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К вопросу об использовании байесовского метода для поиска подводных объектов

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Поиски и изучение подводных антропогенных объектов, в частности исторических кораблей, является одним из наиболее актуальных направлений в современной подводной археологии, охватывающих спектр задач теоретического и прикладного характера. В практике поиска затонувших судов достаточно редким случаем является обнаружения судна на основе заранее (априори) известных данных. В связи с этим, а также использованием определений из области теории вероятности и математической статистики, естественным направлением развития систем поиска стала байесовская статистика, а именно, поисковый метод, нашедший применение в ряде известных зарубежных поисковых проектов. Метод поиска Байеса для установления местоположения затонувших судов, а также их идентификации почти не использовался в отечественной практике подводной археологии. Однако потребность в его применении существует, как это показала экспедиция 2024 г. по поиску транспортного судна «Тбилиси», потопленного в годы Великой Отечественной войны в Енисейском заливе: несмотря на относительно небольшую площадь акватории поисковой зоны, установление местоположения корабля стало весьма трудоемким процессом. В то же время применение байесовского поиска могло бы существенно облегчить данную задачу. В связи с этим в настоящей статье рассмотрена методика применения байесовского поиска для обнаружения затонувших судов (приведен пример построения распределения вероятностей в зоне поиска судна «Тбилиси»). Кроме того, автором рассмотрен вопрос об использовании байесовского метода для идентификации объектов (предложена модель базы данных с включением в нее различных параметров поиска). В качестве реального примера представлены результаты работы экспедиции 2024 г. с описанием исторического объекта, условий поиска, а также проблем, возникших в ходе проведения данной работы.

Ключевые слова: байесовский поиск, подводная археология, кораблекрушение, спутниковые системы навигации, гидролокатор бокового обзора.

On the application of the Bayesian search method for detecting underwater objects

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Underwater archaeology and, in particular, the study of shipwrecked vessels, is one of the most advanced fields in the discipline, covering a range of theoretical and applied problems. In the practice of searching for sunken ships, it is quite rare to find a ship on the basis of previously (a priori) known data. In this regard, as well as in connection with the use of definitions from the field of probability theory and mathematical statistics, Bayesian statistics, namely, a search method that has found application in a number of well-known international search projects, has become the natural direction for the development of search systems. The Bayesian search method for determining the location of sunken ships, as well as their identification, has been almost never used in domestic underwater archeology practice. However, there is a need for its use, as it was demonstrated by the 2024 expedition to search for the transport ship Tbilisi, sunk during the Great Patriotic War in the Yenisei Gulf: despite the relatively small area of the search zone, determining the ship's location became a very labor-intensive process. At the same time, the use of Bayesian search could significantly simplify this task. In this regard, the paper examines the methodology of using Bayesian search to detect sunken ships (an example of constructing a probability distribution in the search zone of the ship Tbilisi is given). In addition, the author considered the issue of using the Bayesian method for identifying objects (a database model is proposed with the inclusion of various search parameters). As a real example, the results of the 2024 expedition are presented with a description of the historical object, search conditions, and problems that arose during this work

Keywords: Bayesian search method, underwater archaeology, shipwreck, satellite navigation systems, side-scan sonar.

Introduction

Underwater archaeology, which includes, among other things, the detection and study of sunken ships, has become one of the most rapidly developing areas of archaeological science in recent decades. This is due mainly to the development of such technical search tools as hydroacoustic systems and underwater robotics. These changes affected both the technical and economic aspects. As a result, underwater search equipment has become widespread. Today, it is purchased by both academic institutions that previously did not have access to it, and various private organizations and individuals [1]. The most accessible search equipment includes, first of all, mobile side-scan sonars (SSSs) that can be used both as additional hardware to the line of civilian echo sounders and small mobile underwater vehicles. Archaeological studies of sunken ships are of significant relevance from both theoretical and practical points of view [2–4]. As historical objects, sunken ships often provide researchers with a unique opportunity to obtain original information about the material culture of the past; in some cases, in addition to material sources, it is even possible to obtain documentary evidence. On the other hand, the study of shipwrecks appears to be an important applied task related to solving the problems of clearing waterways of physical obstacles, which may be sunken ships. Another important task is the environmental monitoring of water bodies: ships, especially those of the industrial era, may pose a threat to the environment with the contents of their holds, which may contain toxic cargo, or with the ship itself and its fuel. In this regard, the detection and study of sunken ships are the most important scientific tasks.

