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Feasibility of the acoustic approach to remote sensing of water current with respect to Fram Strait.

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Results of the computation model of the sound propagation in Fram Strait environment condition is discussed. 3D environment has been simulated with respect to statistical properties of the real cross-section of the strait. The model demonstrates the presents of the stable rays which structure is not changed under the varying environment condition. Travel time variations are presented for the signal propagated along the stable rays through the 200 km path in transverse direction refer to water flow. Obtained data are useful for the estimation of the potential accuracy of the remote sound sensing application for the measurement of the inhomogeneous flow movement. The method developed relies on the advections of small-scale inhomogeneities across the acoustic path and travel-time variations in process of signal crossing the Strait on a number of paths to infer the intervening of fine-scale variability and transverse current. These inhomogeneities produce perturbations in the travel time of the sound and the current can be sensed by generating a time-lagged cross-correlation of the full acoustic field. The linear four element transmission array and the four element receiving array with equally spaced elements were used for calculations. By combining the signals from each transmitter-receiver pair in different ways, a number of different paths position were probed and profile of transverse current along the propagation path was retrieved. Calculations done in frame of ray model of the signal propagation.

INTRODUCTION

Problem of the heat and mass transport is a basic one in the general problem of the climate control in the Arctic. The most convenient method to investigate this important ocean environment pattern is acoustic one due to sound propagation depends on ocean current velocity as well as ocean water temperature. The short acoustic pulse propagation through the varying environment is computer simulated with respect to broad frequency band sounding of Fram Strait environment. The distance between signal source and receivers is regarded 200 *km* to overlap the main stream in the Fram Strait trough. The process of sound propagation is calculated for different pathway directions both transverse, up and down refer to water flow in the frame of ray theory approximation. The depth of the transmitter and the receiver is chosen in relation to sound speed profile which was measured in a course of "Polarstern" expedition in 1993. Each acoustic pulse travels to the receiver along many different ray paths with different travel times because of the channel sound propagation condition. Beside this the travel time changes with respect to varying environment what makes it possible to follow the changing environment in time or another words to follow the velocity of the environment movement in the "frozen" environment approximation. Broad frequency band sounding signals are used to resolve multipath travel times between the sources and the receivers in well known acoustics tomography consideration [1-3]. However there is a principal limitation of developed methods of the ocean acoustic tomography for their application in the regions with the intensive environmental perturbations which can affect essentially the acoustic signal propagation there. This limitation is conditioned on the approximation of the stable sound rays existence.

Such kind of rays can be identified in the process of travel time measurements [4-6] and their structure is not changed under the varying environment condition. It is important to know how this stable rays vary in the definite environment conditions for the developing of the acoustic methods of mass transport control. The most sensitive pattern of sound signal propagation is travel time variation. A change in the acoustic travel time leads to a proportional change in the acoustic phase which can be experimentally measured with a high accuracy at rather low signal-to-noise ratio. The main features of the sound signal propagation can be modeled in frame of 3D computer simulated environment. Results of the computer simulation of the statistical properties of the travel time variations with respect to Fram Strait sounding are summarized in the paper.

1. 3D ENVIRONMENT SIMULATION AND GEOMETRY OF THE PROBLEM.

Ocean current acoustic investigation is usually based on the travel time measurement for the sound signals propagated along some definite pathway. Travel time along the sound ray Γ_i can be defined as:

$$\tau_i \cong \int_{\Gamma_i} \frac{ds}{c(\Gamma_i)}$$

where $c(\Gamma_i)$ - is sound speed along the eigen ray Γ_i, ds - is the element of the ray between the source and the receiver. Travel time variation arises due to $c(\Gamma_i)$ changing. The main reasons that lead to $c(\Gamma_i)$ changing are the season variations, fluctuating water flow, mesoscale $c(\Gamma_i)$ movement, and internal waves. That is why $c(\Gamma_i)$ can be regarded as the sum of the mean value of $c_0(\Gamma_i)$ and its variation with respect to environment changing $c(\Gamma_i)=c_0(\Gamma_i)+\delta c(\Gamma_i)$, where $\delta c(\Gamma_i)$ is defined by the spatial inhomogeneity patterns. The most significantly $c(\Gamma_i)$ is influenced by the temperature variation $\delta\theta(\Gamma_i)$ and water flow velocity fluctuation $u(\Gamma_i)$, where temperature coefficient α for sea water is $4.72 \times 10^{-3} km(^{o}Cs)^{-1}$. Usually they regard the ratio $\delta c / c_0 < 1$, therefore we can define the travel time variation as follows:

