Methods of Implementation of the Review of the Space of Parametric Profiler

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Abstract. The article presents the results of the theoretical justification of the method for implementing the survey of the parametric profiler. With all the advantages of using nonlinear effects and hydroacoustic systems in a parametric transmitting mode for profiling the bottom and bottom sediments, the disadvantage is the small area of the bottom surface, scanned by the transmitting array of the profiler, which leads to the need to choose the method of scanning and sensing modes of the parametric profiler for a vertical profiling scheme. The analysis of the main methods of scanning, such as scanning in two planes with a phased receiving-transmitting array, the use of several phased arrays that scan by sector and scanning by the movement of the antenna carrier, allowed us to determine the main advantages and disadvantages of each method of viewing. The results of the theoretical study allowed us to evaluate the method of scanning by the movement of the antenna carrier and obtain expressions for the stages of the full scanning cycle, as well as to calculate the values of the follow-up period in the radiation mode for the values of the number of wave periods of the difference frequency of the radiated acoustic signal and the distance from the bottom of the transmitting antenna that are most common in real conditions of profiling bottom structures.

1. Introduction
The possibility of using nonlinear effects and adaptive hydroacoustic systems with parametric transmitting mode for profiling the bottom and bottom sediments attracts the attention of both domestic and foreign experts. The use of parametric arrays in hydroacoustic equipment makes it possible, due to their high directivity and low side field level, to increase information content and accuracy in detecting and determining the coordinates of underwater objects, and to obtain additional features for recognition [1-9].

2. Problem Actuality
To date, many results have been published concerning methods for studying the surface and bottom structures of the sea floor using various acoustic systems of single-beam, multi-beam and side scanning. It is recognized that acoustic methods are a useful tool for research, since the attenuation of sound waves in water is lower than that of other methods, such as optical and magnetic. Acoustic methods are successfully used to determine a number of oceanological parameters. The study of acoustic scattering mechanisms and the characteristics of echo signals reflected from bottom structures is important for stratifying layers and determining their spatial characteristics.
In practice, when profiling bottom structures [10, 11], various methods of viewing space are used, such as scanning in two planes with a phased receiving-transmitting array, using several phased arrays that scan by sector, and scanning with the movement of the antenna carrier.

3. Problem Statement

With all the advantages of using nonlinear effects and hydroacoustic systems with a parametric transmitting mode for profiling the bottom and bottom sediments, the disadvantage is the small area of the bottom surface, scanned by the transmitting array of the profiler, which leads to the need to choose the method of scanning and sensing modes of the parametric profiler with a vertical profiling scheme and taking into account critical angles [12, 13].

Mathematically, the expression for exceeding the critical angle can be expressed as:
\[ \sqrt{\theta_l^2 + \theta_t^2} < 22.1, \]
where \( \theta_l \) and \( \theta_t \) – values of the compensation angles in the longitudinal and transverse planes. This equation can also be expressed in terms of direction numbers \( n \):
\[ 4 < n_l + n_t < 30. \]

The values of compensation angles in beam pattern (BP) during scanning can be calculated using the expression.
\[ \theta_n = -\frac{\theta_{\text{max}}}{2} + \left(n + \frac{1}{2}\right)2\theta_{0.7}, \]
where \( \theta_{\text{max}} \) – opening angle when scanning, and \( 2\theta_{0.7} \) – width of the BP.

The resulting angle values are valid for scanning in both planes. It should be noted that simultaneous compensation of the directivity characteristic in two planes for maximum angles is unacceptable, since it will lead to exceeding the critical angle of penetration of acoustic waves into the bottom soil.

The use of a receiving-transmitting phased array in the case of offshore profiling is often impossible, since the radiation time may exceed the propagation time at shallow depths. Receiving a difference frequency wave brings additional difficulties. Since the receiving antenna of the difference frequency wave is non-directional, it is impossible to perform spatial selection of acoustic signals. Selection of the time does not give accurate information about direction of arrival due to multipath signals may overlap each other. The solution to this problem is related to the choice of the optimal method for viewing space with a parametric profiler in a particular situation.