Despite the use of various search equipment, which, as in the case of SSS, allows covering impressive areas of the bottom surface, determining the location of sunken ships remains a complex procedure. Even when the geographic coordinates of the sinking are known, it is not always possible to detect an underwater object, and, taking into account the high cost of search operations, renting a research vessel, expenses associated with the operation of equipment and the work of specialists, the time for conducting field work can be very limited. Geographical and meteorological factors can also become an obstacle to conducting research. In this regard, it is necessary to create an effective search method within which it is possible to preliminarily narrow the search zone to areas where the location of the sunken ship is most likely.

One of the most promising approaches implementing a mathematical model for determining the location of sunken ships is the Bayesian search method. It was named after the 18th century English mathematician Thomas Bayes, known for his work in the field of probability theory and mathematical statistics. Bayes' theorem is well known and has the following form:

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B)},$$

where *P(A)* is the a priori assumption of the probability of a particular event; *P(A|B)* is the probability that *A* is true in case of the a posteriori probability; *P(B|A)* is the probability that *B* will occur if *A* is true; in this case, *P(B)* is a guarantee that event *B* will occur.

The Bayesian search method has found quite productive application in a number of foreign search projects. One of the most famous cases of application of this method is the search for the American nuclear submarine USS Scorpion, which sank as a result of an accident in 1964. As a result of application of this method, the multi-kilometer search zone in the North Atlantic was narrowed down to 300 m^2 [5]. Another significant achievement of this method was the discovery of the American passenger steamship Central America, which sank in 1857. The location of the ship's sinking was known only approximately, since the accident occurred during a storm and the crew did not have the opportunity to accurately determine the coordinates of the ship. In addition, the great depth led to the fact that the ship was at a significant distance from the place where it presumably sank. The search map with the determination of the probability of finding the ship (from 0 to 65%) is shown in Fig. 1.

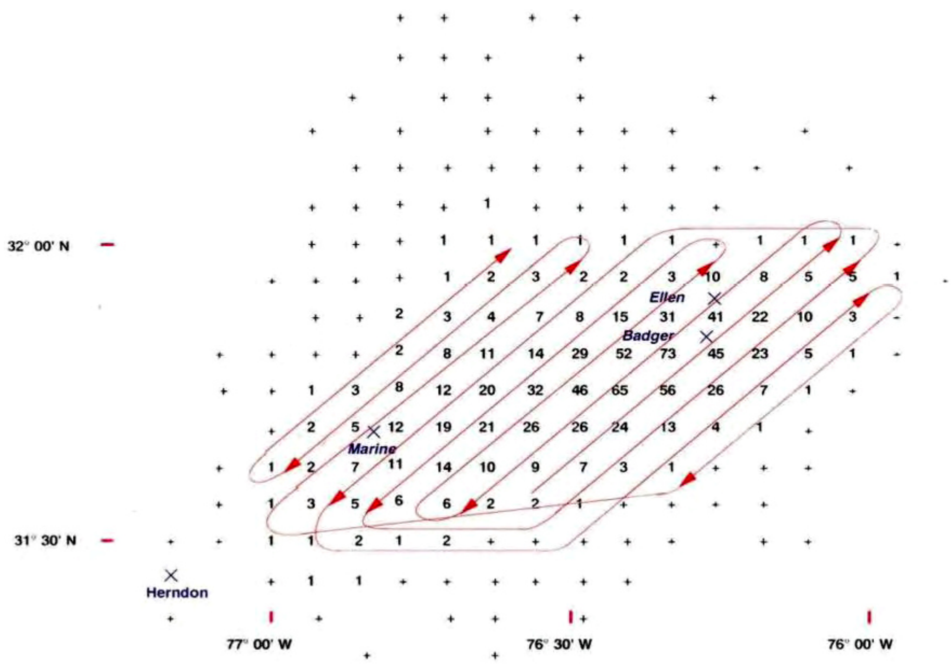


Рис. 1. Графическая модель плотности вероятности поиска парохода Central America, нанесенная на координатную сетку [6]

Fig. 1. Graphical model of probability density of finding the steamship Central America, applied to a coordinate grid [6]

