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Sea reverberation rejection via adaptive beamforming

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Abstract - **This paper investigates effectiveness of sea reverberation suppression by adaptive array processing. The case of monostatic active sonar is considered. The models of multipath echo signal, reverberation and sea surface noise are presented. The model of the array steering vector averaged on medium fluctuations is used for robust adaptive beamforming in a random oceanic waveguide. Computer simulations for typical shallow water conditions are given.**

1. INTRODUCTION

Active signal processing in a random, inhomogeneous medium such as the ocean, has become a problem of particular interest. The oceanic waveguide, because of its rough boundaries, nonstationary character, inhomogeneities and variable velocity of propagation is an extremely complex medium. The structure of signal and noise fields is characterized by interference phenomena caused by refraction and reflections from boundaries and from inhomogeneities in the water column. This phenomena produces the anisotropic properties of interferences (reverberation, sea surface noise). Target detection by monostatic active sonar seriously degrades by reverberation. It's especially true, when echo signal and reverberation are separated by less than a beamwidth of the receiver array. The main means of reducing reverberation level at the output of the receiver, in a temporal domain, are Doppler filtering of tone signals and coherent processing for wideband signals. Our interest here is concerned primary with the adaptive beamforming in an acoustic environment where the dominant interference is reverberation. In recent years, adaptive array processing techniques have been used as means of overcoming the problem of nulling out an interference when it is separated by less than a beamwidth from the desired signal. In other hand, adaptive arrays are capable of operating in uncertain, time-varying environments (it's particularly true for active sonar) changing its beampattern in an optimum manner to reject reverberations.

2. SIGNAL AND NOISE MODELS

The noise environment for sonar systems operating in the ocean is generally a composite of several types of noise. For active sonar system, the noise present at the receiving array is a linear combination of ambient sea noise and reverberation. These two noise fields are combined with the additional noise generated by the receiver equipment (i.e., system noise).

A. Echo signal

Using ray approximation [1,2], the Green's function of oceanic waveguide represents as ray sum of quasi-plane wave fields:

$$G_m(\mathbf{r},\mathbf{r}_0)=\sum_{\mu=1}^{M}A_\mu(\mathbf{r},\mathbf{r}_0)\exp\left\{j\omega\left(\mathrm{t}_\mu(\mathbf{r},\mathbf{r}_0)+\frac{1}{c}(\mathbf{u}_\mu,\mathbf{d}_m)\right)\right\} \quad (1)$$

where M is the total number of rays connecting the observation point $\mathbf{r}$ and the source point $\mathbf{r}_0$, $\mathbf{u}_\mu$ is the direction of arrival of the μth ray, $\mathbf{d}_m$ is the position vector of the mth array hydrophone,

$A_{\mu}(\mathbf{r},\mathbf{r}_0)=\dfrac{\sqrt{f_{\mu}(\mathbf{r},\mathbf{r}_0)\cdot F_{\mu}(\omega,\mathbf{r},\mathbf{r}_0)}}{R(\mathbf{r},\mathbf{r}_0)}$ is the amplitude of the μth ray, $f_{\mu}(\mathbf{r},\mathbf{r}_0)$ is the divergence factor of the μth ray, $R(\mathbf{r},\mathbf{r}_0)$ is the horizontal distance from the source to the point of observation, $F_{\mu}(\omega,\mathbf{r},\mathbf{r}_0)=V_S^{2n_S}V_B^{2n_B}10^{-0.1\beta R(\mathbf{r},\mathbf{r}_0)}$ is the coefficient which takes into account field weakening due to the propagation along the μth ray path, β is the attenuation coefficient, $n_{S,B}$ are numbers of interactions of the μth ray with ocean interfaces, $V_{S,B}$ are surface S and bottom B reflection coefficients for the μth ray, $\mathrm{t}_{\mu}(\mathbf{r},\mathbf{r}_0)$ is the propagation time (ray delay) along the μth ray path.

