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Received November 8, 2012

Abstract—This paper presents results on evaluating the impact of a set of physical and technical factors on the effectiveness of classical and projection fast adaptive algorithms. The factors include the conditions of signal propagation, including multipath; the noise–signal situation; signal fluctuations due to scattering in the medium; the parameters of the receiving antenna, including the amplitude–phase value of element dispersion; and the parameters of the spectral signal analysis at the output of the antenna elements.

Keywords: classical and “fast” projection adaptive algorithms, strong signal fluctuations, detection of weak signals, normalization of strong signals, focusing matrices

DOI: 10.1134/S1063771014030130

Adaptive signal reception methods have been actively developed over the last 40–45 years. Adaptive methods have been developed and implemented in a wide range of technical facilities (radiolocation, communication, and many other fields of knowledge). The main regularities and additional possibilities achieved using adaptive algorithms and methods have been studied.

This work is aimed at an attempt to answer the following questions:
—what are the specifics of the acoustic medium in which hydroacoustic signals propagate;
—whether it is possible to gain significant advantages when adaptive reception methods are used;
—what technical difficulties and complications need to be overcome when designing adaptive receiving tracts.

To limit the range of considered problems, let us concentrate on one (but the most complicated) problem—finding weak, threshold signals in a real marine environment where there is constant navigation and, in addition, the artificial signal sources.

It is known from the theory of the optimum signal reception [1] that if useful and interfering signals consist of uncorrelated plane-wave signals and the noise background is uniform, stationary, with an uneven smooth distribution over the angular coordinates, the noise stability of the optimum antenna is determined by the noise level in the direction of observation and the wave sizes of the antenna. Thus, in the distributed noise field, optimum reception makes it possible to receive only noise concentrated in the vicinity of the direction of observation and almost completely eliminate noise concentrated outside this region.

Under the action of a rather intense plane-wave signal in the vicinity of the main lobe of the optimum antenna, the noise stability of the antenna is worsened by the value of the square of the level of the normalized beam pattern oriented toward the weak signal in the direction toward the interfering source. In addition, at close arrival directions of useful weak and strong interfering signals, there is the problem of the resolution of weak and strong signal marks. It follows from the above that the most dangerous phenomenon during signal reception by real receiving tracts is the contribution of part of the energy of the local source toward the direction of observation due to the expansion of its spatial spectrum owing to distortions of the signal during processing and propagation in the medium.

A scheme with purely plane-wave signals is too simplified for acoustic applications, since acoustic signals almost always propagate under conditions of multipath propagation and in the presence of scattering in the propagation channel [2]. Such an interpretation of the model of the affecting noise from local sources fundamentally complicates the situation in which the adaptive algorithms for the separation of weak signals should solve their problem. This is a consequence of the contribution of part of the energy of the local source toward the direction of observation.

Except for difficulties due to the nature of acoustic signals, there are additional difficulties associated with technical distortions of received signals during pro-
processing in the receiving tracts of acoustic systems [3, 4]. The presence of amplitude-phase errors during the implementation of the weight coefficients in the antenna elements is significant, as well as the limited possibilities of certain algorithms.

The first factor leads to the following: due to the low sound velocity in water, purely plane-wave signals arriving at a large antenna contain a partially coherent anisotropic component, the spatial spectral width of which is approximately two times larger than the opening angle of the beam pattern of this antenna. The second eigenvalues of the sample estimate of the correlation matrix (due to the partially coherent field of the \( m \)th source) are determined by the relation [3]

\[
S_{FSm}(n) = \frac{1}{8} S_{om}(n) L^2 dF \sin \alpha_m, \tag{1}
\]

where \( S_{om}(n) \) is the intensity of the \( m \)th plane-wave signal; \( \alpha_m \) is the arrival angle of the \( m \)th signal with respect to the normal to the antenna axis; \( dF = \frac{\Delta f}{f_p} = \frac{1}{T f_p} \) is the relative spectral analysis frequency with respect to the base (project) antenna frequency \( f_p \), corresponding to the interelement distance \( d_e \), which is the half the wavelength at this frequency; \( T \) is the spectral analysis interval used for preliminary processing of the time signal in the antenna elements before implementation of the adaptive algorithms.

