THE USE OF THE TIME REVERSE ACOUSTICS IN A SHALLOW SEA

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In this report the results of theoretical, numerical and experimental analysis of TRM in a shallow sea are submitted. It is shown that in shallow sea the characteristics of focusing depend first of all on the sizes of the array of imaginary sources which essentially exceeds the sizes of any real array. The method of an experimental research of characteristics of TRM is founded only on the receiving elements and a probe sources is offered. The spatial sizes and the form of focal area of TRM are measured. It is experimentally confirmed the identity of focal area of TRM with one element and the vertical arrays. The estimation of efficiency of such systems is executed.

INTRODUCTION

Acoustic waves are practically unique basis of creation of systems of underwater monitoring of ocean. However at propagation of a wave are used to influence inhomogeneities of environment and are repeatedly reflected from a bottom and a surface of the sea. Especially complex picture of propagation turns out in a so-called shallow sea. At distribution to a shallow sea the signal essentially changes under influence waveguide dispersions. In consequence of that the signal is expanded in time and, signal to noise ratio is down [1].

Long time of effort of hydroacoustic has been directed on struggle against these phenomena. Matched processing with environment (MFP - Match Field Processing) [2] was considered as the basic approach. The idea of this approach consist in attempt of construction to the theoretical to reality theoretical or numerical model of environment and model of distribution in it of acoustic waves. With use of these models algorithms of processing of signals were under construction. Unfortunately, owing to lack of adequate model of the information necessary for construction to solve this problem it was not possible. Non-steady-state environments give obsolescence of model and therefore we must repeat procedure of matching again and again, including measurements of characteristics of environment and calculations of model.

Attempts to solve a problem by remote measurement of environment (an acoustic tomography) also had no special success [3].

All these problems have forced to address to the methods based on the time reversing of signals or TRA - Time Reverse Acoustics [4, 5]. Traditional representation of these methods includes registration of signals come from a probe source (PS) up to receiving-radiating arrays (also called Time Reverse Mirror - TRM) and the subsequent radiation of the registered signals in environment with change of a sign on time. Because of inverse of time, environment compensates delays a component of the signals caused by a dispersion and multi channel of propagation. In a point of an arrangement of a probe source there is the most exact indemnification, due to this the level of a field in this point appears essentially above, than in all other space of environment. That is the method of the reversing allows focusing a field precisely in that place where there was a probe radiator.

Last years many publications, devoted to this problem [6-9] have appeared. In all described experiments the reversing of signals and focusing is carried out with the help of the vertical array which consists of the send-receive elements, capable both to accept signals, and to radiate them. The result of focusing on depth and distances with the help of the reception vertical array was supervised.

1. THE ANALYSIS OF A METHOD OF THE REVERSING OF TIME A SHALLOW SEA

Let's consider the classical circuit of the time reversing of waves in a shallow wave guide. In this case we have the probe source (index) p radiating a broadband signal, the send-receive array (index) s and the reception array (index) r. Let the probe source from a point of space with coordinates $\vec{r}_p$ radiates a signal $x\left(\tau,\vec{r}_p\right)$. On elements k of the reception array according to Duhamel integral the signal will look like:

$$y_k\left(t,\vec{r}_s\right)=\int x\left(\tau,\vec{r}_p\right)h_k\left(t-\tau,\vec{r}_p,\vec{r}_s\right)dt\,,$$

where $h_k\left(t-\tau,\vec{r}_p,\vec{r}_s\right)$ - pulse transfer function from a point p to a point $k\,(s)$.

It is possible to assert, that owing to a principle of reciprocity a transfer function from a point $k\,(s)$ in a point p is equal $h_k\left(t-\tau,\vec{r}_p,\vec{r}_s\right)$ in stationary environment. Infringements of this principle will be observed if a receivers and sources are moving thru environment, as transfer functions in one and in other party will differ.

