Technical Physics, 2022, Vol. 67, No. 9

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Radio communication channel characteristics estimation in the marine environment

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Received February 19, 2022
Revised May 3, 2022
Accepted May 11, 2022

The results of data processing obtained in the course of full-scale experiments on the transmission of a short-wave radio signal in the marine environment using special ball antennas are presented. The capacity of the radio communication channel in the modulation frequency band is estimated. Statistical estimates of signals and noises are obtained, which make it possible to calculate decision-making thresholds based on the theory of statistical radio engineering. It is concluded that it is possible to create a two-way voice radio communication channel between mobile underwater objects.

Keywords: underwater radio communication, radio communication channel capacity, ball antennas, generalized electrodynamics.

DOI: 10.21883/TP.2022.09.54688.43-22

Introduction

The organization of radio communication channels between marine subsurface objects is required for solving many problems related to the exploration and development of the World Ocean [1–3]. At present, for these purposes, ultra-low-frequency radio channels are used, which do not provide sufficient data transfer speed, as well as cable lines, which also have limited communication capabilities with mobile subsurface objects. In addition, sonar systems are widely used to communicate with mobile subsurface objects. However, the characteristics of the propagation of sonar waves in the ocean are largely dependent on the vertical profile of the speed of sound, since marine environment is heterogeneous, which affects the quality of radio communications. The problem of creating radio communication channels in other conducting media (plasma, permafrost) and near the „dielectric–conductor" [4–6] interface is also relevant.

High-frequency transverse electromagnetic waves in a marine environment with high electrical conductivity cannot be used, since they are attenuated in the near zone of the radio signal. As shown in [1], at a frequency of 27 MHz with a water conductivity of 4.77 Si/m, the attenuation level is approximately 195 dB/m. While there are publications [7–11] pointing to the existence of electro-scalar longitudinal waves, which differ in their properties from the widely used transverse electromagnetic waves. It has been theoretically and experimentally shown that electro-scalar waves can propagate in electrically conductive media. There are several different designs of antennas operating on electro-scalar longitudinal waves [7]. However, reliable information on the experiments with high-frequency electro-scalar waves in marine environment has not been found in the available scientific literature.

The purpose of this paper is to present extended results of radio signal processing and assessment of a number of characteristics of a short-wave (SW) subsurface radio communication channel obtained during experiments in 2020 and 2021 in Vladivostok water area. All of them confirmed the theoretical conclusions about the opportunity of transmitting a short-wave radio signal in a subsurface environment using special ball antennas.

1. Basic experiment parameters

Transmitters and receivers connected to specially designed ball antennas were applied in the experiments carried out. Transmitting and receiving antennas, together with radio stations and voice recorders in sealed boxes, were immersed in the sea to a depth of 4 to 10 m on capron halyards. The transmitter antenna emitted modulated high-frequency signals, and the remote antenna received them. Meanwhile, the modulation signal or the intermediate frequency signal was recorded on a digital recorder or on a computer.

The description of the experiment carried out on October 27, 2020, in Novik Bay on Russky Island, is presented in detail in [1]. The purpose of this experiment was to test the fundamental opportunity of transmitting a high-frequency modulated radio signal in sea water. Amplitude modulation of the carrier frequency of 27.4 MHz was used with the „tone call" signal provided by the design of the transmitting radio station. Confident reception of the modulation signal was recorded at a distance of 470.7 m between the transmitting and receiving antennas.

Another experiment was carried out on March 19, 2021, in the area of Skryplev Island in Vladivostok water area. The purpose of this experiment was the subsurface transmission of a high-frequency narrow-band radio signal and the assessment of its parameters. „Shturman 882M“ radio station was used as a transmitting device, the high-frequency output of which was connected to a ball antenna. The carrier frequency was 27.135 MHz. Modulation was not applied. Reception was carried out on an SDR receiver connected to the output of the ball antenna. The receiver local oscillator frequency was set to 27.131 MHz. The receiver was connected to a computer on board the boat using a USB cable. Intermediate frequency signals of approximately 4.000 Hz were recorded on a computer disk. The experiment resulted in recording stable narrow-band radio signal at a frequency of 3960 Hz at distances of 70−80 m between the transmitting and receiving antennas.