$$\delta\tau_i \cong -\int_{\Gamma_i} \frac{ds\,\delta\theta(\Gamma_i)}{c^2(\Gamma_i)} - \int_{\Gamma_i} \frac{u(\Gamma_i)ds}{c^2(\Gamma_i)}$$

For the modeling of sound signal propagation through the number of mesoscale inhomogeneities it is necessary to simulate 3D inhomogeneity structure with definite parameters. Inhomogeneity movement in our case is regarded in frame of "frozen turbulence" model, when the whole environment structure is shifted with the velocity constant in the space. Bear in mind vector type of relation between δc and water flow velocity, one can exclude the temperature dependence for sound speed by δc measurement for the signals propagated in the opposite directions. In this case δc will be defined by water flow velocity component in the sound path direction.

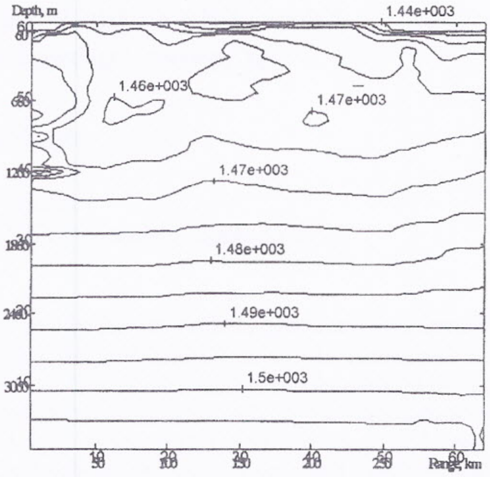


Fig.1.

Cross-section of $c(z)$ spreading along 79°N based on the original data measured in Fram Strait in March 1993 is shown at Fig.1. Here and further the left part of the picture corresponds to the eastern part of the Fram Strait. Considered environment is characterized by minimum value of $c(z)$ at the sea surface (subsurface sound waveguide) that is typical for winter. In the eastern part of the path there is one more minimum $c(z)$ at 600 m depth. It corresponds to the warm water income from the Atlantic at the horizon of 100-400 m depth. In the western part of the strait the cold and less salty Arctic water does not penetrate at the large depths and flows in subsurface layer. The second minimum of $c(z)$ vanishes there. Calculation shows the sound source and the receiver should be placed in this conditions at the depths of 500 m in order rays from the more shallow source to propagate mostly in the subsurface waveguide through the number of inhomogeneities. They can strongly affect the rays so they change their structure (a number of reflections from sea surface). This makes the signal propagation process more comprehensive for the problem regarded. For deeper source the length of the ray cycle increases and the number of ray arrivals to perturbed subsurface layer is decreases at the strait width. Besids deeper rays can touch the bottom and be scattered there. Hence the sea depths at source and receiver sites needs to sufficiently large for sound speed value at the bottom increases the same value in perturbated subsurface layer. Taking this consideration in mind we regard some pathway in the eastern part of the Fram Strait. Sound source is placed in our model at the 500 m depth at distance of 60 km from Prince Karl Land coast and the receiver is placed at the distance of 200 km to the west from the source at the 300 m depth. Calculations reveal the stable rays presence in this source-receiver configuration. These rays have either four or five touchings of the sea surface. Fig.2 shows an example of such rays, which do not lose their type in process of signal propagation in Fram Strait environment.

