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On acoustic tomography method physical advantages in long range ocean inhomogeneities control

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Underwater tomography method based on inhomogeneity perturbed acoustic signal detection during source – receiver trace intersection and corresponding system expected parameters are discussed. Due to sonar signal fast decay with distance, especially in unfavorable rapidly attenuating shallow water regions, long range inhomogeneities (ocean vortices, icebergs, sea mammals, underwater objects) back scatter sonar monitoring is hardly possible. Distance comparison of sonar and tomography system in inhomogeneities monitoring based on functional distance dependence of optimum frequencies is adduced. Physical limits (optimum frequencies, efficiencies) of model object control for two mentioned methods in deep and one of the most unfavorable, in the author view, shallow ocean region are compared. Extra narrow directional parametric array is emphasized as long range tomography monitoring method unique practical solution and its requirements are evaluated. For utmost distance achievement, radiation and receiving ends of tomography system should be designed as narrow directional parametric arrays working on optimal frequency basic propagation (first) mode. Major lobe solid angle should be provided not wider than 0, 03 radians, while array length – not shorter than 100 half wavelength for pump sound field frequency. Resulting estimated pump signal consumption looks like 180-200 kW of acoustic power.

INTRODUCTION

Importance of ocean long range acoustic monitoring was repeatedly mentioned in literature [1-6]. It is shown to be principal in coastal regions control, navigation, fishery and many other fields of human activity. Recently it was presented as possible method of ocean acoustic thermometry program (ATOC) [1, 3], where extremely long source – receiver traces up to several megameters are to be constantly controlled to detect climate changes. However, the main objective of the paper is long range ocean inhomogeneity control related in general to methods of their bistatic location and in particular – to tomography. To see perspectives in the field it is necessary to evaluate few basic physical parameters such as achievable ranges, range dependant optimal frequencies and to compare them to parameters of conventional ocean inhomogeneity control methods, say, back scatter signal detection provided by sonar. Such general estimate could be performed on the basis of ocean major regions acoustic properties statistics [5, 6].

Few recent papers were devoted to specifics of sound scattering by various inhomogeneities [7, 8], to long range propagation losses modeling especially in most unfavorably absorbing shallow water regions [9, 16] and to background noise impeding inhomogeneity control through tomography signal modulation due to scattering on ocean gravitational and internal waves, ocean rough boundary scattering, so called “direct reverberation”, properties and their overcoming methods [10-16].

It is expedient to compare ocean acoustic control methods by required acoustic power criterion. We shall see, that in this field - tomography method offers notable advantage potentially capable to compensate its heavy problems, say, requirement of source positioning on the opposite side of trace and comparably narrow inhomogeneity observation angle complicating its use in regional observation systems.

It follows from hydrolocation equation, say, in the form of [5], that fraction of source energy spent on noise overdue is defined by inhomogeneity scattering crossection. As it is widely accepted, we take elongated spheroid with spherical caps of radius R and length l - as a model inhomogeneity, for instance, model of ocean mammal, fish [2], moving ship or underwater object [7] nor ocean vortex [8]. For the case of backscattering, it will be fair if power consumption is evaluated for most unfavorable model inhomogeneity axial aspect, corresponding to wide scattering minimum, while scattering maximum related to side aspect (narrow reflection speck) is ignored. On the contrary, in the case of tomography, direct scattering intensity angle cosine dependence for model inhomogeneity or for even more coarse - screen model [2], allows to neglect trace intersection at small angles, to evaluate critical power consumption just for side aspect of model inhomogeneity trace intersection.

Mentioned reasons on different critical model choices will be taken into account in two systems comparison. From the point of their substantial difference, their technical parameters (detection potential) on that stage of evaluation are supposed to be equal. For obstacle scattered power estimate we shall use mentioned above rectangular screen model of 100 meters length and 10 meters height. Its scattering crossection equal to $4\pi S^2 / \lambda^2$, where S – screen area and λ – incident sound wavelength, for standard characteristic frequency 1 kHz will come to value $5{,}5{\cdot}10^6$ m^2. For sonar exposed object we take scattering crossection, as usual, the same as for spherical model with equivalent reflection radius 10 meters. The resulting value will be equal to sphere crossection area approximately $3{\cdot}10^2$ m^2, while crossection ratio – $1{,}8{\cdot}\,10^4$,- i.e. more than four orders in favor of tomography (for inhomogeneity – modeling ship or underwater object).