Thus, we see that the Bayesian method can be quite effective in searching for sunken ships. In general, it is one of the few theoretical methods that meet the problems considered within this work. As practice shows, the search for sunken ships, especially in coastal sea zones and inland waters, is carried out mainly unsystematically: known coordinates are entered into satellite navigation cartographic programs in order to conduct an *in-situ* search. This approach places a great burden on a human operator of probing devices, requiring high professionalism and physical exertion. As a result, search operations often turn out to be ineffective. A decrease in an operator's concentration as a result of long monotonous work can lead to the fact that the object is missed and discovered only during the office processing of materials. Despite the obvious need for an effective search method, the use of the Bayesian method for searching for sunken ships continues to be a poorly studied topic. Thus, in the domestic scientific literature only one scientific paper on this problem was found [7]. The situation is slightly better in the foreign literature [8–10], however, these materials cannot be considered satisfactory since there are still no specialized software tools that allow the implementation of the Bayesian search method in practice. Calculations are made manually and, as a rule, relative to already found objects, which has only theoretical significance.

Bayesian search method

The Bayesian search method is quite simple, which is due to the initial probabilistic model. The method is a special case of a decision theory and as such can be built on a set of objective and subjective data, allowing for an optimal decision. As in many search problems, the assumption is based on a limited amount of data; the quality of this data may also be low.

Thus, the first task is to construct an a priori distribution, for which the available data, including incomplete and fragmentary ones, must be arranged in sequential sets, which will be understood as probability scenarios. Then it is necessary to give a quantitative assessment to uncertainties by determining their probability factor. This task is performed by determining the probability of a specific scenario, as well as introducing subjective factors into the calculation. Next, it is necessary to calculate the probability distribution for each of the scenarios, combining the calculations into a priori weights (probabilities of a particular scenario). To do this, when constructing a search model, it is necessary to take into account (if any) the results of previous search work. Note that even in the case of constructing a model solely on the basis of objective and accurate data, the resulting distribution will be considered only an assumption until its truth is proven. For a Bayesian model, as for any statistical model, it is characteristic to reflect the individuality of the decision taken, made on the basis of the best understanding of the problem, as well as taking into account the results of previous searches. However, it must be taken into account that each individual search is an individual case that cannot be reproduced many times to obtain an empirical probability distribution.

Let us turn to the factors that ensure the effectiveness of Bayesian search as a method that allows:

– providing a fundamentally new approach that includes all objective and subjective data on the location of a sunken vessel in order to construct a probability distribution function for finding an object;

– constructing a probability distribution function to narrow the search area in order to increase the effectiveness of the search;

– including new search data in the model, unsuccessful search operations among them, to construct an a posteriori probability distribution function, which underlies the construction of subsequent search routes;

– obtaining analytical calculations of the search process in order to achieve a given level of effectiveness of the latest search activities [9].

A necessary condition for the formation of a search model is the creation of a database that will serve as its basis: it can have various types and forms depending on the requirements of the search model, as well as the autonomy of its operation, so we will consider here only its content. Information on the technical characteristics of a particular ship can be obtained from both unpublished historical sources (archival data) and published ones. The latter include various marine statistical collections containing information on the technical characteristics of ships [10]. Note that some ships were built according to standard projects, therefore, it is sufficient to take into account the characteristics of projects of this type to organize search operations. In general, the following parameters apply to this block of information: length, type of propeller (the ship could be self-propelled or non-self-propelled, motor or sail, etc.), type of cargo and its quantity, carrying capacity. In some cases, it is possible to take into account the type of superstructure, the material from which the hull is made, the number and types of machines, etc. However, as practice shows, these parameters are not always important for conducting a search. The most important information is about the speed and direction of the vessel's movement, and entries from the ship's log about the position of the ship at the time of its loss (this parameter, in relation to historical vessels, is based mainly on dead reckoning data, not astronomical observations).

A separate block is made up of data of a geographical nature: depth, speed and direction of the current, geomorphological features of the bottom of the water area, proximity to land, wind direction, meteorological conditions and other parameters [11]. Information obtained during search operations is entered into the database for the purpose of adjusting the search model (Fig. 2) [12]. This should include data obtained, among other things, using the remote sensing method (aerial photography and space remote sensing). It should be noted that adjusting the geographical coordinates obtained from satellite navigation systems should be considered a separate task.