The signals accepted by elements of the send-receive array, are registered and emitted back on environment with change of a sign on time. Therefore in a point of reception $\vec{r}_r$ the signal can be written down as:

$$\begin{aligned}
&z\left(t,\vec{r}_r\right)=\sum_k\int y_k\left(-\tau,\vec{r}_s\right)h_k\left(t-\tau,\vec{r}_r,\vec{r}_s\right)d\tau=\\
&=\sum_k\int\int x\left(-\tilde{\tau},\vec{r}_p\right)h_k\left(-\tau+\tilde{\tau},\vec{r}_p,\vec{r}_s\right)h_k\left(t-\tau,\vec{r}_r,\vec{r}_s\right)dtd\tilde{\tau}=\\
&\sum_k\int x\left(-\tilde{\tau},\vec{r}_p\right)\int h_k\left(-\tau+\tilde{\tau},\vec{r}_p,\vec{r}_s\right)h_k\left(t-\tau,\vec{r}_r,\vec{r}_s\right)d\tau d\tilde{\tau}
\end{aligned}$$

The internal integral represents not that other, as mutual correlation of two transfer functions:

- from a probe source (point) p up to an element k of the send-receive array;
- from a point of space in which the field is estimated (point) r up to an element k of the send-receive array.

$$\begin{aligned}&\int h_k\left(-\tau+\tilde{\tau},\vec{r}_p,\vec{r}_s\right)h_k\left(t-\tau,\vec{r}_r,\vec{r}_s\right)d\tau=\\&=-\int h_k\left(\tau,\vec{r}_p\right)h_k\left(\tau-\left(\tilde{\tau}-t\right)\right)d\tau=-R_k\left(\tilde{\tau}-t,\vec{r}_p,\vec{r}_r\right)\end{aligned}.$$

Actually this function characterizes spatial-time correlation of a signal in environment. The experimental estimations of spatial correlation is shown, that intervals of spatial correlation have the limits and small sizes, is especial in vertical section in a shallow sea. The maximum of this correlation function in space coincides with position of a probe source.

It is possible to believe [10] (including on the basis of known experimental data) that on elements of the array in a shallow sea (in a wave guide) this function varies weakly. Therefore it let us use average correlation function:

$$\bar{R}\left(\tau,\vec{r}_p,\vec{r}_r\right)=\frac{\sum_k^K R_k\left(\tau,\vec{r}_p,\vec{r}_r\right)}{K},$$

where K - number of elements of the send-receive array and expand $R_k\left(\tau,\vec{r}_p,\vec{r}_r\right)$ in a Taylor series:

$$R_k\left(\tau,\vec{r}_p,\vec{r}_r\right)=\bar{R}\left(\tau,\vec{r}_p,\vec{r}_r\right)+\frac{R_k'\left(\tau,\vec{r}_p,\vec{r}_r\right)}{1!}+\ldots.$$

It is possible to believe, that the second and the subsequent members give the small contribution, especial near to a probe source. If to truncate it, the general result of focusing is independent of number of elements of the probe array.

It seems, the focusing effect needs many elements (mirror), but our analysis shows an opportunity of focusing at use of one element. What's the matter? Actually, no contradiction here is present. In free space the focusing needs many send-receiving elements as spatial correlation has no a maximum whereas in a waveguide it has spatially located maximum.

In most cases it is possible to make separation the spatial and time variables. In this case we shall separate the time and spatial correlation functions.

$$\bar{R}\left(\tau,\vec{r}_p,\vec{r}_r\right)=\bar{R}_s\left(\vec{r}_p,\vec{r}_r\right)\bar{R}_t\left(\tau\right)$$

The accepted signal is simply convolution of a probe signal and this correlation function:

$$z\left(t,\vec{r}_r\right)=R\left(\vec{r}_p,\vec{r}_r\right)\int x\left(\tilde{\tau},\vec{r}_p\right)R\left(t-\tilde{\tau}\right)d\tilde{\tau}.$$

So near a probe source the maximum of the radiated signal will be observed. This maximum will be especially significant if transfer function is more complex and more depends on space. Further this effect will be confirmed both by numerical modeling, and on natural experimental data.

