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Some Aspects of Reflection of Dolphin FM Signals (Whistles) in an Experimental Tank

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Abstract—Reflections of FM signals (whistles) of two Black Sea bottlenose dolphins (*Tursiops truncatus*) from the boundaries of a tank many times smaller than the spatial extent of the signals were recorded for the first time. It is shown that dolphins produce whistles with sound pressure levels (about 2 Pa) only slightly exceeding (by 3–8 dB) the acoustic noise amplitudes of the tank. It has been established that as they propagate, FM signals are repeatedly reflected from the tank boundaries; the shape of the emitted signal is distorted as a result of interference with signals reflected from the boundaries of the tank and acoustic noise. In contrast to the time domain, the FM signal spectrum is more resistant to interference; therefore, the signal-to-noise ratio of the spectral power densities (SPD) of the same signals and their reflections reaches 30–40 dB. The results indicate the advantages of analyzing FM signals and their echoes in the spectral domain.

Keywords: dolphin, FM signal (whistle), echo, matched filter, FM sonar

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INTRODUCTION

The acoustical signals of toothed whales are diverse and represent their main means of complex coordinated social behavior [1]. It should be noted in particular that under insufficient visibility conditions, these signals become the animals' only sensory mediator. However, in the scientific literature, the acoustic signals of animals are described qualitatively: “clicks, buzzing, squeaking, cracking, clapping, barking, screeching, whistling,” etc. [2–4, and others].

To date, it is generally accepted that toothed whales have only one sonar. Sonar probing signals are “clicks,” or ultrashort ultrawideband pulses [5–7]. The echolocation “clicks” of bottlenose dolphins are very short, about 50 μs; therefore, wideband entails frequencies of 2–200 kHz with an energy maximum at frequencies of about 120–130 kHz [8–10].

Meanwhile, hypotheses have been proffered that dolphins can use FM signals (known as “whistles”) in various behavioral contexts [11, 12], to identify themselves by “signature whistles” [13, 14], in determining the direction of movement of a whistling dolphin [15], and to maintain acoustic contact between spatially scattered individuals [16–21] at distances up to 10.5–25 km [17, 21].

FM signals of toothed whales have been studied since the mid-20th century; however, in the majority of studies, signals were recorded in a frequency band only up to 20 kHz. Signal characteristics and their functionality are not considered in light of signal theory and echolocation. These shortcomings were compensated to some extent in [5, 6], where they are considered as multifrequency FM signals. For bottlenose dolphins, these signals cover a frequency range up to 140 kHz; the FM signals time-bandwidth product TW, where T is the average duration of a whistle and W is the average width of its spectrum, reaches of 10^4–10^5. The results of these studies suggest that whistles are probing signals for FM Doppler sonar and FM sonar with pulse compression, or dolphin CHIRP (compressed high-intensity radiated pulse) sonar.

The aim of this experiment is to study certain aspects of the reflection of FM signals of Black Sea bottlenose dolphins (*Tursiops truncatus*) in a tank much smaller than the spatial extent of signals.

EXPERIMENTAL

Method

The acoustic signals of two adult Black Sea dolphins (*Tursiops truncatus*), nicknamed Yasha (a male) and Yana (a female), were recorded in a closed concrete tank with dimensions of 27.5 × 9 × 4.5 m at the Karadag Scientific Station—Nature Reserve, Russian Academy of Sciences. The dolphins have resided in the tank for about 25 years and have normal hearing. Signals were recorded by a two-channel recording system (Fig. 1). The distance between hydrophones I and

II of the recording channels was chosen as 5 m to obtain sufficient interchannel differences in the sound pressure levels (SPL) and time delays of each signal. The recorded signals were matched to specific dolphins taking into account the interchannel differences of time delays and SPLs of each signal, as well the distances between the dolphins, hydrophones, and tank boundaries. The hydrophone immersion depth was 1 m. The channel I hydrophone was located closer to the middle of the tank (Fig. 1, I); the channel II hydrophone (Fig. 1, II) was close to the wall of the tank. In some cases, the positions of the dolphins in the tank with respect to the hydrophones were recorded by a movie camera synchronously with signal recording.