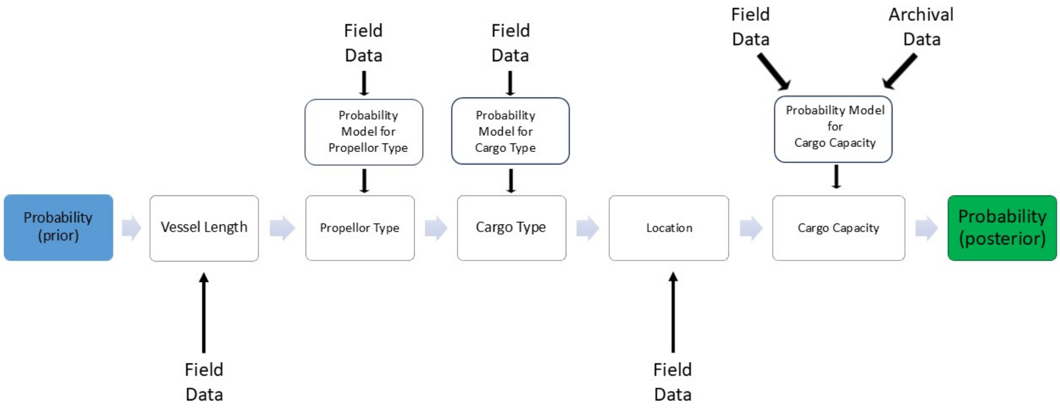


Рис. 2. Схема данных в предполагаемой базе

Fig. 2. Diagram of data input in Bayesian model data base

Above is a database diagram based on the method proposed in [12]. It is a Bayesian method for determining the probability of detecting a particular historical vessel on the basis of a priori probability. During the model operation, it is saturated with actual data, including field data, which allows deriving the a posteriori probability of vessel identification. The proposed method is presented in one of the most original works devoted to the Bayesian search system for sunken ships. Unlike similar thematic publications, the author of the work proposes a method not for determining the location of a vessel, but for its identification. This task is relevant, since in areas of active shipping and deep-water areas, many vessels can be simultaneously located at the same point. The combination of the proposed approach with the classical Bayesian search method allows increasing the probability of detecting a specific vessel.

The Problem of localization. The Tbilisi case in 2024.

In the summer of 2024, a group of researchers, including representatives of the Russian Geographical Society and the Siberian State University of Science and Technology named after academician M. F. Reshetnev (Krasnoyarsk), took part in a search expedition in the Yenisei Gulf (Krestovsky Islands area) to find the remains of the vessel Tbilisi (captain V. K. Subbotin). This vessel was part of a small Arctic convoy traveling from Dudinka to Dickson in September 1943. When approaching Maly Krestovsky Island, the vessel hit a German magnetic mine, previously laid by the submarine U-636, and sank. The ship's logbook recorded the coordinates of the vessel's demise as N 72°25', E 80°36'. The project to organize the search and survey of the vessel, which is a unique historical monument to military operations during the Great Patriotic War (1941-1945), was developed over several years. In the final version, the project was presented as a short-term search expedition, the main search methods for which were SSSs, satellite positioning systems and Earth remote sensing, as well as an unmanned aerial vehicle. In the event of the vessel being discovered, its exploration was to be continued by scuba divers.

Taking into account the known coordinates of the object, the search area was a square with sides of about 1.3 km, which was approximately 1.7 km^2. The depths in the search area are constant and average about 12 m, which allows the range of the onboard beam of the SSS, operating in the megahertz range, to be adjusted to 30–40 m. In order to completely cover the studied water area (with overlapping of the acoustic shadow zone), taking into account the recommended speed of the towed measuring transducer from 1.5 to 3 kn, approximately 3–4 hours will be required. This condition cannot always be met, for example, due to bad weather conditions. In addition, due to the high cost of chartering the vessel from which the search was carried out, no more than 1.5 days were allocated for all search operations.

The experience of the SSS operator allowed determining the exact location of the shipwreck after 3.5 hours of search operations from a small vessel. Subsequent dives to the ship allowed identifying it accurately. The SSS search route was built in the form of concentric circles due to strong wind and large waves (1–1.5 m), which contradicts the traditional search method of tack passages. However, the wind and wave directions did not allow using this method. Obviously, the described search method cannot be considered effective, since it relies solely on the experience of the SSS operator, as well as on chance. Therefore, let us consider the organization of search operations to find the Tbilisi using the Bayesian method.

Bayesian mathematical model

To build a search model, the following steps must be taken:

– put forward the most probable hypotheses about what could have happened to the vessel (the number of hypotheses is not limited);

– for each of the hypotheses, it is necessary to build probability density functions for the location of an object;

– build the probability function of finding a shipwreck at a given point *X* when searching at a given point. It must be taken into account that when search operations are conducted in areas with great depths, this function reflects the depth. In the case of searching in shallow water, the probability of detecting an object increases significantly, since the vessel lies on the bottom in approximately the same place where the dive occurred;

– use the information presented above to build a graphical model of the probability density, which involves multiplying two functions. Thus, finding a shipwreck at point *X* for all points *X*;

– then build a search route from points with the highest probability to points with the lowest one;

– systematically revise all new probabilities during the search. Thus, if at the supposed point X, as a result of search operations, for example, with a side-scan sonar, no ship wreckage was found, then the probability of finding the vessel at this point should be significantly reduced, while the probability for other points should increase.

