POSITION ESTIMATION OF AUTONOMOUS UNDERWATER SENSORS USING THE VIRTUAL LONG BASELINE METHOD

Alexander Dikarev, Stanislav Dmitriev, Vitaliy Kubkin and Andrey Vasilenko

Underwater communication & navigation laboratory, LLC, Moscow, Russia

ABSTRACT

This article contains a description of a mathematical model of an acoustic system for positioning autonomous underwater sensors using the virtual long base method, which can be used during the vessel's collection of information over the deployed underwater network of autonomous sensors (underwater wireless sensors network), during the initial determination of the geographical position of the bottom long baseline elements or search, including cooperative, with the use of a swarm of autonomous surface vehicles (UASV) of emergency submerged objects equipped with an emergency beacon (for example, aircraft and ships); The article provides a scheme of an experimental set of equipment, as well as a description of the conducted field experiments and their results.

KEYWORDS

Underwater positioning system, VLBL, underwater wireless sensor network, emergency beacon positioning

1. INTRODUCTION

There is a wide range of tasks in which it is required to efficiently determine the geographical location of submerged objects, while the external conditions impose restrictions on the use of a long baseline navigation system (for example, time and complexity of deployment) and an ultrashort navigation base (complex hydrological conditions, shallow water depth, high waves etc.), lack of accuracy provided by USBL systems or any weight and size restrictions associated with the applied vessel. Also, in some cases, the deployment of a long baseline (especially a bottom one) is completely unjustified, for example, when quite rare (or single) measurements of the underwater object's position are required, or in case of a search (for example, accidentally submerged objects — ships or aircraft[1][2]) in a fairly wide area, where it is impossible to install a long baseline system of the required dimensions. Particularly noteworthy is the positioning of the nodes of Underwater wireless network of autonomous sensors UWSN[3][4] which often require only a rare or even a one-time estimation of their location. In more detail, the problems of localization of nodes of wireless underwater sensor networks are discussed in [5][6][7].

Problems that discussed above can be successfully solved using a virtual long baseline approach [8][9][10]. The key point here is the immobility of the objects being positioned, which makes it possible to measure distances from different positions on the surface (in the case of the TOA method[6][11]) or pseudo ranges (in the case of the TDOA method [12][13][14]). In both cases, clocks of the requesting system and the desired object are not synchronized. The second option provides the possibility of a cooperative search for an underwater object by a swarm of

DOI: 10.5121/ijwmn.2019.11202

autonomous vehicles [15][16]: an object periodically emitting a navigation signal, allows simultaneous reception on an unlimited number of surface receivers, thereby providing coverage for a theoretically arbitrarily large search area.

Let us consider in more detail the model of the system described in this article.

2. SYSTEM MODEL

The following formatting rules must be followed strictly. Assume there is a submerged stationary object, whose position, expressed in its coordinates x_o, y_o, z_o, has to be estimated. The object is equipped with a hydroacoustic responder beacon, transmitting pressure and temperature sensor readings on request from outside. In general, distance d_o (slant range) to it is estimated on the requesting system as:

$$d_o = (T_a - T_t - T_d)/2 \tag{1}$$

Where T_a - the time of arrival of the response from the responder by the clock of the requesting system, T_t - the time of the beginning of the request signal radiation by the clock of the requesting system, T_d - constant response delay.

If the requesting system moves, and at different points in time measures the distance to the responder, then a set d_{oi} of measurements are formed, matching the locations of the requesting system x_{ri}, y_{ri}, z_{ri}.

The solution to the problem of estimating the location of the desired object for a given set of measurements in general form consists in finding the global minimum of the residual function ε:

$$\varepsilon(x,y,z) = \sum_{i=1}^{N}\left(\sqrt{(x-x_{ri})^2+(y-y_{ri})^2+(z-z_{ri})^2} - d_{oi}\right)^2 \tag{2}$$

However, the sequential set of points obtained in the process of moving the requesting system is, firstly, redundant, and secondly, it is a deliberately disadvantageous arrangement of virtual reference points: in a line and/or group on one side of the desired object with a distance between points less than to the desired object. All of this leads to a "blurring" of the desired minimum of the function ε and/or the formation of false minima that do not correspond to the true position of the desired object. This case is illustrated in Figure 1.