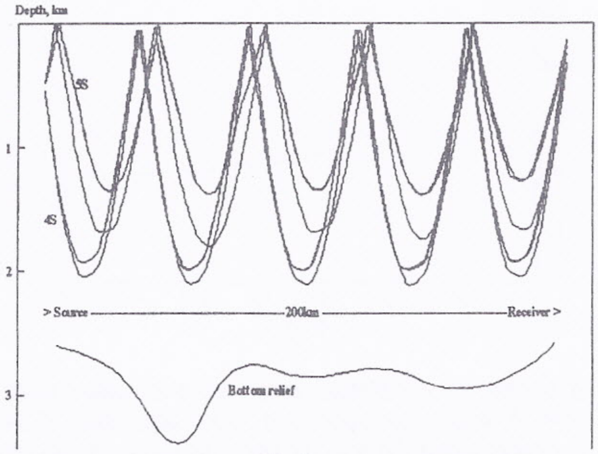


Fig.2.

As it was already mentioned, the environment conditions at the eastern and the western parts of the pathway are different ones. West-Spitsbergen current dominates at the beginning of the pathway and changes futher to the East-Greenland current. They has a constant configuration and therefore we cannot regard them as a random inhomogeneity. As for inhomogeneities we will presume them as a deviations $\delta c\ (z,r)$ from the regular dependence $< c\ (z,r)>$, where z is a depth and r is a distance from the source. Therefore the inhomogeneity $\delta c\ (z_j,r)$ at the horizon z_j at some arbitrary profile $c\ (z,r)$ is defined with respect to the spatial sound speed fluctuation at the z_j horizon. To match the results of computer simulation to real ones, the profile, is shown at Fig.1, was chosen as an initial one $<c(z,r)>$. To preserve the value of the δc fluctuations we normalize the variance of δc by the factor of Δ_0/Δ, where Δ is RMS of $(\delta c - <\delta c>)$ and Δ_0 is RMS of $(\delta c_0 - <\delta c_0>)$. As the variance of δc fluctuation is dependent only on j - the number of horizon z, the main task in calculation is to obtain the more complete data on the field of fluctuations. Data for 2000 environment realizations were generated in the process of computer simulation

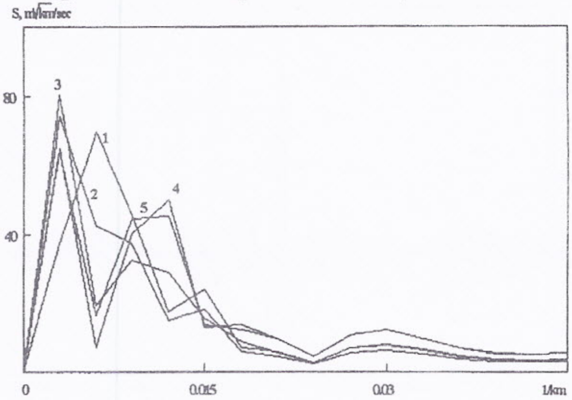
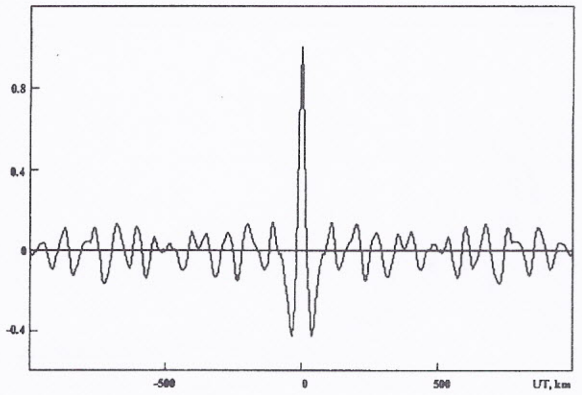


Fig.3.

Fig.3 shows appropriate spatial spectra (or periodograms) of the sound speed variations for the simulated cross-sections separated from initial one at $d = 35\ km$, $250\ km$, $500\ km$, and $630\ km$ respectively. This result seems more realistic in time domain. Actually this space interval corresponds the environment drift in time t with the stream velocity u, so the time delay for the calculated realizations can be defined as $t=d/u$. Therefore the curves 2,3,4,5 correspond to 20 h, 140 h , 280 h and 350 h time delays for the environment velocity drift $u = 1.8\ km/h$

2.SOUND TRAVEL TIME VARIATIONS FOR THE TRANSVERSE SENSING OF THE STREAM.