That is, we have received that:

- environment in this case plays a role of the analog computer calculating mutual correlation;
- the size and the form of a focal area poorly depend on the sizes of the array;
- the operation of the time reversing of signal is equivalent to matched processing field in this case, only instead of numerically constructed replica the signal of a probe source is used.

At numerical calculation of mutual correlation it is more convenient to make operations in frequency area, therefore we shall write down the received result for spectra, believing, that attenuation in environment does not depend on frequency of a signal.

$$Z_{TRM}\left(\omega,\vec{r}_r\right)=R\left(\vec{r}_p,\vec{r}_r\right)X\left(\omega,\vec{r}_p\right)H\left(\omega\right)H^*\left(\omega\right)\approx R\left(\vec{r}_p,\vec{r}_r\right)X^*\left(\omega,\vec{r}_p\right)$$

In case of radiation by a probe source of a signal of type the delta pulse (a short probing pulse) a focal area will have the small sizes in time that is the method is suitable for application in pulse systems. Moreover, due to that the probe signal is known, it is possible to focus any signal which has the frequency band is not fall outside the frequency band of a probe signal.

The focusing effect in a waveguide can be explained as follows. Well-known that for an explanation waveguide propagation of a sound to a shallow sea is frequently used imaginary sources [1]. The array of imaginary sources also focuses a field in methods of the reversing of time of broadband signals and more imaginary sources and more difficultly environment focusing is more effectively. Thus the size of the imaginary array practically does not depend on the sizes of the real array placed in a wave guide, and only from properties of a wave guide. Radiation by all elements of send-receiving arrays only increased the level of signals in environment and the attitude a signal noise, and generally does not lead to improvement of focusing.

2. AN ESTIMATION OF EFFICIENCY OF THE REVERSING OF TIME

Qualitatively this effect also can be explained, using modal representation. The signal of a probe source representing the sum of modes comes to the send-receive array as stretched in time owing to dispersion. Reverse of this signal in time and radiation back to environment leads to that at propagation the dispersion again influences a signal. In this case the modes begin to gather, and in a point of the PS delay between modes becomes equal to zero. However farther they become widely separated again.

Modes exist in all section of a waveguide everywhere adds with different phases. The average level of a field in waveguide will be equal to not coherent summation of modes. At the same time in a point of the PS all modes will gather coherently. This allows getting the simple estimation of efficiency of the time reversing. Increase in the attitude the signal / noise at use of the time reversing is equal to the attitude of a square of the sum to the sum of squares of amplitudes of modes. It allows estimating easily a prize from use TRA.

With use of three typical hydrology's and one experimental, and also 4 types of sediments (mud, sand, limestone, basalt) [11,12] for three-layer model of a waveguide with use of numerical model KRAKEN had been executed estimations of increase in the attitude signal / noise at use TRA. For a distance of 100 km average value 7 дБ (disorder from 2 up to 9 дБ) has been received, and smaller values are received at presence of strong attenuation of the modes due to losses in a sediment layer.

As the focal area and a prize of focusing at use TRA in shallow waveguides is formed only due to the virtual array, there is a question on advantages of use of physical arrays.

Use array allows to receive a prize due to increase of the attitude signal / noise for additive noises, as these noise practically no correlated at distance from receivers already on half of a wave length, while additive noise of the virtual array completely correlated (for the array generated by one elements of the array). Application of the horizontal array allows getting azimuthally selective characteristics of TRA system.

3. NUMERICAL MODELING TRM IN A SHALLOW SEA

For acknowledgement of the received results numerical modeling for an isovelocity waveguide and for the mentioned above 4 types of three-layer waveguides has been executed. For изоскоростного an isovelocity waveguide analytical values of modes and wave numbers were used, and for a three-layer waveguide the numerical values received with the help of model КРАКЕН [13] were used.