Let us imagine a search area divided into a grid, where the probability of finding a sunken vessel in each of the squares is expressed by *P*. The truth of this assumption is expressed by *Y*. If the vessel is not found in a given square, then according to Bayes' theorem, the adjusted probability will be:

$$P = \frac{P(1-Y)}{(1-P)+P(1-Y)} = P\frac{1-Y}{1-PY} < P.$$

If the a priori probability *r* for each square is true, then the a posteriori probability will be expressed as follows:

$$r' = r\frac{1}{1-PY} > r.$$

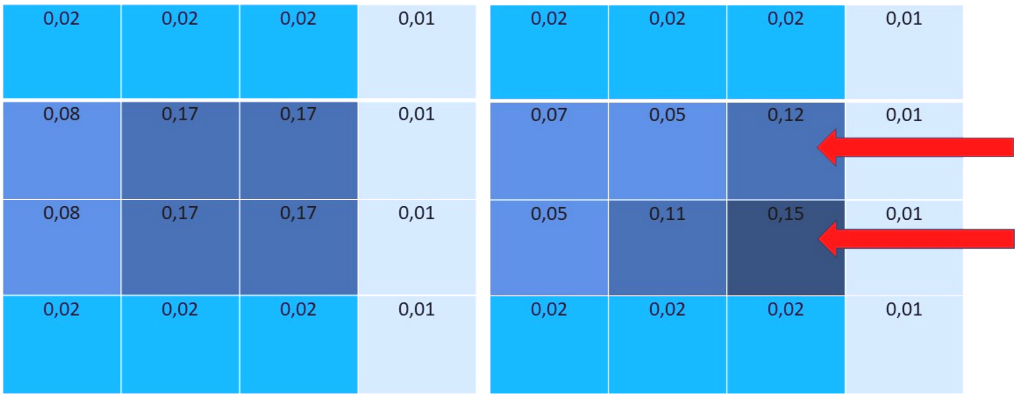
Let us consider a practical method of this approach in relation to searching for a vessel with known parameters (vessel characteristics, geophysical factors and other known variables) using the example of [13; 14].

The first step will be to divide the search zone into squares.

$i = 1$	2	3	4	5
6	7	…		

Next, let us imagine that the probability of detecting an object has the form $Pr(Z_i = 1|Y_i = 1)$, where i is the square index; Z_i are the search results in the *i-th* cell; Y_i is the true position of the underwater object in the *i-th* cell (one means that the object has been found): in this case, $Pr(Y_i = 1)$. It is necessary to take into account that the object may be absent from a given square, which can be revealed during its survey.

Now let us consider the Bayesian method as applied to the search for the Tbilisi. We divide the search zone (1.69 km^2) into a square grid consisting of 16 squares, each of which is ≈105.6^2, which is quite satisfactory, given the length of the vessel is more than 100 m (Fig. 3, *a*). The center of the grid is placed at a point with known historical coordinates. We will determine the highest probability of finding a vessel in the four central squares – 0.17, and the lowest – 0.01. In a similar way, we will construct a probability map by the depths of a given area with probabilities from 0.29 (min) to 0.98 (max). As we know that the average depth in the search zone is 12 m, the squares with the smallest depths will represent a higher probability of finding a vessel in them. Combining these values, we will obtain new probability indicators for each square (Fig. 3, *b*).



a *b*

Рис. 3. Сетка распределения вероятностей:
а – априорная; *б* – апостериорная с учетом глубин акватории

Fig. 3. Probability density map:
a – prior; *b* – posterior based on depth map

As you can see, the most probable squares were 0.12 and 0.15 (marked with arrows). Starting the search from the bottom square, it was possible to establish that the ship is not here. In this regard, we will refine the probability model taking into account this data:

$$P[Q \mid N] = \frac{P[Q](1 - P[Y \mid Q])}{(1 - P[Q] + P[Q])(1 - P[Y \mid Q])},$$

where Q is the presumed presence of an object; N is the absence of an object; Y is the detection of an object. $P[Q]$ and $P[Y/Q]$ are the probabilities derived from the constructed grids.