Reflection by a target is described by equivalent radius $R_T(\omega,\mathbf{u}_{\nu}-\mathbf{u}_{\mu})$, where $\mathbf{u}_{\nu},\mathbf{u}_{\mu}$ are unit vectors that determine directions of the reflected and of the incident waves. Amplitude of coherent echo signal component at a point $\mathbf{r}_R$ is given by the formula [3]

$$\mathrm{G}_m^E(\omega,\mathbf{r}_R,\mathbf{r}_T)=\sqrt{\frac{W_0\gamma_0\rho c}{16\pi}}\sum_{\nu}\sum_{\mu}A_{\nu}(\mathbf{r}_R,\mathbf{r}_T)A_{\mu}(\mathbf{r}_T,\mathbf{r}_R)\cdot$$
$$\exp(j\omega(\mathrm{t}_{\mu}(\mathbf{r}_T,\mathbf{r}_R)+\mathrm{t}_{\nu}(\mathbf{r}_R,\mathbf{r}_T)))\exp\left\{j\frac{\omega}{c}\left(\mathbf{u}_{\mu},\mathbf{d}_m\right)\right\}\cdot \qquad (2)$$
$$R_T(\omega,\mathbf{u}_{\nu}-\mathbf{u}_{\mu})\mathrm{B}_0(\omega,\mathbf{u}_{\mu}-\mathbf{u}_0)S_0(\omega),$$

where W_0 is the emitted power, γ_0 is the directivity coefficient of emitter array , ρc is the wave resistance of medium, $\mathrm{B}_0(\omega,\mathbf{u}_{\mu}-\mathbf{u}_0)$ is the beam pattern of the emitter array, $S_0(\omega)$ is the complex spectrum of the emitted signal. The summation is over all ray paths connecting the emitter-receiver and target.

B. Reverberation

Sound scattering from rough boundaries (surface and bottom) and from volume inhomogeneities is the essential source of reverberation. Accordingly to its generation mechanism, one can distinguish surface, bottom and volume reverberations. Sound scattering is described by the scattering coefficients $m(\mathbf{u}(\mathbf{x},\mathbf{r}_R),\mathbf{u}(\mathbf{x},\mathbf{r}_E),\omega,\mathbf{x})$ which depend on frequency ω, on vectors $\mathbf{u}$ of rays connecting the scattering element at the point of scattering $\mathbf{x}$ with the receiver $\mathbf{r}_R$ and with the emitter $\mathbf{r}_E$. For working frequencies about a few *kHz* the boundary reverberation is a dominant [4]. Formula for angular spectrum of boundary reverberation is derived in [3]:

$$N_R(\omega,t,\mathbf{u}_R,\mathbf{r}_R)=\frac{W_0\gamma_0\rho c}{4\pi}\kappa_0(\omega)\int_S\sum_i\sum_j m(\mathbf{u}_i(\mathbf{x},\mathbf{r}_B),\mathbf{u}_j(\mathbf{x},\mathbf{r}_R),\omega,\mathbf{x})\cdot$$
$$\mathrm{B}_0^2(\omega,\mathbf{u}_i-\mathbf{u}_0)\frac{f_i(\mathbf{x},\mathbf{r}_B)f_j(\mathbf{x},\mathbf{r}_R)F_i(\mathbf{x},\mathbf{r}_B,\omega)\cdot F_j(\mathbf{x},\mathbf{r}_R,\omega)}{R_i^2(\mathbf{x},\mathbf{r}_B)R_j^2(\mathbf{x},\mathbf{r}_R))}\cdot \qquad (3)$$
$$\exp\left\{j\frac{\omega}{c}\left(\mathbf{u}_j,\mathbf{d}_m\right)\right\}W(t-\mathrm{t}_i(\mathbf{x},\mathbf{r}_B)-\mathrm{t}_j(\mathbf{x},\mathbf{r}_R))dS,$$

where $\mathbf{u}_R$ is the observation vector, $\kappa_0(\omega)$ is the spectral density of the emitted signal, W is a window function for integrating through the scattering area S into the time window which are determined by the envelope of emitted signal, $\mathrm{t}(\mathbf{x},\mathbf{r})$ is the time delay for the ray path which connects the points $\mathbf{x}$ and $\mathbf{r}$, F are coefficients that take into account signal weakening on corresponding ray paths due to interactions with ocean boundaries and to absorption in the water, dS is an elemental scattering area. Other notations are introduced above. The summation is over all ray paths connecting the emitter-receiver and scattering element.

C. Sea surface noise

Ambient sea noise is one of the basic interferences disturbing the acquisition of acoustic signals in the ocean. For working frequencies from hundreds of *Hz* to units of *kHz*, the sea surface noise is a dominant. To model the sea surface noise, one admit some uniform distribution of noise sources into the near surface water layer. Corresponding angular spectrum doesn't depend on bearing and is a smooth function on grazing angle. The expression has the form [4]

