ON THE MECHANISMS OF SCATTERING OF LOW-FREQUENCY SOUND ON SURFACE WAVES

Mikhail B. Salin, Oleg A. Potapov, Dmitry D. Razumov, Boris. M. Salin

Uljanov st., 46, Nizhny Novgorod, 603950, Russia

Contact author: Mikhail B. Salin, IAP RAS, Uljanov st., 46, Nizhny Novgorod, 603950, Russia. Fax: +78314160630. Email: mikesalin@hydro.appl.sci-nnov.ru

Abstract: *Narrow-band spectra of sound backscattering were investigated in a series of experiments with frequencies around 1 – 3 kHz. Two types of scattering spectra are distinguished. In the first case, side-lobes are observed at a certain distance from the carrier frequency. This effect is caused by Bragg scattering on surface waves. In the second case, a smooth broadening of the spectrum around the carrier frequency is observed. In this case, the reverberation spectrum is interpreted using the phenomenological model of sound scattering at subsurface inhomogeneities. These inhomogeneities are moving along circular tracks under the action of wind waves currents, which velocities are rather smaller than the phase velocities of surface waves.*

Keywords: *Low-frequency acoustic reverberation, acoustic backscattering, wind waves, surface roughness*

1. INTRODUCTION

The study of sound scattering in the shallow sea, involving measurement of levels and Doppler frequencies of echo signals, is of great interest due to it provides information for estimation of the action range Doppler sonars. This problem is also of interest in context acoustic monitoring of the marine environment. Most of the papers, which are devoted to low-frequency sound scattering, rely on the Bragg scattering on wind waves, and the scattering level is estimated be means of the perturbation theory. However, a number of experiments, for example, [1], showed the surface scattering levels, which exceed the values, predicted by the perturbation theory. Those levels were more consistent with the Chapman-Harris empirical dependence. Deviation from the perturbation theory was observed in a certain range of sound frequencies and wind speeds. The authors of [2] called this effect an "anomalous scattering", and explained it by the presence of air cavities and bubbles in the near-surface layer.

The difference between the sound scattering scenario, connected with air cavities, and the Bragg scattering is not only the scattering strength level, but it is also a change in the Doppler spectrum of the echo signal. In order to perform measurements of the echo spectrum with a resolution of 1 Hz, one needs to transmit an active signal, which band is not more than this value. The range resolution of such signal is 750 m or greater. Moreover, for a number of reasons it is rational to pause 1-2 pulse widths between the end of the transition phase and the beginning of reception. Thus, the experiment on measuring the surface scattering strength with Doppler frequency resolution involves sending a signal to the environment to a distance of several kilometers, which requires sufficiently powerful transmitter and the control of propagation losses along the path for normalization.

Wideband pulses were used in many early surface scattering experiments [1-5] (including in the mentioned above papers). Usually the pulses were generated by explosive sound sources. So only the total level of the scattered signal was estimated. However the Doppler spectrum of reverberation was analyzed in a series of forward scattering experiments [6]. But due to the bistatic geometry of those experiments and due to the usage of CW signals, scattered mainly took place on more intense surface waves of great length. This does not correspond to the type of interference encountered by monostatic long range detection sonars, which use long tonal pulses.

2. EVIDENCE OF THE BRAGG SCATTERING IN AN EXPERIMENT IN THE BAY OF THE LADOGA LAKE

A series of actions was taken to achieve the proper frequency resolution and a high signal-to-noise ratio, while measuring the sound backscattering spectrum in an experiment [7], which was conducted in the gulf of the Lake Ladoga. A radiating phased array antenna, consisting of a vertical line of transmitters, was used. Its pattern was at an angle of 45 ° upward. The CW signal at frequencies 0.6, 1.2, 2.5 and 3.5 kHz was transmitted. A non-directional receiver was located right under the phased array. The transmitting angle exceeded the angle of total internal reflection of the bottom. This setup ensured that the only received signal is a signal that is scattered on the line of sight of the phased array. This greatly simplified the calculations, since the values area of the illuminated surface and the angle of incidence is known. Thus, the scattering levels did not depend on the width of the signal, so a continuous radiation regime was used and the scattering spectrum was analyzed with a resolution of 0.1 Hz.

