УДК 681.883.77

© *А. Д. Консон*[1]*, *А. А. Волкова*[1]

© Перевод: *Е. С. Кочеткова*, 2021

[1]АО «Концерн «Океанприбор», 197376, Чкаловский пр., д. 46, г. Санкт-Петербург, Россия
*E-mail: adkonson@gmail.com

ВЛИЯНИЕ СВЕРХМЕДЛЕННЫХ ФЛУКТУАЦИЙ СИГНАЛА НА ПОМЕХОУСТОЙЧИВОСТЬ ШУМОПЕЛЕНГОВАНИЯ

Статья поступила в редакцию 07.12.2020, после исправления 22.10.2020

На основе лабораторного анализа и обработки случайной выборки натурных записей шумов надводных кораблей, произведенных в акваториях Белого, Баренцева и Норвежского морей проведено исследование влияния сверхмедленных флуктуаций сигнала на помехоустойчивость шумопеленгования. Экспериментально установлено, что в условиях флуктуаций можно обеспечить потенциально высокую помехоустойчивость, если использовать одновременно два времени накопления: малое – несколько секунд и большое – до ста и более секунд. При этом большое время накопления снижает вероятность потери контакта в период флуктуационного снижения уровня сигнала, а малое время накопления может дать существенный выигрыш в дальности обнаружения в интервалы времени, когда процесс флуктуации приводит к кратковременному возрастанию уровня сигнала.

Ключевые слова: гидроакустика, шумопеленгование, помехоустойчивость, сверхмедленные флуктуации сигнала.

© *A. D. Konson*[1]*, *A. A. Volkova*[1]

© Translation: *E. S. Kochetkova*, 2021

[1]JSC “Concern “Oceanpribor”, 197376, Chkalovsky Pr., 46, St. Petersburg, Russia
*E-mail: adkonson@gmail.com

INFLUENCE OF SUPERSLOW SIGNAL FLUCTUATIONS ON THE NOISE STABILITY OF PASSIVE LISTENING

Received 07.12.2020, in final form 22.10.2020

Laboratory analysis and random sample processing of field records of surface ships noise collected in the waters of the White, Barents, and Norwegian Seas were used in the study of ultra-slow signal fluctuations’ influence on the passive listening noise stability. Experiments show that signal fluctuations enable a potentially high noise stability when a short accumulation time interval (a few seconds) and a long accumulation time interval (one hundred and more seconds) are used simultaneously. A long accumulation time reduces the likelihood of contact loss during a decrease in the signal level. A short accumulation time can provide significant gain in the detection range during periods when the fluctuation process leads to a short-term increase in the signal level.

Key words: hydroacoustics, passive listening, noise stability, superslow signal fluctuations.

1. Introduction

Several studies note that when considering the issues of noise stability of passive listening systems, it is necessary to account for physical phenomena that have a random nature in an actual environment and affect the statistical properties of a noise signal [1, 2]. When studying hydrophysical processes in the ocean, stochastic models give an adequate description of physical phenomena. However, there is always a possibility of “hyper-random phenomena” in the terminology of [2]. The study [1] proposes to estimate a signal’s gain decrease associated with the influence of random factors as a “deterioration factor”, which is determined by the ratio of the actual noise stability to the expected. Henceforth, by noise stability, we mean the output signal-to-noise ratio (S/N).

Ссылка для цитирования: *Консон А.Д.*, *Волкова А.А.* Влияние сверхмедленных флуктуаций сигнала на помехоустойчивость шумопеленгования // Фундаментальная и прикладная гидрофизика. 2021. Т. 14, № 3. С. 58—64. doi: 10.7868/S2073667321030059

For citation: *Konson A.D.*, *Volkova A.A.* Influence of Superslow Signal Fluctuations on the Noise Stability of Passive Listening. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2021, 14, 3, 58—64. doi: 10.7868/S2073667321030059

The superslow fluctuations were registered by the authors in the field studies of the spectral-energy characteristics of surface ships' noise signals in the Barents, White and Norwegian Seas [3, 4]. The results showed that superslow signal fluctuations, as a rule, have a period of more than 20 sec and, accordingly, are in the frequency band up to 0.05 Hz. Another noise signal feature of a surface ship (swell conditions) is the periodic amplitude fluctuations caused by rolling [5, 6]. The noise fluctuations' frequency range, in this case, is close to the frequency range of the swell spectrum of the ship and extends to 0.5 Hz.

