

# Acoustic Signals and Echolocation System of the Dolphin

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**Abstract**—Two-channel recording of acoustic signals from two quasi-stationary dolphins has previously suggested that the dolphin echolocation system is more complex than discussed earlier, and includes at least four sonars. In the present work, two-channel recording of signals, analysis and interpretation of their functions were continued in terms of physical acoustics, signal theory and echolocation. The results indicate that the echolocation system of dolphins involves four organs to produce probing signals of five different types, which implies different mechanisms of their processing by the dolphin hearing; its operation corresponds to as many as six varieties of sonar systems. The results are of importance for studying the echolocation system of *Odontoceti* and for improving sonars and radars.

**Keywords:** dolphin, sonar, echo, signal, beam pattern, burst pulse, radar

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## INTRODUCTION

The dolphin echolocator is being studied since 1960s. The echolocation abilities of dolphins regarding discrimination, recognition and classification of underwater objects have been examined [1–10]. As the probing signals, the authors considered the short stereotyped acoustic pulses (~0.05 ms long) with a broad frequency spectrum (2–200 kHz) known as “clicks.” As a rule, each next click was emitted by the dolphin after having received the echo of the preceding click plus a period (15–45 ms) required for echo processing. It has also been shown that in producing and directing the clicks, an important role is played by the right tubular sac, the melon (fat-filled forehead) and the cranial bones [11–15]. Other acoustic signals of the dolphin—“whistles” and burst pulses—have been regarded mainly as communication signals [16–26].

However, two-channel recording of acoustic signals of two quasi-stationary dolphins has given grounds for supposing that the echolocation system of the dolphin, and perhaps *Odontoceti* in general, is more complicated than discussed earlier, and comprises at least four sonars of different types [27]. Each sonar appears to involve a particular organ that independently generates its type of probing sound (clicks, packs of noncoherent pulses, packs of coherent pulses, whistles), and each implies a corresponding mode of echo processing. Consequently, the characteristics of dolphin acoustic signals are determined by their func-

tion and are optimal from the standpoint of contemporary physical acoustics.

The present work continues the study of characteristics and possible functions of dolphin acoustic signals with respect to echolocation, physical acoustics, and signal theory. The particular goals of the work were recording and analysis of acoustic signals of two dolphins of the same species, quasi-stationary in a pool, using a two-channel system in a 0.1–220 kHz range.

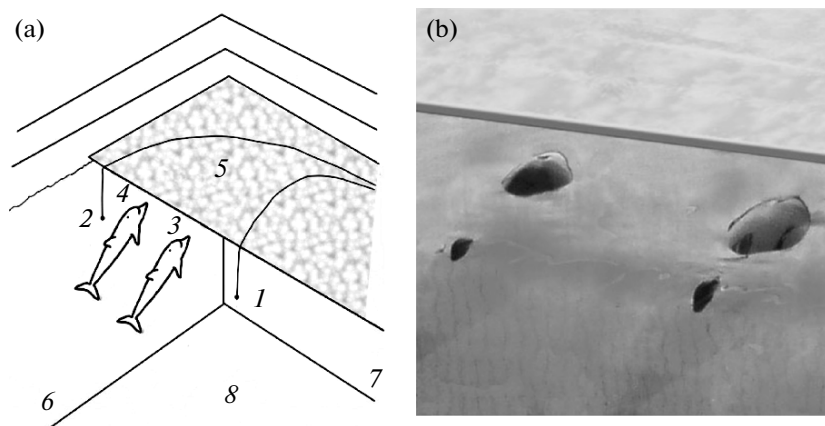
## EXPERIMENTAL

Recording sessions with two adult Black Sea dolphins (*Tursiops truncatus*), male Yasha and female Yana, were run in an indoor concrete pool (27 × 9 × 4.5 m) of the Karadag Natural Reserve, NAS of Ukraine. The dolphins have been kept in pool conditions for about 20 years and have normal hearing.

The experimental setup was the same as previously [27] (see Fig. 1). No special training or food reinforcement was employed. The dolphins produced sounds freely as they wished, being perhaps unaware of being recorded. No other animals were present in the pool during recordings.

The signals were recorded with a two-channel system in the time intervals when the dolphins stayed at the surface near the gangway and were nearly immotile (quasi-stationary) (Fig. 1) relative to the hydrophones and to each other. A two-channel system furnishes not only the temporal but also the spatial information about the signals, which is its main advantage over single-channel recording.

*Editor's Note:* The experimental data contained herein fully correspond to the original publication but authorized amendments in text have been made for the English version. A.G.



**Fig. 1.** (a) Experimental configuration: 1 and 2, hydrophones of channels I and II, positioned 3.5 m apart and 1 m deep; 3 and 4, dolphins Yana and Yasha, staying about 1 m apart; 5, gangway 0.1 m above water; 6, 7, 8, long and short sidewalls and bottom of the pool. Distance from 2 to wall 6, 0.3 m; distance from (1, 2) to wall 7, 3 m. Water depth, 4 m. (b) Dolphins quasi-stationary during signal recording.