Let's regard barothropic type of the water layer movement as a simplest model of the flow. This approximation make it possible to avoid the flow shear shift in this consideration. That is why we regard the inhomogeneity moving without their deformation in frame of 'frozen turbulence' model. In this case the water flow velocity affects the travel time of the sound propagated along the pathway crossing the stream. Travel time calculation for each simulated profile is carried out for the 200 km path. As it has been already mentioned the source location was chosen at 500 m depth. The depth of the receiver is 300 m. In this configuration there is only one stable eigen ray which touches 4 times the sea surface without any reflection from the bottom. As it follows from the calculations the large scale inhomogeneity affects the travel time more strongly, therefore the slow variations dominate in this process. The value of the travel time variance occurs of several tens of milliseconds. Such a variation can be rejected by the Chebyshev filtration. Fig.4 shows the autocorrelation function for the travel time process after Chebyshev filter application with cut-off one period of the function on the realization length



Fig,4,

These data make it possible to evaluate the accuracy of stream velocity measurement by means of travel time variation for the signal crossing the flow. Let's suppose two parallel sound pathways crossing the stream and separated at some distance D and regard the signal propagation along these paths. As far as we use the 'frozen turbulence' model for homogeneous flow in the strait, the environment structure variation in the plane of cross-section of the second path will follow the same pattern in cross-section of the first one with time delay t, which related with distance D and flow velocity u, $t = D/u$. 'Frozen turbulence' model can be usually applied for a distance $D \cong 3\langle L\rangle$, where $\langle L\rangle$ is a spatial scale of environment variance. The accuracy of delay time definition for the high signal-to-noise ratio can be $\Delta t \cong 0.3\Delta\tau$, where $\Delta\tau$ is the width of autocorrelation for the travel time signal variation. This value can be estimated as $\Delta\tau \cong \langle L\rangle/u$. Thus the relative accuracy measurement is $\Delta t/t \cong 0.1$.

3. SOUND SCINTILLATION APPROACH.

The results of principal consideration of the process of the water stream velocity measurement by means of transverse sounding of the flow can be used for the more comprehensive problem, namely estimation of acoustical scintillation method for the environment inhomogeneity transport measurement [7-8]. The simplest putting of this problem is to consider the correlation between the signals passed from the source to a couple of receivers separated in space. We need to calculate the value of signal travel time along the path inclined with respect of the water flow direction. In a frame of our 3D simulated environment we can generate inclined $c(z)$ sections in course of interpolation procedure. Let us consider 200 *km* path between the source located at the same position as it was described above and calculate the travel time variation for the signal propagated through the paths to receivers located at 300 *m* depth and shifted from each other in horizon plane at some angle from the original pathway. We will consider the length of the paths to be the same, that is why the receivers are placed in this model on the arc of the circumference around the source. It is proved that the value of the maximum of the crosscorrelation function of the signals propagated along the diverged paths decreases with the angle of the receivers spatial separation and drops up quite to the value of random variations of the function at the angle 0.125 *rad*. This value is defined by the duration of the signal. 200 signal samples are used for calculation. Value of the correlation maximum dependence on the angle of spatial separation or spatial correlation function is shown at Fig.5.

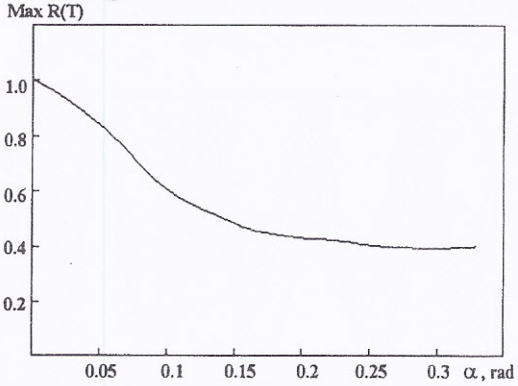


Fig.5.