The refined probability for a square of 0.15, taking into account the given depth of 0.86, is obtained as follows:

$$P[Q \mid N] = \frac{0{,}17(1-0{,}86)}{(1-0{,}17)+0{,}17(1-0{,}86)} = 0{,}03.$$

Thus, the probability of finding the Tbilisi in square 0.17 changed (taking into account the depth) to 0.15, and then to 0.03. This, in turn, increases the probability of finding the ship in other squares:

$$P[Q] = \frac{P[Q]}{(1-P[Q])+P(Q)\cdot(1-P[N \mid Q])}.$$

Thus, the probability of finding an object in adjacent squares increases to 0.12 and 0.13, respectively. Then we continue the search, studying, first of all, the squares with the highest probability. The search result is shown in Fig. 4. As you can see, the vessel was found in the square in which the a priori probability (great depth) was underestimated to 0.05. The depths on the sailing directions for this area turned out to be given without taking into account the location of the sunken vessel, which in this particular case reduced the depth factor to an insignificant value. In practice, starting the search from the square with the highest probability of finding the object is not always the most effective, since in order to get to it one must first go through all the other squares, therefore, when plotting a search route, one should start with the adjacent squares, where the probability of finding the object is lower: especially since, as it can be seen from Fig. 4, there is a probability of finding the wreckage of the vessel in the adjacent squares. This will certainly increase the chances of finding the sunken vessel. However, the use of Bayesian search allows building the most adequate search route by including the necessary factors.

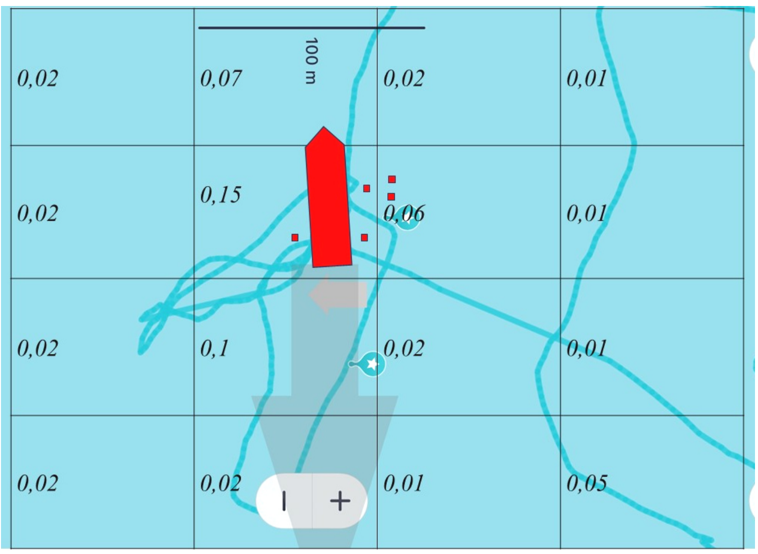


Рис. 4. Зона поиска транспорта «Тбилиси» с нанесением на нее сетки распределения вероятностей.
Пятиугольник – обозначает судно, а квадраты – обломки

Fig. 4. The search area of the SS Tbilisi with the probability distribution grid applied to it.
The pentagon denotes the vessel, and the squares denote the wreckage

Conclusion

As a result of using the Bayesian system of searching for sunken ships, it is possible to significantly increase the efficiency of searching for sunken ships, and to do this in advance. A number of parameters considered in classical models (for example, depth) can be excluded. Additional parameters of an underwater object can be introduced into the search system, allowing not only increasing the probability of its detection, but also its identification. If the size of a vessel is the main factor allowing it to be detected, then such characteristics as the type of a vessel and its propulsion device (self-propelled/non-self-propelled/sail/motor) serve as additional factors facilitating its identification. At the same time, in the absence of information about the hull of a vessel or its decomposition, this factor, as well as information about a vessel's power plants (boilers) and the type of a mechanical propulsion device (propeller, paddle wheel) become the main parameters determining the probability of its detection or identification. Thus, it became possible to successfully combine two directions in the philosophy of Bayesian search for sunken ships. Further development of this method is presented in [15–16] and consists of creating an effective software environment that allows integrating updated databases on underwater objects, new geodata, obtained from SSS and other remote sensing systems, including the Earth remote sensing systems. In further research, we plan to turn to the creation of a similar environment, using such statistical analysis tools as JASP as a basis.

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