However, such estimate is not completely fair for operation frequency choice is partly random. In fact, operation frequencies are to be chosen as optimal for given distance, ocean region and system type from the point of system operation energy minimizing. At that for tomography case as for bistatic location special case, the half of trace length should be taken as extreme detection distance, because in trace central part object sound field shadowing (signal diffraction component) will be minimal, increasing with inhomogeneity trace intersection position distance to trace ends decrease.

By means of approach based on signal and noise frequency spectra power dependencies and sound kilometric attenuation accounting for shallow water regions sea bottom properties [9, 16], expression for optimal frequency derived for standard signal processing in constant relative frequency bands [5] takes the form

$$f_0 = \left[10m \log e \big/ \varepsilon\beta nr \right]^{1/n}, \quad (1)$$

where f_0 - optimal frequency expressed in kHz, e – natural logarithm radix, ε - signal way repetition factor, $\varepsilon = 2$ (for back scattering case). Quantities β_0 and n - factor and exponent factor in expression for signal kilometric attenuation β, taken in the form $\beta = \beta_0{\cdot}f^n$ dB/km, r – distance in km. Parameter m ($m = m_{cf} - m_n + m_{bs} + m_{sni}$) – signal to noise ratio related to system output resulting frequency spectrum exponent factor, consisting of contributions m_{cf}, m_n, m_{bs} and m_{sni} – frequency spectrum exponent factors for radiation concentration factor, noise intensity, body scattering crossection and system random noise immunity respectively, for system energy consumption minimization is discussed. Total signal attenuation on its propagation way for optimal frequency in this approach takes the form

$$B = 2r\beta_0 f^n = 10(m/n)\log e, \quad (2)$$

being invariant to attenuation absolute value and to distance, but could slightly increase with respect to value given by Eq. (2) in shallow water regions due to signal mode structure impoverishment related to higher numbers mode with more steep incidence angles increased attenuation values. This effect is compensated partly by propagation anomaly decrease, but nevertheless leads to substantial corrections of system optimal parameters to be chosen for such conditions and should be taken into account. In particular, it leads to optimal frequency decrease for shallow water regions (c.f. Table 1, below).

For deep water regions at large enough distances and not extremely high signal frequencies, attenuation contribution related to ocean surface scattering phenomena could be safely neglected. The same could be assumed for bottom reflections. Attenuation law there will be governed mainly by ocean media attenuation and, due to its comparatively low spatial variability, allows to use it in any specific region or a group of regions in the form of frequency exponent law generalized (for wide frequency range from 0,05 to 10 kHz) to the form $\beta = 0{,}025{\cdot}f^{3/2}$ dB/km.

It is important, that for deep water region, as well as for any group of such regions, in this approximation, no relationship between signal propagation and attenuation laws with respect to signal frequency is observed, and only their distance relationship remains, it allows to solve specific system optimization problem on the basis of power consumption minimizing, relating unambiguously required sonar system range with signal optimal frequency. Examples of this approach are adduced in [5], where for various types of frequency optimized underwater systems their probabilistic ranges are examined in the frame of propagation anomaly statistics for the aggregate of ocean deep water regions. And even there, sometimes it was necessary to cut total system range on separate fractions with its specific exponent propagation frequency laws.