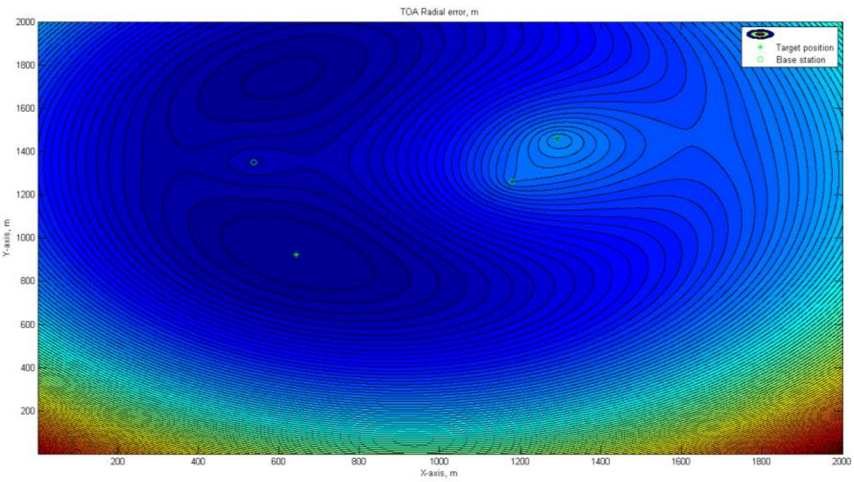


Fig. 1 - False minimum with an unsuccessful selection of base points

Consequently, the problem of estimating the location is now divided into two subproblems: the selection of the optimal base - the selection of the optimal set of measurements to solve the position estimation problem and the actual solution of the position estimation problem. Since, in general, the location of the desired object is unknown even approximately, there is no way to pre-select the optimal trajectory of the requesting system and there are no criteria for selecting the optimal navigation base.

One possible option of the initial base selection may be such a heuristic approach, where the point at which it is supposed to look for a solution selected from the conditions to maximize diversity angular directions α_{mi} from some point $M(x_m, y_m, z_m)$, as the initial stage, it is proposed to choose the geometric center of the entire set of measurements d_{oi}. In this case, it becomes possible to at least get a flat base pattern (rather than a line), on the basis of which one can get the first approximation of the position of the desired object, which one then choose as a point M, and carry out a selection of base points according to the condition of ensuring the maximum variety of angular directions from this point, which in many cases will allow obtaining a figure of the navigation baseline described around the desired object. This strategy is illustrated in Figure 2.

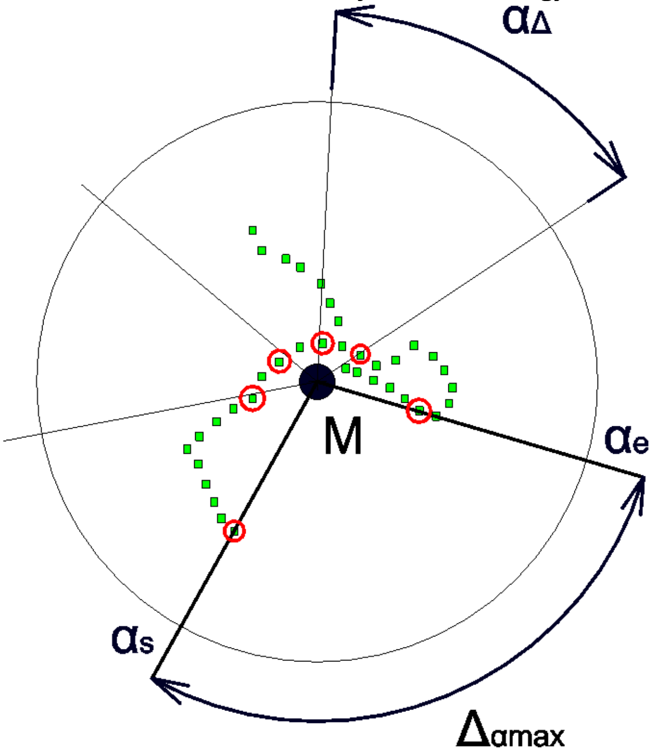


Fig. 2 - Formation of the navigation base from the entire set of measurements, the number of elements of the base is 6

In Figure 2, the rectangles indicate the set of points A_i, representing the trajectory of the requesting system, the circles are points selected as elements of the virtual navigation base.
The angular direction α_{MAi} from the selected point $M(x_m, y_m, z_m)$ to some point $A_i(x_{ri}, y_{ri}, z_{ri})$, at which the distance was measured is determined from a simple trigonometric equation:

$$\alpha_{MAi} = \arctan \frac{\sin(\lambda_M - \lambda_{Ai})\cos\phi_{Ai}}{\cos\phi_M \sin\phi_{Ai} - \sin\phi_M \cos\phi_{Ai} \cos(\lambda_{Ai} - \lambda_M)} \tag{3}$$

where λ_M and φ_M - longitude and latitude of the selected point M, λ_{Ai} and φ_{Ai} - longitude and latitude of point A_i respectively.