2. Experiment results processing

Fig. 1 isomertically shows the power spectrum density (PSD) voiceprint in dBμW of the received amplitude modulation signal („tone call“ signal of the radio station) versus time and frequency for the entire recording period. Power Spectrum Density is denoted as PSD in all graphs. It was obtained using the Fast Fourier Transform (FFT) in a window of 120 s with a time step of 1 s. A Gauss weight window was used. PSD values are given with averaging to the frequency band of 1 Hz. The frequency range on the graph from 0 to 3.500 Hz overlaps the frequency range of the amplitude modulation of radio stations 300−3.400 Hz.

As it follows from Fig. 1, the PSD level drop at low frequencies repeats the frequency response of the demodulation channel of the radio station. The characteristic PSD peaks , reaching 20 dBμW, distributed evenly over the entire frequency range, are visible at the beginning and at the end of the recording in the entire frequency range. The first peak at a frequency of 509−510 Hz corresponds to the fundamental harmonic of the „tone call“ of the transmitting radio station. The observed drop in the PSD level for the time period from 540 to 2.400 s corresponds to the interval when the receiving and transmitting stations were in the submerged condition.

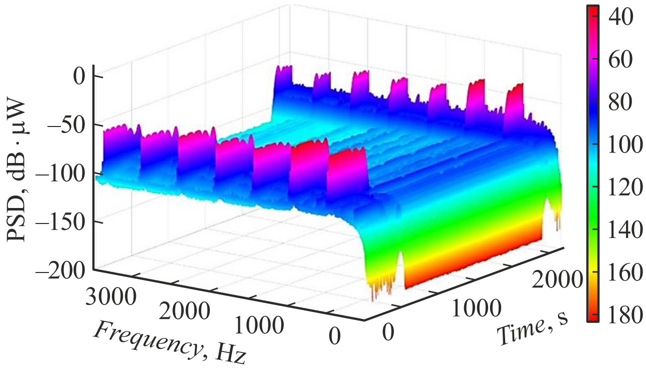

Figure 1. Voiceprint of the PSD of the recorded radio signal.

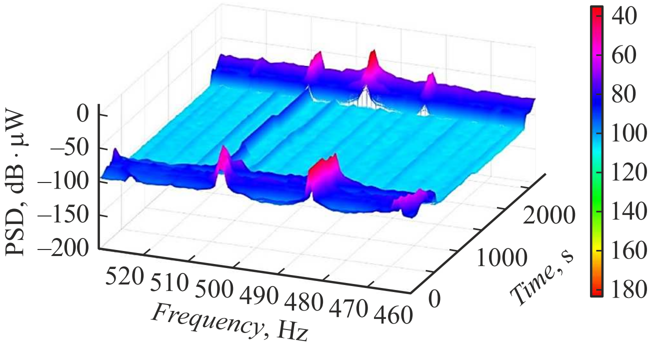

Figure 2. Voiceprint of the PSD of the recorded signal within the interval of 450−550 Hz.

Fig. 2 isometrically shows the PSD voiceprint during the entire recording time for the frequency range in which the fundamental harmonic of the „tone call“ signal of the radio station is located, namely from 450 to 550 Hz. All processing and display characteristics in Fig. 2 are chosen to be the same as in Fig. 1. For the time intervals 540−2.400 s, when both stations were in the complete submerged condition, Fig. 2 clearly shows the fundamental harmonic of the „tone call“ signal at frequencies 509−510 Hz at the PSD level −87.5 dBμW. As can be seen from Fig. 2, the background PSD level at other frequencies is lower than the level of the fundamental harmonic 509−510 Hz by more than 10 dBμW. Before the start of the transit of the transmitting station from the time point of 540 s, a characteristic increase in the center frequency of the „tone call“ signal from 504 to 508 Hz is noticeable, which may be due to the drift of the characteristics of radio stations due to temperature changes after immersing the boxes in sea water. During the transit period, the central frequency of the signal changed in the range from 508 to 510 Hz in the period 540−1.700 s, and after 1.700 s it amounted to 509 Hz.