Hydrophones I and II are piezoelectrical, spherical, 14 mm in diameter, and have a calibrated sensitivity of –203.5 and –206 dB re 1 V/μPa, or 66.5 and 50 μV/Pa, respectively. The uneveness frequency response of the hydrophones was: ±3 dB up to frequencies around 160 kHz and ±10 dB up to frequencies around 220 kHz. Each signal recording channel consisted of a hydrophone, a high-pass filter (0.1 kHz), a voltage amplifier (40 dB), and one channel of a USB-3000 multichannel 14-bit analog-to-digital converter (ADC). The dynamic range of the ADC and signal recording path is about 81 dB (0.1–1600 Pa); the sampling frequency of each ADC channel is 1 MHz. The digitized signals of dolphins were recorded from the ADC to the hard disk of a laptop. The Power-Graph 3.3.8 and Adobe Audition 3.0 software packages were used to record, visualize, and process signals. The spectral power densities (SPDs) of the dolphin FM signals over time (spectrograms) were calculated by 4096-point Fast Fourier Transform.

The experiment was carried out in daytime without special training or food reinforcement for the dolphins. The dolphins produced acoustic signals, freely moving around the tank, apparently unaware they were being recorded. A total of 20 acoustic recordings of dolphin signals were made, one recording per day; the duration of was about 30 min. In total, several thousand dolphin acoustic signals were recorded, consisting of five different classes in accordance with [6]. FM signals were selected for analysis and discussion. As the acoustic signals of the dolphins were being recorded, there were no other animals in the tank.

RESULTS

Among the recorded acoustic signals, there were about 300 FM signals from the dolphins. The SPL of whistles usually did not exceed 2–3 Pa, in rare cases, up to 10 Pa. The fundamental frequency of recorded FM signals varied from 3.5 to 42 kHz. The number of harmonics could be from one to several dozen. The frequency band of FM signals with harmonics could range from 15 to 140 kHz. Spectrograms of FM signals described linearly or nonlinearly increasing or decreasing curves of different steepness, as well as their combinations with repetitions. These curves are called the whistle contour. In general, the shapes of FM signal contours, as well as the fundamental frequencies and, accordingly, the frequencies and number of harmonics of signals, as well as their duration, are consistent with those presented in [3, 13–18, 21–23].

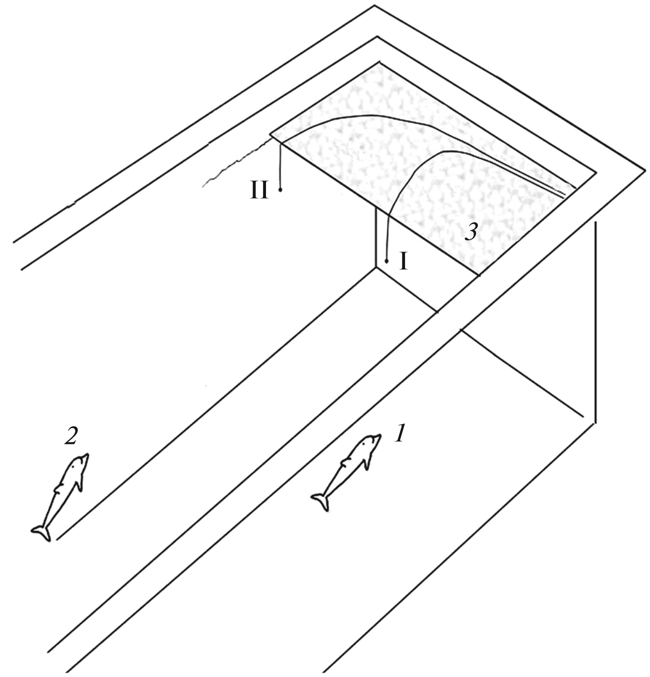

Fig. 1. Configuration of experiment. I and II, hydrophones of recording channels I and II, respectively. *1* and *2*, dolphins; *3*, walkways. Walkway width 3 m, distance between hydrophones 5 m, hydrophone depth 1 m, water level 4 m, distance of hydrophone II from tank wall 0.35 m.

In addition, broadband noiselike FM signals with more than 50 harmonics and a maximum SPL of about 10 Pa (level referenced to 1 m from the dolphin) were recorded. These signals have a sufficient energy level in the audible frequency range; therefore, during reproduction, a person hears them clearly as noise pulses [6].