4. Theory

4.1. Scanning in two planes by a phased receiving-transmitting array

One of the ways to provide scanning above the object at a space angle of at least 40° symmetrical with respect to the vertical axis is sequential scanning in the longitudinal and transverse planes with a phased array. The number of scanned space sectors is calculated as the ratio of the full scan angle to the width of a single directional characteristic [14-16].

For the case when it is necessary to cover a wide viewing sector with a phased array with a narrow partial width of the directional characteristic, it is necessary to form a set of \( n \) transmitters in the longitudinal plane and \( n \) transmitters in the transverse plane. In total, you need to scan \( n^2 \) sectors of space. The scanning angle is limited by the critical angle of penetration of acoustic waves from water into bottom sediments, which is approximately 22.1° for longitudinal waves. For the case \( n=16 \), calculations of the deviation angles showed that it was impossible to scan at the maximum deviation angles in 24 of the 256 scanned sectors. The scanned space will have the form shown in figure 1.
Receiving-transmitting array produces a sequential scan in each sector. For ease of technical implementation, an equi-signal space survey method is usually chosen.

The maximum propagation time for vertical probing is calculated using the expression:

\[
T_{\text{MAX}} = t_i + \frac{2H}{c_v \cos(\theta_{\text{max}})} + \frac{2h}{c_s \cos(\theta_s)} ,
\]

where \(H\) – maximum operating depth, \(h\) – maximum thickness of the bottom layer, \(c_v\) and \(c_s\) – sound speed in the water and sediments, respectively, \(\theta_{\text{max}}\) – maximum angle of deviation during scanning days, \(\theta_s\) – angle of propagation of acoustic waves in sediments, calculated from the Snellius law

\[
\frac{\sin(\theta_s)}{\sin(\theta_1)} = \frac{c_1}{c_2}.
\]

As the depth decreases, the time for viewing space will decrease linearly. The advantages of using scanning in two planes of a phased array are the small size of the antenna system (high-frequency receiving and low-frequency receiving), the need for a single processing path, and easily implemented spatial filtering. Disadvantages – necessity to form a phase distribution in two planes will greatly complicate the radiating path; low optimal speed of the carrier; by reducing the number of partial antennas, you can achieve the desired scan time, but there are gaps in the viewing band.

4.2. Application of multiple phased array scanning by sector

The second method of providing scanning is the use of several receiving-transmitting phased arrays located along the ship, each of which scans in the transverse plane with a fixed angle of deviation in the longitudinal. The geometrical dimensions and layout of the profiler antenna system for a complete version of the series-parallel method of viewing space are shown in Fig. 2.
Figure 2. Geometry of the profiler antenna system for a complete version of the series-parallel method of viewing space.

In the static position, scanning of each phased array in the transverse plane provides information about the sea ground in the solid angle determined by the maximum compensation angle. Spatial filtering of the difference frequency wave is also provided by the receiving linear antenna.

Advantages – short scanning time, easy to implement spatial filtering, there is a potential opportunity to meet the requirements for roll, trim, increasing depth and speed.

Disadvantages – large weight and size, the need for several transmitting and receiving paths, as well as the need to take separate measures to exclude the influence of transmitting and receiving antennas on each other [17-19].

4.3. Scanning by moving the antenna carrier
To get a picture of the bottom structures by parametric profiler, a survey method can be selected that is associated with the movement of the receiving-transmitting antenna system of the profiler due to the movement of the antenna carrier.

Simultaneous scanning with the directional characteristic in the transmitting mode in the traverse plane of the transmitting antenna system allows to detect a band on the bottom surface. The bottom structure scanning scheme corresponding to this variant of the profiler implementation is shown in Fig. 3.