In passive listening, the time accumulation procedure permits isolation of the signal against the background of noise interference [7, 8]. According to the classical stochastic model of noise interference, the duration of accumulation reduces its fluctuation due to the proportional number of uncorrelated samples during the accumulation interval, which determines the choice of the threshold on the solver to ensure the specified detection efficiency. Therefore, the accumulation time is usually chosen in the range from units to several tens of seconds. Here, accounting for collected experimental data [3—6], the property of a noise signal to have energetically significant random fluctuations with a frequency range of up to 0.5 Hz, i. e. with a minimum period of more than 2 sec, cannot be ignored. Since the process of signal fluctuations and the accumulation procedure are in the same frequency-time range, the revealed properties of the noise signal should be taken as an additional condition when solving the problem of signal detection against the background noise.

The goals of this study are to estimate the influence of the signal accumulation time choice on passive listening noise stability with superslow signal fluctuations and to determine the conditions for its increase based on the analysis of experimental material (records of actual surface ships' noises). Evaluation of noise stability is based on the S/N level, which describes a system's ability to detect a target with a particular signal level at a specific distance from the antenna, depending on the accumulation time.

2. Field data collection and processing methods

This study involved laboratory analysis of acoustic signals from surface ships of diverse displacement and hydrological and acoustic conditions in the Barents, White and Norwegian Seas. Laboratory studies included a computer simulation of the signal processing channel using the MATLAB software package. A developed program code read the audio file with experimental data, carried the necessary digital processing of information, and visualized the results.

Input data for laboratory processing consisted of field recordings of acoustic signals collected by the information conservation equipment of the hydroacoustic complex [9]. The conditions for conducting field recordings are similar to [3, 4] and presented in Table 1. The sea surface swell in all cases did not exceed three to four degrees.

Recording in the direction to each ship was executed by dividing the working aperture window of the antenna into two halves, each of which was compensated in the direction to the ship. Thus, we obtained synchronous temporal realizations of the sound pressure a(m) and b(m) from two halves of the antenna. Thus, independent realizations for the signal, and the interference power, were obtained with further processing using the sum-difference scheme [10] (Fig. 1).

The circuits processing shown in Fig. 1 was carried out as follows:

1) files of records with a sampling frequency of $f_{\text{д}} = 16$ к kHz ($\Delta t_{\text{д}} = 0.0000625$ s), duration up to 30 min, containing digitized synchronous time realizations of sound pressure $a(m)$ and $b(m)$, obtained from two halves of the antenna, were fed to the input of the processing algorithm;

2) sequential formation of neighboring samples with a length of $N = 1024$ samples was carried out, which corresponds to a time interval of 0.064 s;

3) the sum and difference processing channels were created, at the input of which, respectively, a sample of the sum process $x(n)$ and a sample of the difference process $y(n)$ were fed;

Table 1

Field conditions

Experiment №	Hydrological and acoustic conditions	Displacement of the ship, tons	Distance to ship, km	Recording duration, min
1	Barents Sea, October	2500	3—5	22
2	Norwegian Sea, December	25 000	5—10	29
3	Norwegian Sea, December	25 000	20—40	28
4	White Sea, June	5000	5—7	30

