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New approach to oceanography research on elongated paths on principles of nonlinear acoustics

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A power parametric array (PA) operating on principles of nonlinear acoustics for waveguide marine research of the main oceanographic features (current, temperature, salinity) in the frequency band of 300-3000 Hz has been developed. An extremely narrow directivity pattern (2° angular resolution) for broadband acoustical signal perfectly couples to single-mode waveguide excitation in the whole frequency band. Specific features of the PA signal's transmission give an opportunity to use the waveguide frequency dispersion for wide frequency-band signal compression during long-range propagation. Relative gain in signal intensity could be realized in the process of such compression at the virtual acoustics barriers in shallow-water. Therefore, nonlinear acoustics opens a new frequency-domain approach for underwater array application. The main objective of this paper is to discuss the primary advantages of such an underwater array, working on the principles of nonlinear acoustics for long-range oceanographic research. Demonstration of the new abilities provided by PA application for remote ocean sensing is expected to yield long-term benefits for practice of ocean acoustics research.

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1. INTRODUCTION

The parametric array (PA) is acoustical nonlinear transduction process, which develops in a medium through the interaction of co-linear, intense sound waves, called pump waves. PA is well known in oceanography as a tool for precision subbottom profiling. The specific feature for PA, is extremely narrow directivity pattern (several degrees in angular resolution normally) for low frequency acoustical signals.[1] The effective width of this directivity pattern is practically constant in a wide frequency range. Sounding signal is forming in the marine environment, which is stimulated by intensity modulated high frequency power acoustical pump (Figure 1). As a result the end-fire array is forming in the marine environment, which excites sharp directional signal radiation at modulation frequency. Such a low frequency signal, generated by parametrical means will propagate in underwater waveguide independently from the pump radiation. Due to non-resonance properties for low frequency signal generation, PA provides sounding signal transmission in extremely wide frequency band (more than 2 octaves).

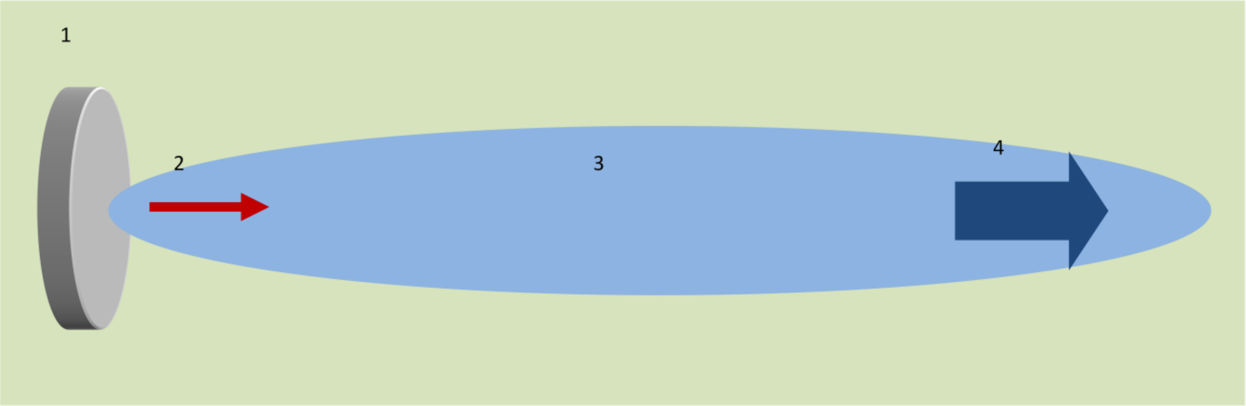


Figure 1. Layout of Parametric Array (PA). 1. High frequency pump transmitter. 2. Intensity modulated high frequency pump transmission. 3. Area of nonlinear acoustic interaction. 4. Low frequency detected signal of PA transmission.

Power PA for waveguide marine research of the main oceanographic features (current, temperature, salinity) has been recently installed in Black sea water area of Sukhum Hydrophysical institute for test. That acoustical system differs from conventional ones relatively small dimension (sizes of transmitting aperture 0.7m×2m in our case), broad frequency band for the sounding signal (300 *Hz* – 3000 *Hz*) and sharp directivity pattern (approx. 2°×8° in the main lobe) for the total frequency band. Practice of parametric arrays application show that they provide the broad frequency band single mode signal transmission, perfectly coupled to layered structure of the ocean waveguide.[2,3] Broad frequency band signal transmission is needed to apply a new approach for the ocean tomography by means of signal processing in frequency domain instead of contemporary known very expensive spatial developed acoustical schemes.[4] Leonid Brekhovskikh marked that PA’s acoustic characteristics may also make it “a perfect tool for ocean acoustics”.[5] The main objective of this paper is to discuss the ability of such underwater array, working on the principles of nonlinear acoustics for long-range hydrographic research. Demonstration of parametric array application for remote ocean monitoring is expected to give a long term consequence for practice of ocean acoustics research.

