Spectral-Correlation Signal Processing in the Infrasonic Frequency Range

B A Kasatkin¹, N V Zlobina¹, S B Kasatkin¹, G V Kosarev¹

¹Institute of Marine Technology Problems FAB RAS, 5a, Sukhanova, Vladivostok, 690091, Russia

E-mail: kasatkas@marine.febras.ru

Abstract. The article discusses hydroacoustic receiving systems, consisting of combined receivers, and the processing of the received hydroacoustic signals. Each module of the sonar system has four channels for receiving information. Spectral processing was carried out using sixteen information parameters, which made it possible to achieve the maximum noise immunity of the receiving system. Correlation processing of signals confirmed the high correlation of signals on the elements of the receiving hydroacoustic system.

1. Introduction
Receiving systems based on combined receivers (CR) are the most informative for studying the sound fields of a shallow sea in the infrasonic frequency range. The combined receiver combines a hydroacoustic pressure receiver and a vector receiver that measures three components of the particle velocity vector. In recent years, there has been a tendency of increasing interest in such systems [1-7]. Extensive studies of sound fields using combined receivers are given in [8-14]. The potential capabilities of a single CR are characterized by its noise immunity [15], which is the most important characteristic of the combined receiver. A quantitative estimate of the potential noise immunity of the combined receiver is presented in [16] and is 20-25 dB. It is of interest to study the potential capabilities of receiving systems, which consist of a set of combined receivers and form a vertically oriented antenna operating in shallow sea conditions in the most informative infrasonic frequency range. It can be assumed that the vertical antenna will have an increased resolution in determining the angular coordinates of the source in comparison with a single combined receiver.

2. Experiment scheme
Spectral-correlation processing of signals, which were received by a vertical antenna from combined receivers, was performed. The experiment was carried out in the Ussuri Bay in the Sea of Japan. The small research vessel and its discrete shaft-blade scale (SBS) components were used as a natural source of noise. A polyharmonic signal in the frequency range of 30-60 Hz and a chirp signal in the frequency range of 30-60 Hz, emitted by a towed electrodynamic emitter, was used as a model signal. The receiving antenna modules RM-1 – RM-3 were installed at the horizons z1 = 40 m, z2 = 37 m, z3 = 34 m, respectively. The sea depth in the experiment was h = 43-44 m. The towing horizon of the emitter was z0 = 10 m.
3. Spectral signal processing

Signal processing includes the spectral analysis of signals in the channels of the combined receiver, the calculation of a full set of informative parameters characterizing the sound field in the scalar-vector description, and the construction of sonograms. The assessment of the potential noise immunity of the combined receiver as part of the vertical antenna was carried out on the basis of scalar-vector information, represented by a set of 16 informative parameters [16] for the discrete components of the SBS. These parameters include the following quantities: the square of the sound pressure \( p^2 \), three components of the real component of the intensity vector \( I_{1x}, I_{1y}, I_{1z} \), three components of the imaginary component of the intensity vector \( I_{2x}, I_{2y}, I_{2z} \), three real components of the rotor of the intensity vector \( (rot_{I1})_x, (rot_{I1})_y, (rot_{I1})_z \), three components of the real part of the pressure gradient vector \( g_{1x}^2, g_{1y}^2, g_{1z}^2 \) and three components of the imaginary part of the pressure gradient vector \( g_{2x}^2, g_{2y}^2, g_{2z}^2 \).

The signal-to-noise ratio S/N was calculated for each of the parameters, and the sonogram for the maximum ratio \( S/N_{\text{max}} \) was calculated in the signal processing unit (SPU). The sonograms of the sound field in the SBS frequency range at the output of the sound pressure channel are illustrated in Figure 1. Sonograms were calculated for the receiving module RM-3 of vertical antenna, in which the modules RM-1 and RM-3 are vertically spaced by 6 m. A significantly higher signal level (by about 10 dB) on the receiving module RM-3, as close as possible to the horizon of the source, can be noted. Of all components of the intensity vector, the maximum ratio S/N corresponds to the vertical channel. Of all components of the rotor of the intensity vector, the maximum ratio S/N corresponds to the component \( (rot_{I1})_y \). Of all components of the pressure gradient vector, the maximum ratio \( S/N \) corresponds to the vertical channel.

![Figure 1](image_url)  
**Figure 1.** Sonogram for the S/N ratio at the output of the sound pressure channel, receiving module RM-3.