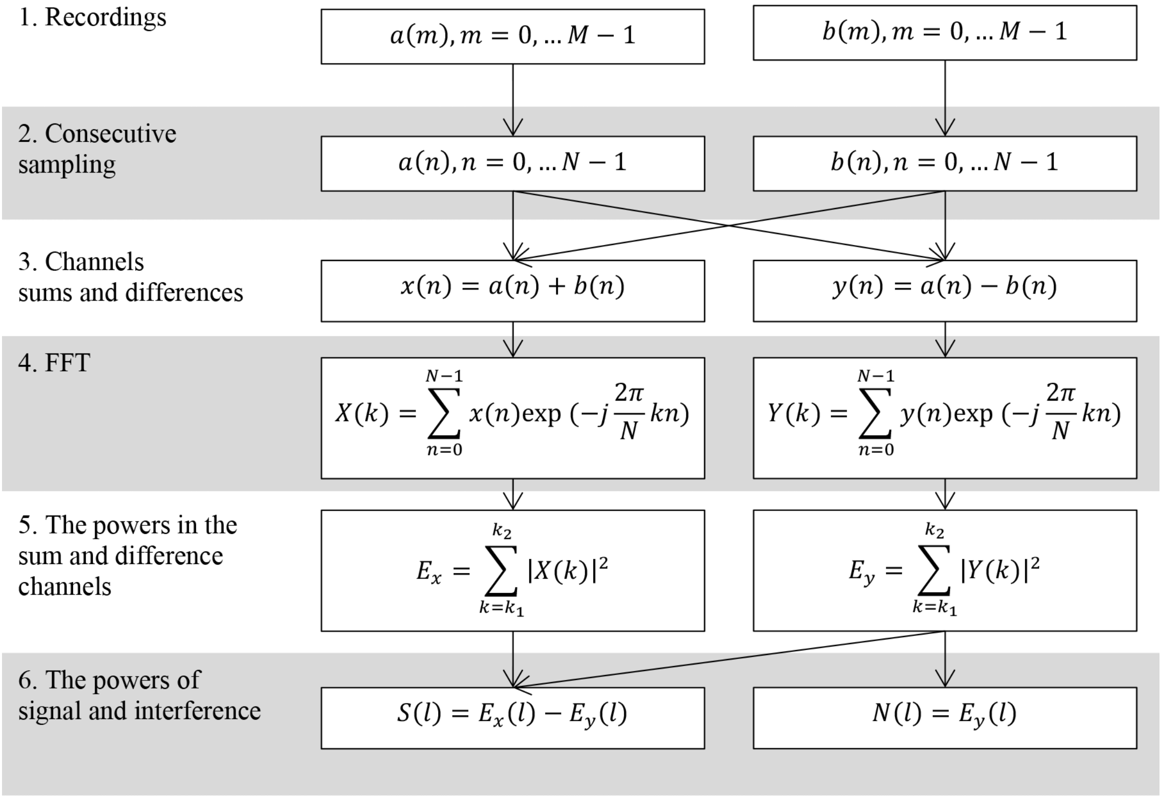

Fig. 1. Block diagram of the algorithm for calculating time realizations of changes in signal power and interference power.

4) or each sequential sample, the fast Fourier transform (FFT) procedure was carried out to obtain complex Fourier spectra of processes in the sum channel $X(k)$ and the difference channel $Y(k)$;

5) the powers of the processes in the channel of the sum E_x and the channel of the difference E_y was determined within the boundaries of the specified frequency range;

6) sequential samples of discrete values of time realizations of the signal power $S(l)$ and the interference power $N(l)$.

At the output of processing records according to the scheme in Fig. 1, we have discrete values of time realizations of the signal power $S(l)$ and the interference power $N(l)$ with a sampling interval $\Delta t_2 = 0.064$ s and up to 30 min duration.

3. Methodology and results of the research

To estimate the current values of the signal power $S(t)$, the interference power $N(t)$ and S/N $Q_i(t)$ at different time intervals, samples of time-series with a duration of T_i seconds (where $i = 1, 2, 3$ is a number of the used accumulation time), within which the processes' accumulation occurred.

The S/N in each sample was obtained with the equation:

$$Q_i(t) = \frac{\frac{1}{T_i}\int_0^{T_i} \tilde{S}(\tau)\,d\tau}{\frac{1}{T_i}\int_0^{T_i} N(\tau)\,d\tau}, \qquad (1)$$

where T_i is a variable time of accumulation $T_1 = 2$, $T_2 = 16$, $T_3 = 128$ s.

Based on work [8], the S/N at the output of the direction-finder for our case can be expressed in the form:

$$Q_i(t,z) = \psi(t,T_i)F(t)\Phi(z)T_i, \qquad (2)$$

where $\psi(t,T_i)$ describes the process of random fluctuations of the signal at the chosen accumulation time: T_i;

$F(t)$ –is a function describing the S/N at the input of the direction finder in the absence of signal fluctuations;

$\Phi(z)$ – is a function that describes the influence of the parameters z of the noise direction-finder on the output S/N;

z – parameters of the antenna and the frequency filter of the sound direction-finder;

T_i – accumulation time.

As can be seen from (2), the expected value of the output SIR should increase with increasing accumulation time, which is consistent with the classical theory of signal detection.