The distance between hydrophones 1 and 2 was chosen to be 3.5 m in order to get a required inter-channel difference in signal levels and arrival times, and in order that the hydrophones were in the far acoustic field of the dolphin ( $\sim 1.5$  m). The hydrophones were also submerged to 1 m to reduce the probability of shielding the signal to the distal hydrophone by the other dolphin's body. To record the reflected signals, hydrophone 1 was positioned at mid-width of the pool while hydrophone 2 was close to the side wall (Fig. 1a). With this setup, all recorded signals with their reflections were assigned to the sender dolphin. Along with that, we registered the dynamics of interchannel levels, i.e. the changes in signal beam patterns. To this end, we examined the differences in arrival times and amplitudes for the two hydrophones with reference to the known distances between dolphins, hydrophones, and pool borders.

Two piezoceramic spherical hydrophones 14 mm in diameter had calibrated sensitivity of  $-203.5$  and  $-206$  dB re  $1 \text{ V}/\mu\text{Pa}$  ( $66.5$  and  $50 \text{ } \mu\text{V}/\text{Pa}$  respectively). The frequency flatness was  $\pm 3$  dB up to  $\sim 160$  kHz and  $\pm 10$  dB up to  $\sim 220$  kHz. Each recording channel consisted of the hydrophone, a  $0.1$  kHz high-pass filter, a  $40$  dB voltage amplifier and one channel of a multi-channel 14-bit analog-to-digital converter USB3000. The ADC had a dynamic range of  $81$  dB and a sampling frequency of  $1$  MHz for each channel. The digitized signals were continuously recorded to a notebook hard disk. Recording and processing was performed using PowerGraph 3.3.8 and Adobe Audition 3.0 packages. Spectra and sonograms were computed using 1024-point fast Fourier transform with Hamming weight function.

The acoustic pulses had a complicated shape, so to measure their duration the level was chosen to be  $-20$  dB. A large number of records were made for reli-

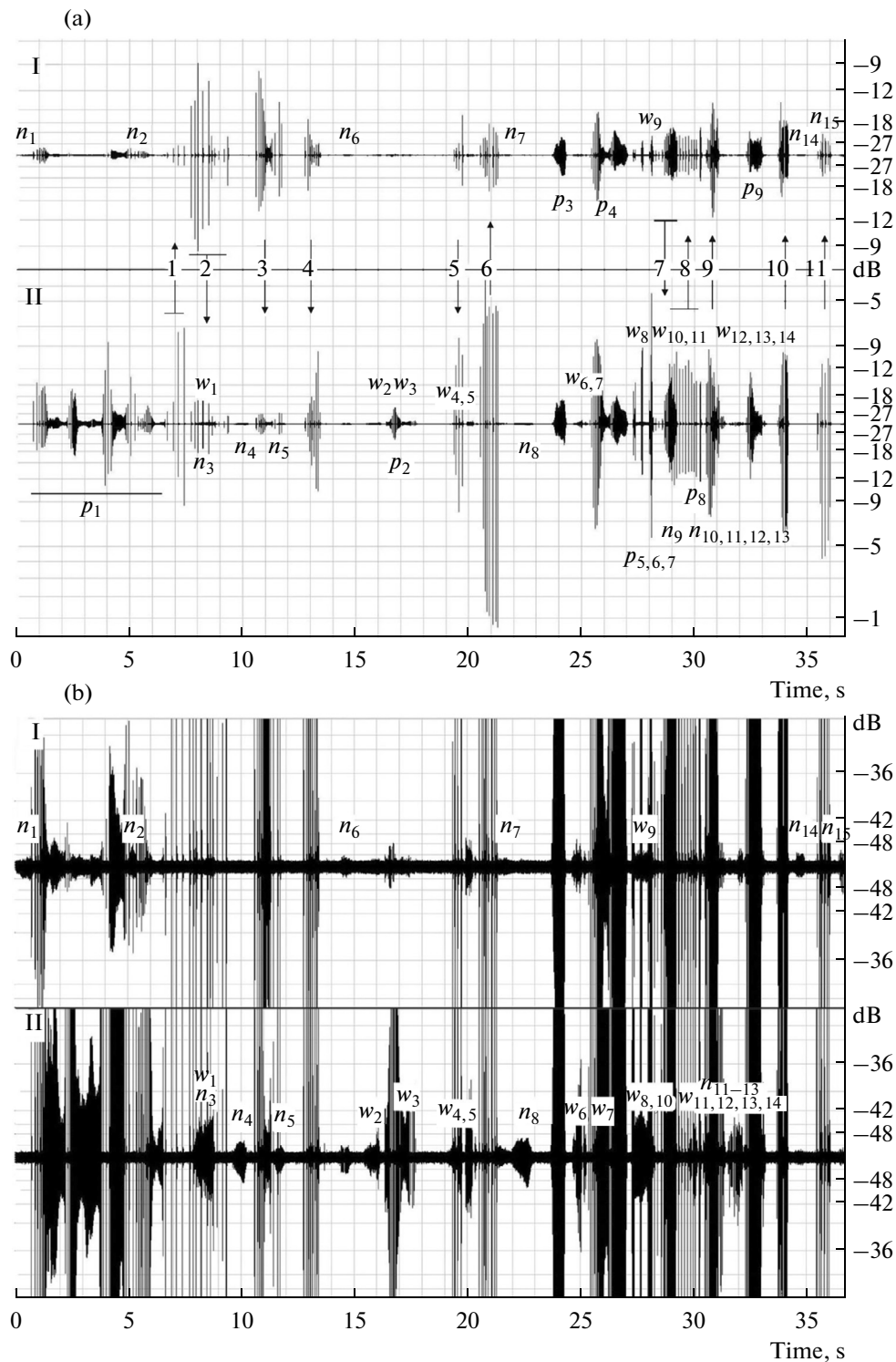
ability. One of the most typical records was chosen for the present analysis and discussion (Fig. 2).

