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Experimental Verification of Deep-Water Acoustic Communication Performance Aimed at Positioning of Autonomous Underwater Vehicle

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Abstract: The paper presents the results of the experimental verification of the feasibility of data exchange with a deeply submerged autonomous underwater vehicle (AUV) aimed at its inverse positioning using acoustic communication. The tests were conducted in the equatorial zone of the Indian Ocean near the island of Sumatra in the water area with the average depth of 4700 m. The data obtained are compared with the results of simulation performed for the same conditions.

Keywords: autonomous underwater vehicle (AUV), acoustic communication, sonar modem, underwater vehicle positioning.

1. INTRODUCTION

One of the urgent problems regarding AUVs for various applications is to determine their location at depths greater than 4000 m. AUV underwater position can be determined by different methods [1]:

- autonomous navigation using an inertial navigation system, acoustic log, and echo sounder;
- positioning using bottom responder beacons and passive underwater landmarks;
- positioning using natural geophysical (bathymetric, magnetic, and gravitational) fields.

However, in many situations, for various reasons, the methods mentioned above cannot be applied or do not provide the required positioning accuracy. In these cases, acoustic communication is most helpful since it allows the distance between correspondents to be determined with high accuracy using data exchange between modems. It is also possible to determine the bearing towards to the source using the short baseline (SBL) and ultra-short baseline (USLB) methods [1]. Acoustic positioning data (at least the range information accompanying the signal exchange between hydroacoustic modems) can be combined with autonomous navigation data, which provides the AUV with more reliable and accurate estimates of its location during autonomous underwater operation.

If high-precision georeferencing is required when using acoustic communication, one of the correspondents, in this case the support vessel, shall have such georeferencing.

This paper considers an important example of high-precision AUV inverse positioning capable of providing the approach to a bottom object with known geodetic coordinates using acoustic communication with a correspondent on the sea surface that determines its location using DGPS signals. While the AUV is moving under water, it must be informed of its current coordinates generated by the support vessel using its acoustic modem which, in addition to the transducer, has an USBL antenna (hydrophone array). The fact that the AUV does not determine its location itself, but receives this information via a communication channel from the support vessel, determines the inverse nature of the positioning.

The problem is that in the absolute majority of experimental studies on mutual positioning via acoustic communication, both communication devices were about 10 km apart at comparable depths. We could not find any publications which would consider the case of acoustic communication between correspondents that were several kilometers away from each other vertically, exchanging navigation data and determining mutual slant ranges at the same time. The material closest to this subject-matter was published in [2], however, positioning and acoustic communication were performed separately (using different devices), and the problem of inverse acoustic positioning (estimation of the AUV current location on the support vessel with its immediate return to the AUV via the acoustic modem) was not touched upon at all.

For this reason, the objectives of this work are the following:

- experimental verification of the feasibility of exchanging data with a deeply submerged AUV via acoustic communication in the amount sufficient to solve positioning problems (tens-hundreds of bytes), and, thus, implementing inverse USLB positioning of a deeply submerged AUV;
- testing the possibility of theoretically predicting the quality of acoustic communication.

During the tests, we used the experimental data obtained in the equatorial part of the Indian Ocean within the framework of the European-Indonesian project GETEWS [3]; in which Evologics, Germany, was one of the project participants.

The paper is structured as follows: Section 2 describes the test conditions, Section 3 discusses the simulation results of the acoustic communication, Section 4 presents the data obtained in the experiments, and Section 5 contains conclusions.

2. TEST CONDITIONS

The tests were carried out in the equatorial part of the Indian Ocean near the island of Sumatra at coordinates 00°2.65'S, 096°57.75'E on board the German research vessel Sonne [3].

The ocean depth at the test site was on average 4700 m. The wind speed varied from 5 to 14 m/s. Figure 1 shows the vertical sound speed distribution (VSSD), which is typical for tropical and subtropical regions of the World Ocean. It remains to be studied to what extent the results obtained with digital acoustic communication will change in other, e.g. Arctic, waters with a typical VSSD.

Acoustic communication was provided with the use of Evologics S2CR7/17 modems based on Sweep-Spread Carrier – S2C technology [4]. The modems operated in the frequency range of 7–17 kHz with an effective frequency band of 6.8 kHz. The beam pattern of their transducer is shown in Fig. 2.