Let us consider the experimentally obtained change in the *S*/*N* for different accumulation times T_i.

First, the effect of accumulation on fluctuations was estimated separately for signal and noise. Figure 2 shows the changes in the interference power, and Fig. 3 presents variations in the signal power during the observation time at different accumulation times in one of the experiments (record No. 3). For the convenience of the analysis, when producing figures (Fig. 2, 3, see Inset), the signal and interference powers were normalized to their average values in realizations. A significant decrease in signal fluctuations and noise with an increase in the accumulation time was observed for all experiments.

In our experiments (the analysis of field recordings of the signal), the recording duration $t_{\max}$ (>20 min) significantly exceeded the interval (period) of the slowest variation of the signal and noise power (<1 min) for the selected accumulation times T_i. Then, for each experiment *j* a constant average value of the *S*/*N* $Q_i(t)$, obtained for any (three different) accumulation times is justified:

$$\frac{1}{t_{\max}} \int_0^{t_{\max}} Q_i(t)\,dt = C_j \approx \text{const}. \tag{3}$$

This is viable because the accumulation and averaging procedures are linear. This is indicated by the calculation results given in Table 2.

Transformation (2) provides a transition to a relative parameter, which will allow comparing the estimates of noise stability at different values of the accumulation time T_i. For comparative studies, similarly to [1] that introduced a “deterioration factor”, we can use a parameter that allows considering the set of time dependences of the output *S*/*N* at different accumulation times during the observation ($T_{\max} >> T_i$) in one experiment *j*:

$$\gamma(t) = \frac{Q_i(t)}{C_j}. \tag{4}$$

Figure 4 shows an example of the presentation of experiment No. 3 through the parameter γ. A significant change in the parameter $\gamma(t)$ depending on the accumulation time T_i is apparent. Similarly, with a decrease in the value of T_i the parameter $\gamma(t)$ variations increase.

To obtain reliable results, the experiments were carried out at sufficiently strong *S*/*N* (antenna output about 2). Finally, note that the processes in Fig. 3 and 4 are similar due to the weak influence of noise fluctuations on the last result (Fig. 4, see Inset), which confirms the validity of assumption (3).

Based on the experimentally obtained values of the parameter $\gamma(t)$, we proceed to assess the influence of superslow signal fluctuations on the detection process at different values of the accumulation times T_i. To do this, we introduce several assumptions that simplify the analysis, which will not fundamentally affect the research result. Thus, in our experiments, the average cylindrical law of signal propagation can be adopted.

Therefore, in the absence of signal fluctuations, its level at the receiver input can be determined in our case as P/r, where P is the radiation signal level, r is the distance to the source, which is considered relatively constant over the observation time $t_{\max}$. Having accepted the above assumptions as valid, the parameter C_j according to (3) is expressed through the value of the signal level at the receiver input in the absence of signal fluctuations and a weak influence of interference fluctuations in the form:

$$C_j = k_j \frac{P}{r}, \tag{5}$$

where k_j is a proportionality factor for experiment *j*.

Table 2

Average values of *S*/*N* in experiments

Accumulation time T_i, s	Experiment number *j*			
	1	2	3	4
2	1.86	2.72	1.49	1.65
16	1.86	2.73	1.49	1.66
128	1.90	2.80	1.46	1.72

Hence, according to (4) and (5), for the parameter γ:

$$\gamma(t)=\frac{Q_i(t)}{k_j}\frac{r}{P}, \tag{6}$$

Thus, the parameter $\gamma(t)$ shows the change in noise stability during observation at the selected accumulation time T_i relative to the possible noise stability in the absence of superslow signal fluctuations.

At each observation point of each experiment, different values of the parameter $\gamma(t)$ at various accumulation times can be interpreted as a change in noise stability when changing the system parameters. In addition, the noise stability through the parameter $\gamma(t)$ can be estimated as a change in the detection distance r at a fixed signal level $P=\text{const}$ and the accepted detection threshold specified through the value of the *S/N* $Q=Q_{por}$. To demonstrate it consider two accumulation times T_1 and T_2. The observed $\gamma(T_1) < \gamma(T_2)$, through (6) result in $r_1 < r_2$. As a result, we find that the noise stability of the system at the accumulation time T_2 is higher than at T_1.