In shallow water regions conditions dependence of signal propagation and attenuation laws on layer depth and bottom acoustic parameters accounting for their rapid spatial variability even in comparably small distance fractions, complicates optimization problem solution substantially not only for regions group but even for each specific region as well. In that case system efficiency comparison could be performed for specific examples of regions with spatially homogeneous depth and bottom properties distributions. Typical region bottom model used for signal propagation and attenuation predictions adduced in [9] comprises – sediment layer of 40 – 60 m thickness with sound velocity close to 1500 m/s with attenuation factor 0,01. The layer is positioned on solid basement with longitudinal wave velocity 1700 m/s with attenuation factor 0,02, with transverse waves velocity 400 m/s with attenuation factor - 0,05, density $2{\cdot}10^3$ kg/m^3. There is above 200 meters depth water layer with sound velocity negative gradient of an order of $1{\cdot}10^{-4}$ m^{-1}. But even such idealized shallow water region model with depths 200 – 250 meters give rather diverse estimates for attenuation of practical signals. Examples of signal propagation and attenuation predictions in wider spectrum of bottom models are given in [16].

For instance, multimodal signal kilometric attenuation laws fitting experimental data observed in resembling Barents sea region were derived in the form $\beta = 0{,}5{\cdot}f^{3/4}$ and $\beta = 0{,}3{\cdot}f^{2/3}$ dB/km, while for one (basic) mode signal - $\beta = 0{,}4{\cdot}f$, where frequency f is expressed in kHz [9].

For cylindrical law propagation anomaly A is expressed in the form $A = r/r_0$, where r- distance, while r_0 – so called transitional distance, which in the approximation used looks like the value of an order of layer depth - H. The value r_0 together with corresponding anomaly value should be related to mode composition observed for given distance and frequency ranges, while in fact, signal physically complete mode composition in shallow water regions is retained for small enough distances from the source only. Beyond these limits signal mode structure impoverishment leads not only to propagation anomaly decrease, but to definite kilometric attenuation decrease as well. The distance, where the only basic first mode is retained could be predicted for low signal frequencies by means of mode attenuation [9], if drastic (more steep then linear) increase of kilometric attenuation with mode number predicted by this model will be taken into account. For instance, if for specific distance basic mode attenuation achieves a value of 2-3 dB, then other modes contribution could be neglected. According to numerical modeling [9], for mentioned above conditions on frequencies 40 – 50 Hz kilometric attenuation of the basic mode looks like 0,01- 0,02 dB/km, so that one mode propagation model will be realistic beginning from the distances 100-150 km. For distance 1000 km basic mode attenuation is equal on the average to not more than 15 dB. However, it should be taken into account, that transition to one-mode signal propagation in cylindrical law model leads to substantial anomaly losses (N times, where N – modes quantity for conditions of equal excitation level). These signal power losses, however, could be substantially compensated by means of waveguide one-mode excitation using so called “matched” vertical radiating array or elongated sharply directional, say, parametric horizontal array.

SYSTEMS COMPARISON

Comparison of two long range inhomogeneity control methods (systems) tomography and backscatter will be executed for long enough distances - from 100 to 500 km, corresponding in tomography case to trace length from 200 to 1000 km. It is substantiated by the general problem of inhomogeneity control range development and mentioned above proposed ATOC ranges [1, 3].