It should be noted that there are other characteristic frequencies in Fig. 2, which are present before the beginning of the transit of the transmitting station. However, there are no lines of these frequencies in the period 540−2.400 s. During the transit, the voiceprint shows weaker characteristic frequencies, which are absent in the initial and final periods of the recording. In order to understand their origin, a spectral analysis of the recording was carried out with one large window in the time interval of 600−2.400 s, followed by averaging the PSD over frequency to a resolution of 1 Hz. This spectrum in dBμW units for the operating range of the radio station 300−3.400 Hz is shown in Fig. 3.

The fundamental harmonic level 510 Hz is marked with a flag in Fig. 3. As it follows from this figure, the subsurface signal spectrum existing during the transit period has many

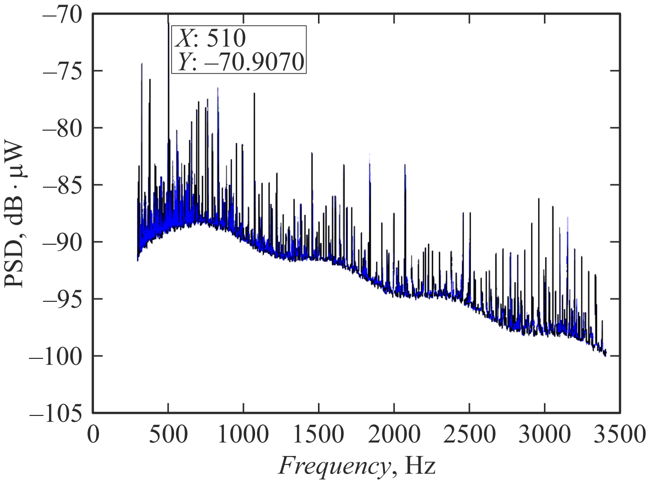

Figure 3. Power spectrum density for the window 600–2.400 s with the resolution of 1 Hz.

characteristic maxima. Some of them are explained by the broadband spectrum of the „tone call“ signal. The item of the presence of a large number of other harmonic components in the spectrum of the subsurface signal tested by a ball antenna requires additional research.

Taking into account the large number of multiple frequencies in the spectrum of the „tone call“ signal of the radio station, the frequencies 454–455 Hz were chosen, which lie below the frequency range of the fundamental harmonic. Signals at these frequencies were considered as noise. This allowed to compare the power levels of the narrow-band envelopes of the signal and noise in the time interval of subsurface propagation in order to assess the data transmission rate in the radio communication channel. The corresponding PSD are shown in the graphs (Fig. 4) with averaging over windows with a duration of 1 s. Throughout the entire time of subsurface propagation, the PSD level of the noise envelope was approximately -100 dBμW. The PSD level of the signal envelope P_s together with its own noise P_0 in the period of 400–1000 s was approximately -91 dBμW. Therefore, the difference in the levels of PSD signal and noise $(P_s + P_0)/P_0$ is 9 dB, i.e. a signal with noise exceeds the noise level by 7.94 times.

The calculation of the traffic-carrying capacity of the communication channel or data transmission channel depending on the frequency width of the channel and on the signal-to-noise ratio is given by the Shannon's formula [12]:

$$I = B \log_2(1 + P_s/P_0), \tag{1}$$

where I — traffic-carrying capacity of the channel bit per second, [bps], B — channel bandwidth, [Hz], P_s — signal power, [W], P_0 — noise power, [W]. In the considered narrow-band case $B = 2$ Hz, taking into account the bandwidth of the filter, therefore, from formula (1) we obtain

$$I = 2 \log_2 7.94 = 5.98 \text{ bps}. \tag{2}$$

Thus, under the conditions of the experiment, the specific throughput of a radio communication channel with a width of 1 Hz turned out to be approximately 3 bps. This value can be increased by transmitter power, directional antennas, and special modulation techniques. The radio signal transmitted in the course of the described experiment at a distance of up to 470 m after its conversion into sound, is well audible at a frequency of 509 Hz. Thus, the fundamental opportunity of transmitting a high-frequency modulated radio signal in sea water has been experimentally proven.