One of the modems was located near the sea surface at a depth of 9 m. The other one was attached to the sound speed meter and was smoothly submerged with it on a cable tether from 50 down to 4253 m. One after the other, the modems emitted differentially phase-manipulated signals almost vertically: requests – downwards and responses – upwards. During the dive, the current depth and sound speed, as well as all emitted and received phase-manipulated signals, were periodically archived.

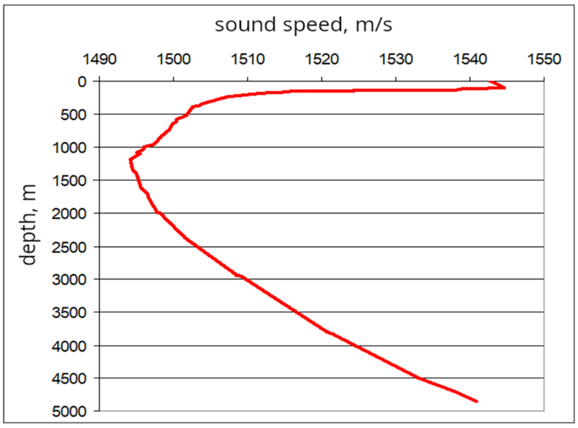


Fig. 1. Vertical sound speed distribution

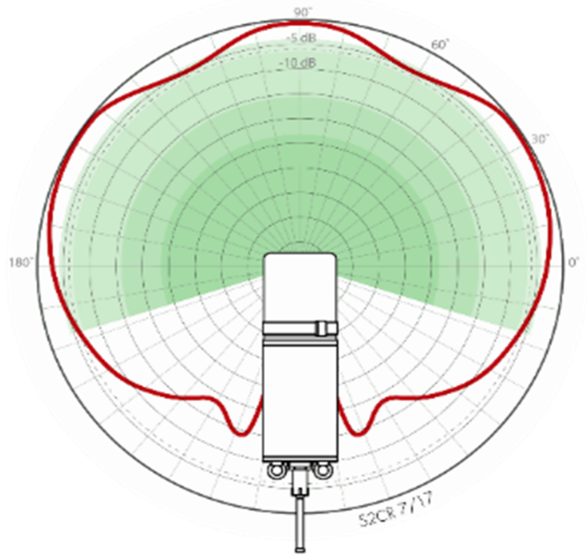


Fig. 2. The beam pattern of the modem transducer in the vertical plane. (The figure is borrowed from the Evologics website)

3. SIMULATION RESULTS

The communication signal transmitted from the source to the receiver was modeled by means of a software package for calculation of the transfer characteristic of the medium [5]; it was a sequence of sync pulses of data symbols (up to 64 bytes). In this case, each of the sync pulses and data symbols contained linearly swept carrier. The volume scattering of propagating signals was modeled using the method presented in [7]. The modelling of the received phase-shift keyed signal with continuous (linear) spectrum spreading was based on the approach in which the model of such a signal was divided into two parts: first, a mathematical model of the received signal consisting of a sum of multipath components at the receiver's predetector point (under the assumption of a ray model of signal propagation), and, second, mathematical model of the volume signal scattering.

It was assumed that volumetric reverberation is caused by multiple reflections of the signal from small scatterers in the water column (a cloud of air bubbles, ship's wake, school of fish, plankton, etc.). In particular, the following assumptions were made:

a) small scatterers are rather dense, therefore, they cannot be neglected for the operating frequencies of the acoustic modem;
b) the duration of the communication signal sync pulse (4 ms) is small, and therefore, the product of the sound speed and the signal duration is less than the cross-section of the scattering surface projection onto the horizontal plane;
c) secondary reverberation is weak and can be neglected.

This allowed the generation of models of data symbol sequence and their processing using the S2C modem emulator.

During the oceanic tests within the GETEWS project, the performance of acoustic communication was directly studied in physical experiments under various conditions. For each experiment, there was an extended description of the environmental parameters, which were used then in the modeling and processing of the received signals in order to obtain numerical results of the application of acoustic communication under the given conditions and compare them with the results of the physical experiments.

The simulation involved the calculation of the communication signal characteristics at the input of the receiving modem, in particular, its level (in dB) and integrity (in the form of a coefficient of correlation with the reference signal). In so doing, we took into account:

- the parameters of the modems (frequency range, transmit power, directional characteristic);
- their relative position, environmental parameters (VSSD, sea noise level, spatial sound attenuation coefficient, coefficients of sound reflection from the bottom and surface).