We begin with optimal frequencies ratio for systems under comparison $k = f_{01} / f_{02}$ for deep water regions aggregate and mentioned specific shallow water region respectively. It follows from Eq. (1), that $k = (m_1 / m_2)^{1/n}$. Let us suppose that both systems are operating on the basis of linear radiation and receiving arrays. Then exponent factors in expression for signal to noise ratio spectra defined above related to array concentration m_{cf} and to immunity m_{sni}, with respect to noise for two systems coincide $m_{cf1} = m_{cf2} = m_{sni1} = m_{sni2} = 1$. For model inhomogeneity in backscatter sonar system we suppose scattering crossection increasing with frequency square root, so that $m_{bs1} = 1/2$, while for tomography system for flat screen inhomogeneity model, correspondingly, $m_{bs2} = 2$. For noise spectrum we take $m_n = -2$. As a result, for total exponential factor m in signal to noise ratio spectrum with respect to system output we obtain $m_1 = 9/2$ for backscattering, and $m_2 = 6$ for tomography systems respectively. For deep water regions attenuation law exponent factor is equal $n = 3/2$, and optimal frequencies ratio $\kappa = f_{01} / f_{02} = (m_1 / m_2)^{1/n} = 0{,}7$. In conditions of specific shallow water region for one of predicted attenuation laws $n = 3/4$, while for other $n = 2/3$ and, correspondingly, we receive values $\kappa = 0{,}92$ and $\kappa = 0{,}91$ respectively. Thus, we see, that in spite of substantial difference in obstacle scattered sound power, optimal frequencies for both cases in rather different attenuation conditions are very close. In following calculations we shall suppose them to be equal, while for exponent factor m in expression for optimal frequency, we shall use its average value ($m = 5{,}2$). Now we could define frequency optimized scattering crossection ratio for two systems depending on operation distance minimizing their sound power consumption. This ratio is proportional to frequency in 3/2 power. By substitution in Eq. (1) of $m = 5{,}2$, values of β_0 and exponent factors n for deep water regions aggregate and specific shallow water conditions we could calculate values for various system operation ranges. They are adduced in Table 1 for mentioned above model inhomogeneity with characteristic length $l = 100$ m. Upper table part is related to deep water regions data, while lower – to specific shallow water region data. To avoid propagation anomaly excessive losses all estimates are based on systems one-mode waveguide excitation by means of matched vertical radiation array or equivalent horizontal sharply directional parametric array. We could see, that in specific shallow water region for system range 100 km and optimal frequency 0,45 kHz attenuation losses are close to at least 20 dB. It is supposed that signal reception is based also on slowly decaying mode, and in particular, one-mode principle. Then, estimate of tomography method advantages $\Delta\Phi_{dB}$ with respect to backscatter sonar method based on acoustic power consumption minimization will be expressed as a sum of scattering crossection ratio of objects and difference of total signal attenuation depending on exponent factors m_1 and m_2 of systems compared and attenuation exponent factor n in accordance to Eq. (2). Thus

$$\Delta\Phi_{dB} = 10\log(f_0\Sigma_0) - 10\left((m_1 - m_2)\big/ n\right)\log e\,, \qquad (3)$$

where f_0 – optimal frequency in kHz, $\Sigma_0 = 1{,}8\cdot 10^4$ – systems scattering crossection ratio for frequency 1 kHz, m_1 – total spectrum exponent factor m for backscatter system, m_2 – for tomography system. Optimal frequency distance dependence estimates in deep water regions aggregate obtained by Eq. (1) for $m = 5{,}2$ and $\Sigma_0 = 1{,}8\cdot 10^4$, $m_1 = 9/2$, $m_2 = 6$ and $n = 3/2$ are presented in Table 1 upper part. While specific shallow water region estimates obtained for $n = 3/4$, are presented in - lower part.

It should be noted however, that one-mode waveguide excitation together with one-mode signal reception are supposed for all distances from 100 to 500 km. It is also supposed that optimal frequencies for distances exceeding 400 km will be no longer decreased by basic mode attenuation rapid increase for signal frequencies below 0,04 kHz, i.e. with frequency value approaching to waveguide mode critical frequency. Anomaly losses in one-mode propagation will increase linear with signal frequency, decreases exponent factor m down to 4. And at last, in the frequency range below 0,15 kHz obstacle scattering crossection for both systems will be assumed equal and varying with frequency decrease in accordance to square law, which yields for $m_{cf} = 2$, $m_{sni} = -1$, $m_{bs} = -3/2$, $m_n = -2$ total exponent factor value $m = 3/2$, where factor m_{sni} accounts for propagation anomaly losses spectrum frequency dependence influence.

Results of systems comparison are presented in Table 1, where $\Delta\Phi_{dB}$ reflects tomography power consumption advantages and f_0 (kHz) shows optimal frequency value.