Further, to select points-virtual elements of the navigation base, the following steps are performed:
- the whole set of measurements is sorted by the angular direction α_{MAi}, and there are two such neighboring points A_i and A_{i+1}, for which the absolute difference modulus $\Delta\alpha$ will be the maximum of the entire set. These points can be considered the boundaries of the entire available angular range. This operation must be performed because, in the general case, the angular directions α_{MAi} do not necessarily evenly fill the entire circle; At this stage, the starting α_s and the ending α_e angles of the available angular range are determined, the angular range α_r itself:

$$\alpha_r = 2\pi - (\alpha_e - \alpha_s) \tag{4}$$

- At this stage, the desired angular directions are determined in which it is necessary to install the virtual elements of the navigation base. The desired angular gap $\alpha\Delta$ between the elements is defined as:

$$\alpha_\Delta = \alpha_r /(N_B - 1) \tag{5}$$

Where N_B - the required number of virtual elements of the navigation base.
For the case where $\Delta\alpha_{max}$ is lower than $\alpha\Delta$, the last decreases accordingly to (6), otherwise it may turn out that measurements with angular directions α_s and α_e will be selected as base elements, while the angular distance between them will be less than $\alpha\Delta$, which, in turn, for small N_B will result in an uneven arrangement of the base elements in the angular direction.

$$\alpha_\Delta = \alpha_\Delta - \frac{(\alpha_\Delta - \Delta_{\alpha\max})(N_B - 1)}{(N_B - 2)N_B} \tag{6}$$

- The desired angular directions α_{Bi} are determined at this stage.

$$\alpha_{Bi} = \alpha_s + i \cdot \alpha_\Delta, i \in 0..N_B - 1 \tag{7}$$

- at the final stage, such N_B measurements are selected from the entire set, in which the angular directions are closest by value to the desired ones.
Now, the solution of problem (2) is possible by one of the optimization methods. However, as it is often the case, and as mentioned above, there is no guarantee in selecting the optimal base configuration, and the residual function may have false minimums. To solve this problem, one can apply the following approach, which is a rough estimation of the position of the global minimum using the one-dimensional optimization method. It is worth mentioning that this approach is applicable only in the case of the distance measuring method when the distances to the desired object are measured directly.

So, since the distance to the virtual elements of the navigation base and the depth of the transceiver of the requesting system and the desired object are known, the desired object is located on circles in which centers there are virtual base points. The x and y coordinates of the desired object, in this case, are expressed through the angle β:

$$\begin{aligned} x &= x_{rn} + d_{rn} \cos\beta \\ y &= y_{rn} + d_{rn} \sin\beta \end{aligned} \tag{8}$$

x_{rn}, y_{rn} and d_{rn} - the coordinates of the nearest base point and the projection of the slant range to it, respectively. Having performed a complete search over β in the range from 0 to 2π with a certain step (in this work, a search with a step of 10 degrees and then a search with a step of 1 degree in the range of +/- 10 degrees from the previous minimum position are used), one can obtain an approximate position of the global minimum of the function (2), which then will be used as the initial one for solving a two-dimensional problem.

Figure 3 shows a comparison of the effectiveness (number of iterations) of solving the problem of estimating the location of the desired object of random data with and without the application of preliminary one-dimensional optimization.

Figure 4a and b show the distribution of errors (distances from the actual position of the object to the calculated one) on the same random sample, for the variant without preliminary optimization and with such. A random error with a uniform distribution and an amplitude of 1 meter was injected into the distance measurements.