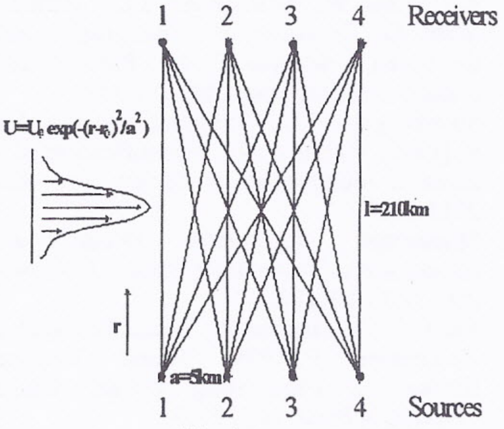
It is seen the correlation drops twice at spatial angle of 0.15, which corresponds to 30 *km* separation of the receivers along the arc. As while as the receivers are separated in the space the maximum value of the correlation is delayed with respect to the distance of the receiver separation and the flow velocity as well. These results are useful for evaluation of spatial characteristics of the flow and appropriate antenna pattern realization of signal scintillation method of the water stream velocity measurement. The fact of travel time fluctuations are proved to be co-related for the signals crossed the stream along the paths at small angles with respect to each other, makes it possible to consider the probing of their fluctuations by means of underwater array.

Let's regard for example the symmetrical array consisted of four equally spaced sources and four receivers (as it is shown at Fig.6). The base of the sources is placed 210 km apart from the base of the receivers. The simulation has been done for the spaces a between the array elements both the sources and the receivers are equal to 5 km. Therefore the network from 16 paths, which covers the area between sources and receivers, is regarded there. Inhomogeneities of the medium while they are flowing through the area covered by this network will affect the travel time for the signals, propagated along each of these paths. If we suppose the inhomogeneities to be slightly changed in process of their movement in the regarded area (model of 'frozen turbulence'), then travel time fluctuations of the signals propagated along the different paths will be retarded with respect to each other at different times and this time lag will be defined as function of velocity of inhomogeneity flow u_0 and the distance of its movement trajectory from the base of sources r or the receivers l-r. Here l is the distance between the array bases. From simple geometrical considerations one can determine these time lags as follows:

Table 1.

$$\begin{array}{llll}
t_{44}=0 & t_{34}=\dfrac{a(l-r)}{u_0 l} & t_{24}=\dfrac{2a(l-r)}{u_0 l} & t_{14}=\dfrac{3a(l-r)}{u_0 l} \\[2ex]
t_{43}=\dfrac{ar}{u_0 l} & t_{33}=\dfrac{a}{u_0} & t_{23}=\dfrac{a(2l-r)}{u_0 l} & t_{13}=\dfrac{a(3l-2r)}{u_0 l} \\[2ex]
t_{42}=\dfrac{2ar}{u_0 l} & t_{32}=\dfrac{a(l+r)}{u_0 l} & t_{22}=\dfrac{2a}{u_0} & t_{12}=\dfrac{a(3l-r)}{u_0 l} \\[2ex]
t_{41}=\dfrac{3a}{u_0 l} & t_{31}=\dfrac{a(l+2r)}{u_0 l} & t_{21}=\dfrac{a(2l+r)}{u_0 l} & t_{11}=\dfrac{3a}{u_0}
\end{array}$$

The first figure of the index means the number of the sources, and the second one corresponds to receiver position.



Fig,6,

Let's regard, for example, the flow of the medium as a spatial restricted stream with the exponential profile both in horizontal and vertical planes. Co-ordinate for maximum of the stream r_0 corresponds to one of the places where sound rays enter the subsurface ocean layer, where inhomogeneities are the most essential. For the definition we choose r_0=85*km*, where 4s ray touches the ocean surface the second time on the way along the path between the source and the receiver.

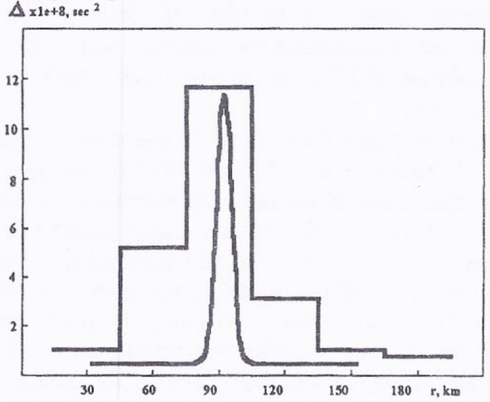


Fig.7.

Travel time variation via the array tuning distance r. Smooth line - profile of current.