Distances – operation ranges r (km)		100	200	300	400	500
Standard deep water regions conditions	f_0 (kHz)	2,00	1,30	1,00	0,80	0,70
	$\Delta\Phi_{dB}$	40	39	38	37	36
Specific shallow water region conditions	f_0 (kHz)	0,45	0,23	0,15	0,05	0,04
	$\Delta\Phi_{dB}$	30	25	23	0	0

Table 1

Table data evidence, that in deep water regions aggregate substantial tomography advantages are evident up to longest ranges. On the contrary, in specific shallow water regions, in particular, in Barents see region [9], for the case of maximum ranges tomography advantages (for chosen purely "diffraction" signal model) are not so undoubted. Various other parameter differences are to be in view in choice between two systems there.

To conclude this section let us make remarks on ocean vortexes observation options for two systems. It is shown in [8] that for such localized flows produced by symmetric motions, vortex distribution angular structure could be predicted. It acquires quite simple form, which leads to scattering amplitude angular structure. It follows from corresponding general expression in [8], that scattering amplitude will vanish in backscattering direction as well as in incident wave plane. It should be noted that scattering amplitude observed in back direction vanishing is most general property of sound scattered on continuous vortex flows. This property is characteristic not only for localized vortex flow, but for free (or wake) turbulence scattering as well [7]. These arguments propose solution of system comparison problem in the cases of ocean vortexes, internal waves and ship turbulent wakes observation [8]. Backscattering system is useless in this field and could not be compared to tomography system. In the same time it should be noted that mentioned vortex structures with continuity breaks, situated close to rigid boundaries could sometime give faint back scattered signal due to sound reflections from mentioned flow inhomogeneities.

In the part related to tomography system signal modulation noises for deep and several (presumably, Arctic) shallow water regions due to interaction with ocean non stationary structure we should point to experimental statistical parameters evaluation and proposed methods of their distance behavior prediction [11, 13-15]. Special attention was devoted to signal - internal wave interaction [10, 14]. Such kind of noises attaining signal amplitude several percent value are related to general signal stability which is not taken into account in Table 1 data. They provide additional difficulties in tomography inhomogeneities control, even in simplest form. We have pointed to the kind of "transparency window" in mentioned ocean noise spectrum revealed experimentally (frequency range near 2 - 6 mHz) and validated by ocean wave structure statistics [12]. Modulation amplitude slight distance increase (slow enough) should be mentioned as well [14] in conclusion.

It is shown that for both system types the only efficiency increasing and power consumption decreasing way lays in ocean wave guide one-mode excitation concurrent with one-mode signal reception on specific distance optimal frequencies. Basic difficulty observed on this way is low frequency high spatial resolution array design and construction, which obviously lead to their inadmissible dimensions in array traditional design versions.

PARAMETRIC ARRAY

Practically unique way to get over these difficulties is to use actual enough technical solution – linear sea bottom radiation array based on nonlinear frequency transduction (decrease) and signal reception array based on the same principle [17-18].

In this section we shall try to develop requirements for these parametric array parameters. On the basis of one of the simplest - horn array model [17], valid in the extreme case where characteristic frequencies ratio *F/f* is much smaller than characteristic signal attenuation length r_d to Frauengopher zone dimension r_f ($r_f = S/\lambda$) array ratio, evaluated with respect to pump signal frequency, parametric radiation amplitude p_{pr} could be expressed in the following way:

$$p_{pr} = fSp_0/2rc \qquad (4)$$

where, $f = F_1 - F_2$ - parametric radiation residual frequency, F_1, F_2 – biharmonic pump signal frequencies, p_0 – pump signal amplitude ($p_0^2 = 2w\rho c$), w – pump signal power, L – array length, and S – array radiating area (for linear array we assume $S = L\lambda/2$), λ – pump signal wavelength, ρ and c – ocean media density and sound velocity, α - amplitude attenuation factor for pump signal frequency (r_d = 1/2 α), r - distance. For multi wavelength dimension horn array as a sound source of high directivity, expression (4) is valid in approach, where the distance on which radiation cone envelopes all waveguide thickness exceeds so called "pump length" $2FL/f$ - observed outside waveguide. But single excited mode cylindrical propagation will still be achieved. While horn array radiation directivity angle $\Omega = (\lambda/L)$, and angle related to single mode $\gamma = \pi\lambda/2H$, then (if $\Omega > \gamma$) these angles ratio will characterize unnecessary modes excitation losses.