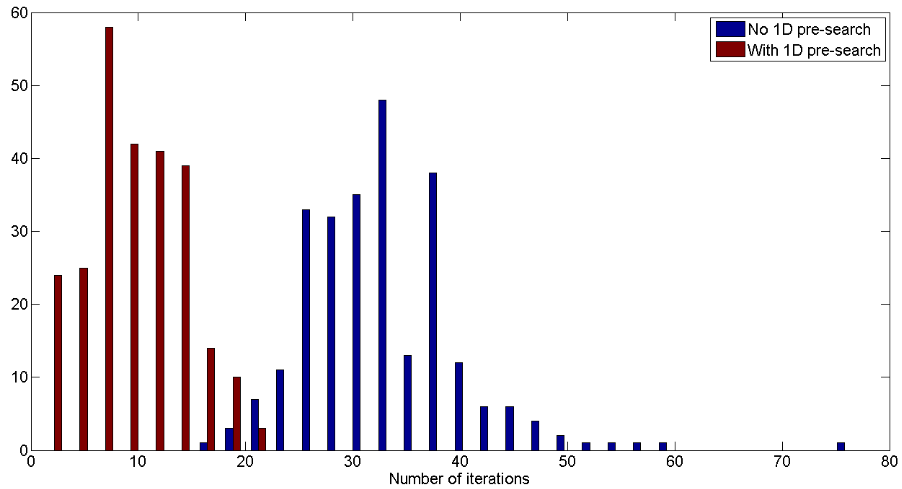
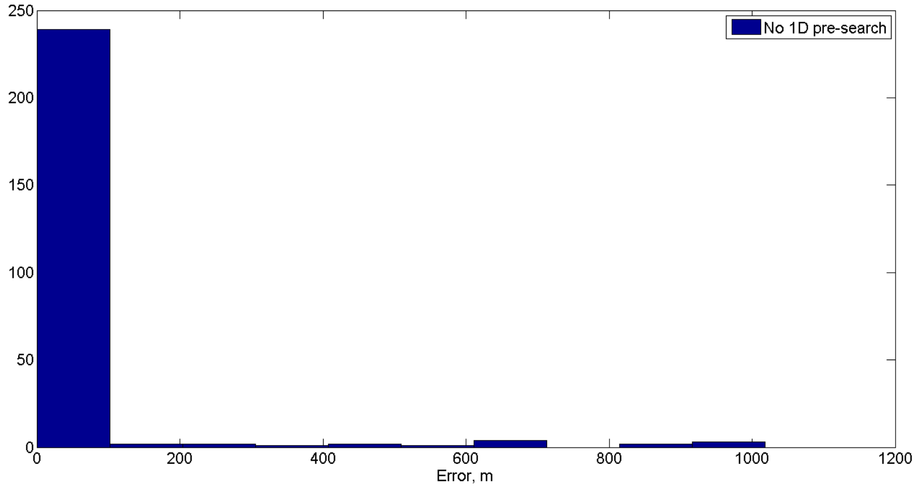


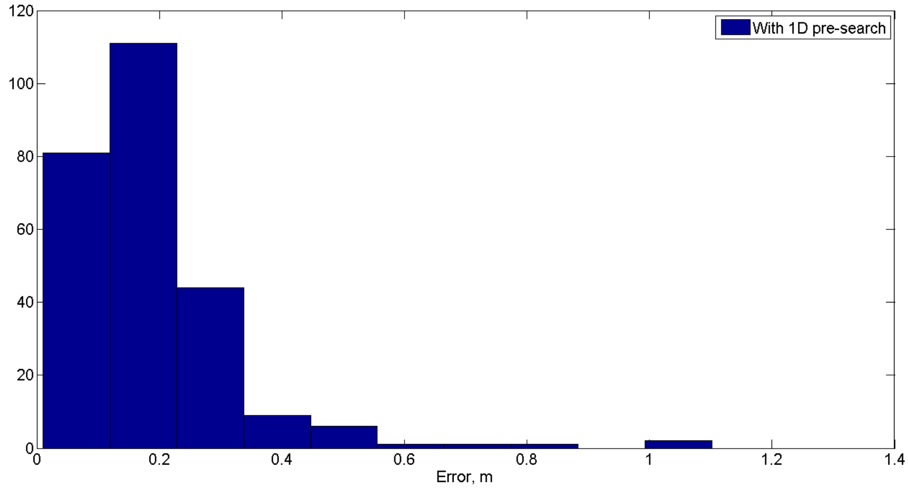
Fig. 3 - The number of iterations to obtain convergence without the use of preliminary one-dimensional optimization and with such. Sample size 256, number of base stations 4

The two-dimensional problem was solved using the Nelder – Mead method[17], and the value of the residual function (2) at the output of one-dimensional optimization was used to specify the initial size of the simplex.

As can be seen from Figure 3, a preliminary one-dimensional optimization, firstly, almost eliminates falling into a false minimum, and secondly, significantly reduces the number of iterations required to achieve a solution with satisfactory accuracy. In this case, the one-dimensional optimization procedure has a fixed execution time, which is also important for real-time systems.



a)



b)

Fig.4 - the distribution of the error of estimating the location of the desired object without the use of one-dimensional preliminary optimization (a) and with the use of such (b). Sample size 256, number of base stations 4

From histograms in fig. 4a) by significant errors of hundreds of meters it is clear that the search went to a false minimum, and in fact, this led to an absolutely wrong result, at the same time according to the histogram in fig. 4b) when using preliminary one-dimensional optimization, this situation is not observed, and the positioning error has a value comparable to the artificially introduced error (~ 1 m).

3. Experimental Setup

A set of experimental equipment consists of the following parts:
The desired underwater object - the responder beacon, which was used as a standalone RedGTR[18] modem in an autonomous version with a built-in pressure sensor. A modem with a battery pack was mounted on a pole with a load and float, providing a vertical position in the submerged state. The modem, among other things, supports the transmission of readings from the

built-in depth and temperature sensor, has a fixed signal length (400 ms), allows operation in the request-response mode, and supports a simple NMEA0183-like interface protocol. It also has small dimensions, weight, and provides communication range of up to 8000 meters. A submersible stand with a modem is shown in Figure 5.