Field of each mode created by a harmonious probe source on one element n of the vertical send-receive array we shall write down as:

$$p_m(n) = A\psi_m\left(Z_{SRA}(n)\right)\psi_m\left(Z_p\right)\exp\left(ik_m r_{SRA-p}\right),$$

where ψ_m - the vertical form of a mode m, k_m - wavenumber of a mode m, Z_p - depth of a probe source, $Z_{SRA}(n)$ - depth an element n of the send-receive array, r_{SRA-p} - a horizontal distance between the send-receive array (SRA) and a probe source (p), A - a constant.

Full field we shall write down:

$$P(n) = \sum_m p_m(n).$$

The reversing of time is expressed as change of a sign of index of exponent. Each accepted mode, emitting back with change of a sign, raises all spectrum of modes. Therefore we shall write down a field at a control hydrophone in the following kind.

$$p_{cont}(r) = \sum_m\sum_l\sum_n \psi_l\left(Z_{SRA}(n)\right)\psi_l\left(Z_{cont}\right)\exp\left(ik_l r\right)p_m(n),$$

where Z_{cont} - depth of a control hydrophone, r - a distance from the send-receive array up to a control hydrophone, l - modes formed by the send-receive array. Moving a control hydrophone on a waveguide it is possible to measure a field created by the array of inverted time.

How the formula will change if the probe source will radiate a broadband signal. In any point of space different modes will come with delay determined of their group speed. For example, the mode of number m radiated by a probe source and reemitting by send-receive array in a mode l will come to a point r with delay $\tau_{mn=}\dfrac{i\left(k_m r_{SRA-p} - k_l r\right)}{\omega}$. In this case the amplitude of the coming signal will be defined by amplitude of pulse (or amplitude of autocorrelation function of a signal for match processing) on this delay. Next expression was applied to modeling the reversing of broadband signals:

$$p_{cont}\left(r\right)=\sum_{m}\sum_{l}\sum_{n}\psi_{l}\left(Z_{SRA}\left(n\right)\right)\psi_{l}\left(Z_{cont}\right)\exp\left(ik_{l}r\right)p_{m}\left(n\right)R\left(\tau_{ml}\right)$$

For calculation of a field on a control hydrophone modes and wavenumbers an isovelocity waveguide and modes and wavenumbers calculated by KRAKEN were used.
For an isovelocity waveguide with thickness H wavenumbers and modes of number m [13] are:

$$k_{m}=\sqrt{\frac{\omega^{2}}{c^{2}}-\left[\left(m+\frac{1}{2}\right)\frac{\pi}{H}\right]^{2}}\ ,$$

$$\psi_{m}\left(z\right)=\sqrt{\frac{2}{H}}\sin\gamma_{m}z\ ,$$

where $\gamma=\frac{1}{H}\left(m+\frac{1}{2}\right)\pi$, z - depth.

It is necessary to take into account, that in field calculation the complex wavenumbers, which take into account modal losses and getting by KRAKEN were used, that is:

$$k_{m}=k_{m}+i\beta_{m}.$$

The inverted field in a waveguide calculated for a single send-receive element, and for the various size of arrays. In all calculation the average frequency of a signal was equaled 500 Hz, a band of 500 Hz, thickness of a waveguide was equaled 100 m, thickness of a layer of sediments was equaled 10 m.

As investigated to expect, for isovelocity a waveguide with absolutely reflecting boundaries the inverted field created by the array and a single source appeared practically identical. Addition of losses due to a sedimentary layer worsened focusing by a monopole is more than more loss.
In fig. 1 levels of the inverted field in a waveguide are resulted depending on a distance and depth for isovelocity waveguide with a basalt sedimentary layer and a basalt rock (waveguide Pekeris) near a probe source (a distance of 5 km) for the array and a monopole. In fig. 2 sections of this field through focus on a vertical and distances are resulted.