Figure 3. Scanning when the antenna carrier is moving.
This way of scanning is possible only when the antenna carrier is moving. Since scanning in the longitudinal plane is carried out due to the movement of the carrier, in order to prevent gaps in the scanned surface, the distance traveled by the carrier during scanning should not exceed the diameter of the spot, scanned by one BP.

The advantages of this method are simplicity of implementation, small dimensions, one receiving and radiating path is needed.

Disadvantages – long scan time, the inability to view without moving the media, the possibility of skipping at high speeds.

5. Theoretical evaluation of the method of scanning by the movement of the antenna carrier

In the static position of the carrier, scanning in the transverse plane provides information about the bottom structures in the solid angle, determined by the sum of the directional characteristics of each of the transmitting antennas. The translational displacement of the profiler antenna system in the direction of the antenna carrier movement allows you to get information about the internal structure of the bottom in the field of view.

To ensure sufficient angular resolution in the transverse plane and save energy resources of the profiler, the viewing sector in the transverse plane in the parametric profiler can be covered with a rolling of several partial BP. In the case of five partial directional characteristics, the complete sensing cycle includes the steps shown in table 1.

| Cycle | Action | Interval between the previous and current probe pulses |
|-------|--------|-------------------------------------------------------|
| 1     | Radiation and reception in the left sector 2 | $\tau_1 + \frac{2H}{c_w}$ |
| 2     | Radiation and reception in the left sector 1 | $\tau_1 + \frac{2H}{c_w \cdot \cos(2 \cdot \Delta \theta)} + \frac{2h}{c_s \cdot \cos(2 \cdot \Delta \theta)}$ |
| 3     | Radiation and reception in the Central sector 0 | $\tau_1 + \frac{2H}{c_w \cdot \cos(\Delta \theta)} + \frac{2h}{c_s \cdot \cos(\Delta \theta)}$ |
| 4     | Radiation and reception in the right sector 1 | $\tau_1 + \frac{2H}{c_w} + \frac{2h}{c_s}$ |
| 5     | Radiation and reception in the right sector 2 | $\tau_1 + \frac{2H}{c_w \cdot \cos(\Delta \theta)} + \frac{2h}{c_s \cdot \cos(\Delta \theta)}$ |

To simplify the scan scheme (equal-interval option), the maximum value of the interval between the previous and current probing pulses can be selected. In this case, the only variable parameter included in the equation is the distance of the radiating surface of the antenna from the bottom H. Therefore, the period of probing pulses may vary from cycle to cycle depending on the distance of the radiating surface of the antenna from the bottom.

The calculated values of the follow-up period in the mode of short pulse transmission in the form of one, two, three periods of the difference frequency $F = 10$ kHz for various distances from the bottom of 5, 20, 100 m and the maximum penetration into the ground of 10 m are shown in table 2.
Taking into account the features of the nonlinear method of creating a field of probing signals, it is necessary to use a phased array in the radiation mode to form spatial channels of transmission-reception of the profiler [20].

6. Conclusion
Analysis of methods for scanning with a parametric profiler and calculated expressions allows to draw the following conclusions: with a vertical profiling scheme, it is necessary to choose a method for viewing space and probing modes of a parametric profiler and take into account critical angles; the use of a receiving-transmitting phased array in the case of profiling on the shelf is often impossible, since the radiation time may exceed the propagation time at shallow depths; for the practical implementation of a parametric profiler, the most suitable method is scanning by the movement of the antenna carrier.