Fig. 1 shows an example of scattering spectra for two carrier frequencies: 1240 Hz and 2520 Hz. The local maximum is clearly seen on the spectra near the Bragg frequency. (That is the frequency of the surface wave, which length is the twice sound wavelength, with the correction due to the projection at a known incidence angle.) The experimental spectra are in good agreement with the theoretically estimated curves in terms of level and shape. Theoretical estimates are obtained basing on the perturbation theory. There were two types of measurement of surface roughness that were used to get the theoretical estimate. First, the frequency spectrum of the surface roughness $S(\Omega)$ was measured by a spar-buoy and dispersion relation for surface waves was used to extrapolate the spectrum to the wave number domain. Second a video recording and processing technique was used to directly measure the space-time spectrum $S(K, \Omega)$, and the dispersion relation was no longer used in the calculation. The detailed procedure of scatted spectrum calculation is given in [7].

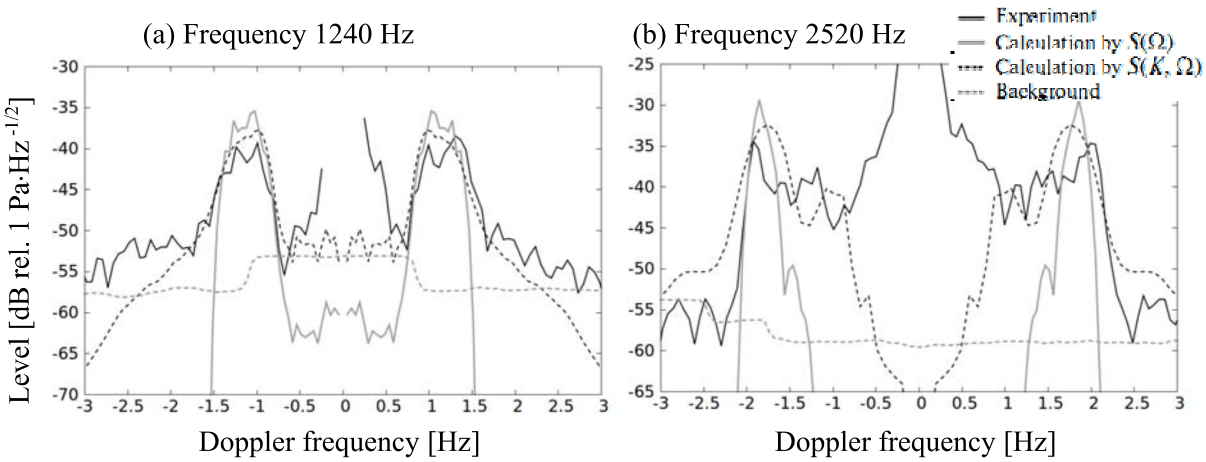

Fig. 1. Spectrum of the surface backscattering, when a beam is incident at an angle of 45°. The Lake Ladoga, 2013.. The levels correspond to the received signal the certain experimental geometry and the source level.

Since the water area was closed from strong winds, the surface roughness was low. The spectral maximum was at 1 Hz. The maximum of the scattering spectrum actually corresponds to the Bragg frequency, and not to the maximum of the wave spectrum, as in forward scattering experiments.

3. EVIDENCE OF "ANOMALOUS" SCATTERING IN AN EXPERIMENT AT THE GORKY RESERVOIR

An experiment, which took place at the Gorky reservoir, was conducted in such a way as to reproduce the classical monostatic location scenario. The reservoir size is approximately 5 x 50 km, an average depth is 10 m. There can be notable surface roughness, if the wind direction is along the reservoir. On the day of the experiment, the significant wave height was 21 cm.

The boat with the receiving-transmitting complex was anchored in the middle between the banks. A non-directional transmitter was set on the bottom, and the receiving phased array was set, using weights and buoyancies, in a horizontal position, at 5 m above the bottom. The receiving phased array consisted of 32 hydrophones equally spaced along the aperture of 6.2 m. The transducer emitted pulse signals with carrier frequencies of 1320, 2020 and 3020 Hz (near the resonance of the source) and with an envelope in the form of a Hann window of duration 1, 2, and 4 s. The spacing between pulses was sufficient, so that the reverberation effects from the previous one decayed before the beginning of the next pulse.