Visual analysis of the spectrograms of recorded dolphin FM signals revealed multiple echoes (Figs. 2–4). Reflections replicate the shape of the contours of the fundamental frequency and harmonics of the FM signals, with different time delays relative to them (Table 1). The delay of each successive echo is an integer multiple of the delay between the corresponding signal and the first echo. As an example, Fig. 2 shows an FM signal produced in motion by Yasha near (about 2–3 m) the channel I hydrophone (denoted *1* in Fig. 1). The time delays between signal reflections are about 9–12 ms (Fig. 2, Table 1). In this case, the SPD level of the FM signal on channel I is approximately 20 dB more than on channel II. There are seven signal harmonics on channel I; on channel II, four. The frequency band of this FM signal with harmonics is about 119 kHz. Fig-

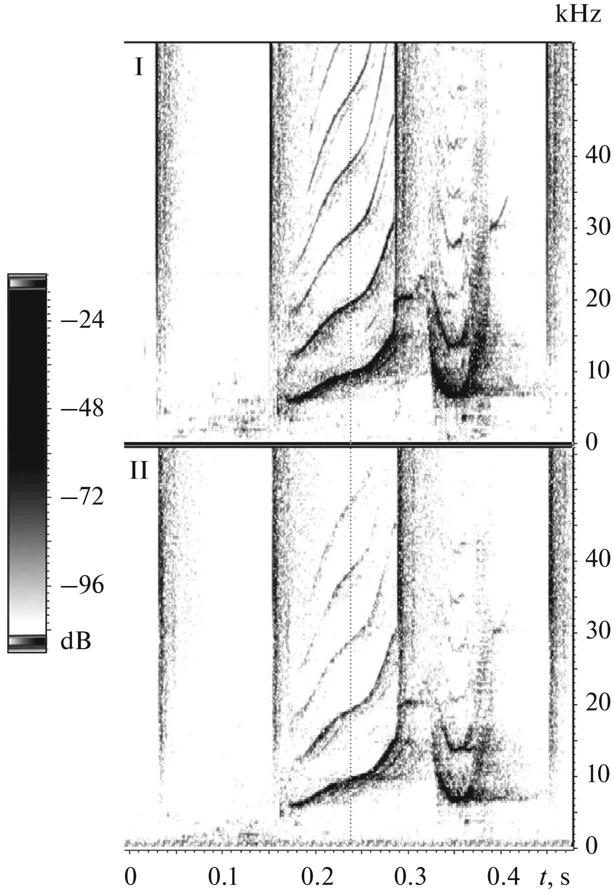

Fig. 2. FM signal and four clicks produced by dolphin Yasha (spectrogram). Distance from dolphin to hydrophone (channel I) 2–3 m; I and II, hydrophones of first and second signal recording channels, respectively.

ure 2 shows only the spectrogram region containing echoes of the FM-signals. The table takes into account only the harmonics with respect to which the echo time delays are measured.

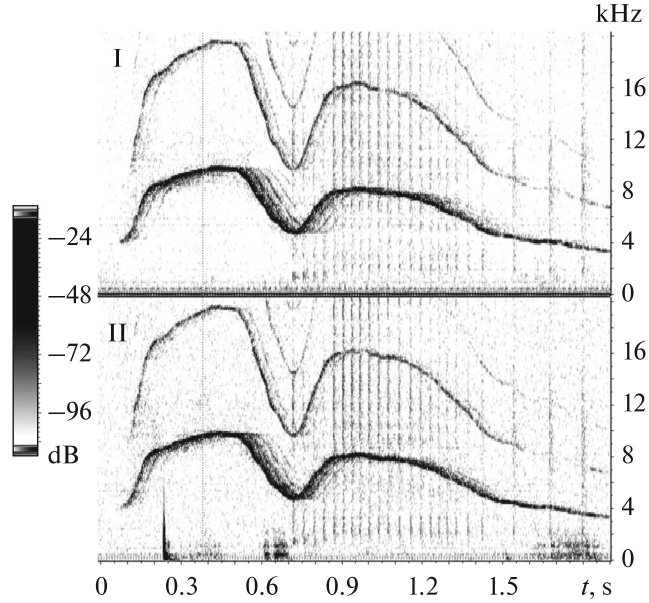

Fig. 3. FM signal and "clicks" produced by dolphin Yana (spectrogram). Distance from dolphin to hydrophones ~12–15 m; I and II, hydrophones of first and second signal recording channels, respectively.