2. HISTORICAL REVIEW

To our knowledge, there was only one actual long-range ocean experiment using a parametric array for up to 1000 km range signal propagation.[6,7] This experiment was performed in the early 1990s during the cruise of the Russian research vessels *Academician B. Konstantinov* (ABK) and *Academician N. Andreyev* (ANA) in the region of Kamchatka and Kuril in the Pacific ocean. The 6 m long and 2 m high side-scanning array in the bow of the ABK was used as a parametric array with pump wave power of 20 kW at the primary frequency of 3 kHz. This array transmitted parametric signals in a frequency range of 230-700 Hz. The horizontal directivity width for the pump transmission was approx 4° in the main lobe. The directivity pattern of parametric signal as well as propagation characteristics of sharply directed parametric radiation through synoptic ocean vortices were measured then. The angular directivity pattern was measured to be almost constant in the frequency range of signals used and close to the squared pump wave angular pattern (Figure 2).

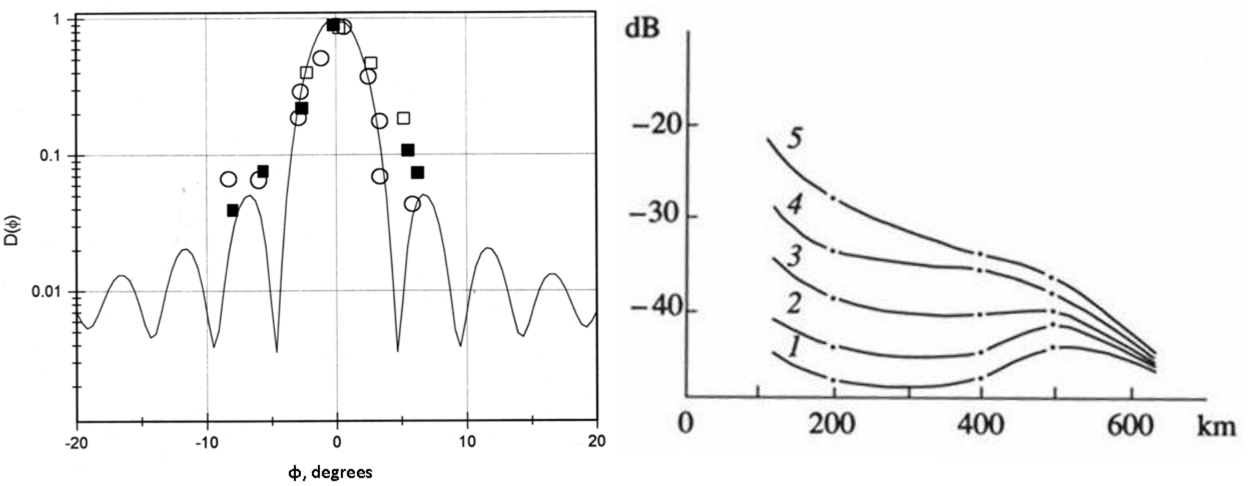
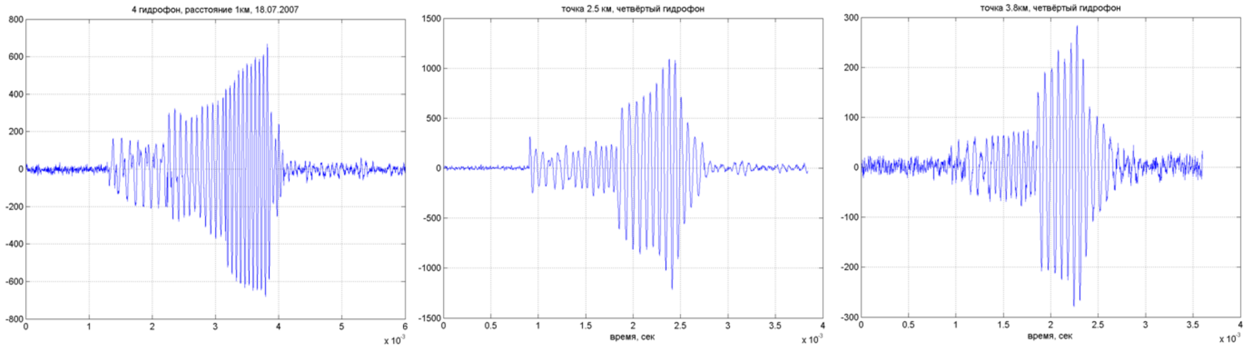