Summing up the travel time fluctuations for the signals passed along the different paths with appropriate time lags leads to the rise of the correlated fluctuations with respect to number of signal realizations N (that is in 16 times), whereas the other fluctuations in process of random summation will be increased only in proportion of $N^{1/2}$ (or in 4 times in our case).

It is worth to take into consideration that such a summation has some sense only for signal fluctuations, which are conditioned by the fine structure of the hydrographical inhomogeneities with a spatial scale less or of order of the space between the array elements. The large structure, spatial scale of which is more then the dimension of the array base will simultaneously influence the signals passed along the whole network of the paths. Therefore there are no any sufficient phase shift in travel time fluctuations caused by the large scale inhomogeneities. For this reason low frequency fluctuations were rejected passing the signals through the filter, frequency band of which is defined by the transfer of the inhomogeneity which scale is in the range of 4 - 7 *km*. This range is conditioned by the mentioned above the array dimension and is related to the limites of 'frozen turbulence' model application. It is known this model is valid for the medium transfer at the range of 3-4 eddy spatial scale. At larger distances the eddy shape changes and looses the relation to its original form. Another words, the medium perturbation is proved to be uncorrelated. Thus the spatial scale of 4 *km* seems to be the upper limit in the spectrum for the inhomogeneities which can be regarded in the frame of 'frozen turbulence' model at the array aperture of 15 *km*. Spatial resolution of 30 *km* shown at Fig.7 is caused by the spatial intervals between 3D environmental samples used in process of computer simulation. In our case this interval was 5/7 *km*, or 7 environmental samples are used in space between the adjacent elements of the array. Simulation with such a spatial interval makes it possible to resolve the velocity of the inhomogeneity transfer with the distance resolution of 1/7 from the total path length of 210 *km*, or 30 *km*.

1200 signal realizations for each of 16 paths were used in process of summing up of travel time fluctuations. Correlation time interval for the inhomogeneity can be estimated as a ratio L/u, where L is a spatial scale of the inhomogeneity (L = 4-7 *km*). For any reasonable value of u, the time lags of the signal t_{ij} are proved to be much more then signal travel time along the path. For this reason we do not consider the difference in the lengths of the paths, or the difference in the average meaning of travel times. Moreover this figure of the signals is rejected in process of signal processing.

Therefore the process of determination of the eddy transfer as a function of the distance of its trajectory from the array base can be considered in the next way:

Travel time fluctuations for the signals propagated through the whole network of the paths (16 pieces of them) are registrated;

Received multitude of data is passed through the band pass filter. The filter frequency band are conditioned by the current velocity and geometry of array;

Time lags for the signal processting are defined with respect to Table 1. These values are proved the function of u_0 and r; Multitude of travel time realizations summing up with respect to time lags; For chosen r the value of u_0 varies such a way to reach the maximum in resulting variation of the travel time fluctuations; This maximum determines the value u_0 under the chosen distance r.

As far as the eddy position r is located along the ray trajectory, which has a cyclic type as it is shown at Fig.2, there is a possibility in principal to define the current velocity profile in vertical plane as well. But this possibility is strongly conditioned by the inhomogeneity distribution in depth of the ocean. In Fram Strait condition the hydrographic inhomogeneities are concentrated in the upper 500*m* layer. Therefore the real possibility of this scintillation method is limited only in this subsurface ocean layer.

CONCLUSION.

The process of 3D environment computer simulation has been done in assumption of isotropic random sound speed variation distribution in the plane in each horizon. Original data, used in the environment simulation process, are obtained in the course of 1993 "Polarstern" expedition. RMS statistical property of the media are conserved both in horizontal and vertical sections of the environment in process of computer modeling. Simulated field of environment inhomogeneities was used for the modeling of sound signal propagation. Sound speed variation leads to variations in travel time for the signals and limits therefore the accuracy of the acoustical method of remote ocean sensing. But at the same time it provides an opportunity to control the ocean flow in process of transverse sounding in the frame of 'frozen turbulence' flow model. Velocity of flow can be calculated there from the time delay between the signals propagated along the parallel spatially separated paths. It was defined the spatial-time correlation function of the signal. Obtained data can be used in process of estimation of sound scintillation method application for the measurement of the perturbation movement in the random flow.

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