Figure 3 shows an example of the spectrogram of one of Yana's FM signals, which she produced in motion from a distance of about 12–15 m from the hydrophones, approximately denoted *2* in Fig. 1. In this case, in the region of the fundamental frequency of the signal spectrogram, four echoes were recorded on channel I (Table 1) with a time delay relative to the fundamental frequency of about 36 (first echo), 72 (second echo), 108 (third echo), and 144 ms (fourth echo). On the second channel, four echoes were recorded with delays that are multiples of about 31 ms. The delay between echoes is an integer multiple of the delay between the fundamental frequency of the signal and the first echo. Near the first harmonic of the

Table 1. Main characteristics of dolphin FM signal echo

Distance from dolphin to hydrophones, m	2–3		12–15		18–21			
Recording channel	I	II	I	II	I	II	I	II
					first FM signal		second FM signal	
Number of fundamental frequency echoes	1	3	4	4	4	2	5	3
Delay of fundamental frequency echo, ms	12.8 ± 0.21	12.11 ± 0.19	35.95 ± 0.35	31 ± 1.3	35.23 ± 1.05		35.62 ± 0.65	34.7 ± 1.25
Number of harmonics FM signal	5	3	1	1			1	1
Harmonic echo delay, ms	9.02 ± 0.32	12.18 ± 0.016	36 ± 0.35	36 ± 0.41			31.2 ± 0.65	33.94 ± 1.85

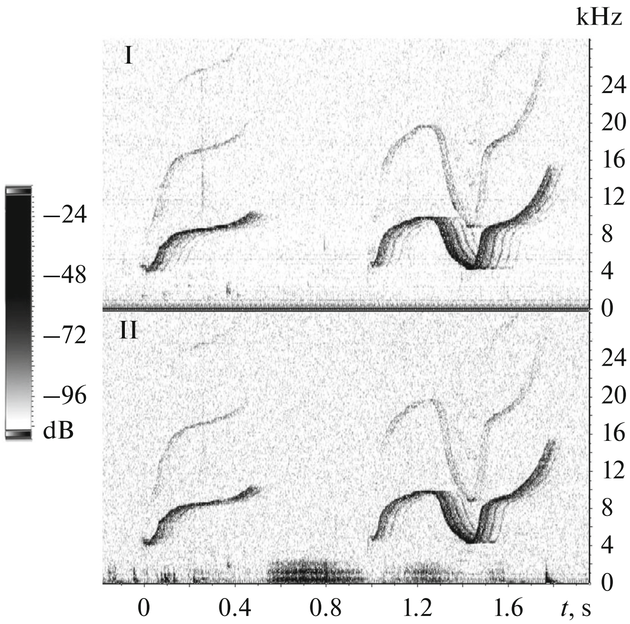

Fig. 4. Two FM signals produced by Yana (spectrogram). Distance from dolphin to hydrophones ~18–21 m; I and II, hydrophones of first and second signal recording channels, respectively.

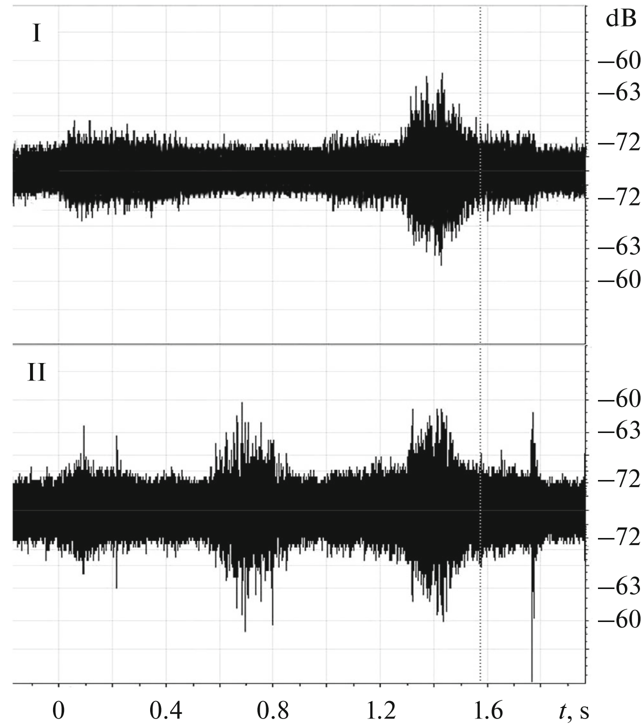

Fig. 5. FM signals shown in Fig. 4 (time domain). *X* axis, time *t*, s. *Y* axis, sound pressure level in dB re 1000 Pa. I and II, hydrophones of first and second signal recording channels, respectively.

whistle, its reflection is also recorded. Interchannel differences in SPD signal levels are not noticeable.