Figure 2. (Left) Directivity pattern of parametric signal transmission; □– frequency 230 Hz (distance 200 км),○ – frequency 400 Hz (distance 200 км), ■ – frequency 230 Hz (distance 1000 км). (Right) Range dependence for the parametric signal intensity; 1 – 230 Hz, 2 – 300 Hz, 3 – 400 Hz, 4 – 500 Hz, 5 – 600 Hz).

The average level of parametric signals as a function of frequency measured showed that the efficiency of parametric array increased with signal frequency. This feature of the parametric array led to an interesting result—leveling of the spectral components of the intensity with distance (Figure 3). In this experiment signal levels for a frequency range from 230 Hz to 600 Hz are similar at a distance of about 600 km. The parametric sonar was used to investigate synoptic eddy structure at far distances. A region of the Kuril Strait with typical ocean eddies was chosen for this experiment at the range of 400 km. [6]

3. SINGLE-MODE FREQUENCY DISPERSION FOR A PARAMETRIC SIGNAL IN A MARINE WAVEGUIDE

In shallow-water, the sound field usually consists of a series of modes exhibiting frequency dispersion of the speed of signal propagation. The value of the dispersion depends, among others, on the vertical sound speed profile. The frequency dispersion provides either a spread in time of short broadband pulses that travel long distances, or concentration of acoustic signal energy within a short time interval when the frequency modulation of the signal corresponds to the dispersion conditions of the medium. In the latter case, focusing of the acoustic signal or the signal compression in time should be considered. A parametric array signal has been used to experimentally observe the compression effect.2,3 The acoustic signal in this experiment was transmitted by a narrow beam parametric array. The sea depth at the site of the experiment was 2.5–3 m. The parametric array was constructed in the form of a mosaic of piezoceramics elements, half of which transmitted a high-frequency pumping signal at one frequency, and the other half transmitted a signal at a slightly different frequency. The average primary frequency (pumping frequency) was 150 kHz. The difference frequency, the signal of interest, was within 5–20 kHz. The power of the array amplifier was 1 kW for each of the pumping frequencies. The receiving array was constructed in the form of a vertical chain of eight hydrophones, spaced at 0.25 m and mounted on a metal rod. The rod was positioned vertically at the bottom so that the chain of hydrophones covered the whole waveguide. A sequence of pulses was transmitted. The duration of a single pulse was 2 ms, and the interval between pulses was about 300 ms. Signals were simultaneously received from all of the individual hydrophones of the vertical array. The measurements were carried out for transmitter–receiver distances of 1 to 5.6 km. The frequency–time characteristic for pulses with initial duration of 2 ms and a carrier frequency linearly modulated within 7–15 kHz was investigated while pulses propagate through the shallow-water waveguide (Figure 3).



a) b) c)

Figure 3. Parametrically generated chirp signal transformation in process of shallow-water propagation. a) - distance 1 km, b) – 2.5 km, c) – 3.8 km. Signal body is compressed with the distance. Small forerunner before the body of the signal corresponds to the higher harmonics. Signals are shown in arbitrary units, which correspond for a) 50 Pa, for b) 87 Pa, and for c) 22 Pa, time in msec.

The received signals from the vertical chain of hydrophones at a distance more than 1000 m from the source show that the major part of the energy was concentrated in the middle of the waveguide. A detailed analysis shows that the signals received by different hydrophones of the receiving array were in-phase throughout the whole waveguide depth, which indicates that there was a predominance of the single-mode propagation at the first mode of the signal. Thus, under the given experimental conditions, the parametric array excited the lowest mode of the waveguide. The signal frequency sweep runs from low to high frequencies, which correspond to normal waveguide dispersion, i.e., to the case where the group velocity of signal propagation increases with frequency.

