

Fig. 2. Same as fig. 1 at 42 Hz. Note *bearing bias* of the Bscan.