The level of the emitted communication signal in the 1kHz vicinity of the 12 kHz frequency reduced to 1 m was 185 dB//1 μPa. The level of sea noise reduced to the 1 kHz frequency and a bandwidth of 1 Hz was selected from [6] using the Knudsen curves for the 12 kHz central frequency of the converter and an average wind speed of 9 m/s and was 45 dB//1 μPa. The density of the upper layer of polygenic sediments typical for the test area (red deep-sea clays) was taken to be 1410 kg/m^3, and the sound speed in their upper layer was 1650 m/s, while the reflection coefficient from the bottom was 0.192. The coefficient of reflection from the surface was taken to be 0.999, and the sea noise levels were the same over the entire depth interval of 9–4253 m. The rest of the environment parameters were given above.

Table 1 shows two examples of the multipath structure of the communication signal at the input of the receiving modem at depths of 50 and 4253 m (all rays that arrived at the modem input are indicated taking into account VSSD and the relative positions of the emitting and receiving modems).

Table 1. Characteristics of signal rays at the input of the receiving modem at a depth of 50 and 4253 m (according to the simulation results)

Ray no.	Ray sliding angle at the modem input, deg*	Ray path length, m	Ray path time, s	Number of ray reflections		Ray propagation anomaly, dB**	SNR, dB
				from surface	from bottom		
Depth of the emitting modem – 9 m, depth of the receiving modem – 50 m, horizontal distance between the modems – 50 m							
1	39.33	64.7	0.0419	0	0	–2.2	84.6
2	49.70	77.3	0.0501	1	0	–3.8	81.5
Depth of the emitting modem – 9 m, depth of the receiving modem – 4253 m, horizontal distance between the modems – 750 m							
1	79.83	4309.8	2.8599	0	0	–15.1	29.0
2	79.87	4327.5	2.8714	1	0	–15.1	28.9
3	–82.09	5506.7	3.6395	0	1	–29.6	10.5
4	–82.12	5524.6	3.6511	1	1	–29.7	10.4
5	86.89	13981.7	9.2632	1	1	–37.7	–18.4
6	86.89	13999.7	9.2749	2	1	–37.7	–18.4

** Ray sliding angle is an angle in the vertical plane between the horizon and the direction of ray arrival (with "+" if the ray came from above, and with "–" if it came from below).*

*** Ray propagation anomaly is the ratio of the actual energy of a ray to its energy if it were propagating in a homogeneous, infinite medium with attenuation. The anomaly takes into account the focusing/defocusing of the ray tube and the losses due to reflection of the ray from the boundaries of the waveguide.*

In both cases, the emitting modem was located at a depth of 9 m. It follows from Table 1 that two signal rays with a high signal-to-noise ratio (SNR) arrive at the modem located at a depth of 50 m: one is direct, the other is reflected once from the sea surface. At a depth of 4253 m (i.e. 457 m from the bottom), the number of signal rays that arrived at the modem input increased to six. One of them is direct, the second is reflected once from the surface, the third is reflected once from the bottom, and the fourth is reflected both from the surface and from the bottom. The fifth ray traveled from the emitting modem to the bottom, then to the surface, and then in the opposite direction to the receiving modem. The trajectory of the sixth ray repeated the trajectory of the fifth, except that it was preceded by a reflection from the surface. With an increase in the path length, the SNR naturally decreases.

The relative position of the emitting and receiving modems during the submergence of the latter is given in the first three columns of Table 2.

Table 2. Characteristics of the communication signal at the input of the receiving modem during its submergence (depth of the emitting modem – 9 m)

Depth of the receiving modem, m	Horizontal distance between modems, m	Slope distance between modems, m*	Data rate, bit/s	SNR, dB	SSR, dB	SIR, dB
50	5	50.25	4900	72.5	80	12.32
250	50	254.95	4200	61.0	77	12.61
500	75	505.59	4500	52.0	74	16.15
1000	120	1007.17	4500	43.2	67	13.81
1500	200	1513.27	4500	39.8	60	12.08
2000	300	2022.37	4100	37.5	53	10.53
2500	400	2531.80	4100	35.4	47	7.22
3000	500	3041.38	4100	33.4	41	8.05
3500	600	3551.06	3000	31.5	35	6.70
4000	700	4060.79	3000	29.8	29	5.90
4253	750	4584.76	3000	29.0	24	5.03