Experiments have shown that acoustic pulses received at different distances varied in their shape as they propagate in the waveguide. Pulse duration was reduced by a half or greater when the signal propagates in the waveguide over a distance of at least 3 km. To achieve complete synchronicity of arrival times of all the frequency components of the signal, a special type of frequency modulation would be necessary corresponding to the characteristic features of dispersion in the waveguide. Since the dispersion of the sound speed propagation depends nonlinearly on frequency, the frequency modulation should also be nonlinear to obtain the maximum compression of the signal. The limiting duration of the signal τ is in inverse relation to the effective frequency band Δf of its spectrum $\tau \cong (\Delta f)^{-1}$. On the other hand, the signal duration T_0 of the pulse under the condition of its complete compression at a distance L is determined by the frequency dispersion $\partial c / \partial f$ and signal bandwidth Δf.

$$T_0 = L \frac{\partial c / \partial f}{c^2} \Delta f \, , \tag{1}$$

where c is sound speed. Thus, in the case of the signal compression due to waveguide dispersion, the signal intensity may increase by factor of $T_0 / \tau >> 1$. At the same time, an increase occurs in the signal-to-noise ratio by the recording equipment during the signal reception time.

4. PARAMETRIC ARRAY APPLICATION FOR REMOTE LONG-RANGE MARINE SOUNDING

A. TECHNICAL DETAILS OF THE PARAMETRIC ARRAY

Power experimental tool operating on principles of nonlinear acoustics (parametric array) for shallow-water marine monitoring of the main hydrographical features (current, temperature, salinity) at the range of at least 500 km in frequency band of 300-3000 Hz has been developed as a result of the #3770 ISTC project implementation (Figure 4). So far such investigations on elongated paths in wide frequency band were practically unavailable. The developed model of parametric array is placed now on the bottom at 40 m depth in the Black sea water of Sukhum Hydrophysical research institution for the test and could make a basis of elongated stationary research path in the Black sea to investigate new approaches for remote acoustical marine research.

Figure 4. General view of the parametric array before installation in the sea

Technical features of the array:

- Main sizes – 2 m * 0.7 m;
- Pump frequency – 20 kHz;
- Signal frequency band – 0.3-3 kHz;
- Electric power in the pulse – 200 kW;
- Pulse duration – 100 ms;
- Signal reduced level –205 dB re 1 mcPa*m at 1kHz;
- Directivity – 2° vertically, 8° horizontally in the whole frequency range;
- 24 independent channels for signal amplification with digital signal forming.

Preliminary research and modeling shows PA could provide broad frequency band single mode sound signal excitation in marine waveguide. Therefore the principles of parametric array application promise the new ability for the long-range multi-frequency acoustics experiment in complex oceanography environment, when wide frequency band single mode transmission coupled to the ocean waveguide is needed. We expect that technical features of the installed PA are sufficient to investigate underwater waveguide and water current in the east part of the Black sea (Figure 5)

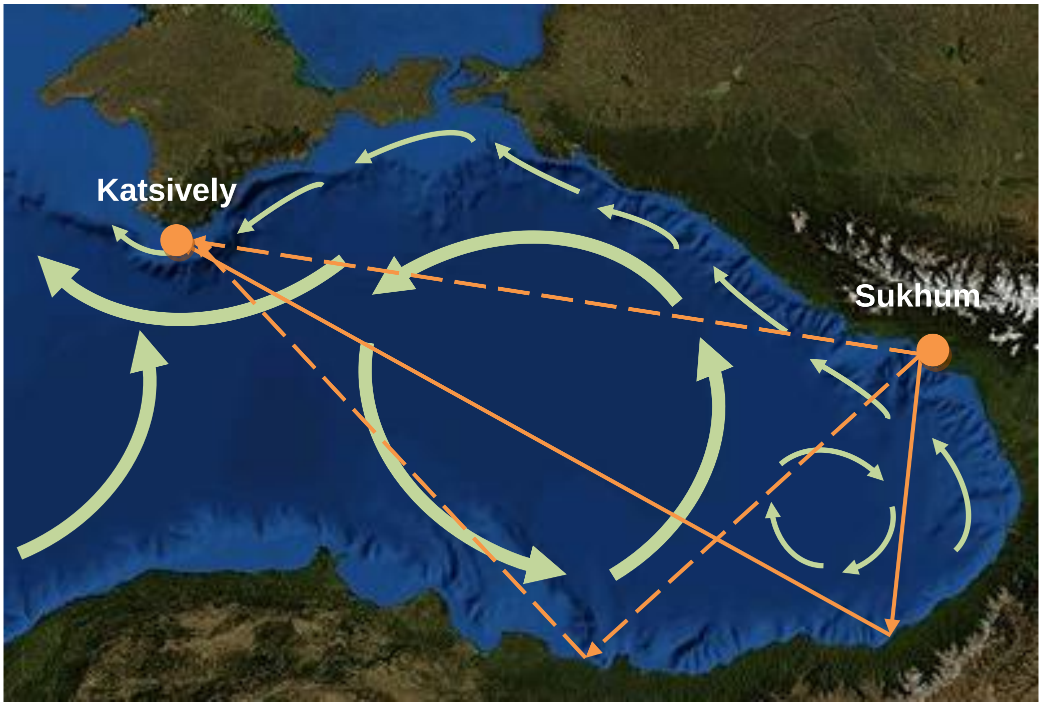


Figure 5. Black sea acoustical range.