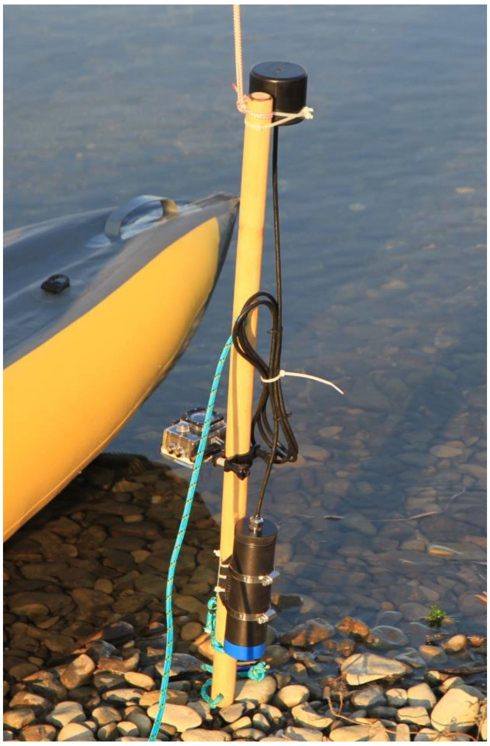
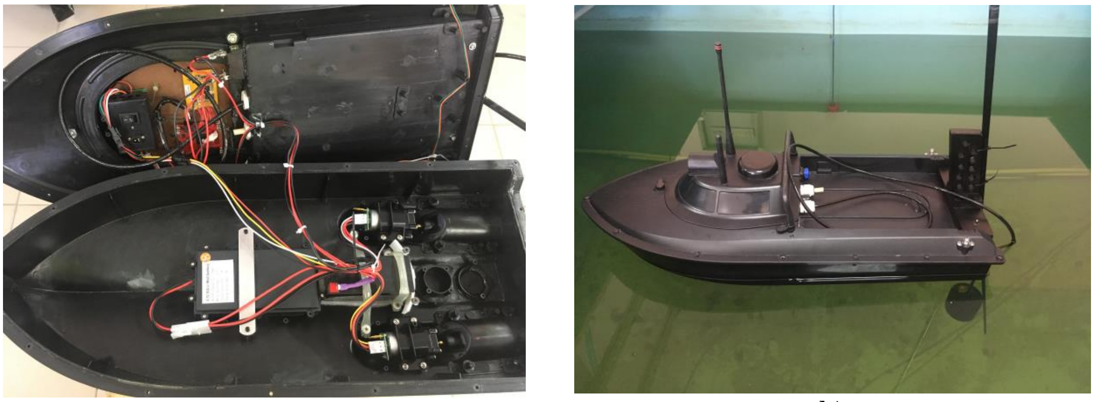


Fig. 5 - Submersible stand with a RedGTR modem

The requesting system consists of a small radio-controlled vessel equipped with a GPS/ GLONASS receiver, a motherboard based on the STM32F429 processor[19], a RedGTR modem, and a digital radio module[20]. Appearance and internals of the vessel are shown in the photo in Fig. 6



a) b)

Fig. 6 - Appearance (b) and internals (a) of a test vessel

The scheme of the requesting system is shown in Figure 7.