Signal processing consisted of the following operations: (1) heterodyning on the carrier frequency, (2) determining the starting time of each pulse, (3) phasing along the series of bearings, (4) calculating the narrow-band short-time Fourier transform (spectrogram), using the window length that is equal to the original pulse width and using 75% overlapping.

Thus, the data for each sounding regime were represented as an array $P(\tau_j, f_k, n, \theta_m)$, which is a function of the delay τ_j, f_k is the Doppler frequency, n is the number of the pulse in the sequence, θ_m - bearing.

First of all, let us consider the scattering spectra constructed for the signal along the bearing $\theta_{m*} = 90°$, which is along the long side of the reservoir, so that the coastline does not limit the propagation. And let us consider a strobe with some number $j*$, that is goes after τ_{j*} interval after the transmission moment. The spectra were averaged energetically over the ensemble of pulses.

An example of such scattering spectra is shown in Fig. 2 (solid line). Functions are normalized to a maximum, because the experimental conditions did not allow carrying out normalization in absolute units. The curves have a shape close to Gaussian with center at zero Doppler frequency. The graph also shows the normalized spectra of the signal recorded directly at the time of emission (black dashed line) to show that the signal spectrum is indeed broadened due to the scattering in the medium.

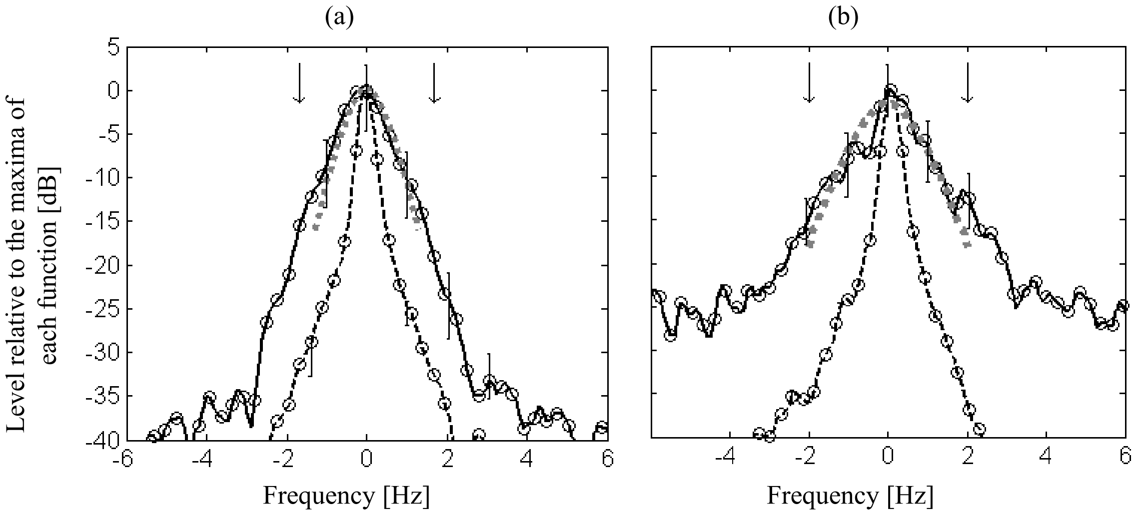

Fig. 2. The normalized spectrum of the echo signal for one bearing (solid line) in a strobe, delayed for τ_{j*}= (a) 3.1 s, (b) 6.3 s, the normalized spectrum of the transmitted signal (black dashed line) and the theoretical estimate (gray dots). The maxima of all curves are set to 0 dB. Frequency (a) 1320 and (b) 2020 Hz, pulse width 4 s. Gorky reservoir, 2016

A local maxima should arise in the spectrum near Doppler frequencies in case of the Bragg scattering on wind waves. These frequencies are indicated by the arrows on the figure. There are practically no apparent extremum in the pointed part of the spectrum.