**The slant distance was estimated by recalculating the one-way propagation delay of the communication signal through the vertical section of the sound speed in the corresponding depth interval, while the two-way propagation delay was defined as the time interval between the start of emission (i.e., emission of a sync pulse) with an accuracy of 2 μs (half the sampling time) and the time of the sync pulse reception of the response signal (also with an accuracy of 2 μs). The fixed processing time of the signal received by the responding modem was taken into account when estimating the two-way propagation delay of the signal in water. The one-way propagation delay was defined as half the two-way propagation delay. To ensure high accuracy of the emission time and precise estimation the sync pulse reception time, the modem was equipped with an interlevel interface, which allowed taking into account the shifts in the operating time of the physical and logical levels, in particular the shifts in the clock of the receiving-emitting path in relation to the computer clock (owing to such an interface and the corresponding acknowledgement, the computer always had at its disposal actual time keeping of signal emission into water and detection of the response signal sync pulse).*

The ray structure of the signal at the input of the receiving modem was taken into account in the following calculations:

- SNR, i.e., the ratio of the total energy of the communication signal to the energy of sea noise (Table 2, column 5). Note that at all depths of the receiving modem, the SNR exceeded 29 dB;
- signal-to-scattering ratio (SSR), i.e., the ratio of the energy of the communication signal arriving via coherent rays to the energy of the communication signal scattered by inhomogeneities in the propagation medium [7] (Table 2, column 6);
- signal-to-interference ratio (SIR), i.e., the ratio of the energy of the most energy-intensive signal ray to the total energy of all interference, including the remaining signal rays (Table 2, column 7).

Models of communication signals at the input of the receiving modem, formed with due regard for their ray structure, as well as SNR, SSR and SIR, were used to estimate the efficiency of communication by means of S2CR7/17 modems. In particular, the following calculations were performed within this study:

• phase scattering diagrams illustrating the interference effect on the informative parameter (phase difference between adjacent data symbols) (Fig. 3);

• data transfer rates that ensure reliable communication (the error in identification of 1 bit of the message did not exceed 10^{-2}), and this value was determined by the applied algorithm of forward error correction coding based on the BCH method with a 30% code redundancy. The simulation has shown that the messages with a bit error of less than 10^{-2} were received at a data transfer rate of 4900 bit/s at depths of 9–200 m; 4100 bit/s at depths of 200–300 m; 4500 bit/s at depths of 300–800 m; 4100 bit/s at depths of 1800–3400 m; and 3000 bit/s at depths of 3400–4253 m. The above data transfer rates represent idealized values, i.e. the coding rate of the bit stream on the interval of data packet transmission as part of a communication signal. Since, in addition to the data packet, the communication signal also contains 2 sync pulses and a header with service data, the effective data transfer rate (bit stream rate in the user interface) is always lower than the idealized one. Depending on the ratio between the lengths of the payload data section and the service data section and taking into account the time overhead for emission of the sync-pulses, the effective data transfer rate can decrease by 15–30% compared to the idealized one. In scenarios that assume the need for acknowledgement of the delivered data, the effective rate also depends on the distance between the interacting modems and the number of redelivered (damaged) data packets. Usually, during a two-way exchange with acknowledgement in the environmental tasks of practical interest, the effective data transfer rates are within 30–50% of the idealized rate.

It is important to note that the models do not take into account dynamic changes in the environmental parameters and, as a consequence, changes in the channel pulse response.