$$\begin{cases} N_+^S(\omega,\chi,\mathbf{r})=\dfrac{\kappa_S(\omega)\exp(-2\beta R_+)}{c_1^2(1-V_S^2V_B^2\exp(-2\beta R_0))}\cdot \\ (c_S^2\sin^{2m-1}\chi_S+K\exp(-\beta R_0)V_S^2c_S^2\sin^{2m_b-1}\chi_B) \\ N_-^S(\omega,\chi,\mathbf{r})=\dfrac{\kappa_B(\omega)\exp(-2\beta R_-)}{c_1^2(1-V_S^2V_B^2\exp(-2\beta R_0))}\cdot \\ (c_S^2V_S^2\sin^{2m-1}\chi_S+K\exp(-\beta R_0)c_S^2\sin^{2m_b-1}\chi_B), \end{cases} \qquad (4)$$

where $\kappa_S(\omega)$ is the spectral density of noise sources, R_0 is the cyclic distance (horizontal length of one ray path cycle), R_+ and R_- are horizontal lengths of going "up" and "down" ray paths connecting the array phase center to the surface, $c_{1,S,B}$ is the sound speed value at receiver depth, near the surface and near the bottom, m and m_b are power orders in pattern formulas for surface sources and of virtual bottom sources using for taking into account the bottom scattering, $K = \kappa_B/\kappa_S$ is a coefficient that is equal to the ratio of the spectral density of imaginary bottom sources to the spectral density of surfaces sources, $\chi_{S,B}$ are rays grazing angles near the surface and near the bottom.

3. ADAPTIVE BEAMFORMING

At some frequency ω, the Cross-Spectral Density Matrix (CSDM) of distributed interference (the ambient sea noise, reverberation) is given by the expression

$$\mathbf{Q}^{d}_{mn}(\omega,t,\mathbf{r})=\int_{\Omega} N(\omega,t,\mathbf{u}(\Omega),\mathbf{r})\exp(j\frac{\omega}{c}(\mathbf{u}(\Omega),\mathbf{r}_m-\mathbf{r}_n))d\Omega,$$

where $\mathbf{r}_{m(n)}$ is the coordinate vector of the $m(n)$th array element, $N(\omega,t,\mathbf{u}(\Omega),\mathbf{r})$ is the instantaneous frequency-angular spectrum of the interference.

Let's write CSDM of the received field in the matrix form

$$\mathbf{R}=\mathbf{S}+\mathbf{Q},\ \mathbf{Q}=\mathbf{Q}^{d}+\sigma_0^2\mathbf{I}\ \text{, and }\ \mathbf{S}=\mathbf{G}\mathbf{G}^{H}\ ,$$

where $\mathbf{Q}^{d}$ is the CSDM of distributed interference, S is the CSDM of echo signal, σ_0^2 and $\mathbf{I}$ are variance of system noise and identity matrix, respectively. The superscript 'H' denotes the Hermitian conjugate. The echo signal's vector $\mathbf{G}$ has the form

$$\mathbf{G}=[\mathrm{G}^{E}(\omega,\mathbf{r}_1,\mathbf{r}_T),\mathrm{G}^{E}(\omega,\mathbf{r}_2,\mathbf{r}_T),\ldots,\mathrm{G}^{E}(\omega,\mathbf{r}_M,\mathbf{r}_T)]^{T},$$

where $\mathbf{r}_n$ is the radius-vector of the nth hydrophone.

For obtaining the numerical evaluations of effectiveness of reverberation suppression, the follow quantity is introduced

$$g=10\lg\frac{SNR_A}{SNR_C} \qquad (5)$$

where SNR_A and SNR_C is the signal-to-total noise ratio at the output of the adaptive beamformer and conventional beamformer, respectively

$$SNR_A=\frac{\mathbf{W}_A^{H}\mathbf{S}\mathbf{W}_A}{\mathbf{W}_A^{H}\mathbf{Q}\mathbf{W}_A},\qquad SNR_C=\frac{\mathbf{a}(\theta,\omega)^{H}\mathbf{S}\mathbf{a}(\theta,\omega)}{\mathbf{a}(\theta,\omega)^{H}\mathbf{Q}\mathbf{a}(\theta,\omega)}$$

For linear, equispaced array, a steering vector $\mathbf{a}(\theta,\omega)$ has the form

$$\mathbf{a}(\theta,\omega)=[1,\exp(j\frac{\omega}{c}d\sin\theta),\ldots,\exp(j\frac{\omega}{c}d(M-1)\sin\theta)]^{T} \qquad (6)$$

where θ is the look direction in vertical plane, d is the element spacing, M is the number of hydrophones, c is the sound speed. The adaptive weight vector has the form [6]

$$\mathbf{W}_A(\omega)=\frac{\mathbf{R}^{-1}\mathbf{a}(\theta,\omega)}{\mathbf{a}(\theta,\omega)^{H}\mathbf{R}^{-1}\mathbf{a}(\theta,\omega)} \qquad (7)$$

Efficiency of reverberation rejection is defined by relationship between different components that form CSDM $\mathbf{R}$ (echo signal, reverberation, sea surface noise and system noise). Efficiency also depends on validity of assumption about model of the vector $\mathbf{a}(\theta,\omega)$, amount of correlation of the echo signal's rays etc.