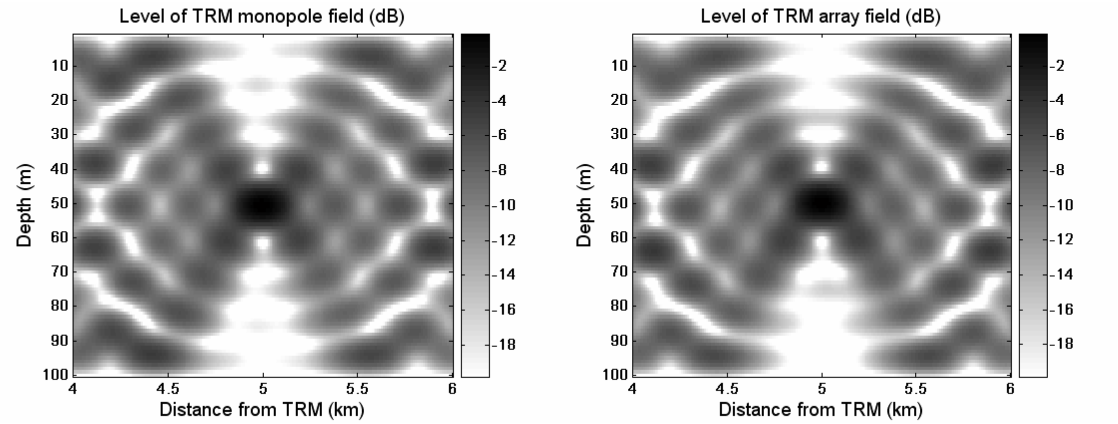

Fig.1 Levels of the inverted field in a waveguide are resulted depending on a distance and depth for isovelocity waveguide with a basalt sedimentary layer and a basalt rock (waveguide Pekeris) near a probe source (a distance of 5 km) for the array and a monopole. Array from 10 to 80 m, step 5m, monopole 50 m

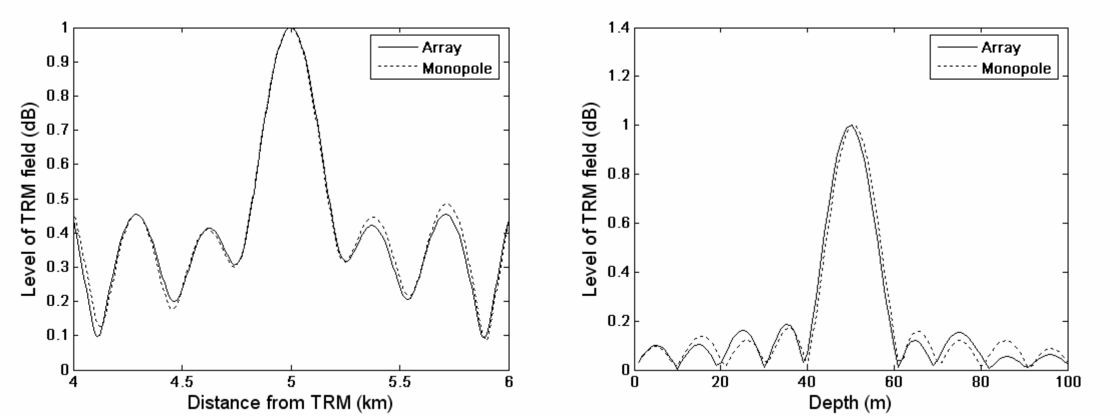

Fig.2 Sections of reversing fields through focus for a vertical and distances. Conditions of measurements as on fig.1

In fig. 3 levels of the inverted field in a waveguide are resulted depending on a distance and depth for an experimental spring sound speed profile in a waveguide with sand sediment layer and a basalt rock near a probe source (a distance of 50 km) for the array and a monopole. In fig. 4 sections of this field through focus on a vertical and distances are resulted.