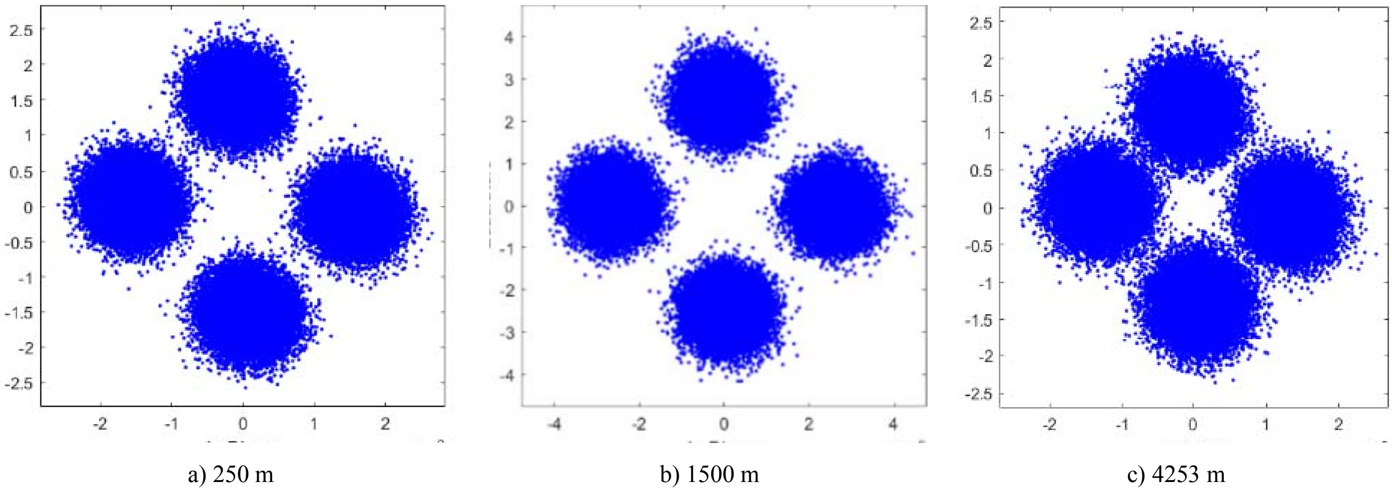


Fig. 3. Phase scattering diagrams of signals at different depths calculated for 10 000 symbols (the abscissa and ordinate axes show the phase differences between adjacent message/data symbols in radians).

4. RESULTS OF THE EXPERIMENTS

The experiments consisted in alternate data exchange between two modems, one of which was fixed stationary at a depth of 9 m, and the second, attached to a sound speed meter, was smoothly submerged together with it on a cable tether from 50 to 4253 m. The transmitted signal with a duration of 0.5 s included:

• a pulse providing adjustments of the automatic gain control unit of the receiving modem;

• two sync signals;

• a block of transmitted differentially phase-manipulated symbols of the payload data.

During the submersion, the current depth and sound speed on the horizon of the submerging modem, as well as all communication signals transmitted and received by both modems, were periodically archived.

During the experiments, the algorithms implemented in the receiving modem constantly adjusted the data transfer rate depending on the changing pulse response of the hydroacoustic channel, measured using a sync signal, so that the transmitted data could reach the destination with a bit error of less than 10^{-2}. To match the data transfer rates, the modems exchanged compact pulse response metrics, including them in the header section of the communication signal during each exchange.

During the data exchange, the modems also collected so-called debugging data, containing estimates of the phase and amplitude of the received signal.

Figure 4 compares the data transfer rates with a bit error of 10^{-2} obtained as a result of the simulation and experiment.

Figure 5 shows scatter diagrams for different depths containing phase and amplitude estimates. It is important to note that the scatter plots corresponding to shallow and extreme depths show a larger spread than the scatter plot corresponding to the intermediate depth. A similar result was obtained in the simulation (Fig. 3).

The data recorded during the experiments allowed us to estimate how close the model and experimental results were. Figure 6 shows the signal recorded by the upper modem during the reception of data from the lower one, transmitting them from the maximum depth of 4253 m.