## RESULTS

Figure 2 displays the temporal sequence of all acoustic signals produced by dolphins in the  $36.7$  s of recording. The signals produced by dolphins Yana and Yasha are accordingly marked in channel I and channel II. Because of the broad dynamic range of sound pressure level (SPL), the span of the ordinate in Fig. 2a is chosen to show all signals. Whistles and coherent pulses have lower SPL ( $-60$  to  $-36$  dB re  $1000 \text{ Pa}$ ) and are thus shown in a more convenient scale in Fig. 2b (while signals with  $\text{SPL} > -30$  dB are cropped).

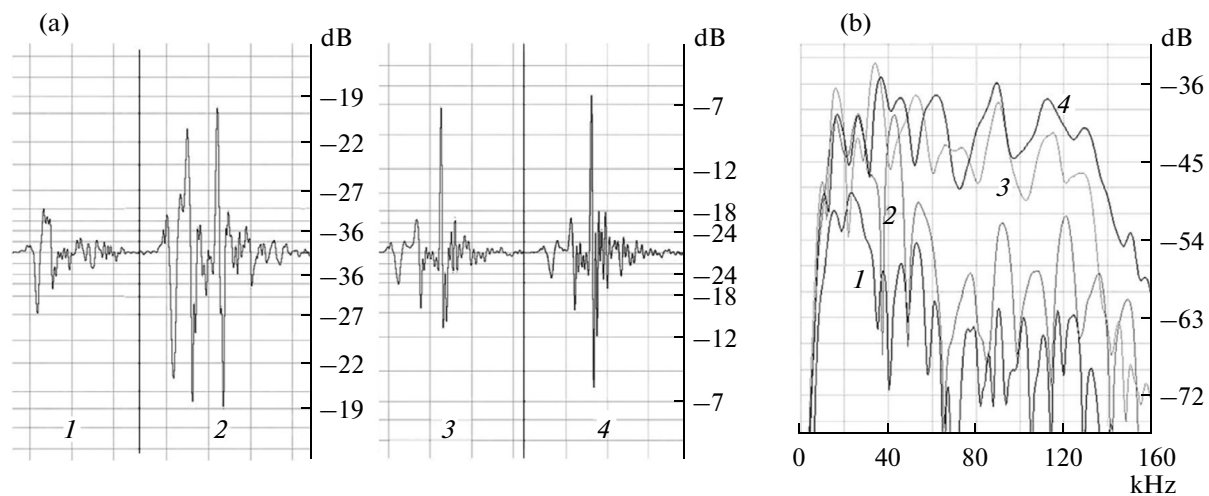
Dolphins produced pulses in packs. As a rule, packs of the same type are separated by intervals (hundreds of milliseconds to seconds) far longer than interpulse intervals ( $t_{mi}$ ) in packs ( $0.8$ – $300$  ms). The horizontal line in pack designation (Fig. 2) indicates duration. The acoustic signals of dolphins thus registered have been divided into five types in accordance with their characteristics.

Packs of noncoherent pulses (Figs. 2, 3, 7, Table 1) are denoted by symbol "arrow/ $n$ " (where  $n$  is the ordinal number of such signal) at the place of signal localization. The arrows are directed from the signal producer. The shape of these pulses was complex (Fig. 3) and changed from pulse to pulse within each pack. Therefore, the spectrum of each pulse has many ( $20$ – $30$ ) extrema varying in position and level in every pulse; it is for this reason that such pulses have been named noncoherent [27]. The energy of spectral components steeply drops at frequencies below  $10$  kHz and above  $140$  kHz (Fig. 3). The SPL of noncoherent pulses could be  $15$ – $1000$  Pa. The pack comprised  $4$ – $24$  pulses with interpulse intervals of  $260$ – $18$  ms. As a



rule, the interpulse intervals smoothly changed through the pack, and the relative change could reach 9.72 (Table 1). The duration of noncoherent pulses changed from 0.14 to 0.6 ms.

Packs of versatile pulses (Figs. 2, 4, 5, Table 2) are described for the first time; they are denoted as  $p_n$  (where  $n$  is the ordinal number of the signal) at the place of occurrence. The shape of these pulses was also



**Fig. 3.** Shape (a) and spectra (b) of four noncoherent pulses (1, 2, 3, 4) of pack 1 (Fig. 2a, channel II) emitted by Yasha from 6.66 to 7.40 s of recording. (a) SPL (dB re 1000 Pa) vs. time, 0.1 ms per line; (b) spectral density (dB) vs. frequency.

complex. Interpulse intervals, amplitude, shape, and spectrum of versatile pulses could smoothly (from pulse to pulse) change within a pack. SPL was 3–590 Pa, and the sonogram encompassed 3–200 kHz. The spectrum of versatile pulses had many extrema and covered frequencies from 14–47 to 56–126 kHz at –6 dB. With decreasing amplitude of pulses in the pack, the level of high-frequency components declined (Table 2). The pulse sequence in the beginning of the pack, as a rule, had large interpulse intervals, which could smoothly vary (Figs. 2, 4). On the other hand, there were packs where pulses had identical shape with constant interpulse intervals ( $p_8$ , Fig. 5), being thus mutually coherent. The duration of versa-