The sonogram clearly shows the discrete components of the shaft-blade scale, among which the largest amplitude corresponds to the blade frequencies of 3 Hz, 6 Hz, 9 Hz, etc. These components
correspond to a 3-blade propeller making 60 revolutions per minute. The sonograms at the SPU output are illustrated in Figure 2. The signal-to-noise ratio at the SPU output increased after processing all the scalar-vector information, and the sonogram clearly shows not only the blade frequencies, but also the shaft frequencies, going with a step of 1 Hz over the entire observation interval.

![Figure 2. Sonograms for the S/N ratio at the SPU output, receiving module RM-3.](image)

It should be noted that all discrete components of SBS in the range of 1-20 Hz, presented on the sonograms, are less than the first critical frequency for the model Pekeris waveguide. The noise immunity of the CR in the definition of work [3] is determined by the difference between the signal-to-noise ratio logarithmic levels at the SPU output and the sound pressure channel, it is 20-25 dB. The maximum (potential) noise immunity corresponds to weak signals that were not recorded by the sound pressure channel, but are well recorded at the SPU output after processing all scalar-vector information.
4. Correlation signal processing

Figure 3 explains the coefficients of autocorrelation $K_{pp} (\tau)$ and cross-correlation $K_{px} (\tau)$ in the channels of the combined receiver for the receiving module RM-3. It can be noted that the cross-correlation coefficients are maximum in the horizontal channels of the CR (0.53-0.28) and minimum in the vertical channel (0.24-0.19). In addition, the cross-correlation coefficients decrease as the CR moves away from the water-seabed interface. Figure 4, 5 explain the coefficients of autocorrelation $K_{ii} (\tau)$ and cross-correlation $K_{ik} (\tau)$ ($i, k = vx, vy, vz$) in the vector channels of the combined receiver for the receiving module RM-3. A feature of the correlation characteristics is the presence of a modulation component, which is caused by the discrete components of the SBS. They are equal to 3Hz for RM-3 and 6Hz for RM-1 and RM-2. Another feature is the extremely small width of the maximum of the autocorrelation function in vector channels in comparison with the width of the maximum of the cross-correlation functions obtained with the participation of the sound pressure channel. Correlation coefficients $K_{vp} (\tau)$ have a minimum duration $\Delta \tau = 35 \text{ms} = 1/\Delta f$ ($\Delta f$ - frequency band of the radiated chirp signal).
Figure 4. Coefficients of autocorrelation $K_{xx}$ and cross-correlation $K_{xy}$, $K_{xz}$ in vector CR channels, receiving module RM-3.

Correlation coefficients $K_{rr}(\tau)$ have a long duration $\Delta \tau = 200 \text{ms} >> 1/\Delta f$. Therefore, the correlation processing of the chirp signal in the vector channels of the CR gives the maximum gain in the signal-to-noise ratio $Q = 10 \log(\Delta f \Delta \tau_0) = 21 \text{dB}$. A complete set of autocorrelation and cross-correlation functions (correlation coefficients) form a symmetric $4 \times 4$ matrix $K_{ik}(\tau)$. Its diagonal elements are even functions of the argument $\tau$, and the off-diagonal elements of the matrix contain even (cosine) and odd (sine) components.

The use of 16 informative parameters in the spectral-correlation processing of signals at the output of the vertical antenna from the CR allows to effectively solve the problem of detecting low-noise sources with increased noise immunity and range, as well as the problem of determining the angular coordinates of the target with an increased angle resolution. The sliding angle at the receiving site can be determined by the following formulas, taking into account the results of cross-correlation processing of signals in the channels of the receiving modules RM-1 and RM-3.

$$\beta = \arcsin \left( \frac{c_1 \Delta \tau_{13}}{l_{13}} \right),$$

$$\beta = \arctg \left( \frac{F_x}{F_y} \right),$$

where $\Delta \tau_{13}$ is point of time corresponding to the maximum of the cross-correlation function $F_{13}(\tau) = F_1(t) \otimes F_3(t-\tau)$, $c_1$ is the sound speed in water, $l_{13} = 6 \text{m}$ is the distance between the receiving modules RM-1 and RM-3, $F_x(\tau) = P(t) \otimes V_x(t-\tau)$, $F_y(\tau) = P(t) \otimes V_y(t-\tau)$ - cross-correlation functions for vertical and horizontal channels of the receiving module RM-1, taken at $\tau = 0$.