Figure 4 shows an example of a spectrogram of two FM signals produced by Yana in motion from the maximum possible distance to hydrophones in the tank, about 18–21 m. In the region of the fundamental frequency and first harmonics of the signals, a different number of echoes with different time delays was recorded (Table 1). Interchannel differences in the SPD levels signals are insignificant. Analysis of acoustic signal recordings showed that in the frequency domain, dolphin FM signals have no deformations as a result of interference with their reflections. Moreover, the SPD of the FM signals is much larger (by 30–40 dB) that that of the acoustic tank noise (Figs. 2–4). In contrast, in the time domain, the same FM signals (Figs. 4, 5) are hardly distinguishable from the acoustic noise of the tank. The SPL amplitude of the noise on channels I and II is about –72 and –70 dB re 1000 Pa (Fig. 5), respectively. The SPL amplitude of the first and second FM signals exceeds the that of noise by 3–5 and about 8 dB, respectively. The maximum SPL values at the beginning and end of these FM signals practically coincide with the maximum levels of the ambient acoustic noise of the tank, and only closer to the middle of the signals do their SPLs reach maximum values, exceeding the noise level by 3–8 dB. Reflections of FM signals in the time domain were not visually detected.

DISCUSSION

In this study, reflections of dolphin FM signals were recorded for the first time for toothed whales. The fact that echo signals are clearly visible in a tank much smaller in size than the spatial extent of the signals was also unexpected. Given these most interesting results, let us discuss some aspects of the reflection of dolphin FM signals in the tank and the possibilities of their analysis.

Considering that the tank length is about 27.5 m, the width near the hydrophones is about 9 m, and the sound velocity is about 1500 m/s, the double sound path time between the far walls of the tank is about 36 ms, and between the side walls near the hydrophones it is about 12 ms.

The echoes of dolphin FM signals with different time delays less than 30 ms seem to be the superposition of numerous echoes, seen in these figures as a thickening of the signal contour line and its expansion in varying grayscale (Figs. 2–4). Apparently, the maximum number of single reflections of FM signals and their harmonics is concentrated in this region of time delays, among which are echoes from the water surface, the bottom, and the walls of the tank. Echoes with large time delays are obviously multiple reflections of FM signals from the tank boundaries as they propagate along or across the tank. Consequently, echo delays close to 36 and 12 ms (Table 1) indicate that the echo signal travels a double path along or across the tank, respectively, recorded each time by the hydrophones of both channels.

Analysis of the recordings also indicates that with increasing distance (Figs. 2–4), the number of the highest-frequency harmonics and the interchannel difference of the SPD of FM signals decrease. These indicate a high degree of attenuation of the high-frequency components of the FM signals and their directivity.

Figures 4 and 5 show the same FM signals in the frequency (spectrogram) and time domains as an example. The maximum SPL amplitudes of these signals reach only 0.25–0.5 Pa and only slightly exceed the SPL of acoustic noise in the tank. The spatial extent of the considered FM signals (taking into account their duration $t_w = 0.5–1.8$ s and sound speed in water $c_0 \approx 1500$ m/s) is about $L_w \approx t_w c_0 \approx 750–2700$ m, which is ten times larger than the size of the experimental tank. Dolphin FM signals have low SPLs close to the noise level of the tank (Fig. 5). As they propagate in the tank, they are repeatedly reflected from the tank boundaries and interfere with their reflections. It is known that the waveform due to repeated superposition with echoes is significantly deformed in the time domain. Meanwhile, their echoes are significantly masked by extended higher-level FM signals and acoustic tank noise, which makes it difficult to analyze echo signals in the time domain.

In contrast, as follows from the results of this study, in the frequency domain, FM signals do not have deformations as a result of interference with reflections. Signal-masking of reflections is absent, and the SPD of FM-signals and their reflections are much higher (by 30–40 dB) than the SPD of the acoustic tank noise (Figs. 2–4). Moreover, FM signals have a duration three to four orders of magnitude longer than that of dolphin pulse signals, which provides them with a relatively large energy, which is confirmed by their significant travel time and multiple reflections in the tank (Figs. 2–4). Given the results of this work, it can be assumed that dolphins analyze FM signals and their echoes in the frequency domain. This is also supported by the low signal level, commensurate with the noise level in the time domain. If it is assumed that a dolphin analyzes FM-signal echoes, then what analysis mechanism does the dolphin use for this? In this case, it is of interest to analyze the time delays of FM-signal reflections. To answer this question, we consider FM signals (whistles) in light of the theory and technology of noiselike signals.

