Decision-making algorithm for the optimal installation of receiving antennas of stationary hydroacoustic communication systems for dispatching geospatial processes

A A Ovodenko¹, Ja A Ivakin¹,²,³, I A Selesnev² and E A Frolova¹

¹Saint-Petersburg State University of Airspace Instrumentation, 67A, Bolshaya Morskaya Str., Saint-Petersburg, 190000, Russia
²JSC “Concern “OKEANPRIBOR””, 46, Chkalovsky pr., Saint-Petersburg, 198226, Russia
³St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences, 39, 14-th Linia, VI, St. Petersburg, 199178, Russia

E-mail: rechina@mail.ru

Abstract. The article considers metrological aspects of decision-making on the installation of receiving antennas of stationary hydroacoustic communication systems at the stage of designing the infrastructure for dispatching spatial processes based on modeling and visualization of expected receiving zones using intelligent geoinformation systems. The issues of intellectual decision support for optimal spatial installation of receiving antennas are considered. The influence of the quality of information support of geoinformation systems on the accuracy of the results of calculating the expected reception zones of hydroacoustic communication systems in various hydro-acoustic conditions was evaluated. A new efficiency indicator is proposed in the form of the volume of the reception area. This article is devoted to the meaningful disclosure of these concepts and indicators.

1. Introduction

The intensive development of the Arctic regions, the need to solve the problems of dispatching geospatial processes in the underwater and under-ice space objectively stimulates the development of sound underwater (hydroacoustic) communication systems and the corresponding stationary-installed (positional) infrastructure. Hydroacoustic communication systems are widely used for solving problems of information support for search and rescue operations, fishing, as well as protection of marine economic activity, which are further understood as geospatial processes, according to research [1, 2]. At the same time, positional hydroacoustic communication systems, the antenna systems of which for a long time (autonomous hydroacoustic communication systems) or until the end of their service life (stationary hydroacoustic communication systems) are located in a fixed place with specified coordinates \((\lambda_0, \phi_0)\), play a large role in solving these problems and at a certain depth \(h_0\).

Currently, in addition to monostatic hydroacoustic communication systems with a single antenna (operating in active or passive modes), active systems with spaced radiation and reception (so-called bistatic hydroacoustic communication systems and multi-static hydroacoustic communication systems) are also widely used. Designing such systems and making a decision on the rational choice of the antenna location for stationary or autonomous hydroacoustic communication systems in a given area...
of a geographical theater is a rather difficult task in terms of evaluating the achieved efficiency of maintaining a stable information transmission channel. Moreover, in bistatic and multi-static systems, this applies to the installation of both receiving and radiating antennas.

The effectiveness of maintaining a stable channel for transmitting information of the hydroacoustic communication systems depends on numerous factors. While some of them are specific hydroacoustic-acoustic conditions at the antenna location in a given time, determined by the vertical distribution of sound speed, water depth, bottom topography, etc. That is why there is an intellectual problem of choosing a rational spatial installation of receiving antennas of positional hydroacoustic communication systems, which is solved using specialized software and geoinformation tools. The quality of their implementation directly affects the accuracy of the calculation results of the expected communication zones of hydroacoustic communication systems in various hydrological and acoustic conditions, and ultimately, the effectiveness of their application. The disclosure of the features of this influence allows to specify its essence and offer a comprehensive indicator for evaluating the effectiveness of maintaining a stable information transmission channel in various hydrological and acoustic conditions.

The task of the optimal choice of spatial coordinates \((\lambda_0, \varphi_0)\) and the depth of the receiving antennas of positional hydroacoustic communication systems \((h_0)\) seems extremely difficult, because the hydrological-acoustic conditions in various regions of the World Ocean have considerable variability simultaneously both in space and in time (month, season).

2. Improving the process of creating and developing positional hydroacoustic communication systems

Evaluation of the effectiveness of designed hydroacoustic communication systems is usually performed using special software tools (hydroacoustic calculation systems or simulation modeling hardware and software systems).