Beyond distance r_d, equal to $1/2\alpha$, parametric radiation amplitude will decrease in accordance to cylindrical propagation law. Far from the source sound field will be defined by single most slow attenuated mode. Multimode object scattered field should also be receipted by matched long enough sea bottom array, say, parametric array with reception angle of an order of opposite parametric array radiation angle, which leads to substantial inhomogeneity control noise immunity increase. We are going to evaluate power consumption in tomography system for trace length 1000 km and object estimated range 500 km. It is disadvantageous to use characteristic array frequency ratio too high – we shall assume it to be equal to 10. In theory transduction efficiency could not exceed 0,1. But in fact, maximum efficiency will not exceed squared ratio value and will comprise less that 1 percent [18]. Region depth is supposed to be H = 200 m. Due to frequency band limits array length will be equal to 100 half wavelength.

At first let us assume that parametric signal amplitude observed on characteristic attenuation distance r_d = 1/2 α is 100 Pa, while necessary pump signal power will be defined by signal to noise ratio residual with respect to value required by trusty object detection condition. Using Eq. (4), substituting f = 40 Hz, we obtain $p_0^2 = 2w\rho c$ = 0,6 $\cdot 10^{12}$ Pa^2, w = 180 kW, array length L = 200 m, $2\alpha = \beta/10\log e^2 = \beta_0 f^n/8{,}7$ = 0,4·0,4 / 8,7 = 0,025 km^{-1}, and signal attenuation characteristic distance $r_d = 1/2\alpha$ = 40 km corresponding to 100 Pa, while for 500 km distance - 35 Pa signal amplitude value is expected.

Evaluating excessive mode excitation losses we note radiation angle $\Omega = (\lambda/L)$ = 0,02. It should be compared to single mode accounting angle $\gamma = \pi\lambda/2H$ = 0,03. For the case $\Omega < \gamma$ this type of losses vanished. Attenuation losses rate comprises 0,015 dB/km [9] for 40 Hz basic mode and they reach 500·0,015 = 7,5 dB. Decreased signal amplitude value near object is p_1 = 12 Pa. For multimode signal propagation in model object scattered field receiving array arriving signal amplitude p_2 could be calculated by means of expression $p_2 = p_1 \cdot R \cdot A^{1/2}/2r$, where $A^{1/2} = (r/r_0)^{1/2}$ comprises propagation anomaly effect and r_o – is of an order of layer depth H. By means of matched receiving array of length L = 2000 m, extracting signal basic mode (as the only useful due to natural mode structure impoverishment) we shall obtain for p_2 on 500 km distance with one-mode anomaly $A = r \cdot \lambda \ / \ 2H^2$ and additional 7,5dB attenuation: p_2 =0,4 p_1 $(R /2 H^2) \cdot (\lambda / 2)$ = 1,5·10^{-3} Pa.

Sea surface noise for wind of force 5 are taken as a basic noise source for signal observation – it represents noise spectrum with amplitude frequency density on standard frequency 1kHz 2·10^{-3} Pa/Hz$^{1/2}$ and spectrum shape inversely proportional to f above 0,1 kHz, and to - $f^{1/2}$ below 0,1 kHz. Then noise spectrum density p_n for frequency 0,04 kHz will reach value of 3·10^{-2} Pa/Hz$^{1/2}$, and accounting to its decrease by array signal concentration (directivity) for reception angle $\Omega = \lambda / 2L$ in $(2\pi / 0{,}01)^{1/2}$ = 25 times, we shall observe noise amplitude level p_n = 1,2·10^{-3} Pa/Hz$^{1/2}$. If already mentioned surface sources weakening effect due to one-mode reception provision (approximately 15 dB – for basic mode signal receipt) would be taken into account, then for noise spectrum amplitude we obtain p_n = 2,4·10^{-4} Pa/Hz$^{1/2}$. It leads to final estimate of signal to noise ratio as 14 dB which for Gauss noise statistic distribution means desirable signal detection probability 0,9 with false alarm probability less then 10^{-4}. According to our predictions it requires up to 180-200 kW pump sources acoustic power consumption on tomography system radiation end.