B. CIL PARAMETERS MONITORING

The Black sea underwater waveguide is formed by upper warm layer of water and cold intermediate layer (CIL). Therefore the waveguide thickness monitoring could provide rather valuable information on cold store in the sea at this region. Direct measurements of vertical distribution of temperature and salinity at the path of hundreds km long by salinity-temperature depth probe is very difficult and expansive. Permanent monitoring of CIL parameter dynamics at elongated paths could be done by acoustical means. And problem of CIL parameters determination could be solved by means of wide frequency band acoustical pulse.

Measurements of sound speed value averaged along the path could be founded at one of the typical acoustics effects in underwater waveguide – mode dispersion. Mode dispersion in underwater waveguide means that the mode of the same number has different speed of propagation for different frequencies. Therefore transmitted signals change their form in process of propagation and this changing could be experimentally measured. One should know the mode speed propagation to retrieve vertical profile of sound speed in underwater waveguide.

The most informative for sound speed in underwater waveguide is dispersion of the modes with lower numbers from the first to the third one. It related to the fact that eigen function that modes are concentrated in underwater waveguide and their speed is the most sensitive to underwater waveguide profile. Figure 6 shows sound speed profiles in Black sea underwater waveguide for different months. Figure 7 shows eigen functions for the first and the second mode in frequency range from 200 Hz to 1200 Hz.

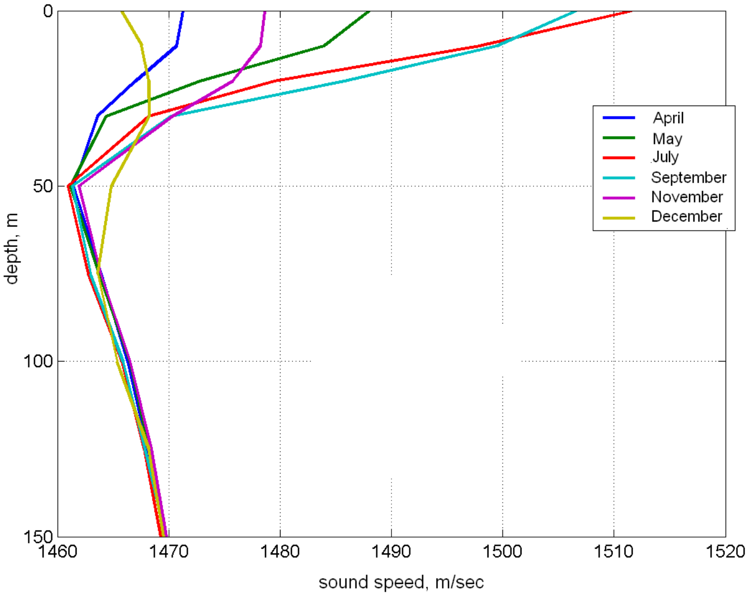


Figure 6. Sound speed profiles in Black sea underwater waveguide for different months from climate base from April (blue) to December (yellow).