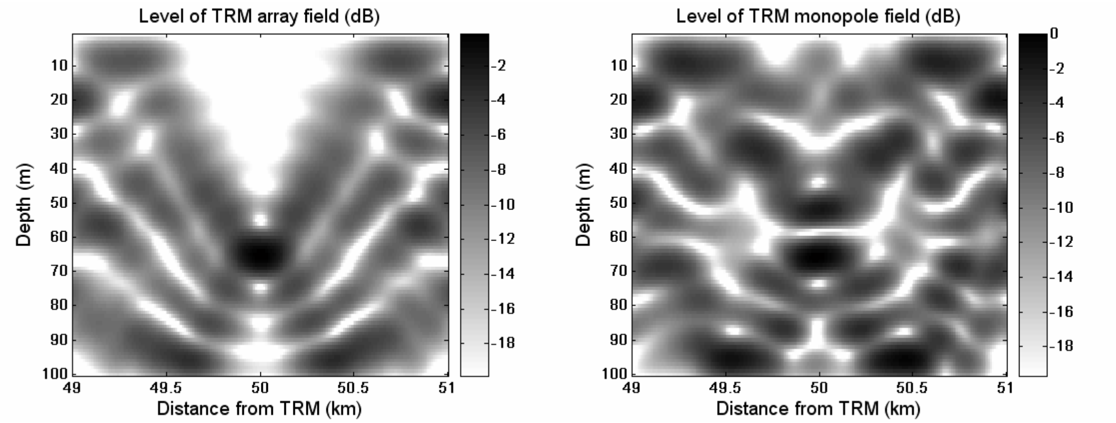

Fig.3 Levels of the inverted field in a waveguide are resulted depending on a distance and depth for real waveguide with a sand semimetal layer and a basalt rock near a probe source (a distance of 50km) for the array and a monopole. Array from 10 to 80 m, step 5m, monopole 35 m

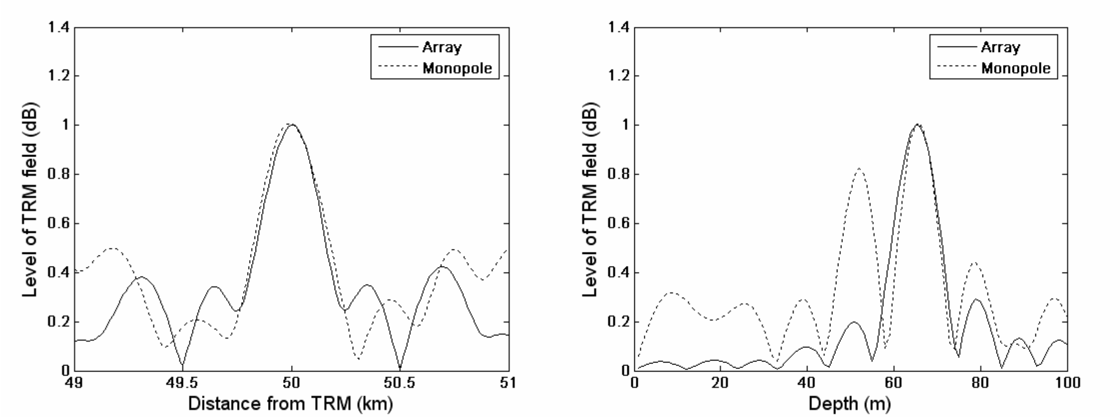

Fig.4 Sections of reversing fields through focus for a vertical and distances. Conditions of measurements as on fig. 3

It is well visible the expansion of a focal area with increasing of absorption of the modes.

4. THE NUMERICAL REVERSING OF TIME OR THE EMPIRICAL MATCH FIELD PROCESSING

The analogy of the reversing of time to a match processing allows offering numerical analogue of the time reversing. Receiving signal of a probe source is correlated with a signal accepted from a source placed in a controllable point of environment. In this case realization of the scheme of measurements become easier, that allows to carry out experimental researches with smaller expenses. First, there is no necessity to use the send-receive array, it is enough to have instead of it the reception array. Instead of reception (the control array) it is possible to use moved single (monopole) source. It is possible to use a probe source after the probe signal has been radiated and registered as such source.