Theory of sound scattering on a group of moving particles [8] was exploited to describe the measured spectra. The particles, most probably air bubbles, are assumed to be moving along circular trajectories, forced by orbital currents of wind waves. The theoretical estimate of the spectrum is plotted with a gray dashed line in Fig. 2 in the range 0÷-15 dB. The following parameter values were used, while calculating the theoretical estimate. The frequency of the energy-carrying waves was measured by a string wave gauge and was 0.4 Hz, the RMS value of the velocity of the oscillating flow at the surface was 0.24 m/s. The depth of the exponential decay of the bubbles concentration was fitted so that the computed spectrum match the shape of the measured spectrum, and this depth appeared to be 0.5 m. The scattering force of the particles is not used due to the lack of the normalization of the received signals.

There are other features, noted in the experiment. First, scattering has an almost isotropic pattern. Fig. 3 shows spectra, which were averaged in a same way (averaging over the pulse number, at one delay), as a function of bearing. Second, the scattering spectra fluctuate quite strongly from pulse to pulse. Fig. 4 shows a series of spectra as a function of the pulse number. The dispersion of the spectral components, considered as a function of the pulse number, is represented in the form of error bars on Fig. 2.

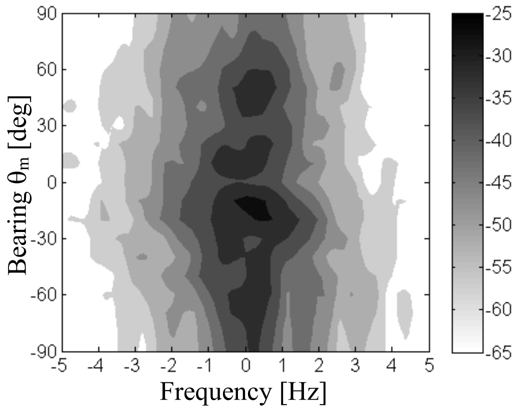

Fig. 3. Spectrum of the echo signal gated with a delay of τ_{j*} = 2.6 s, averaged over a series of pulses and plotted as a function of bearing. Frequency 2 kHz, pulse width 2s.

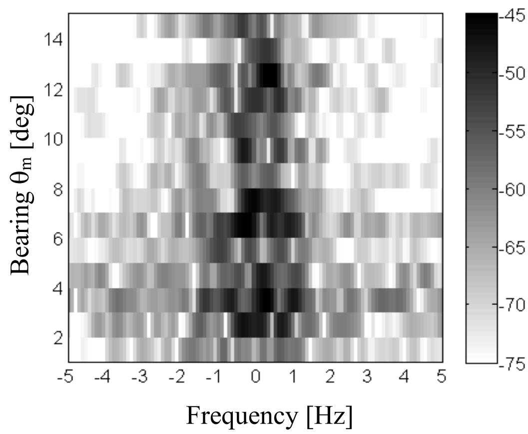

Fig. 4. Spectrum of the echo signal gated with a delay of τ_{j*} = 6.2 s, plotted as a function of the pulse number. Frequency 2 kHz, the pulse width 4 s.

4. ANALYSIS OF PREVIOUSLY PUBLISHED RESULTS OF EXPERIMENTS IN THE PACIFIC OCEAN

Authors of [9] published an example of an echo signal spectrum, where one can simultaneously observe Bragg and "anomalous" scattering effects. That experiment was carried out in the Pacific Ocean, in the region near Kamchatka. A rather powerful acoustic source was used. The carrier frequency was 250 Hz, and the pulse width was 100 s. Fig. 5 reproduces a curve, taken point by point from the figure in [9]. A theoretical function, calculated according to the recently developed theory [8, 10], is plotted on the same graph. The theoretical function includes scattering by moving near-surface particles (with matched parameters) and Brag scattering on the resonance component of the wind waves. The first term forms a wide distribution around the zero Doppler frequency, the second - a narrower peak in the vicinity of the frequency of 0.66 Hz. The authors of [9] did pay attention on the Bragg peak, but the wide spectrum near zero Doppler frequency was not interpreted by them in any way. The explanation of the wide spectrum was obtained already in the recent series of papers, including [8, 10] and this one.