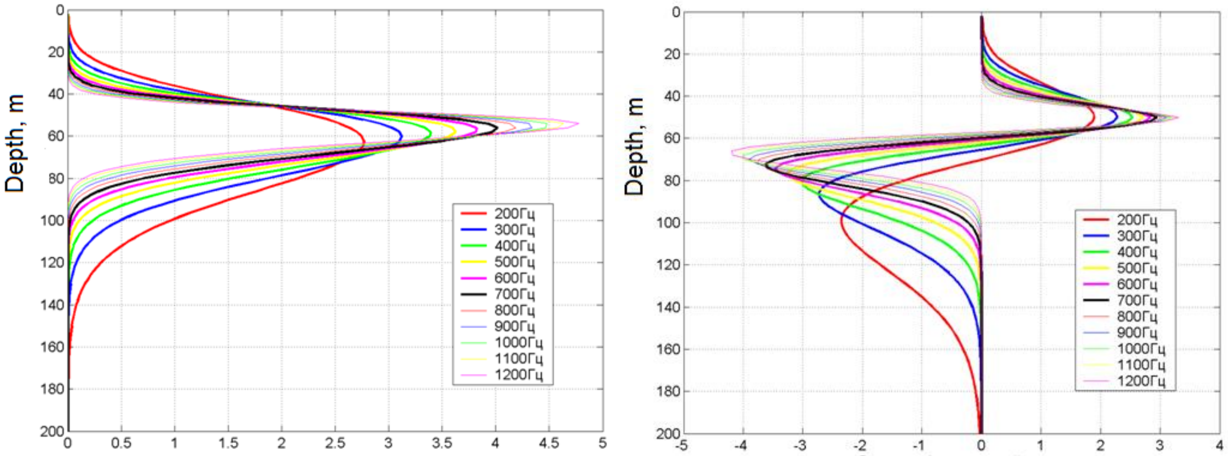


Figure 7. Eigen functions for the first (right) and the second (left) mode in frequency range from 200 Hz to 1200 Hz for September sound speed profile.

One could see at Figure 7 that eigen functions in wide frequency band follow the specific features of the sound speed profile and therefore the waveguide mode investigation for broadband parametrical sound signal could retrieve sound speed profiles and monitor cold intermediate layer in the Black sea.

Figure 8 demonstrates sound speed dispersion for the first mode in 200 Hz – 1200 Hz for September waveguide profiles shown at Figure 6. That is seen typical for underwater waveguide dispersion, when the first mode speed decrease with frequency, or time delay increases with frequency. Results of simulation for signal form distortion at the range from 1 km to 500 km distances are shown at Figure 9. A short pulse was excited at the first mode of waveguide in frequency band of 200-1200 Hz for the September profile (Figure 6). The signal is still rather short (duration less than 5 ms) at a distance of 1 km, but at 500 km its duration is about 80 ms with emphasized frequency modulation.

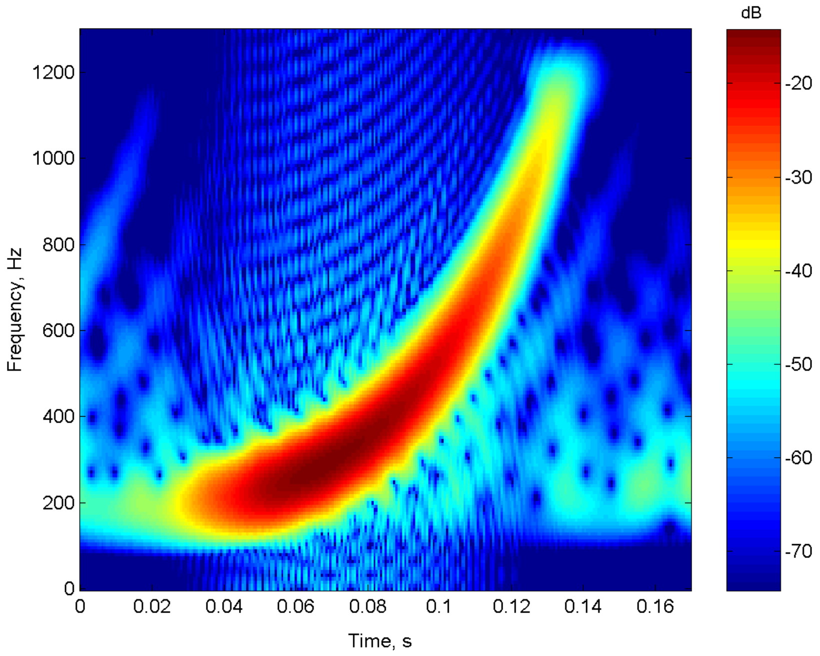


Figure 8. Frequency dispersion (time delay as function of signal frequency) for frequency range of 200 Hz to 1200 Hz for September sound speed profile at the path of 500 km.

Variation in the lower part of sound speed profiles (under waveguide axis) are minor in a year and the main waveguide variation is related to heating or cooling the upper layer (Figure 6). That leads to remarkable change in dispersion of envelope speed of signal modes, propagated in underwater waveguide.