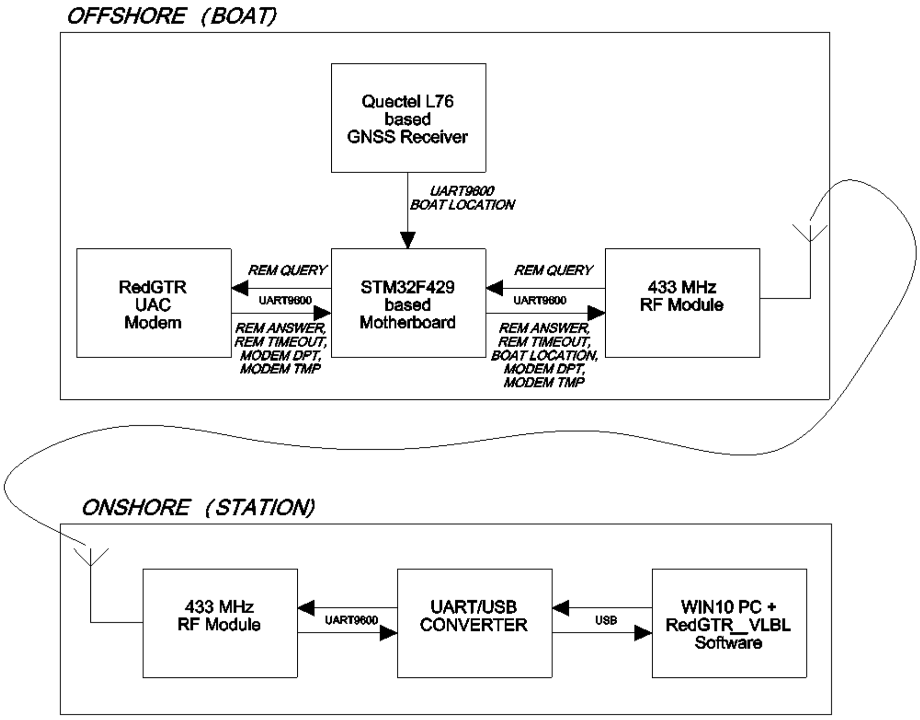


Fig. 7 - Scheme of the requesting system

The experimental test consisted of the following steps:

- alternately at the bottom of the reservoir in two places there was a submersible stand;
- the vessel described above, which was controlled by radio from the shore, moved along a free trajectory through the reservoir. On command by a specially developed software, the source code of which is freely available [21], requests were periodically initiated from a modem located on the ship to a modem located on a submersible stand. At the same time, the ship's computational module transmitted its GPS location data and retransmitted the beacon response over the radio; The frequency of requests was limited only by the modems themselves and amounted to about 1 time in 2 seconds. The time of one request-response transaction is made up of double the duration of the modem signal T_s = 400 ms, the fixed response delay T_d = 800 ms, and the double propagation time of the signal depending on the slant range between the transponder and the inquiring system.

The speed of the vessel varied from 0 to 1 m/s. The experiments were carried out in June 2018 at the mouth of the Pichuga River, at the place of its inflow into the Volgograd water reservoir (48°59'12.86''N 44°43'52.24''E). The depths in the places of the experiments varied from 2 to 20 meters, the bottom is sandy and rocky, the width of the river at the place of work is 350 meters.

In the course of the work, the following data were recorded:
- the initial position of the responders before diving using a GPS/GLONASS receiver based on a Quectel L76[22];

- the position of the vessel according to the built-in GPS/GLONASS receiver;
- the depth of the modem of the requesting system;
- water temperature according to the data of the modem's built-in sensor of the requesting system;
- temperature according to the built-in modem sensor on the desired object;
- depth according to the built-in modem's sensor on the desired object;
- distance (slant range) from the requesting system to the desired object with reference to the geographical location of the requesting system, where the measurement was made;
- the calculated geographic location of the desired object;

4. Experimental Results

The main results of this work are the tracks stored in the Google KML format, containing the following data:

- a track movement of the requesting system (vessel), according to the onboard GNSS;
- a track containing the points at which distance measurements were made to the desired object;
- a track containing points obtained by calculating the coordinates of the desired object, according to the procedure described in this paper;
- the marked point that has a minimal radial error (the value of the function ε according to (2));
- the marked point at which the respondent was actually submerged;

Tracks containing data from two experiments are available on GitHub [23] [24] along with the source code of the application [21].

The distance of the modem of the requesting system from the surface of the water varied from 0.5 to 0.75 meters.

The depths of the respondents were 13.2 and 16.5 meters for the first and second experiments, respectively.

Fig. 8 shows a screenshot of the main application window in the process of work (the first experiment).