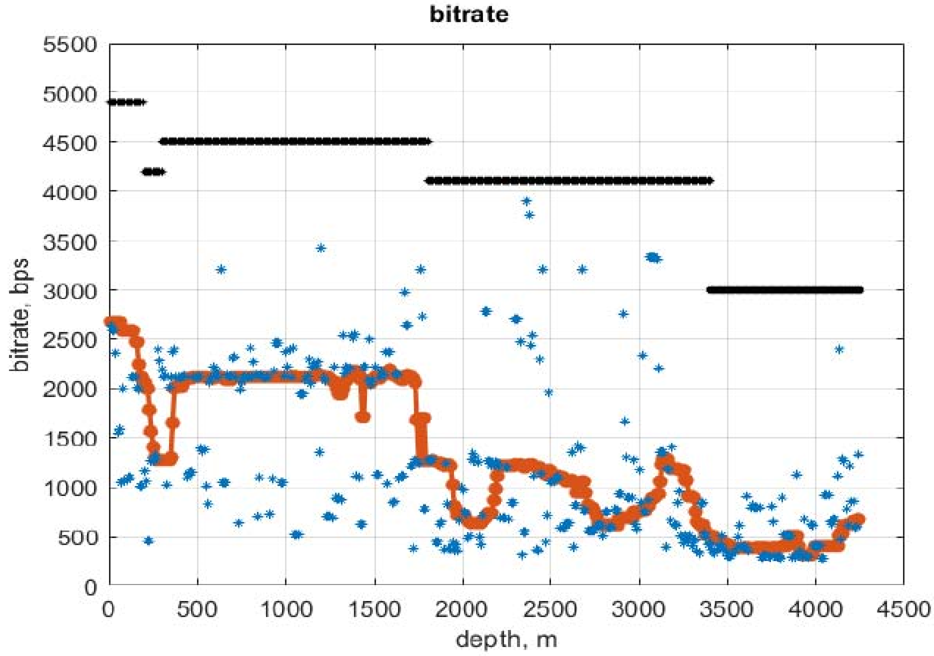
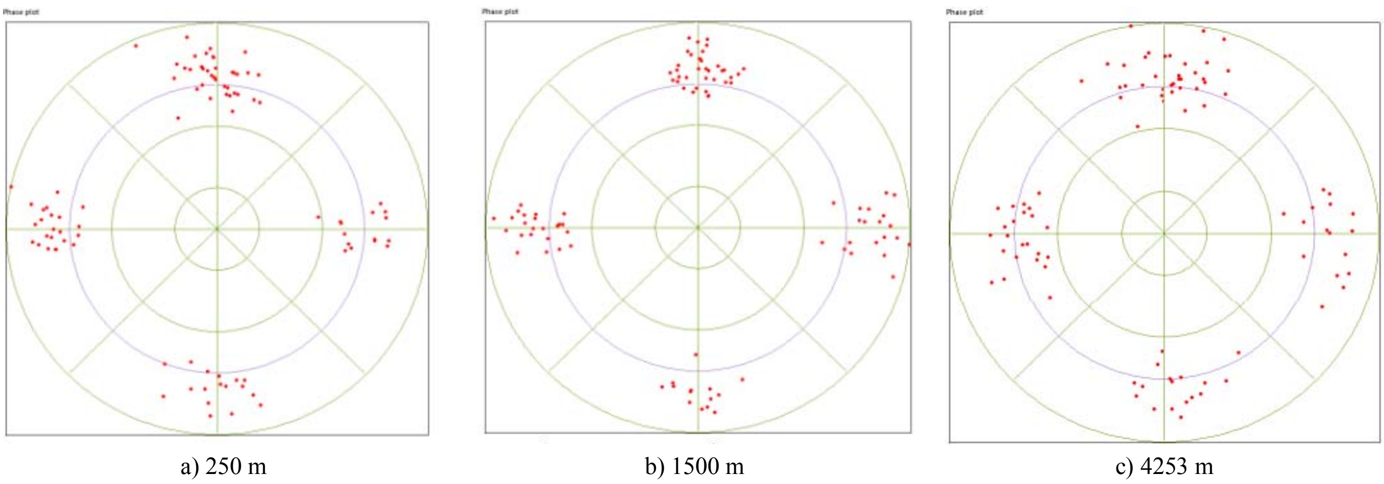


Fig. 4. Comparison of data transfer rates with a bit error of 10^{-2} obtained as a result of simulation (horizontal lines in black) and experiment (blue markers, average values are indicated by a red line).



a) 250 m b) 1500 m c) 4253 m

Fig. 5. Phase scatter diagrams of signals at different depths calculated for 10 000 symbols (the abscissa and ordinate axes show the phase differences between adjacent data symbols in radians).

Since the signal in Fig. 6 preceding the first pulse represents ambient noise (a mixture of sea and ship noise), the signal following the block of the transmitted symbols includes a mixture of ambient noise and reverberation caused by multipath propagation of the communication signal. This makes it easy to calculate the SNR and SIR; they were 14.4 and 6.35 dB, respectively. In Fig. 6, the abscissa axis is calibrated, with the readings following at 4 μs intervals.