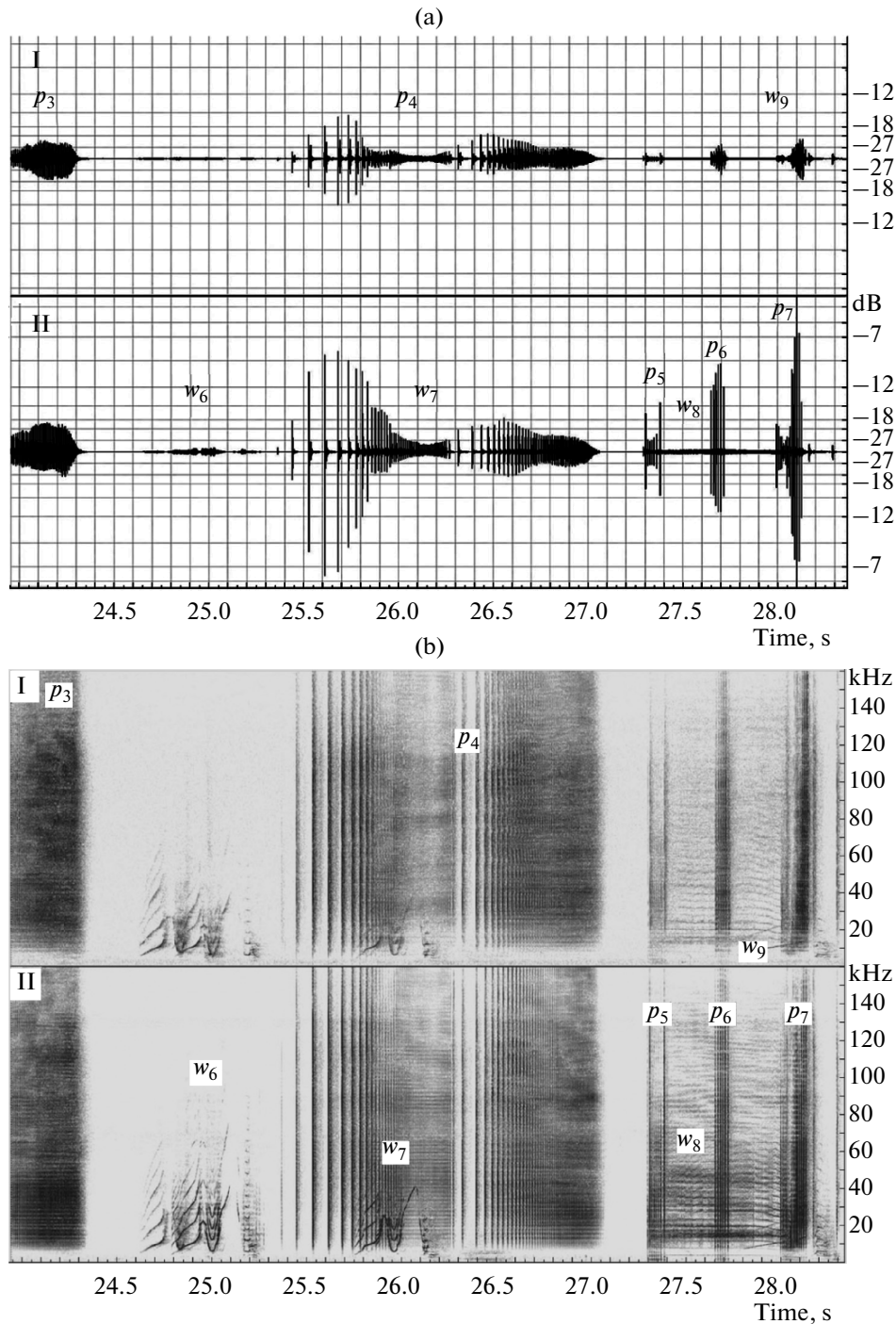
tile pulses varied within 0.08–0.37 ms, and pack duration from 5920 to 43 ms.

The interpulse intervals varied from 165 to 1.08 ms. The relative change in interpulse intervals within a pack ranged from 40.75 to –1.14 (minus signifying an increase in interpulse intervals through the pack) and did not depend on pack duration. Packs of versatile pulses comprised from 6 to 108 pulses and even 375 in  $p_1$  (Table 2). Pack  $p_1$  is conventionally marked as consisting of four subpacks (1–1)–(1–4) in accordance with the change in pulse amplitude, from maximal to minimal. The characteristics of each next pack of versatile pulses substantially differed from the preceding one.

**Table 1.** Main characteristics of noncoherent pulses

Pack no.	Number of pulses in pack	Mean spectral width (kHz, –6 dB)	Mean pulse duration, ms	Interpulse intervals, ms	Relative change in interpulse intervals	Pack duration, ms
1	4	13–115	0.23	254–219	1.16	743
2	10	10–118	0.25	260–125	2.08	1640
3	18	21–125	0.19	123–33	3.73	1110
4	8	29–127	0.26	109–80	1.36	660
5	4	19–125	0.27	170–98	1.73	390
6	8	21–121	0.14	175–84	2.08	780
7	23	26–103	0.6	175–18	9.72	1080
8	12	22–111	0.15	99–109	1.10	1220
9	24	12–127	0.3	50–29	1.72	970
10	12	19–140	0.2	58–26	2.23	510
11	6	16–122	0.25	130–83	1.57	560

The “interpulse intervals” column gives the maximal and the minimal values of intervals in the pack.