Near the direction to the strong signal, this partially coherent component due to the increase in fluctuations and masking action of its regular component, hampers detection (resolution) of the weak signal. The second factor leads to additional components appearing in the interfering signal, which complicate the noise situation and require additional resources from the adaptive algorithm to overcome them.

Below we briefly consider, following [5–7], algorithms (Section 1) and the features of their application with allowance for the specifics of the formation of acoustic signals in the marine environment (Section 2). The effect of acoustic physical factors on the properties of the sample estimates of the correlation matrices is analyzed using a model experiment (Section 3.1), and the bearing profiles of different variants of algorithms are considered (Section 3.2). In Section 4, the means of increasing the efficiency of adaptive algorithms in acoustic observation systems are formulated.

1. ADAPTIVE ALGORITHMS FOR SEPARATION OF WEAK SIGNALS

1.1. Classical Algorithms

Classical algorithms are well known from the extensive literature, see, e.g., [8, 9]. They are studied in detail during detection and resolution of weak and strong signals. However, these studies, as a rule, are performed as applied to plane-wave signals for minimum implementation errors of the receiving tracts and for a sample volume that makes it possible to achieve their possibilities. Much attention is paid to the possibility of the resolution of signals, i.e., obtaining separate marks of each observed signal, which determine its parameters (arrival direction, amplitude, etc.).

Algorithms with normalization of strong signals can yield significant possibilities for improving resolution ability. An extensive list of classical algorithms modified by normalization is given in [5]. Let us choose from this list one of the best (as to the resolution ability) classical algorithms, the EV (Johnson) algorithm, in the classical and normalized modifications and consider their operation under conditions of the multipath propagation and the presence of scattering.

The EV (Johnson) algorithm after normalization of strong signals takes the form

\[
S_{jj} = \frac{V^{\ast T}_j \left[ E - \sum_{m=1}^{M} U_m U_m^{\ast T} \right] V_j}{V^{\ast T}_j \hat{\mathbf{R}}^{-1} \sum_{m=1}^{M} \frac{1}{\lambda} U_m U_m^{\ast T} V_j}, \tag{1.1}
\]

where \( \hat{\mathbf{R}} = \frac{1}{K} \sum_{k=1}^{K} \mathbf{X}_k \mathbf{X}_k^{\ast T} \) is the sample estimate of the correlation matrix consisting of \( K \) samples of the input mixture, and \( \lambda_m \) and \( U_m \) are its eigenvalues and eigenvectors.

A quantity inverse to the denominator in relation (1.1) forms the classical Johnson algorithm when detecting \( M > M_i \) signals, and the numerator provides the normalization of \( M_i \) strong signals. The suppression of the \( M_i \) interfering signals in the numerator of the algorithm (1.1) is provided by \( M_i \) eigenvectors corresponding to the largest eigenvalues.

The following relation is a modification of the Bartlett algorithm with normalization of local noise after calculation of \( M_i \) largest eigenvalues \( \lambda_m \) and the corresponding eigenvectors \( U_m \):

\[
S_{\text{BEVN}} = \frac{V^{\ast T}_j \left[ \hat{\mathbf{R}} - \sum_{m=1}^{M_i} \lambda_m U_m U_m^{\ast T} \right] V_j}{V^{\ast T}_j \left[ E - \sum_{m=1}^{M_i} U_m U_m^{\ast T} \right] V_j}. \tag{1.2}
\]

Operations similar to (1.1) are implemented in relation (1.2) but \( M_i \) strong signals are suppressed in the numerator, and the denominator provides normalization of the output effect in the directions toward strong signals.

The parameters of algorithms (1.1) and (1.2) are:
— the number of antenna elements \( L \);
— the sample volume for estimating the correlation matrix (to \( 4L \)).