7. References
[1] Korneliussen R J 2000 Measurement and removal of echo integration noise ICES Journal of Marine Science 57 pp 1204-1217
[2] Kozaczka E, Grelowska G 2017 Theoretical model of acoustic wave propagation in shallow water Polish maritime research 2(94) Vol 24 pp 48-55
[3] Yang J, Khim-S, Woon-S, Meng-H and Yong-H 2005 Open abstract View article, Beamwidth Control in Parametric Acoustic Array Japanese Journal of Applied Physics 44 (9A) 6817-6819 DOI: 10.1143/JJAP.44.6817
[4] Elizabeth Skinner, Matthew Groves, Mark K 2019 Hinders Demonstration of a length limited parametric array Applied Acoustics 148:423-433 DOI: 10.1016/j.apacoust.2019.01.001
[5] Hanyun Zhou S H Huang Wei Li 2020 Parametric Acoustic Array and Its Application in Underwater Acoustic Engineering Sensors 20 2148 doi:10.3390/s20072148
[6] Westervelt P J 1963 Parametic acoustic arrays J. Acoust. Soc. Am. 35 535–537
[7] Humphrey V F 2000 Nonlinear propagation in ultrasonic fields: Measurements, modelling and harmonic imaging Ultrasonics 38 267–272
[8] Li H X, Tao C H, Goloshubin G, Liu C, Shi S H, Huang G N, Zhang H, Zhang J, Zhang X F 2018 A Modified Biot/Squirt Model of Sound Propagation in Water-Saturated Sediment Physics Acoustic 64 pp 453-458
[9] Brink K, Pedlosky J 2018 Rossby Waves with Continuous Stratification and Bottom Friction Journal of Physical Oceanography 48(9) 2209-2219
[10] Kirichenko I, Starchenko I 2019 Directivity of hydroacoustic systems with parametric array in marine conditions Journal of Physics: Conference Series 1353(1) 5
[11] Ding D 2004 A simplified algorithm for second-order sound beams with arbitrary source distribution and geometry (L) J. Acoust. Soc. Am. 115 35–37
[12] Martynyuk A P, Kazakova E V 2011 On the acoustic Doppler log error with a phased array antenna Gyroscopy Navig. 2 39–45 https://doi.org/10.1134/S2075108711010056
[13] Bernard E, Jakubiak C J, Miksis-Olds J L, Penvenne J & Holliday D 2006 Calibration of a Steered Phased-Array Sonar for use in Fish Detection OCEANS 1-5

Table 2. Calculated values of the follow-up period in the transmission mode.

| Number of periods | Distance from the bottom, m |
|-------------------|-----------------------------|
|                   | 5                           | 20                          | 100             |
| 1                 | 18.3 ms                     | 38.7 ms                     | 147.8 ms        |
| 2                 | 18.4 ms                     | 38.8 ms                     | 147.9 ms        |
| 3                 | 18.5 ms                     | 38.9 ms                     | 148.0 ms        |
[16] Balasubramanian K and Rajaravivarma V 2002 Electronic scanning of sonar beam from a phased array of acoustic transducers controlled through programmable digital delay lines Proceedings of the Thirty-Fourth Southeastern Symposium on System Theory (Cat. No.02EX540) Huntsville, AL (USA) pp 366-370 doi: 10.1109/SSST.2002.1027069

[17] Xiang Pan, Jingning Jiang and Nan Wang 2017 Evaluation of the Performance of the Distributed Phased-MIMO Sonar Sensors 17 133 doi:10.3390/s17010133

[18] Xiang Pan, Jingning Jiang, Si Li, Zhenping Ding, Chen Pan, Xianyi Gong 2018 Coherent and Noncoherent Joint Processing of Sonar for Detection of Small Targets in Shallow Water Sensors (Basel) 18(4) 1154 Published online 2018 Apr 10 doi: 10.3390/s18041154

[19] Lijie Yang, Ruirui Dang, Chunyi Song, Zhiwei Xu 2018 Reference Phase Stabilizer for Distributed Underwater Sonar Systems Sensors (Basel) 18(12) 4279 Published online 2018 Dec 5. doi: 10.3390/s18124279

[20] Kirichenko I A 2018 Parametric antennas in the mediums with hydrophysical inhomogeneities: theory and experiment In book: Exploration and Monitoring of the Underwater Environment of the Shelf Zone (Wiley) pp 25-56

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