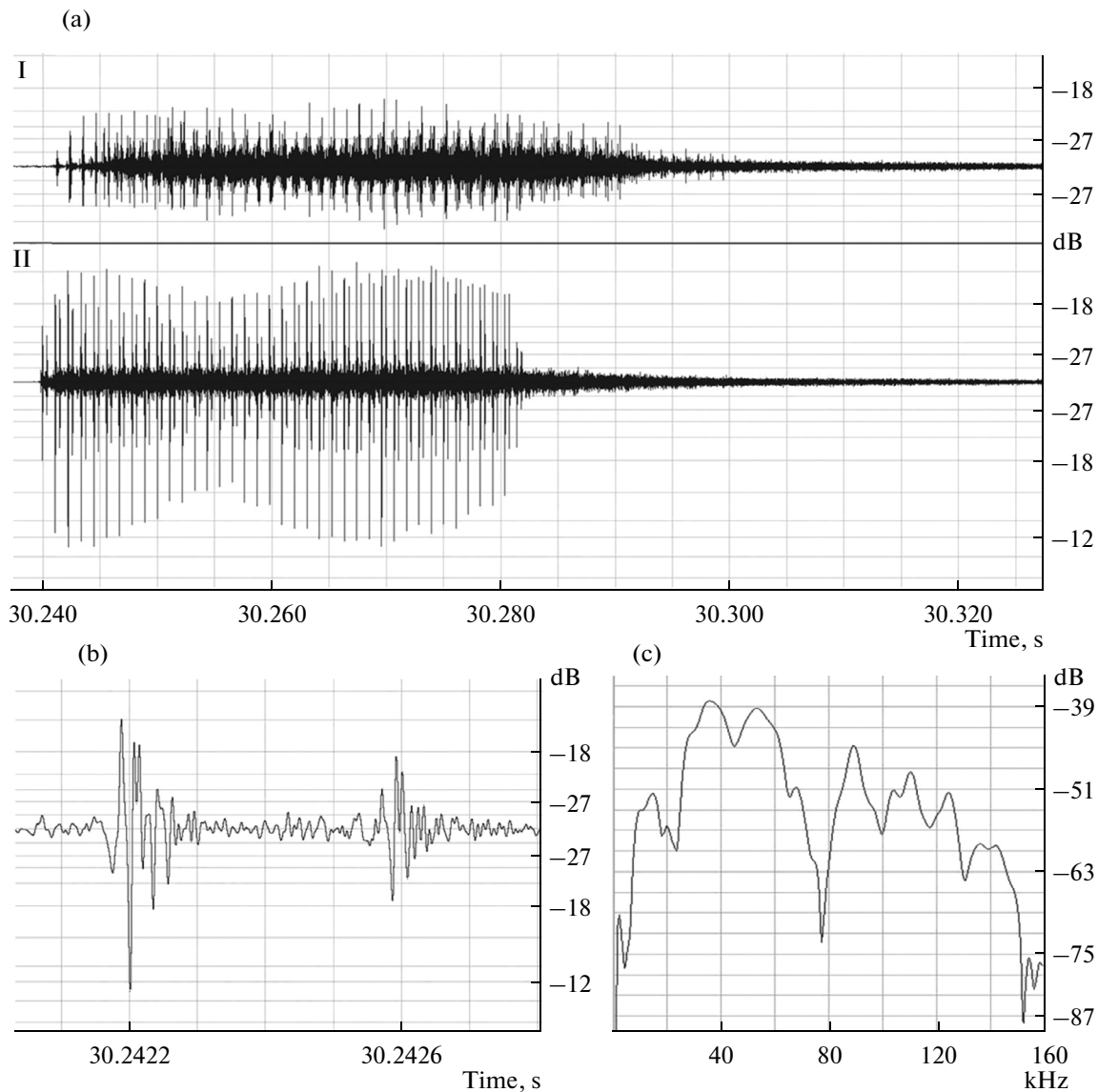


**Fig. 4.** Shape (a) and sonogram (b) of packs of versatile pulses ( $p_3$ – $p_7$ ) and whistles  $w_7$ – $w_9$ . SPL, dB re 1000 Pa; I and II, recording channels as in Fig. 2.

The duty factor for a pulse pack, i.e. the ratio of pulse duration ( $t_i$ ) to the interpulse interval ( $t_{mi}$ ), at high repetition rates reached 13% (Table 2). As will be seen below, the shape of versatile pulses may smoothly change through the pack in a broad range. Beside that, the dolphins do change the interpulse intervals in packs of such pulses and the direction and width of

their beam patterns; that is why such pulses are called versatile.