No modulation was applied in the experiment conducted on March 19, 2021. Direct recording of the intermediate frequency was used, the peak of which fell at a frequency of 3.960 Hz, at a transmitter frequency of 27.135 MHz and a local oscillator frequency of 27.131 MHz.

For analysis, the obtained intermediate frequency signal was passed through narrow-band filters 3.959–3.961 Hz to assess the mixture of the noise signal and 3.999–4.001 Hz to assess the noise level at close frequencies. After filtering, the Hilbert transform and PSD of the mixture of the noise signal were applied, and the noise was assessed in a bandwidth of 2 Hz. Figure 5 shows the dependences of the PSD of the envelopes for a signal with noise and for noise on time for a record with a duration of approximately 360 s.

The most stable signal recording refers to the time period of 108–197 s of the record. The noise signal level was -84.4 dBμW, and the noise level was -113.1 dBμW. Thus, the ratio of the PSD of the noise signal to the PSD of the noise was 28.7 dB. This corresponds to the value in formula (1) $(P_s + P_0)/P_0 = 741$. As a result, for the band 2 Hz, the assessment of the channel capacity is:

$$I = 2 \log_2 741 = 19.07 \text{ bps}. \tag{3}$$

In terms of 1 Hz of the frequency band, the specific traffic-carrying capacity of the radio communication channel obtained in the experiment is assessed at approximately 9.5 bps.

Figure 6 shows the power spectrum density of the mixture of a noise signal in the frequency range of

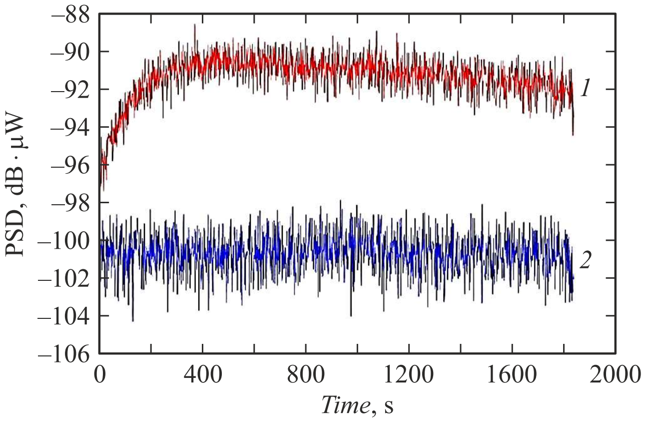

Figure 4. Modulation power spectrum density: *1* — noise signal, *2* — noises.

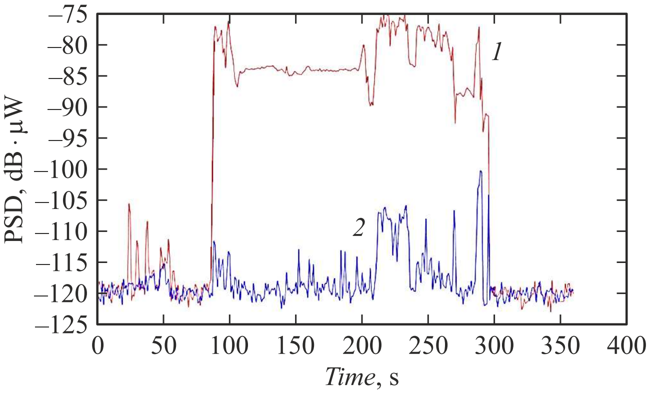

Figure 5. Power spectrum density of the envelopes: *1* — noise signal, *2* — noise in the experiment dated 19.03.21.