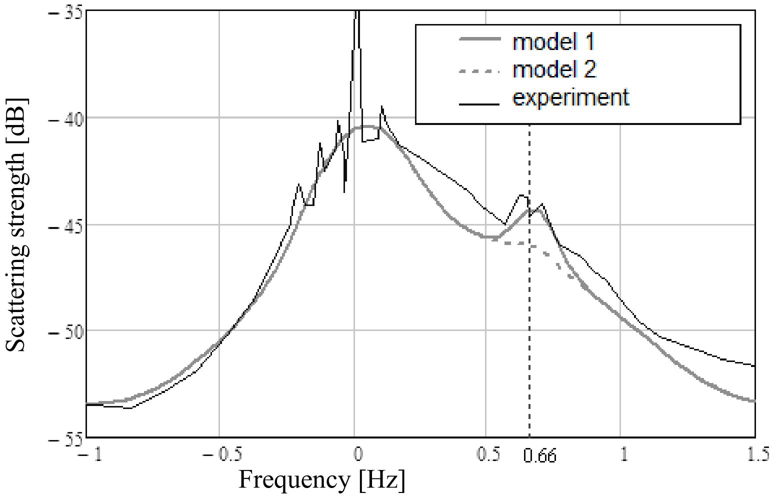

Fig. 5. Spectrum of the echo signal, the experimental curve is reproduced from [9].

5. SUMMARY

At calm sea state the sound backscattering signal comer right from wind waves with the corresponding lengths due to the Bragg resonance. This and leads to the appearance of a Doppler peak in the scattered signal spectrum. At strong wind the reflection from local scatterers, which are moving in the near-surface layer, appears to be the dominant scattering mechanism. These scatterers oscillate in the field of wind waves, thus the spectrum of the scattered signal also contains Doppler frequencies, but these frequencies are much lower than in the case of Brag scattering on surface waves.

6. ACKNOWLEDGEMENTS

Experimental equipment was developed with the support of the Program of state Academy of sciences for 2013-2020 years, section 12.18. The theoretical studies were supported by the Russian scientific foundation, project No. 14_17_00667.

REFERENCES

[1] **P.M. Ogden, F.T. Erskine**, Surface scattering measurements using broadband explosive charges in the Critical Sea Test experiments, *JASA*, 95 (2), pp. 746-761, 1994
[2] **T.H. Neighbors, L. Bjorno**, Anomalous low frequency sea surface reverberation, *Hydroacoustics*, 4, pp. 181-192, 2001.
[3] **I.B. Andreeva, E.G. Harat'yan**, Scattering sound by the ocean surface and near-surface sound-scattering layers, *Akust. zhurn*., 12 (4), pp. 399-404, 1966 [in Russian].
[4] **R. J. Urick**, *Principles of Underwater Sound*, McGraw-Hill, New Yotk, 1975

[5] **D.D. Ellis**, Modeling and analysis of target echo and clutter in range-dependent bistatic environments: FY13 annual report for ONR, *Defence Research Reports, Canada*, Doc. No.: ECR 2013-154, 2014.
[6] **A. V. Lebedev, B. M. Salin,** Effects of localization of the areas of sound scattering by surface wind waves, Acoustical physics, 50(6), pp. 704-716, 204
[7] **M. B. Salin, O. A. Potapov, B. M. Salin, A. S. Chashchin,** Measuring the characteristics of backscattering of sound on a rough surface in the near-field zone of a phased array, *Acoustical physics*, 62 (1), pp. 74-88, 2016
[8] **B. M. Salin, O. N. Kemarskaya, P. A. Molchanov, M. B. Salin**, Study of the mechanism for broadening of the spectrum of a low-frequency reverberation signal for sound scattering by near-surface inhomogeneities under conditions of intense wind waves, *Acoustical physics*, 63(2), pp. 338-345, 2017
[9] **B. C. Averbakh, L. F. Bondar', V. N. Golubev et al,** *Akust. zhurn.*, 36 (6), pp. 1119-1121, 1990 [in Russian].
[10] **B.M. Salin, M.B. Salin,** Mechanisms for the formation of spectral characteristics of low-frequency reverberation and forecast, *Acoustical physics*, 2017 [in print].