Acoustic signals with a time-bandwidth product $TW \gg 1$ are called spread-spectrum, or noiselike signals. A large TW value, where T is the average duration of a whistle and W is the average width of its spectrum, entails a complicated signal structure and large information content, whereas a small product characterizes simple signals. The product TW of a dolphin's FM signal, taking into account only the deviation of the fundamental signal frequency, reaches 10 251; taking into account the signal harmonics, about 49 000; and even more for noiselike whistles, about 108 000 [6]. The complicated spread-spectrum acoustic FM-signals of dolphins in their evolution have developed and improved over tens of millions of years, along with their echolocation system and hearing. Consequently, the optimal efficiency of these systems is governed by the physical characteristics of signals and methods by which dolphins process them [6]. The advantages gained by the dolphin's echolocation system via the use of spread-spectrum signals and their corresponding processing methods can be explained by the well-known concepts of signal theory.

For optimal reception of echo signals on a noise background in echolocation technology, matched filtering or optimal correlation reception is used. In this case, modern echolocation systems with spread-spectrum signals gain increased noise immunity, which is determined by the well-known ratio

$$q^2 = 2TW\rho^2, \tag{1}$$

where $\rho^2 = P_S/P_N$ is the power signal-to-noise ratio at the receiver input, and $q^2 = 2E/N_P$ is the signal-to-noise ratio at the matched filter or correlation receiver output, where E is the signal energy and N_P is the SPD of interference in the signal frequency band. For this, it suffices to choose a spread-spectrum signal with a sufficient product TW (1). Reception of spread-spectrum signals by a matched filter or correlation receiver amplifies the signals by $2TW$ times. Quantity $K = q^2/\rho^2$ is called the signal gain during processing. Relation (1) is fundamental in the theory of communication systems with spread-spectrum signals. Meanwhile, spread-spectrum signals are used in echolocation devices for measuring the target range R and Doppler shift of an echo signal f_d.

The measurement accuracy and resolution of the sonar in terms of range R increases with broadening of the frequency band of a spread-spectrum signal and with an increase in the signal-to-noise ratio q^2. The larger q^2 and signal duration T, the higher the measurement accuracy and resolution for determining the relative radial velocity V_r.

For spread-spectrum signals, it is possible to independently change the spectral width W and duration T in the joint measurement of range R and relative radial velocity V_r of the target. In other words, the shape of the whistle contour may be different; it need only correspond to the amplitude–frequency and phase–frequency characteristics of the auditory matched filter to solve the corresponding echolocation task. Therefore, when dolphins analyzing whistles using ordinary hearing, various shapes of the whistle contour can be used in the problems considered in [11–21].

When processing a spread-spectrum signal with a matched filter, the signal is compressed over time and amplified due to in-phase addition of the signal components, obviating the need for a signal power amplifier. It is important that pulse compression makes it possible to use the relatively large energy of a long pulse with a time resolution like that of a short pulse. The response of the matched filter for an FM signal with duration T and spectral width W is a narrow pulse or a central peak and side pulses or side peaks. The amplitude of the central peak V and its duration $\tau_0 \approx 1/W$. The amplitude of side pulses is $v_{\max}$. The wider the spectrum of the signal, the shorter the duration of the central peak. Spread-spectrum signals with a large product TW have properties that are written as follows:

$$T/\tau_0 \approx TW, \quad (2)$$

$$V/v_{\max} \approx (\alpha TW)^{1/2}, \quad (3)$$

where α is some constant depending on TW.

Ratio (2) determines the compression of complex signals—the ratio of the signal duration to the duration of the central peak. Compression is approximately equal to the product TW of the signal.

Relation (3) characterizes the suppression of side peaks. The greater TW of the signal, the greater the suppression of side peaks. The narrower the central peak of the ACF of the probing sonar signal, the higher the resolution of the sonar on time and Doppler shift and the accuracy of measuring the target's range and radial velocity.

Note that the matched filter and the correlation receiver are equivalent in terms of signal detection. However, the correlator is a device with time-varying parameters and can flexibly adjust to a changing signal (like an active filter), while the matched filter is tuned to one particular signal. Nevertheless, the use of each device is determined by the ease of implementation.