High values of the parameter $\gamma(t)$ indicate a high noise stability of the system. To evaluate the change in the noise stability of the system at different accumulation times in each experiment integrally, we will proceed as follows.

Consider for each accumulation T_i the total observation time t_i for those periods when the noise stability, expressed in terms of the value of the parameter γ, is equal or above a certain threshold value $\gamma > \gamma_{por}$. Next, we define the relative duration of observation ΔT of the event $\gamma > \gamma_{por}$ as the ratio of t_i to the entire observation time $t_{\max}$: $\Delta T_i = {}^{t_i}\!/_{t_{\max}}$. The value of the parameter ΔT_i depending on γ_{por}, is reasonable consider as the final indicator of relative noise stability in the observation process when using the accumulation T_i. Then we can analyze the relative capabilities of the system to solve the detection problem with different values of the parameter T_i. Having $\Delta T(T_2) > \Delta T(T_1)$, we obtain that the noise stability of the system in the experiment with the accumulation of T_2 is higher than with T_1.

The results for all experiments are presented in Figure 5. The graphs show how the total observation time changes under the same conditions for different accumulation time T_i with a change of the parameter γ_{por}. As expected, with a decrease in the γ_{por} threshold, the observation time increases.

Following the goals of our research, we analyze the influence of the accumulation time T_i choice on the noise stability of a passive listening system in the presence of superslow signal fluctuations using the ratio of the values ΔT_i in the selected parameter γ_{por} ranges.

In Figure 5, according to the adopted model:

– the region $\gamma_{por} \approx 1$ corresponds to the conditions of detection, when the value of Q_{por} is close to the average value of the *S/N* Q_i, which corresponds to the conditions of the absence of fluctuations;

– the region $\gamma_{por} < 1$ corresponds to the conditions of detection at small distances, when a drop in the signal level during the fluctuation is permissible;

– the region $\gamma_{por} > 1$ corresponds to the conditions of detection at large distances, when the signal level increases in the process of fluctuations.

Then, in the presented figures, an important pattern is apparent. At small detection distances, when $\gamma_{por} < 1$, a target can be observed consistently for a long time, and an increase in the accumulation time leads to an increase in noise stability. Observing $\Delta T(T_{128}) > \Delta T(T_{16}) > \Delta T(T_2)$ which corresponds to the observation conditions when in the process of fluctuations, the signal level drops relative to the possible average value in the absence of fluctuations. It becomes apparent how fluctuations in the direction of decreasing the signal level reduce the detection distance relative to the conditions for the fluctuations' absence. Thus, comparing to the case of $\gamma_{por} = 1$, which corresponds to the conditions for the absence of fluctuations, a decrease in the signal level due to fluctuations leads to a reduction of the target detections distance 2—3 times compared to the potential (as can be seen in the graphs).

Another feature is observed at $\gamma_{por} > 1$, which corresponds to large detection distances. Then, a significant gain in the detection distance (up to 1.5 or 2 times) relative to the conditions for the absence of fluctuations can be obtained with a decrease in the accumulation time, as indicated by the relation $\Delta T(T_{128}) < \Delta T(T_{16}) < \Delta T(T_2)$. This happens when the fluctuation process leads to large values of the signal level. In this case, the total observation time under these conditions will hardly exceed 20—30 % of the potentially possible observation time in the absence of fluctuations. Experiment No. 1 is indicative, when, to ensure the highest noise immunity under conditions of signal fluctuations, both short and long accumulation times should be used simultaneously. In this case, the observation time will be 50 % for each of the two extreme values of the accumulation time, at once, in favor of a short accumulation time – for the maximum detection range.

The use of two accumulation times for signal detection under conditions of slow fluctuations has a simple physical interpretation. Long accumulation times allow the negative peaks of the signal to be averaged with higher values, thereby raising the signal level under these conditions. The short accumulation time allows the use of short-term large increases of signal fluctuations, without averaging them with lower values of the signal level.

4. Conclusion

The processing results of the representative experiments in three seas for various targets showed a significant effect of superslow signal fluctuations on the noise stability of passive listening.

It was found that, under conditions of superslow signal fluctuations, it is possible to provide a potentially high noise stability if the accumulation time is chosen correctly.

It was experimentally established that, in the presence of fluctuations, it is possible to provide a potentially high noise stability if two accumulation times are used simultaneously: a short one within a few seconds and a long one covering up to one hundred or more seconds. At the same time, a long accumulation time is effective when the signal level drops. A significant gain in the detection range can be obtained at times when the fluctuation process leads to a large signal level; for this, a short accumulation time should be used.