Since the echo signal is the superposition of correlated arrivals, the adaptive beamformer (7) suffer from echo signal cancellation. To overcome this phenomena, spatial smoothing techniques [6] and multiple point constraints beamforming [7] are applied. Moreover, since the directions of arrival (DOA) of echo signal are usually not known a priori, it is needed to estimate DOA's, using some direction-finding technique (such as MUSIC [8] or maximum likelihood estimator [9]).

As oceanic waveguide is unstable and its parameters are fluctuated, the model of the array steering vector (6) no longer corresponds to real observation conditions. Small deviations of actual angle of arrival from assumed one in (6) can lead to signal cancellation at the output of the receiver array. It is especially true for high signal-to-noise ratio scenario. To improve processing efficiency, it is necessary to incorporate the appropriate model of the array steering vector for random media into spatial processing algorithm. The model of the array steering vector averaged on angle of arrival fluctuations can be written as follows (normal law of medium parameters fluctuations is assumed) [3]

$$\bar{\mathbf{a}}(\theta,\omega)=\left[1,\ \exp\left\{j\frac{\omega}{c}d\sin\bar{\theta}-\frac{1}{2}\frac{\omega^2}{c^2}d^2\sigma_\theta^2\right\},\ldots,\right.$$
$$\left.\exp\left\{j\frac{\omega}{c}d(M-1)\sin\bar{\theta}-\frac{1}{2}\frac{\omega^2}{c^2}d^2(M-1)^2\sigma_\theta^2\right\}\right]^{T} \qquad (8)$$

where $\bar{\theta}$ is the mean angle of arrival, σ_θ^2 is the variance of angle of arrival fluctuations in the vertical plane. Variance of angle of arrival fluctuations can be computed by using *a priori* information about correlation functions of inhomogeneities of ocean environment. Unlike the model (6) which is only suitable for "frozen" deterministic media, the spatial filtering window in the model (8) is widened accordingly to variance of the angle of arrival fluctuations. Applying the steering vector (8) to adaptive spatial filter design (7), we will obtain more robust response at the array output.

4. SIMULATION RESULTS

On the basis of models (2-4), the numerical codes were written [3]. To evaluate the effectiveness of reverberation suppression via adaptive array processing, a number of computer simulations were conducted. The main objective in these simulations was to determine the adaptive array gain g (5) in reverberation-limited hydroacoustic conditions. For sound speed profiles typical for shallow water propagation (fig. 1, Barents Sea, winter conditions), the arrival structure of echo signal (fig. 2), the angular power spectrum of composite (surface, bottom reverberation and sea surface noise) interference (fig.3) are presented. The initial data for simulation was chosen as follows : the linear array consisting of 15 sensors with half wavelength spacing at the frequency 3 kHz, signal duration 0.5 s, the emitted acoustic power 1000 Wt, the emitted beampattern - omnidirectional, target equivalent radius 5 m, target at a depth 100 m and a range from 1 km to 30 km (range increment 0.5 km), wind speed 10 m/s.

Fig. 4 depicts the adaptive array gain g versus target range. From figures, it is clear, that for distances up to 10 km, effectiveness of reverberation suppression is a high and g=6-14 dB. This is due to strong anisotropic properties of sea reverberation at short distances. Then, the reverberation angular spectrum is "saturated" and become more smoothed and g does not exceed 3-6 dB.

5. CONCLUSION

In the presented paper, the effectiveness of sea reverberation suppression by adaptive array processing is considered. The model of the array steering vector averaged on medium fluctuations is used for robust adaptive beamforming in a random ocean environment. The proposed model is less sensitive to mismatch between the assumed and actual sound propagation model. In conclusion, we notice that presented results on reverberation rejection determine the upper bound of adaptive array gain (i.e., do not include the effects of array imperfections, errors in estimating of CSDM, etc.). These problems and ways of their overcoming are considered in [3] and to be presented in future work.