Both estimates according to formulas (1) give close values of the slip angle $\beta = 11-12^\circ$ and make it possible to determine the effective value of the phase velocity of propagation of normal waves
\[ c_{\text{ph}} = c_i / \cos \beta, \] averaged over the operating frequency band of the chirp signal. Knowledge of the effective phase velocity of propagation of a group of normal waves in the operating frequency band is necessary, for example, to organize coherent processing of signals at the aperture of a horizontally oriented antenna, which solves the problem of source direction finding.

Figure 5. Coefficients of autocorrelation \( K_{yy} \), cross-correlation \( K_{yz} \) and autocorrelation \( K_{zz} \) in vector CR channels, receiving module RM-3.

5. Results
Spectral processing of signals was carried out by 16 parameters, which characterize the scalar-vector structure of the sound field. The use of a full set of informative parameters allowed increasing the noise immunity of the CR up to 20-25 dB. The use of a vertical antenna from combined receivers in the experiment made it possible to reveal the predominant localization of the sound field near the source horizon. Correlation processing of signals at the output of the vertical antenna from combined receivers was performed using complex chirp signals. The data obtained confirm the high correlation of signals on the elements of the vertical antenna and the prospects of its use for detecting a source of noise signals and increasing the accuracy of determining its angular characteristics, bearing and elevation.

6. References
[1] Gordienko V A, Gordienko T V, Krasnopistcev N V, Nekrasov V N 2014 Vector-phase methods and the development of advanced new-generation acoustic systems (in russian) Moscow University Physics Bulletin 2 pp 3-21
[2] Nekrasov V N 2018 Applied hydroacoustics problems solved when using systems with vector receivers (in russian) Environmental, industrial and energy safety – 2018. Proc. of the Int. Scientific and Practical Conference (Sevastopol: Sevastopol State University) pp 864-868
[3] Guo X, Yang Se, Miron S 2015 Low-frequency beamforming for a miniaturized aperture three-by-three uniform rectangular array of acoustic vector sensors J. Acoust. Soc. Am. 138(6) pp 3873-3883
[4] Korenbaum V, Tagiltsev A 2014 Development of vector sensors for flexible towed array J. Acoust. Soc. Am. 135(4) pp 2396
[5] Jin M, Ge H, Li D, Ni C 2018 Three-component homovibrational vector hydrophone based on fiber Bragg grating F-P interferometry Applied Optics 57(30) pp 9195-9202
[6] Li Z, Chen H 2017 Method for measuring self-noise of vector hydrophones Journal of Marine Science and Application 16(3) pp 370-374
[7] Duan W, Kirby R, Prisutova J, Horoshenkov K V 2013 Measurement of complex acoustic intensity in an acoustic waveguide J. Acoust. Soc. Am. 134(5) pp 3674-3685
[8] Zakharov K L 2014 Frequency-angular characteristics of the hydroacoustic signal when using the vector-phase method (in russian) Sustainable innovative development: design and management 10(3) pp 148-163
[9] Pereselkov S A, Kaznacheev I V, Tkachenko S A 2017 Using of vector-scalar receiver for a moving sound source localization in ocean waveguide (in russian) Proceedings of Voronezh State University. Series: Physics. Mathematics 1 pp 39-56
[10] Mikhailov S G 2020 Direction finding with a vector–scalar receiver in the field of anisotropic interference Acoustical Physics 66(2) pp 152-161
[11] Gorelov A A, Smaryshev M D 2018 Modeling of processing algorithms for processes at the output of a combined receiver and combined array channels Acoustical Physics 64(2) pp 245-251
[12] Morgunov Y, Golov A, Burenin A, Unru P, Rodionov A, Statsenko L 2018 An Experimental Study of the Special Aspects of Scalar-Vector Sound Field Spatial Structures in the Shallow Sea Area Applied Sciences 8(2) pp 157
[13] Dahl P H, Dall’Osto D R 2020 Vector Acoustic Analysis of Time-Separated Modal Arrivals From Explosive Sound Sources During the 2017 Seabed Characterization Experiment IEEE Journal of Oceanic Engineering 5(1) pp 131-143
[14] Raghukumar K, Chang G, Spada F, Jones C 2020 A Vector Sensor-Based Acoustic Characterization Sistem for Marine Renewable Energy Journal of Marine Science and Engineering 8(3) 187
[15] Gordienko V A 2007 Vector-phase methods in acoustics (in russian) (Moscow: Fizmatlit)
[16] Kasatkin B A, Zlobina N V, Kasatkin S B, Zlobin D V, Kosarev G V 2019 Shallow sea acoustics in scalar-vector description Theory and experiment (in russian) (Vladivostok: IMTP FEB RAS)