5. Funding

The work was carried out at the expense of the Fund for Scientific and Technical development of JSC “Concern” Oceanpribor”.

Литература

1. *Лаваль Р.*, *Лабаск И.* Влияние неоднородностей и нестабильности среды на пространственную и временную обработку сигналов // Подводная акустика и обработка сигналов / под ред. Л. Бьёрнё. М. : Мир, 1985. С. 43—68.
2. *Горбань И.И.* Обработка гидроакустических сигналов в сложных динамических условиях. Киев. : Наукова думка. 2008. 276 с.
3. *Волкова А.А.*, *Консон А.Д.* Натурные исследования сверхмедленных флуктуаций шумового сигнала надводного корабля // Гидроакустика. 2017. № 30(2). С. 52—59.
4. *Волкова А.А.*, *Консон А.Д.* Спектральные свойства флуктуаций подводного шумоизлучения морских судов // Труды XIV Всероссийской конференции «Прикладные технологии гидроакустики и гидрофизики». СПб. : ЛЕМА, 2018. С. 427—429.
5. *Консон А.Д.*, *Волкова А.А.* Обнаружение амплитудной модуляции подводного шумоизлучения морских судов при качке на фоне сверхнизкочастотных флуктуаций // Фундаментальная и прикладная гидрофизика. 2019. Т. 12, № 2. С. 12—19. doi: 10.7868/S2073667319020023
6. *Кудрявцев А.А.*, *Лугинец К.П.*, *Машошин А.И.* Об амплитудной модуляции подводного шума морских объектов // Акустический журнал. 2003. Т. 49, № 2. С. 224—228.
7. *Гаткин Н.Г.* и др. Помехоустойчивость типового тракта обнаружения. Киев : Техніка, 1971. 202 с.
8. *Зарайский В.А.*, *Тюрин А.М.* Теория гидролокации. Л. : Военно-морская ордена Ленина и Ушакова академия, 1975. 605 с.
9. *Антипов В.А.*, *Макарчук Ю.И.*, *Обчинец О.Г.*, *Охрименко С.Н.*, *Сергеева Н.П.* Консервация информации гидроакустического комплекса (ГАК) корабля и ее дальнейшее использование // Гидроакустика. 2015. № 22(2). С. 93—97.
10. *Афанасьев А.Н.*, *Знаменская Т.К.* Способ классификации гидроакустических сигналов шумоизлучения морского объекта / Патент РФ № 2546851. Опубликовано 10.04.2015. Бюл. № 10. МПК G01S3/80.

References

1. *Loval’ R.*, *Labask I.* Influence of inhomogeneities and instability of the environment on spatial and temporal processing. *Underwater Acoustics and Signal Processing* / Ed. by L. Bjorno, *M.*, *Mir.* 1985. C. 43—68 (in Russian).
2. *Gorban’ I.I.* Processing of hydroacoustic signals in complex dynamic conditions. *Kiyev*, *Naukova dumka*, 2008. 276 p. (in Russian).
3. *Volkova A.A.*, *Konson A.D.* Field observations of superslow fluctuations of noise signal of surface ship. *Hydroacoustics*. 2017, 30(2), 52—59 (in Russian).

4. *Volkova A.A.*, *Konson A.D.* Spectral properties of underwater noise emission fluctuations of sea vessels. *Proceedings of XIV all-Russian Conference «Advanced Technologies of Hydroacoustics and Hydrophysics»*. *St. Petersburg*, 2018. P. 427—429 (in Russian).
5. *Konson A.D.*, *Volkova A.A.* Detection of amplitude modulation of sea vessel underwater noise emission at rolling and pitching at background of ultralow frequency fluctuations. *Fundam. Prikl. Gidrofiz.* 2019, 12, 2, 12—19 (in Russian). doi: 10.7868/S2073667319020023
6. *Kudryavtsev A.A.*, *Luginets K.P.*, *Mashoshin A.I.* Amplitude modulation of underwater noise produced by seagoing vessels. *Akust. Zh.* 2003, 49, 2, 184—188. doi: 10.1134/1.1560380
7. *Gatkin N.G.* et al. The immunity of the standard tract detection. *K.*, *Tekhnika*, 1971, 202 p. (in Russian).
8. *Zarayskiy V.A.*, *Tyurin A.M.* Sonar theory. *Leningrad*, *Naval Academy of the order of Lenin and Ushakov*, 1975, 605 p. (in Russian).
9. *Antipov V.A.*, *Makarchuk J.I.*, *Obchinets O.G.*, *Ohrimenko S.N.*, *Sergeeva N.P.* Preservation of ship integrated sonar system information (ISS) and its further use. *Hydroacoustics*. 2015, 22(2), 93—97 (in Russian).
10. *Afanas'ev A.N.*, *Znamenskaja T.K.* Method of classification of hydroacoustic signals of sea object noise emission. *Invention RU* № 2546851. Date of publication 10.04.2015. Bull. № 10. Int.Cl. G01S3/80.