The analysis of such scheme similar analysis mentioned above allows getting:

$$Z_{DTRM}\left(\omega,\vec{r}_r\right) =\approx R\left(\vec{r}_p,\vec{r}_r\right) X\left(\omega,\vec{r}_p\right) X^{*}\left(\omega,\vec{r}_p\right)$$

Presence of an additional factor as a spectrum of a signal of a probe source is not an obstacle for comparison of results of measurements based on two these scheme. Moreover, it is possible to assert, that the spectrum of a probe signal should be known practically always and divided by a spectrum allows to believe that both schemes of measurements equivalent.

It is obvious, that both considered schemes of focusing are equivalent to within known factor. It allows estimations of characteristics executed with the help of one scheme to transfer on another.

It is obvious, that such way allows to focus the array not only to a known signal (equivalent probe), but also at a known probe signal to focus the array to any signal which emitted from a place of a probe source and have the spectral band which is not exceeding a frequency band of the probe source.

Unfortunately, the scheme with the time reversing of the radiating array during each moment of radiation allows focusing the array only to a point of an arrangement of one probe source. For refocusing of the radiating array to another point outside of focal area of the first probe source it is necessary to use a new session of radiation of signals from other probe source and already during other moment of time. That is focusing of the radiating array in various points of space demands significant time expenses. The reception array may be easy refocused to necessary quantity of points of space at any moment.

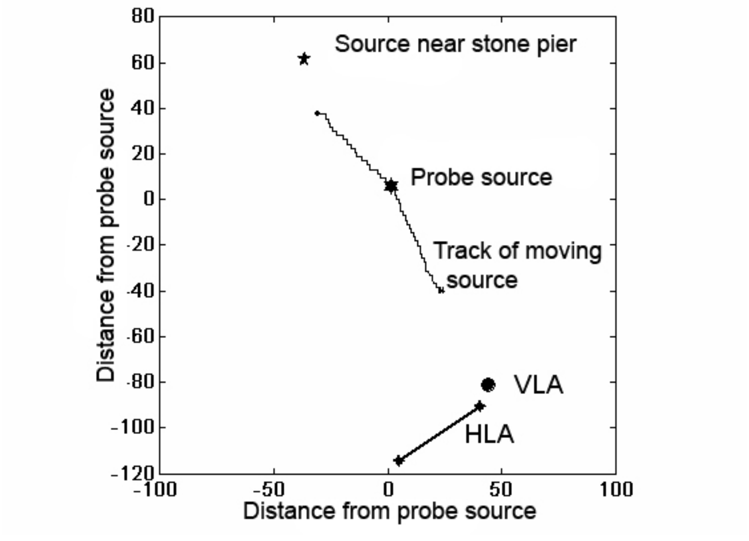

Fig.5 Scheme of measurement of focal area size

5. MEASUREMENT OF A FOCAL AREA OF SOURCES USING THE TIME REVERSING

Experiments on research of a focal area of sources using the time reversing have been executed in 2006[14]. The acoustic path has been organized between the sea terminations of two piers. For research of characteristics of a focal area the radiator moved with the help of a working boat on the fixed depth. near a floating pier horizontal and vertical reception 64 elements arrays have been established. For an estimation of spatial position of a source of radiation the satellite navigating system (GPS) was used.

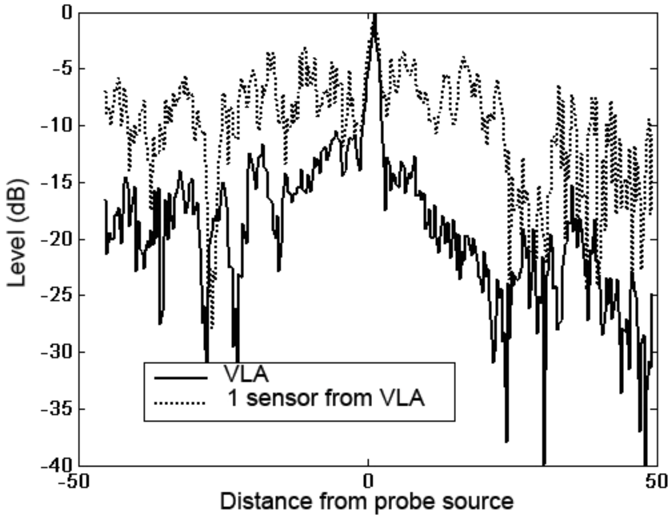

Fig.6 Sections of matrix mutual correlation function through a maximum on a distance for all array and one hydrophone with not coherent averaging