Packs of coherent pulses (Figs. 2, 6, Table 3) are denoted  $n_n$  (where  $n$  is the ordinal number of such pack) at the place of pack localization. The shape of these pulses was complex. The spectrum of coherent pulses occupies frequencies from 2.9–15 to 3.9–

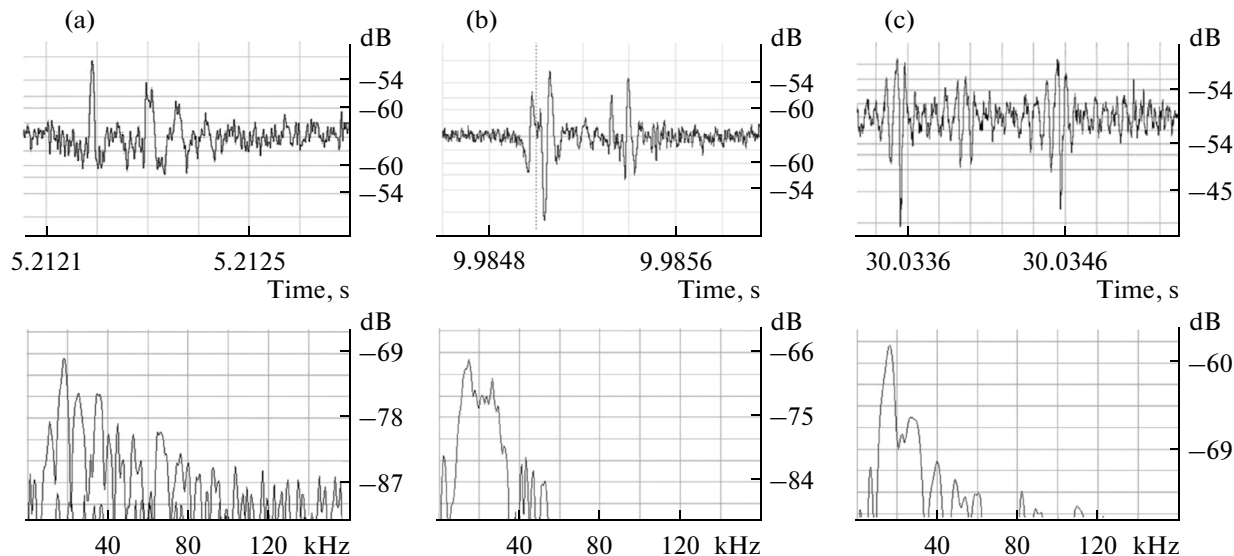


**Fig. 5.** (a) Pack of versatile pulses  $p_8$  recorded in two channels; (b) single pulse and its delayed reflection from wall 6 (Fig. 1); SPL, dB re 1000 Pa. (c) Spectrum of the single pulse (spectral density in dB).

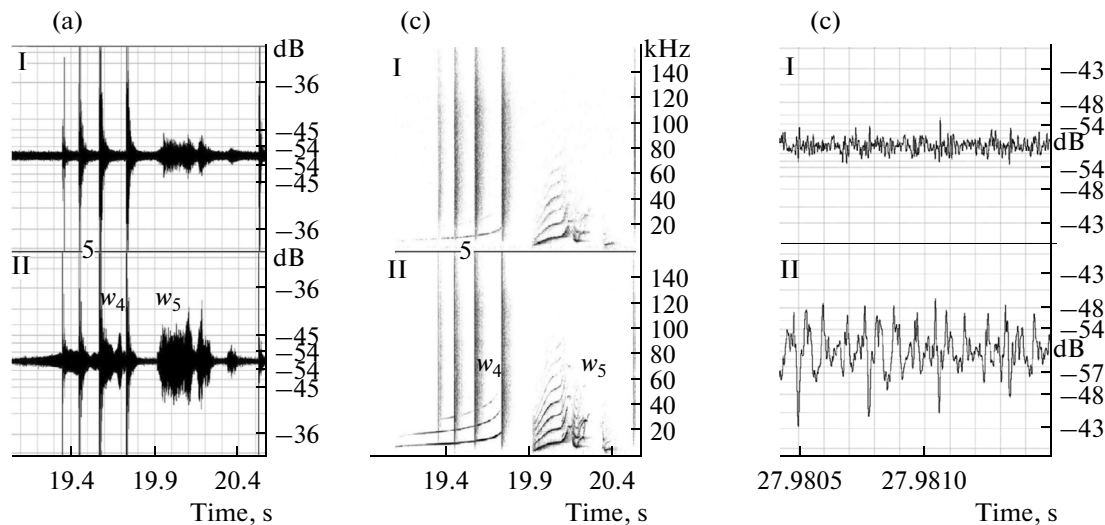
85 kHz (at  $-6$  dB) and can have many maxima and minima. There occur packs of relatively narrow-band pulses and of broader-band ones, but as a rule the energy maximum is at relatively low frequencies (10–30 kHz, Fig. 6, Table 3). From pack to pack the shape and spectrum of such pulses differ substantially. However, within a pack the pulse shape is consistent and the spectrum is unchanged, therefore such pulses have been called coherent [27]. The duration of these pulses was 0.1–1 ms. Unfortunately, their SPL rarely exceeded the noise level by 20 dB, so pulse duration was measured at the level of  $-12$  to  $-20$  dB. The interpulse intervals in coherent pulse packs as a rule smoothly decreased from the start to the end of the pack in a 39.0–0.8 ms range and rarely changed oppositely, but could as well stay unchanged (Table 3). The relative change in interpulse intervals within a pack

ranged from 6.6 to  $-2.6$  (minus signifying an increase in interpulse intervals through the pack) and did not depend on pack duration. The pack duration varied from 37 to 910 ms, the number of pulses in a pack varied from 8 to 423. The duty factor in some cases reached 20–40% (Fig. 6, Table 3). The characteristics of each next pack of coherent pulses substantially differed from the preceding one.