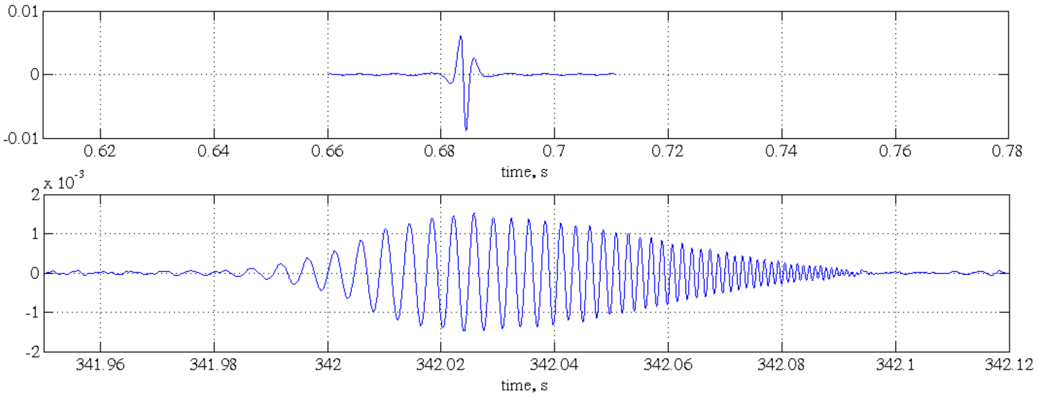


Figure 9. First mode excitation. Pulse in frequency band of 200-1200 Hz (top). The same signal at the 500 km distance. Abscissa axis – propagation time in sec.

We could offer the next scheme for acoustical monitoring of CIL dynamics at the elongated paths with parametric array. Parametric array, due to it sharp directivity signal transmission, provides an opportunity efficiently excite waveguide modes of the first numbers in wide frequency band. Beside this wide frequency band of signal transmission in single mode could obtain the more detail information on mode dispersion in the waveguide.

The scheme supposes transmission of wide frequency band sound signals. These signals should be received by vertical chain of the gages for spatial mode filtration. One should measure travel time for separate modes of the first numbers in the total frequency band of the signal and therefore sound speed averaged along the path. At the next step one could retrieve mean profile of sound speed propagations due to measured sound speed for different modes. As CIL salinity is very conservative (with minor variations), retrieved sound speed profile leads to retrieve the temperature profile along the path. This retrieval reliability could be increased if additionally use the data of direct measurements of temperature and salinity in same separate points of the path.

That acoustical method provides an ability to make measurements round of the year with high temporal resolution.

5. SIGNAL COMPRESSION AND ACOUSTICAL BARRIERS

Consequently to single mode waveguide dispersion, conditions arise to concentrate the energy of wide frequency band acoustical signal at the appointed distance. Such a concentration could be arranged because of compression of the frequency modulated signal. In fact duration of the frequency modulated signal will be reduced in proportion of distance of signal run r, and reduction of signal duration we could define as

$$\Delta T = rc^{-2}\frac{\partial c}{\partial f}\Delta f \qquad (2)$$

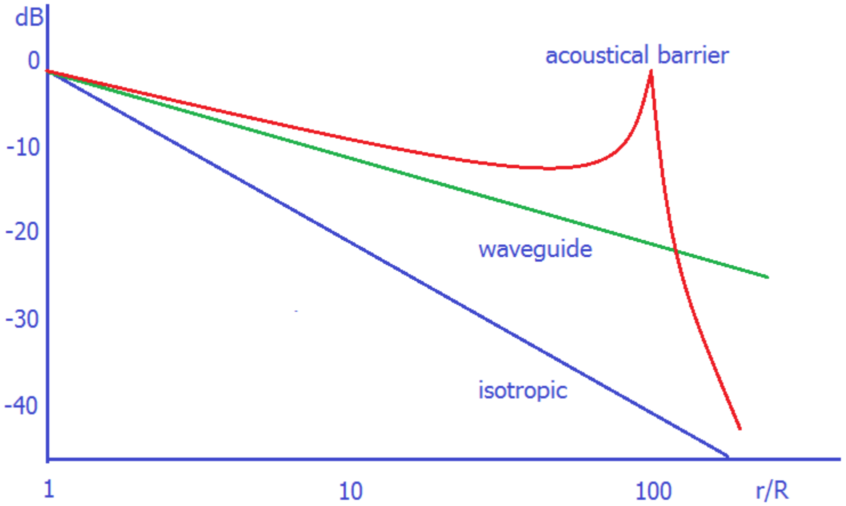


Figure 10. Acoustical signal intensity dependence in dB on the range r/R. (Blue) –isotropic case $I/I_0(R/r)^2$, (green) – perfect waveguide case $I/I_0(R/r)$, (red) – frequency modulated signal in the waveguide Eq.(3), R – spatial scale of acoustical field reduction.