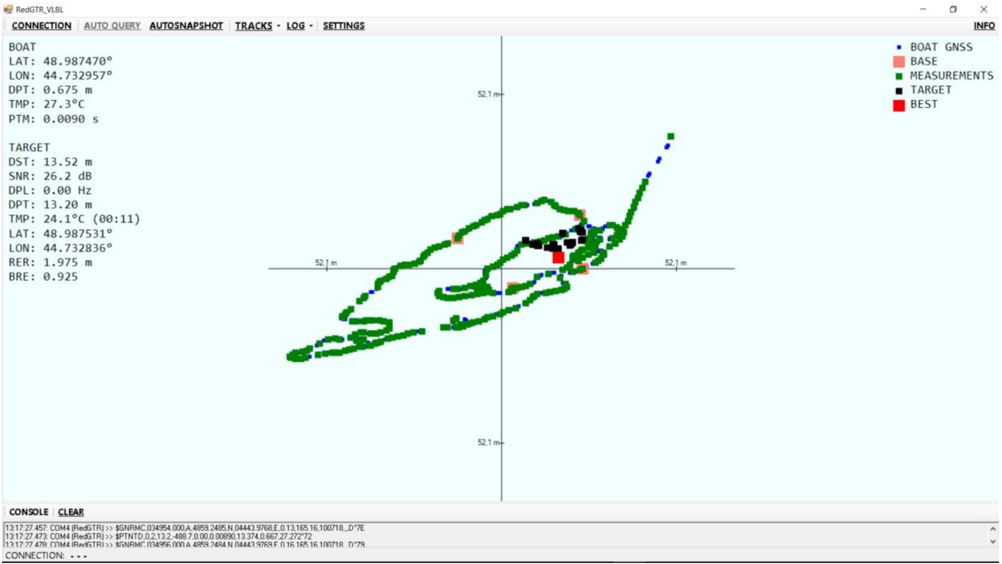


Fig. 8 - Screenshot of the main application window

As can be seen from Figure 8, the described system allows not only to monitor the location of the object being searched for but also to correct the vessel's heading, determine the depth of the object being searched, as well as the water temperature using its built-in sensor. The RER and BRE fields correspond to the current and best values of the residual function (2). According to the calculated positions of the object, the deviation from the real position obtained using GNSS just before the submersion is in the range of 2-2.5 meters in both experiments, which is comparable with the accuracy of the used GNSS modules [22]. A general view of the tracks obtained in this work is presented in Fig. 9 and 10.

Fig.9 - Screenshot of the GoogleEarth application window with tracks obtained during the first experiment

Fig.10 - Screenshot of the GoogleEarth application window with the tracks obtained during the second experiment

5. CONCLUSION

The results of mathematical modeling and field experiments confirm:
- the adequacy of the system model to real conditions;
- the ability to ensure the localization of stationary submerged objects, equipped with responders using mobile surface uninhabited vehicles; If it is necessary to localize several underwater objects at the same time (for example, nodes of an underwater wireless network of sensors), the selected scheme as a whole can be saved with the only exception that all objects will be polled in turn, which will correspondingly increase the localization time;
- the accuracy of the location estimation of the underwater objects in the experiments performed is comparable to the declared accuracy of the used GNSS receivers;
- the need to apply the proposed method of pre-refinement of the location.

Further studies in this area are planned using the TDOA method, which will allow the use of a much simpler device mounted on an underwater object, so-called pinger that does not contain a receiving hydroacoustic unit; At the same time, this scheme will allow excluding the transmitting hydroacoustic unit from the system that performs the search, and also allows, as already mentioned, to apply cooperative search using a swarm of surface vehicles.

REFERENCES

[1] BEA – Bureau of Enquiry and Analysis for Civil Aviation Safety, “Final report on the accident on 1st June 2009 to the Airbus A330-203”, June 2009, pp. 1–223, 2012

[2] Barmak, Rafael & L S C De Oliveira, André & São Thiago, Pedro & V R Lopes, Marco & Cernicchiaro, Geraldo & dos Santos, Francisco. (2017). Underwater Locator Beacon signal propagation on tropical waters. 10.1109/RIOAcoustics.2017.8349738.

[3] Akyildiz, I.F. and D. Pompili, 2005. Underwater Acoustic sensor Networks: Research Challenges A survey, pp: 257-279

[4] Manjula R.B., Sunilkumar S. Manvi, 2011. Issues in Underwater Acoustic Sensor Networks, International Journal of Computer and Electrical Engineering, Vol.3, No. 1, February, 2011, pp.101-102

[5] Long Cheng, Chengdong Wu, Yunzhou Zhang, Hao Wu,Mengxin Li, Carsten Maple., A Survey of Localization in Wireless Sensor Network. Hindawi Publishing Corporation International Journal of Distributed Sensor Networks Volume 2012, Article ID 962523, 12 pages doi:10.1155/2012/96252

[6] Ravindra S., Jagadeesha S. N., Time of arrival based localisation in wireless sensor networks: a linear approach. Signal & Image Processing : An International Journal (SIPIJ) Vol.4, No.4, August 2013

[7] Chien-Chi Kao, Yi-Shan Lin, Geng-De Wu and Chun-Ju Huang, A Comprehensive Study on the Internet of Underwater Things: Applications, Challenges, and Channel Models. Sensors 2017, 17, 1477, doi:10.3390/s17071477

[8] LaPointe, Cara E. G.. “Virtual Long Baseline (VLBL) Autonomous Underwater Vehicle Navigation Using a Single Transponder.” (2006).

[9] Sarah E Webster, Ryan M Eustice, Hanumant Singh, and Louis L Whitcomb, Advances in single-beacon one-way-travel-time acoustic navigation for underwater vehicles. The International Journal of Robotics Research Vol 31, Issue 8, pp. 935 – 950

[10] JoÃo Saúde, Antonio Pedro Aguiar, Single Beacon Acoustic Navigation for an AUV in the presence of unknown ocean currents, IFAC Proceedings Volumes, Vol. 42, Issue 18, 2009, pp. 298-303, ISSN 1474-6670, ISBN 9783902661517, https://doi.org/10.3182/20090916-3-BR-3001.0057.