Whistles (Figs. 2, 4, 7, Table 4) are denoted  $w_n$  (where  $n$  is the ordinal number of the whistle) at the place of occurrence. The SPL of whistles reached 2–16 Pa. The range of their duration was 30–1020 ms. The fundamental frequency of whistles varied from 3.8 to 42 kHz, and the number of harmonics from 2 to 16 (Figs. 4, 7, Table 4). The number of harmonics, as a rule, was greater at the hydrophone proximal to the whistling dolphin than at the distal hydrophone. Har-



**Fig. 6.** Shapes (top) and spectra (bottom) of coherent pulses. (a) Single pulse of pack  $n_2$ , (b) single pulse of pack  $n_4$  and its delayed reflection from wall 6 (Fig. 1); (c) superposition of whistle  $w_{11}$  with a pair of coherent pulses of pack  $n_9$  (interpulse interval 1 ms, DF 30%) and their delayed reflections from wall 6. Top, SPL, dB re 1000 Pa; bottom, spectral density in dB.



**Fig. 7.** Comparison of (a) SPL (dB re 1000 Pa) in channels I and harmonics (b) of whistles  $w_4$  and  $w_5$  in channels I and II. (c) A fragment of noise-like whistle  $w_8$ .

monics occupied a frequency range up to 100 kHz. We have registered two noise-like whistles  $w_8$ ,  $w_{10}$  with SPL up to 10 Pa and more than 50 and 28 harmonics respectively (Figs. 2, 4, Table 4). The spectral components of these whistles in the range of dolphin hearing smoothly decayed with increasing frequency to a level of  $-15$  dB (at 135 kHz).

## DISCUSSION

In total, within 36.7 s of recording (Fig. 2, Tables 1–4) the dolphins produced: 11 packs of non-coherent pulses comprising 129 pulses; 9 packs of ver-

satile pulses comprising 721 pulses; 15 packs of coherent pulses comprising 1545 pulses; and 14 whistles; this is consistent with earlier results [27]. Thus, dolphins use a broad assortment of sounds even in the daytime. It may be supposed that noncoherent pulses are mainly used for communication, while the rest serve for orientation in the pool, to feel own movement relative to the other dolphin, the gangway, the pool walls and bottom, and to monitor the pool space at distances exceeding the visual transparency of water ( $>5$  m).

Dolphin's signals cover frequencies up to 250 kHz, but considering that their hearing threshold markedly

**Table 2.** Main characteristics of versatile pulses

Pack no.	Number of pulses in pack	Mean pulse spectral width (kHz, -6 dB)	Mean pulse duration (ms)/DF(%)	Range of interpulse intervals, ms	Relative change in interpulse intervals	Pack duration, ms	
1-1	86	23-124; 14-54	0.15/2%	165-7	23.57	1585	5920
1-2	96	30-125; 11-111	0.08	80-8.8	9.09	1535	
1-3	92	33-125; 8-34	0.09	148-4.3	34.42	1010	
1-4	101	28-121; 10-46	0.19	163-4	40.75	1642	
2	44	47-126; 23-71	0.11	83-19	4.37	1360	
3	71	23-113; 23-106	0.22	27-4.7	5.74	590	
4	108	26-120; 16-50	0.14	86-5.5	15.63	1710	
5	8	21-59; 24-40	0.16	18-11	1.64	90	
6	6 pairs	1(14-41) 2(21-90)*	1(0.21) 2(0.2)*	14-16 0.72-0.77**	-1.14	46	
7	18	19-56; 9-20	0.14	13.1-7	1.87	135	
8	39	27-90	0.14/13%	1.08	1	43	
9	46	33-123; 24-103	0.37/5%	64-6.7	9.55	680	

In the "spectral width" column, the first value is for pulses of maximal amplitudes, the second one is for minimal. \* 1st and 2nd pulses in pair. \*\* Between pulses in pair. DF, duty factor.

**Table 3.** Main characteristics of coherent pulses

Pack no.	Number of pulses in pack	Pulse spectral width (kHz, -6 dB)	Mean pulse duration (ms)/DF(%)	Range of interpulse intervals, ms	Relative change in interpulse intervals	Pack duration, ms
1	51	13-24	0.2	12.5-5.9	2.12	462
2	112	16-37	0.3	4-3	1.33	393
3	98	8-18*		12.7-5.9	2.15	840
4	86	11-26	0.18	13-5	2.60	600
5	138	10-20	0.35	3.8-3.3	1.15	820
6	16	14-38	0.35	33-28	1.18	400
7	230	14-19	0.38	3.3-2.9	1.14	690
8	125	10-28	0.23	27-4.1	6.58	910
9	32	12-21	0.3/30%	1-2	-2.00	34
10	75	11-55	0.17/20%	0.97-0.8	1.21	65
11	423	8-24	0.1/11%	0.85	1.00	360
12	15	9-35	0.38	22-28	-1.27	880
13	10	2.9-3.9	1/40%	2.5-6.5	-2.60	37
14	126	15-41	0.2/5%	4.6-3.3	1.39	470
15	8	11-85	0.28	34-39	-1.15	280

The first figure in "range of interpulse intervals" column denote the interval in the beginning of the pack; the second one, in the end.

\* Pack emitted simultaneously with whistle  $w_1$ . DF, duty factor.

risers above 135 kHz, the signal spectra and sonograms (Figs. 3-7) are shown only up to 160 kHz.