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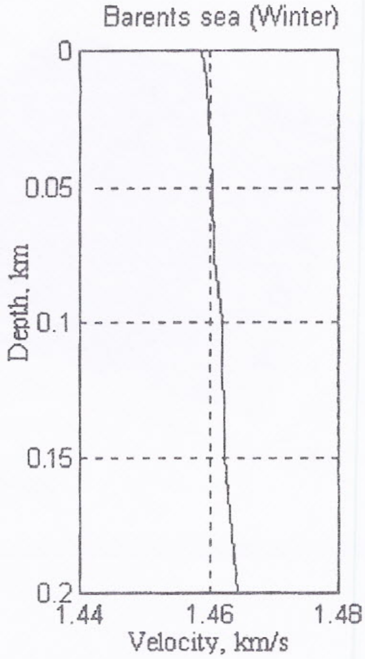

Figure 1. Sound Velocity Profile used in simulation.

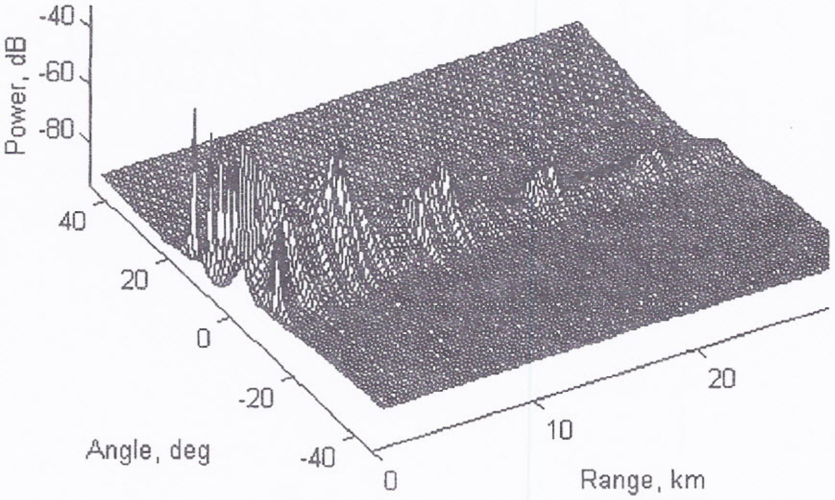

Figure 2. Angular structure of echo-signal versus target range.

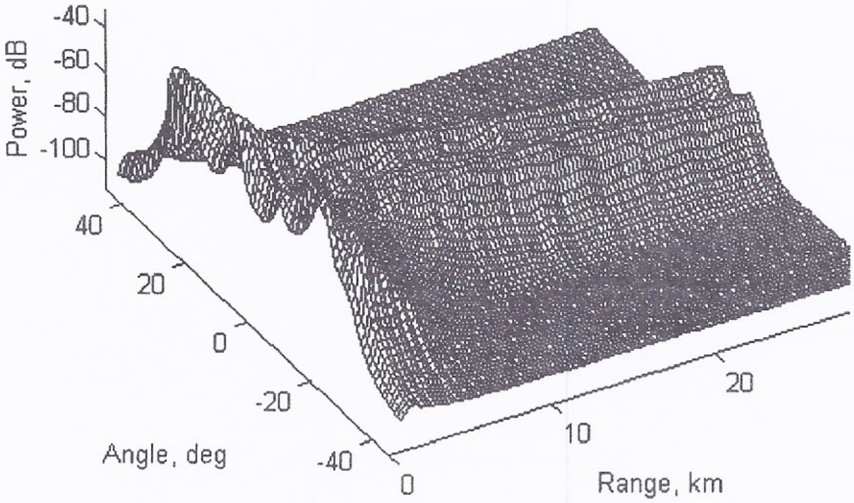

Figure 3. Interference angular power spectrum versus range.

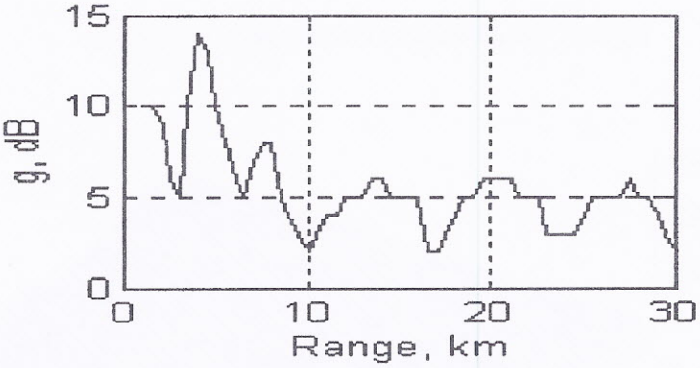

Figure 4. Adaptive array gain versus range.