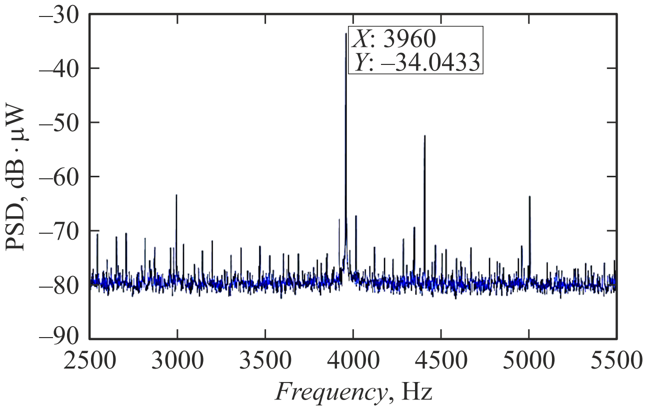

Figure 6. Power spectrum density of the noise signals in the bandwidth of 2.500−5.500 Hz.

2.500−5.500 Hz. The flag marks the frequency 3.960 Hz, the level of which is $-34.0\,\text{dB}\mu\text{W}$. The tone signal closest to it in terms of $-52.5\,\text{dB}\mu\text{W}$ is at a frequency of 4.407 Hz. There are no more powerful level noises in the considered frequency range of 2.500−5.500 Hz. Thus, the ratio of the PSD level for signal with noise to the PSD of noise in the specified range is 18.5 dB or 70.79 times. Therefore, when organizing a radio communication channel in the band from 2.500 to 5.500 Hz, taking into account the actual level of signals and noise in this range, its traffic carrying capacity will be:

$$I = \frac{5500 - 2500}{2} \log_2 70.79 = 9218\,\text{bps}. \qquad (4)$$

This traffic carrying capacity is enough to organize a high-quality voice communication channel between mobile subsurface objects.

The PSD pattern given in Fig. 6 shows that, in addition to the narrow-band signal generated by the radio transmitter, other narrow-band tones exist in sea water in the considered frequency range, in particular, at frequencies of 3.000 Hz (-63.4 dBμW), 4.407 Hz ($-52.5\,\text{dB}\mu\text{W}$), 5.001 Hz ($-63.6\,\text{dB}\mu\text{W}$) and others. Taking into account local oscillator frequency, which was set in the receiver at 27.131 MHz, these frequencies correspond to the values of absolute radio frequencies equal to 27.099040, 27.100447, 27.101041 MHz, respectively. The origin of these frequencies and their sources have not been specified.

For this experiment, the signal recorded at local oscillator frequency and converted into an audio file is well audible at a frequency of 3.960 Hz.

Conclusion

In this paper, the characteristics of the amplitude modulation signal and the local oscillator frequency, signal without the use of modulation for high-frequency SW signals as a result of their propagation over various distances in the marine environment are obtained. The calculated power spectrum density of a mixture of noise signals and separately for noise are presented. The specific traffic carrying capacity of subsurface communication channels are assessed in terms of 1 Hz frequency bands.

The results of the study indicate the opportunity of creating small-sized SW radio stations with ball antennas that provide voice communication between subsurface mobile objects within a few kilometers.

It has been noticed that the spectra of signals recorded using subsurface ball antennas (Fig. 3 and 6) include other narrow-band harmonics, the presence of which cannot be explained only by multiple frequencies of the „tone call“ or other reasons. It can be assumed that the sources of these signals are in the air, and the signals themselves, being transformed, pass through the „air–water“ interface and then propagate under water in the form of electro-scalar waves.

The obtained experimental data fully confirm the opportunity of organizing high-frequency radio communication channels in the subsurface conditions of marine environment using the proposed ball antennas. The obtained results can be used, for example, in signaling and communication systems during the operation of subsurface production complexes and for solving many technical problems.

Funding

The work was carried out as part of the programs to improve the competitiveness of the Tomsk Polytechnic University and the Far Eastern Federal University.

Conflict of interest

The authors declare that they have no conflict of interest.

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