How can a matched filter be organized in a dolphin's hearing? This question is not simple and obviously requires further research. However, it can be assumed that each time an FM signal (whistle) is produced, the dolphin's hearing organizes a hearing filter matched with a specific signal, with appropriate amplitude–frequency and phase–frequency characteristics. Therefore, all signal reflections, like a dolphin's sonar probing signal with pulse compression or FM Doppler sonar, will be recorded at the output of this filter as separate responses, with different time delays (determined by the range of reflectors and their relative radial velocity). The time resolution between responses is determined by the time-bandwidth product TW of the FM signal. It is important that in this case, the noise immunity of these sonars is significantly increased. Dolphins can produce different types of signals simultaneously in the common frequency band [6]. Under these conditions, significant crosstalk occurs (both between signals from one dolphin and signals from counterparts); therefore, analysis with a matched hearing filter is the best way to combat crosstalk and other noise uncorrelated with the dolphin signal. In this case, the dolphin's echolocation system will utilize the advantages of the spread-spectrum signals, discussed above.

Based on the characteristics of the above-mentioned FM signals of the dolphins in this study, for $TW = 10^4–10^5$, the spread-spectrum signal gain during processing, based on (1), $K = q^2/\rho^2 = 2TW \approx 10^4–10^5$. The signal duration T (in our case $T \approx 0.5–1.8$ s) will be compressed to the duration of the matched hearing filter response and, on the basis of (2), will be $\tau_0 \approx T/TW \approx (0.5–1.8)/(10^4–10^5) \approx 18–50$ μs. The ratio of the amplitude of the central peak response V of the matched filter to the amplitude of the side pulses of the response $v_{\max}$, based on (3), in this case will be

$$V/v_{\max} \approx (\alpha TW)^{1/2} \approx (10^4)^{1/2} \approx 100.$$

For an SPL of the FM signal of about 2.5 Pa (level referenced to 1 m from the dolphin), whistles travel more than 300 m along the tank (Fig. 4), five times the double sound path along the tank. The maximum SPL of FM signals from bottlenose dolphins known from the literature—amplitude values—are about 180 dB re 1 μPa [24], and the averaged values are about 170 dB (*rms*) re 1 μPa [20], respectively, which is almost 1000 times higher than those recorded in the tank (Figs. 2–5). Taking this into account, the maximum coverage ranges of dolphin FM sonars in the open sea, with maximum SPLs of FM signals and matched hearing filter processing of echo signals, as calculations [25] have shown, can be close to the maximum distance of acoustic contact between dolphins, 10.5–20 km [17, 20]. The directivity pattern of FM signals [26] and dolphin hearing [27] is low in this frequency range, due to which FM signals are emitted and hearing accordingly receives echoes from almost the entire space around the dolphin. At the same time, the accuracy in localizing sound sources at these frequencies is high [28], reaching 1° due to binaural determination of the position of the sound source (echo). In light of these data, it can be assumed that FM sonars have a maximum range, the best time resolution (18–50 μs), and, accordingly, a range resolution of 0.027–0.075 m, as well as better noise immunity among sonars of dolphin.

At the same time, probing FM signals (whistles) of hypothesized dolphin sonars [5, 6] and bat echolocators [29, etc.] use the same frequency range of 2–120 kHz and contain harmonics; the signal duration is comparable. Similarly, the contours of changes in their frequency of FM-signals (linear or nonlinear increase, or decrease in frequency with time at different rates, and their combination with repetitions) are similar. There are no fundamental differences between the FM signals of dolphins and bats. Such probing signals (only without harmonics) use FM Doppler and FM pulse-compression sonars and radars (neglecting the carrier frequency of the latter). These spread-spectrum signals have high correlation properties, so it is not surprising that they are used by various aerial-terrestrial, and marine mammals (Cetacea and Chiroptera), as well as in technology for high-accuracy determination of the range and Doppler shift of a target.

The results reviewed in this paper provide additional evidence for the hypothesis on the functionality of dolphin FM signals as probing signals for FM Doppler sonar and FM pulse-compression sonar [5, 6].

STATEMENT ON COMPLIANCE WITH ETHICAL STANDARDS

The study complied with all applicable international and national guidelines for the care and use of animals, as well as the principles of the organization at which the study was carried out.

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