[11] K. W. Cheung, H.C. So, W.-K. Ma and Y.T.Chan, (2004) "Least squares algorithms for time-of-arrival based mobile location," IEEE Transactions on Signal Processing, vol.52, no.4, pp.1121-1128.

[12] Abdulmalik S. Yaro, Muazu J. Musa, Salisu Sani, Abdulrazaq Abdulaziz, 3D Position Estimation Performance Evaluation of a Hybrid Two Reference TOA/TDOA Multilateration System Using Minimum Configuration, International Journal of Traffic and Transportation Engineering 2016, 5(4): 96-102

[13] Fatima S. Al Harbi, Hermann J. Helgert. An Improved Chan-Ho Location Algorithm for TDOA Subscriber Position Estimation, IJCSNS International Journal of Computer Science and Network Security, VOL.10 No.9, September 2010

[14] Y. T. Chan, and K. C. Ho, "A simple and efficient estimator for hyperbolic location," Signal Processing, IEEE Transactions on, vol. 42, no. 8, pp. 1905-1915, 1994.

[15] Wei Zhao, Zhenmin Tang, Yuwang Yang, Lei Wang, and Shaohua Lan, "Cooperative Search and Rescue with Artificial Fishes Based on Fish-Swarm Algorithm for Underwater Wireless Sensor Networks," The Scientific World Journal, vol. 2014, Article ID 145306, 10 pages, 2014. https://doi.org/10.1155/2014/145306.

[16] B. T. Champion and M. A. Joordens, "Underwater swarm robotics review," 2015 10th System of Systems Engineering Conference (SoSE), San Antonio, TX, 2015, pp. 111-116. doi: 10.1109/SYSOSE.2015.7151953

[17] J. A. Nelder, R. Mead; A Simplex Method for Function Minimization, The Computer Journal, Volume 7, Issue 4, 1 January 1965, Pages 308–313, https://doi.org/10.1093/comjnl/7.4.308

[18] RedGTR underwater acoustic modem specification, https://github.com/ucnl/Docs/blob/master/EN/Modems/RedGTR/RedGTR_Specification_en.pdf, retrieved on 10 Jan 2019

[19] STM32F429 Cortex-M4 Processor product datasheet www.st.com/resource/en/datasheet/stm32f427vg.pdf, retrieved on 18 Aug 2018

[20] DRF7020D27 27 dBm ISM RF Transceiver Module, Product datasheet, http://dorji.com/docs/data/DRF7020D27.pdf, retrieved on 18 Aug 2018

[21] https://github.com/ucnl/RedGTR_VLBL, retrieved on 18 Aug 2018

[22] Quectel L76 Compact GNSS Modules, Product datasheet, https://www.quectel.com/UploadFile/Product/Quectel_L76_GNSS_Specification_V1.4.pdf

[23] https://github.com/ucnl/RedGTR_VLBL/blob/master/Samples/Tracks/10-07 2018_RedGTR_VLBL_Test_1.kml, retrieved on 18 Aug 2018

[24] https://github.com/ucnl/RedGTR_VLBL/blob/master/Samples/Tracks/10-07-2018_RedGTR_VLBL_Test_2.kml, retrieved on 18 Aug 2018

Authors

Alexander Dikarev

received his M.Eng in Launching equipment of rockets and cosmic apparatus from Volgograd Technical State University, Russia. He has 10 years experience in underwater acoustic comm unication and navigation system design and development: in Research Insitute of Hydroacoustic Communications (Volgograd, Russia), The University Of Manchester (UK), now he is R&D Director in Underwater communication & Navigation laboratory (Moscow, Russia)

Stanislav Dmitriev

received his M.Sc in Radiophysics in Volgograd State University, Russia. He has 10 years of experience in Underwater Acoustic communication & navigation system design & development: in Research Insitute of Hydroacoustic Communications (Volgograd, Russia), now he is Engineering Director in Underwater Communication & Navigation laboratory (Moscow, Russia)

Vitaliy Kubkin

received his M.Eng in Volgograd Technical State University, Russia. He has 10 years of experience in Underwater Acoustic communication & navigation system design & development: in Research Insitute of Hydroacoustic Communications (Volgograd, Russia), now he is Senior Researcher in Underwater Communication & Navigation laboratory (Moscow, Russia)

Andrey Vasilenko

Received his M.Sc in Radiophysics in Volgograd State University, Russia. He has more than 15 years of experience in Underwater Acoustic communication & navigation system design & development: in Research Insitute of Hydroacoustic Communications (Volgograd, Russia), now he is Chief Electronics Engineer in Underwater Communication & Navigation laboratory (Moscow, Russia)