In traditional systems of hydroacoustic calculations, the simplest and most common model of a flat-layered inhomogeneous medium with a flat bottom is usually used. In this case, the effectiveness is evaluated by calculating the so-called "expected range of hydroacoustic communication systems", which is the same for all directions of observation at a fixed depth of the used communication channel.

Thus, the traditional approach to solving this problem requires either approximate estimates for area and season averages of hydrological-acoustic conditions, usually using systems of hydroacoustic calculations with simplified models of a flat-layer environment with a flat bottom, or expensive field studies for a long time (at least a year).

To improve this process (creation and development of positional hydroacoustic communication systems), in order to reduce time and costs, it is promising to use intelligent geoinformation tools with databases on the bottom and the average vertical distribution of sound speed for different observation times (month, season) or oceanology data.

The most advanced modern hardware and software systems use a more complex model of a two-dimensional inhomogeneous environment with a variable bottom relief and a changing vertical distribution of sound speed along the propagation path. This allows to calculate and visualize real three-dimensional communication zones of hydroacoustic communication systems and any of its projections or sections in any direction in the vertical plane and on any horizon.

In general, the reception area of hydroacoustic communication systems is constructed relative to the location (coordinates) of the receiving antenna of GAS \((\lambda_0, \varphi_0, h_0)\) and defines a spatial area in the coordinates "bearing-distance-depth" \((\alpha, r, h)\), at the entrance to which the underwater object establishing the connection can be identified with a given probability of correct identification, i.e. within which the condition is met:

\[
P_{\text{no}}(\alpha, r, h) \geq P^*_{\text{no}},
\]

where \(P_{\text{no}}(\alpha, r, h)\) is a probability of correct identification of the object establishing the connection depending on the distance, depth, and direction;
$r$ is a horizontal distance to the object establishing the connection;
$h$ is a depth (immersion) of the object establishing the connection;
$\alpha$ is a bearing on the object establishing the connection;
$P_{no}^*$ is the specified (normative) value of probability of correct identification of the observed object.

Modern visualization tools for the expected reception zones of the hydroacoustic communication systems allow to display arbitrary values of probability of correct identification in the form of a color scheme, depending on the spatial coordinates. However, as a rule, it is customary to consider the boundaries of communication zones with a fixed probability of correct identification, equal to $P_{no}=0.9$.

In general, the general view of the expected communication zone of hydroacoustic communication systems is determined by the operating characteristic of the receiver and the corresponding complex spatial dependence of the input signal / noise ratio. Under the conditions of the zonal structure of the field, the communication zone can be a complex set of unconnected areas of acoustic illumination and shadow zones.

Figure 1 shows an example of the calculation and construction results of the expected communication zone for a low-frequency multi-static hydroacoustic communication system with three receivers ($b=60$ km away from the emitter), in the Barents Sea (the sea depth in the region is up to 275 m) in the winter period (January, PRPD), when placing antennas at the depth of $h=60$ m, using a model of a two-dimensionally inhomogeneous marine environment (180 directions of calculation relative to the emitter and relative to each of the receivers): view of the expected communication zone at the horizon $h=80$ m (with mapping) for a fixed threshold value of correct identification probability $0.9 \leq P_{no}(r, \alpha) \leq 1$ (figure 1, a); view of the expected communication zone in polar coordinates on the horizon $h=80$ m, for arbitrary values of correct identification probability $0 \leq P_{no}(r, \alpha) \leq 1$ (figure 1, b).

![Figure 1](image1.png)

**Figure 1.** Calculation results of the expected communication zone of multi-static hydroacoustic communication system using simulation data in geoinformation systems.

Based on the research, it can be concluded that for an accurate evaluating the effectiveness of positional hydroacoustic communication systems and especially of low-frequency bistatic hydroacoustic communication system and long-range multi-static hydroacoustic communication systems (with emitter and receiver spaced apart over significant distances) a strict alignment of the expected communication zones to the area map, taking into account the exact coordinates of the installation of the emitter and receiving antennas, the real bottom topography and variables in space vertical distribution of sound speed with a given grid based on geographic coordinates.