Figure 7 shows a fragment of a signal similar to the one presented in Fig. 6, but at the correlator output. To demonstrate in detail the acoustic activity accompanying the signal reception, we chose a short time interval to accommodate a pair of sync pulses by which the receiving modem estimates the pulse characteristic of the signal propagation medium and uses it in processing the data packets following these pairs. For convenience of examining this short interval, we chose a much smaller time scale than in Fig. 6.

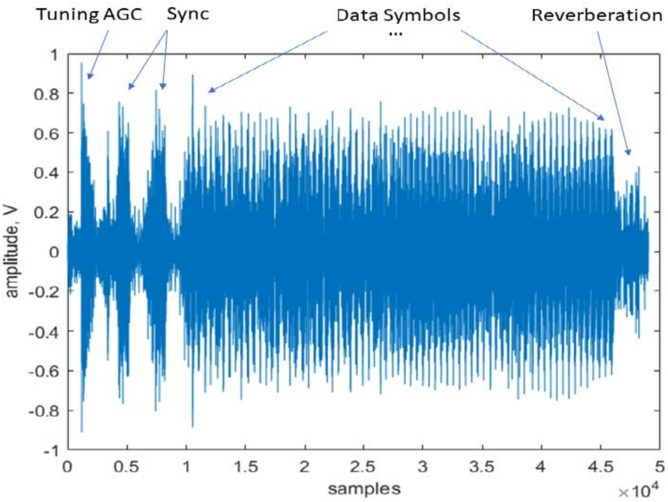


Fig. 6. Communication signal received by the upper modem when receiving data from the lower modem at a depth of 4253 m.

In Fig. 7, the abscissa axis is also calibrated, with the readings following at 4 μs intervals. It can be seen that in addition to the signal that arrived along the most energy-intensive ray, a number of other signals arrive at the receiver due to multipath propagation of the communication signal. The largest of them is apparently a reflection from the surface. The ratio between the dominant and the other signals is 10.7 dB.

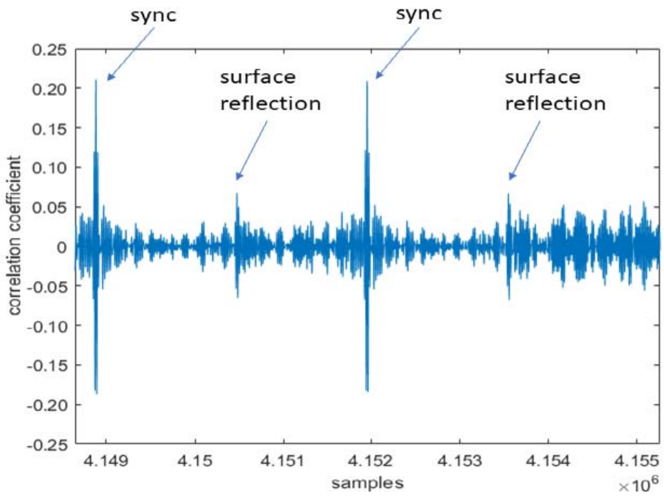


Fig. 7. Communication signal received by the upper modem when receiving data from the lower modem at a depth of 4253 m.

5. CONCLUSIONS

1. The feasibility of implementing acoustic communication between a surface vessel and a deeply submerged underwater vehicle for exchanging data packets from tens to hundreds of bytes in size, sufficient to deliver navigation information, for example, in the tasks of AUV inverse USBL positioning, has been experimentally confirmed.
2. In the experiment, the propagation of a communication signal between two modems on the surface and at depth was carried out at an angle of 10º from the vertical. Since during inverse positioning, they will be located on a straight line close to the vertical in order to minimize the distance between the modems, the obtained experimental and simulation results can be extended to these conditions before obtaining new results under other conditions.
3. The theoretical model allows the SIR to be calculated with an error not exceeding 3.5 dB. At the same time, the minimum error of 1.3 dB corresponds to the maximum vertical distance between the modems.
4. The theoretical model shows an overestimated data transfer rate compared to the physical experiment. It is noteworthy that the discrepancy in speeds significantly depends on the depth of signal transmission: the greatest difference is observed for the minimum and maximum vertical distances between the modems with good correspondence of speeds at medium depths. This fact requires additional research. At the moment, to obtain the actual data transfer rate, the calculated value must be multiplied by 0.3–0.5 depending on the depth range.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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