As a signal the pulses of frequency modulation by duration 10 mc with linear frequency modulation in a range from 1.2 up to 3.2 kHz were used. The period of repeating is equal 2 c.

The estimation of the longitudinal sizes of a focal area was carried out by calculation of mutually correlation function of the accepted pulses and a signal accepted from the middle of a track of boat (as probe source) was used. In fig. 5 the scheme of measurements is resulted. For comparison of focusing properties processing was carried out for one hydrophone and all array. For a single hydrophone not coherent average intensity of signal of all hydrophones was calculated with the purpose of reduction of a dispersion of additive noise.

In fig. 6 dependence at a distance of a maximum of mutual correlation function of the accepted pulses and a probe pulse for the vertical array is resulted. It is well visible that in the field of a focal area both curves well coincides that confirms that focusing properties of arrays are defined by the size of the array of virtual sources. Outside of a focal area the form of curves is defined first of all by additive noise. As indirect acknowledgement of it that fact serves that outside of a focal area the difference of levels corresponds to a difference of prizes 64 element arrays at coherent average concerning not coherent.

With the purpose of check of efficiency of application of focusing of the receiving array the scheme of sounding using at processing the matching with a signal of a source (i) and time reverse focusing (ii) has been realized. As probe the source near a stone pier which signal was accepted 18 hours prior to measurements was used. The sounding signal was radiated from a track of a moving source.

In fig. 7 echograms corresponding to focusing to the probe signal near a stone pier and the matching with a signal are resulted. Change of processing has not led to change of a level of reverberation, however focusing of the reception array to a pier has led to increase an echo of a signal from it by 9-10 dB.

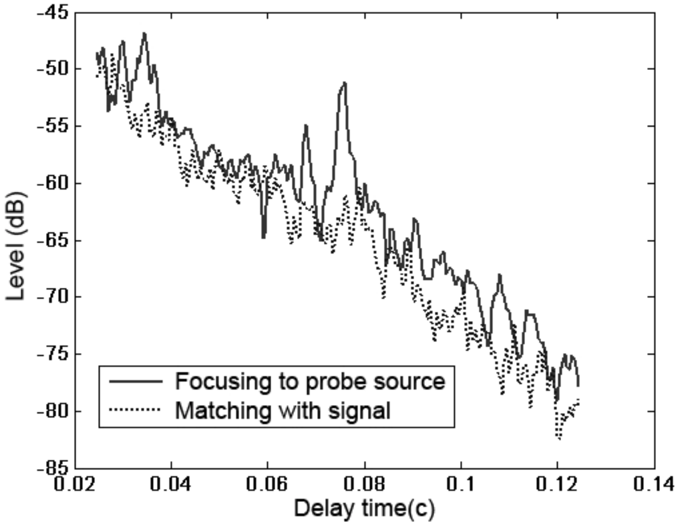

Fig.7 Echogram corresponding matching with signal of source (dotted line) and focusing to probe source near a tone pier (a continuous line)

6. RESULTS

Let's bring some results of the carried out researches. The basic results are the theoretical and experimental proof of the dominating contribution to effect of focusing of an acoustic field in a shallow sea of the array of imaginary sources. This effect distinguishes by use of the reversing of time of broadband signals in acoustics of a shallow sea.

Also the proof of use only the reception array (application of the simplified scheme of research of the time reversing) and the probe source allows to carry out researches of time reversing applied for anyone scheme is important.

Besides it is shown, that application of modal representation of a field allows estimating efficiency of TRA in different waveguide.

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