Currently, simulation modeling hardware and software complexes have been created [3-8], designed to evaluate the effectiveness of any hydroacoustic communication systems. In particular, the hardware and software complex for simulation and evaluation of the effectiveness of underwater surveillance and communication systems is designed to simulate the dynamics of the functioning of
underwater surveillance systems and hydroacoustic communication systems for various purposes and configurations in various spatial situations, hydrological-acoustic conditions, and noise and signal conditions, with the use of marine geoinformation systems: including distributed positional (stationary and autonomous) active-passive hydroacoustic communication systems operating in various modes, including bistatic and multi-static modes.

One of the proposed modeling goals is the intellectual support of the synthesis process of the designed hydroacoustic communication system by (sequential) evaluating the effectiveness of various options for its construction.

First of all, this applies to the positional (first of all, stationary) component of the system, to justify the most appropriate rational composition, coordinates of the antenna devices installation and basic technical solutions, as well as to analyze the possible (necessary) build-up of elements of the mobile component of the system in order to achieve the necessary values of the performance indicators of sound communication.

It is proposed to use as the main indicator of the effectiveness of lighting underwater environment of positional hydroacoustic communication system are not expected the traditional range, not the area of the expected zone of observation at a given horizon beyond the area of the vertical zones of the connection in coordinates "distance-depth" in one of the directions of observation, but "the volume of space corresponding to the target threshold of correct identification probability".

The algorithm for calculating the volume of the "spatial communication zone" for the set value of correct identification probability and the set limits of the underwater object's depth is implemented in the software and hardware complex of simulation modeling and effectiveness evaluating the underwater surveillance and communication system as a separate task. At the same time, the intellectual support of solutions based on geoinformation systems of the process of creating and designing hydroacoustic communication systems is to provide information for solving the optimization finding the maximum volume of illuminated space as a function of the coordinates of the antenna location within a given geographical area, with fixed technical characteristics of hydroacoustic communication systems, interfering conditions, and given acoustic characteristics of the object establishing the connection, and the observation time (i.e., hydrological acoustic conditions are integrally characterized by the vertical distribution of sound speed). Then the problem of installation of receiving antennas of positional hydroacoustic communication system within the framework of the geospatial processes dispatching infrastructure can be presented as the statement of the corresponding optimization problem (2) - (5).

Moreover, the optimization problem can be solved as in the general case

\[ V_{III}(\lambda_0, \varphi_0, h_0) \rightarrow \max_{\lambda_0, \varphi_0, h_0} \{ V_{III}(\lambda_0, \varphi_0, h_0) \} , \]

and, in the case of already selected coordinates of the installation location, by changing only the depth of the antennas

\[ V_{III}(\lambda_0, \varphi_0, h_0) \rightarrow \max_{h_0} \{ V_{III}(h_0) \} \bigg|_{\lambda_0, \varphi_0 = \text{const}} . \]

This approach can be used primarily for hydroacoustic communication systems, whose operating period is limited to one or two months (a season), when the hydro-acoustic conditions (vertical distribution of sound speed) can be approximated as unchanged. In the case of stationary hydroacoustic communication systems, whose service life is calculated for a long period, measured in years, and sometimes even decades, it is necessary to take into account seasonal changes in hydro-acoustic conditions (primarily, the vertical distribution of sound speed), by averaging the volume of the expected observation zone for four seasons (N=4) or twelve months (N=12):
\begin{align*}
V_{3H}(\lambda_0, \varphi_0, h_0) \rightarrow \max_{h_0} \left\{ \frac{\sum_{i=1}^{N} V_{3H}(h_i)}{N} \right\},
\end{align*}

(4)

\begin{align*}
\max_{h_0} \left\{ V_{3H}(h_0) \right\} \bigg|_{\lambda_0, \varphi_0 = \text{const}},
\end{align*}