К статье *Консон А.Д., Волкова А.А.* Влияние сверхмедленных флуктуаций сигнала на помехоустойчивость шумопеленгования

Konson A.D., Volkova A.A. Influence of superslow signal fluctuations on the noise stability of passive listening

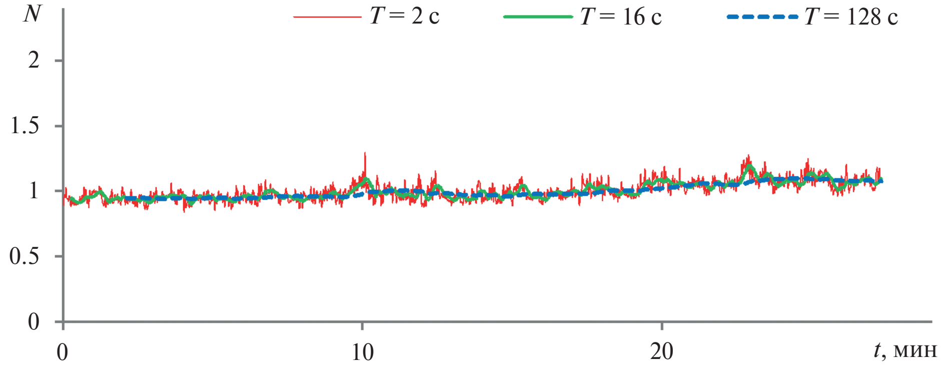

Fig. 2. Interference power (normalized to mean value).

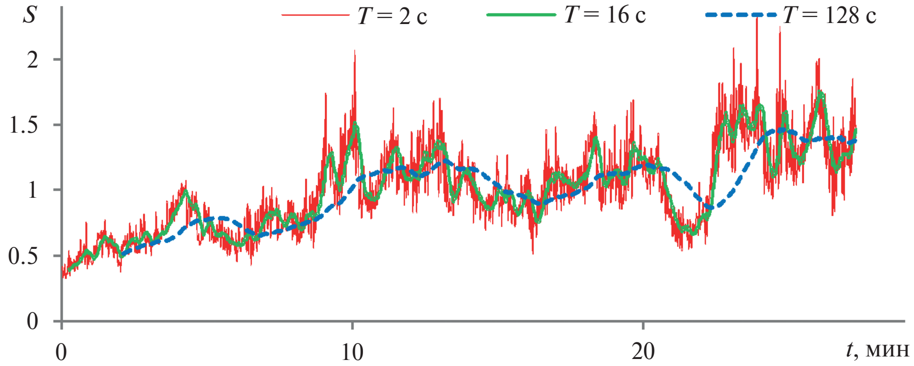

Fig. 3. Signal power (normalized to mean value).

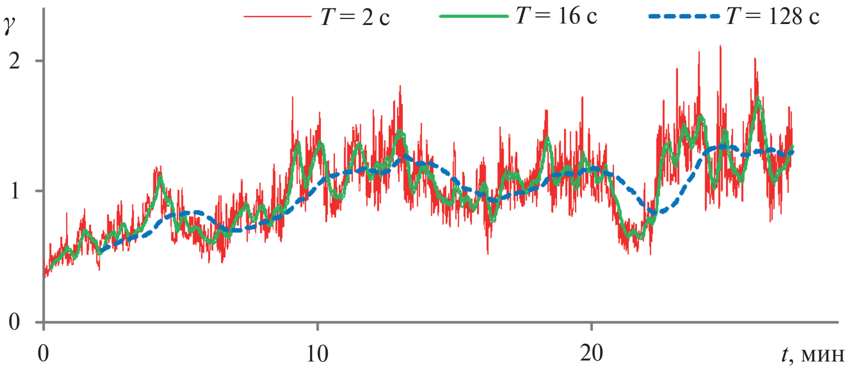

Fig. 4. The relative value of the OSB according to (4): $\gamma(t) = {Q_i(t)}/{C_j}$.