REFERENCES

[1] Tolstoy A., Diachok O., Frazer L.N. Acoustic tomography via matched field processing // J. Acoust. Soc. America, v.89, №2, P.1119-1127 (1991)

[2] Ye Z. Theoretical description of possible detection of swimbladdered fish in forward scatter // J. Acoust. Soc. America, v.98, №5, pt.1, P.2717-2725 (1995)

[3] Ingentio F. Scattering from an object in a stratified medium // J. Acoust. Soc. America, v.82, №4, P.2051-2059 (1987)

[4] Borodin V.V., Galaktionov M.Yu. Fundamentals of the high-frequency forward scattering sonar // Fields in Oceanic Waveguides, Coll. Papers, Ed. V.A. Zverev, v.2, Nizhniy Novgorod, P.259-355 (1998)

[5] Sukharevsky Yu.M. Statistics of deep water oceanic regions basic acoustic parameters and probabilistic range of sonar systems // Acoust. Phys., v.41, №5, pp.749-763 (1995)

[6] Sukharevsky Yu.M. Decrease in acoustic fields of sonar objects in realistic ocean physical conditions and their acoustic undetectability criteria. // Acoust. Phys., v.45, №2, pp.230-235 (1999)

[7] Alekseev V.N., Semenov A.G. On wake role in sound scattering on moving body // Acoust. Phys., v.46, №6, pp.641-647 (2000)

[8] Alekseev V.N., Semenov A.G. Sound scattering by localized flows // Acoust. Phys., v.42, №3, pp.315-321 (1996)

[9] Ageeva N.S., Krupin V.D. Shallow water modes frequency response behavior due to variability of sediments layers longitudinal waves velocity and water layer sound velocity profiles // Acoust. Zh., v.30, №5, pp.577-584 (1984)

[10] Khrekov A., Semenov A., Skvortsov A. and Susarov V. Effect of natural internal waves on sound amplitude fluctuations in shallow water arctic region // Proceedings of the European conference on Underwater Acoustics, Luxembourg. Ed. M. Weydert, Elsevier publication London New York. P.351-355 (1992)

[11] Khrekov A., Semenov A. and Susarov V. Experimental comparison of sound amplitude fluctuations statistical characteristics in deep and shallow water sub arctic regions // Proceedings of the European conference on Underwater Acoustics, Luxembourg. Ed. M. Weydert, Elsevier publication London New York. P.329-333 (1992)

[12] Semenov A.G. On optimization possibility for ocean acoustic tomography system // Journal de Physique IV, Colloque C5, supplement au Journal de Physique III, V.4, P.1087-1090 (1994)

[13] Bespalov L.A., Derzhavin A.M., Semenov A.G. Natural variability of hydrodynamic and acoustic fields in the ocean in the ultra low frequency range // Acoust. Phys., v.44, №5, pp.507-515 (1998)

[14] Derzhavin A.M., Semenov A.G. On natural variability of sound field in long-range ocean propagation // Acoust. Phys., v.45 №2 pp.172-181 (1999)

[15] Derzhavin A.M., Semenov A.G. Sound fluctuations caused by internal waves in a shallow sea // Acoust. Phys.,, v.47, №2, pp.210-219 (2001)

[16] Bespalov L.A., Derzhavin A.M., Kudryavtsev O.V., Semenov A.G. Modeling of the seismoacoustic field of a low-frequency source with allowance for the structure of the ocean bulk // Acoust. Phys., v.45, №1, pp.19-30 (1999)

[17] Naugolnykh K.A., Ostrovsky L.A. Nonlinear wave processes in acoustics, Moscow, Science (1990)

[18] Truchard J.J. Parametric receiving array and scattering of sound by sound // J. Acoust. Soc America, v.64, №1, P.280-285 (1978)