(5)

\begin{align*}
\max_{\lambda_0, \varphi_0, h_0} \left\{ V_{3H}(\lambda_0, \varphi_0, h_0) \right\},
\end{align*}

(6)

\begin{align*}
\max_{h_0} \left\{ \frac{\sum_{i=1}^{N} V_{3H}(h_i)}{N} \right\} \bigg|_{\lambda_0, \varphi_0 = \text{const}},
\end{align*}

(7)

The solution to this optimization problem provides the best option for the installation of receiving antennas of positional hydroacoustic communication systems for spatial process dispatching.

3. Conclusion

Thus, when using the system of hydroacoustic calculations integrated into the geoinformation tools built into the hardware-software complex of simulation and justification of the configuration of installing the antenna of underwater observation system and communication with the calculation of indicators of effectiveness of the form \( V_0 \) (volume of communication zones) and \( S_0 \) (area of cross-section of communication zones), it is possible to solve a separate problem of justification (search and select) the most rational option for constructing a system that maximizes the desired volume \( V_0 \) or the area \( S_0 \).

The main feature of the advanced design systems of positional hydroacoustic communication systems is the possibility of multi-level processing of geospatial data that characterize receivers, objects that establish communication and the environment, as well as dispatchable geospatial processes. At the same time, the intelligent geographic information systems have the most developed capabilities for multi-level processing of geospatial data.

The proposed approach to the choice of installation of receiving antennas of positional hydroacoustic communication systems when creating the infrastructure for dispatching geospatial processes using as an intelligent support a modern hardware and software complex that implements the specified choice for such an efficiency indicator as the volume of communication zones in real hydrological-acoustic conditions, can significantly improve the accuracy of efficiency estimates and the quality of decision making, which is comparable in quality to a traditional approach to solving this problem, requiring expensive field studies for a long time.

In order to improve (to reduce, to simplify, and to cut the cost) the process of installing the receiving antennas of positional hydroacoustic communication systems when creating an infrastructure for dispatching geospatial processes as a means of automated justification of design decisions, it is promising to use intelligent geoinformation systems with databases on the bottom and the average vertical distribution of sound speed for different observation times (month, season). This will ensure a qualitative increase in capabilities for dispatching geospatial processes in the underwater (including under-ice) environment.
Acknowledgements
This research was supported by the Russian Foundation for Basic Research (project No. 18-07-00437).

References
[1] Potapychev S and Ivakin Ya 2018 Intellectual decision-making support in the geospatial processes dispatching of maritime transport Bulletin of the State University of Sea and River Fleet named after Admiral S.O. Makarov 4(50) 857-69
[2] Potapychev S, Ivakin Ya and Ivakin R A 2019 Support model for dispatching geospatial processes of water transport based on situational management Bulletin of the State University of Sea and River Fleet named after Admiral S.O. Makarov 5(57) 842-55
[3] Intelligent Geographical Information Systems for Marine Environment Monitoring 2013 (St. Petersburg: Nauka) p 284
[4] Popovich V V, Ermolaev V I, Leontiev Yu B and Smirnova O V 2009 Modeling of hydroacoustic fields based on the intellectual geographic information system Artificial Intelligence and Decision Making 4 37-44
[5] Guchek V I, Ermolaev V I and Popovich V V 2012 Intellectual GIS-based monitoring systems Defense Order 2(21) 58-61
[6] Ermolaev V I 2014 Use of geospatial data in management of a marine distributed surveillance system Information Technologies in Management (Saint Petersburg: JSC "Concern "Central research Institute" Electroprivor») pp 272-6
[7] Ermolaev V I, Karishnev N S, Popovich V V and Potapychev S N 2017 Indicators of the tactical situation for operators of hydroacoustic means Marine Radioelectronics 3(61) 28-33
[8] Ermolaev V I 2016 Use of intellectual GIS by designing GAS Regional Informatics 446-50