К статье *Консон А.Д., Волкова А.А.* Влияние сверхмедленных флуктуаций сигнала на помехоустойчивость шумопеленгования

Konson A.D., Volkova A.A. Influence of superslow signal fluctuations on the noise stability of passive listening

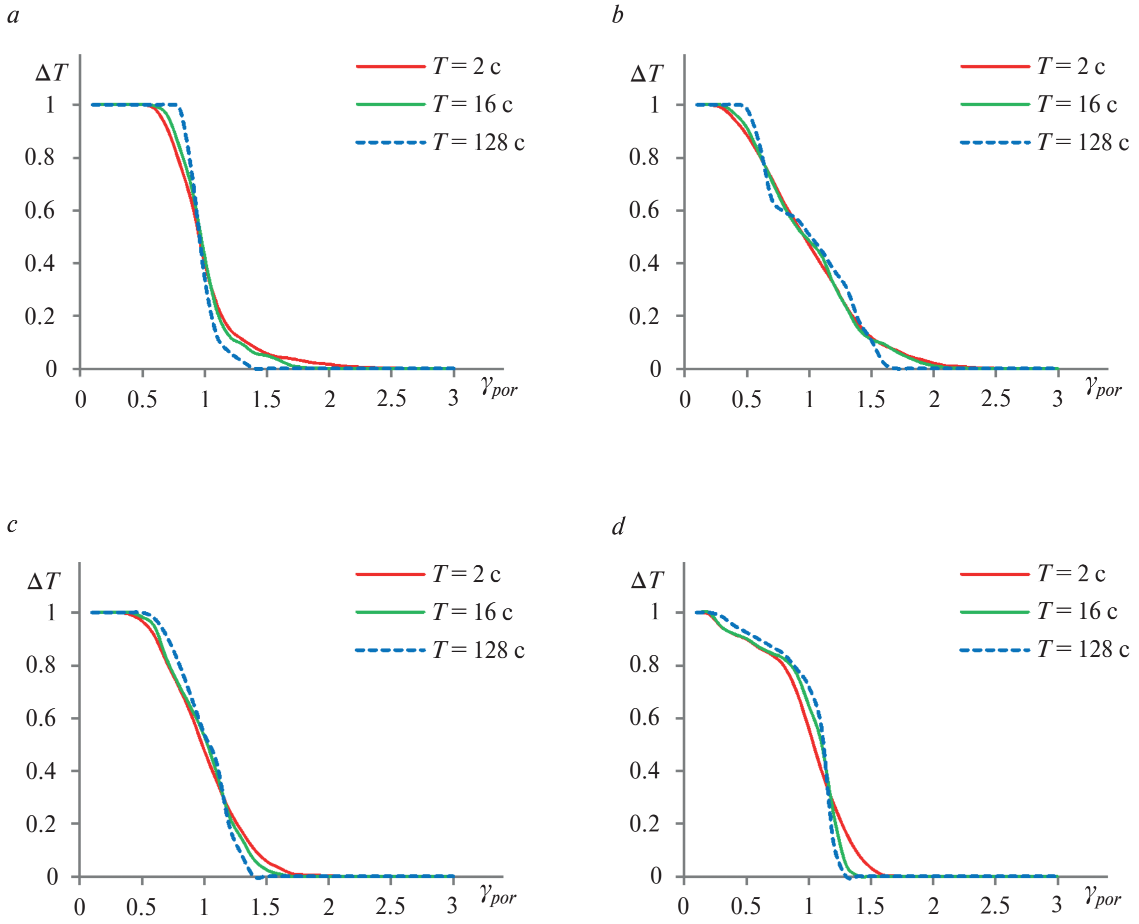

Fig. 5. Duration of observation for experiments. *a* –No. 1; *b* –No. 2; *c* –No. 3; *d* – No. 4.