Thus, duration of the frequency modulated signal in process of it propagation in the waveguide decreases with the distance $T(r)=T_0-\Delta T$, where T_0 is an initial signal duration. T_0 in there turn should be coupled with waveguide dispersion $\partial c/\partial f$ and distance of maximum compression L accord to Eq. (1). Therefore we obtain the equation for sound signal intensity in the waveguide with respect to the law of energy conservation. And one should mind there that accuracy of the signal duration $\tau=\Delta f^{-1}$ is related with it frequency band Δf

$$I(r)=I_0(R/r)\left(\frac{T_0}{T+\tau}\right)=I_0\frac{R}{L}\frac{L}{r(1-r/L+\tau/T_0)}, \qquad (3)$$

here R is a spatial scale for waveguide propagation, L is a distance of maximum signal compression.

For wide frequency band signal $\tau / T_0 << 1$ and relative intensity $I(r)/I_0$ reaches maximum when $r = L$ (Figure 10 (red)). Maximum value of the ratio $I(r)/I_0$ is depended on dispersion properties of the waveguide and squared frequency band and accord to Eq.(1) – Eq.(3) could be defined as

$$\left.\frac{I_{max}}{I_0}\right|_{r=L} = rc^{-2}\frac{\partial c}{\partial f}\Delta f^2 \tag{4}$$

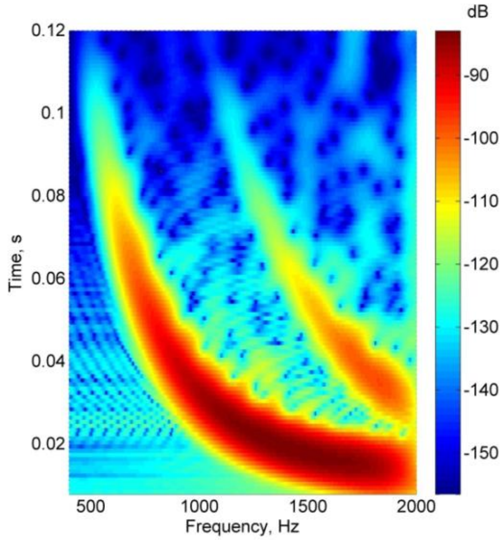


Figure 11. Time delay on frequency for acoustical signal at 420 km in shallow-water in Yellow sea.

Ratio of I_{max} / I_0 rapidly increases with the signal frequency band and could reach 1 in order for more then octave frequency band.

Opportunity to concentrate of the acoustical signal energy at the defined distance makes conditions to arrange virtual acoustical barrier – limit area with increased intensity of acoustical signal. Behind such a barrier signal duration will increase and it intensity will fall rapidly. Intensity gain at the barrier area with respect to convenient waveguide propagation could reach several ten times.

Figure 11 shows an example of acoustical dispersion in shallow-water area in Yellow sea. Such dispersion makes an opportunity to arrange an acoustical barrier at 420 km distance by signal modulated in frequency band of 500 Hz – 2000 Hz (Figure 12). Calculation shows that signal intensity gain in the barrier area will be 22 times in this case.

Figure 12. Layout of acoustical barrier at 420 km from the source in shallow-water of Yellow sea

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6. CONCLUSION

Preliminary analysis of abilities of developed parametric array and brief historical review lead us to the following conclusion.

1. Parametric array application could provide acoustical single mode excitation in wide frequency band in the waveguide.
2. Research of specific features of wide frequency band single mode propagation of the acoustical signal will show the way to retrieve the underwater waveguide profile.
3. Frequency modulated wide frequency band acoustical signal could be compressed with arranging of acoustical barrier with increased signal intensity at the defined distance of the waveguide if modulation corresponds to dispersion properties of the waveguide. Position of such a barrier is defined by conditions of the waveguide propagation, waveguide dispersion and frequency band of the signal. Intensity gain at the barrier with respect to convenient waveguide propagation could reach several ten times.
4. Signal compression and arranging of the virtual acoustical barriers are pure linear acoustical processes. But to realize them single mode wide frequency band acoustical signal is needed in the waveguide. It is shown that such a signal could be excited in the marine waveguide due to sharp directed parametric array. Therefore, methods of nonlinear acoustics open frequency dimension for acoustical remote ocean sounding.

ACKNOWLEDGMENTS

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