Either dolphin could produce acoustic signals of different types simultaneously (Figs. 2, 4, 7). For example, Yasha simultaneously emitted a coherent pulse pack  $n_3$  and a whistle  $w_1$ ; or a whistle  $w_3$  and a versatile pulse pack  $p_2$ ; or a noise-like whistle  $w_8$  and

versatile pulse packs  $p_5$ - $p_7$ ; or a noncoherent pulse pack 8, whistle  $w_{11}$  and coherent pulse pack  $n_9$ ; or a noncoherent pulse pack 9 and a coherent pulse pack  $n_{11}$ . Consequently, noncoherent pulses, whistles, and coherent pulses appear to originate from three different organs of the dolphin, which is consistent with earlier results [27]. Considering also the substantial



**Table 4.** Main characteristics of whistles

Whistle No.	Whistle duration, ms	Range of fundamental, kHz	Number of harmonics	Interchannel SPL difference, dB
1	930	4–22.8	5	12
2	640	7.5–21.9	4	20
3	390	7.5–11.1	4	18
4	630	7.4–18.2	4	16
5	490	4.6–27.9	10	7
6	610	4.5–40.7	16	12
7	430	4.4–41	5	15
8	1020	3.9 (3.9–135)	>50 nl	12
9	370	6.9–13.1	2	
10	165	11 (11–135)	>28 nl	8
11	395	5.5–36	8	3–6
12	30	5.4–5.6	5	10
13	370	3.8–35.4	15	7
14	400	4.5–42		18

(nl) Noise-like whistle, parenthesized is its frequency spectrum with harmonics at –15 dB.

**Table 5.** Characteristics of dolphin's probing signals

Type of signal	Mean duration $\Delta t$ , ms	Mean spectral width $\Delta f$ , kHz	Time-bandwidth product $B = \Delta t \cdot \Delta f$
“Clicks”	$0.012 \pm 0.002$	$90 \pm 5.5$	1.1
Coherent pulses	$0.315 \pm 0.215$	$15.7 \pm 10.9$	4.96
Versatile pulses	$0.166 \pm 0.08$	$79.3 \pm 22.9$	13.2
Noncoherent pulses	$0.258 \pm 0.123$	$104 \pm 9.2$	26.9
“Whistles”	$490 \pm 264$	$20.9 \pm 13.8$ (100)	10251 (49000)

Parenthesized values include harmonics.

difference in the characteristics of versatile and coherent pulses (Figs. 2, 4–6, Tables 2, 3, 5) and the similarity of SPL and spectral width of versatile and noncoherent pulses, we can suppose that the coherent and the versatile pulses are produced by different (yet unknown) organs, whereas versatile and noncoherent pulses are produced by the same putative organ.

It must be noted that in this experiment (Fig. 2), just as previously [27], the dolphins produced no clicks of their best-studied sonar [8], which may be explained by their melons being above water (Fig. 1b). Indeed, they did emit clicks (12  $\mu$ s at –20 dB) while solving other echolocation tasks in submerged position (Table 5). From the standpoint of signal theory, clicks are coherent ultra-broadband ultra-short signals. Consequently, the dolphin perhaps has at least four organs to independently produce five types of acoustic signal (clicks, packs of noncoherent or versatile pulses, packs of coherent pulses, and whistles).

Knowing the law of sound pressure decay in a spherical wave and taking the distances from either dolphin to the proximal and the distal hydrophone as 1 m and 3 m respectively, for omnidirectional emission the SPL at the distal hydrophone is expected to be 8–10 dB lower than at the proximal one. Yet the two-channel recording (Figs. 1, 2) reveals interchannel differences in SPL distinct from 8–10 dB (Figs. 2, 4, 5, 7, Table 4), which is indicative of directionality and spatial variation of the beam pattern emitted by a stationary dolphin. However, exact quantitative assessment of the dolphin beam pattern oscillation requires special research.

Noteworthy is the significant (up to two orders of magnitude) variation of interpulse intervals ( $t_{mi}$ ) in packs (Tables 1–3). In terms of echolocation, unique ranging of the target is possible at low repetition rates of probing pulses, when  $t_{mi} > t_{2w}$  (time of sound traveling two ways, to target and back). Yet in this case we get greater uncertainty in measuring the Doppler shift in

the echo. Thus, at low repetition rates the dolphin perhaps measures the distance to target, using clicks, coherent and versatile pulses, and also noncoherent pulses. It is also known that clicks are used by the dolphin for discrimination, recognition and classification of underwater objects [1–10].

Along with that, the use of coherent probing signals (clicks, coherent and versatile pulses) implies coherent processing of the echoes [27]: coherent acquisition of useful echo, coherent compensation of interfering reflections and echo processing in the “moving target indicator” (MTI) mode known in echolocation technology. The MTI improves the noise-immunity of the echolocation system in isolating the useful moving echo from the background of stationary reverberation interference, owing to mutual suppression of echoes from stationary clutter and accumulation of echoes from useful moving objects.

At high pulse repetition rates, when in packs  $t_{mi} < t_{2w}$ , it is possible to uniquely measure the echo Doppler shift. In this case the dolphin’s probing signal implies echo processing in the pulsed-Doppler sonar mode, widely used in technical echolocation. As distinct from frequency-modulated (FM) Doppler sonar, a coherent pulse pack has a discrete spectrum, with interline distance equal to the pulse rate. Upon reflection from a moving target, the lines of the channel pack spectrum shift in frequency according to  $f_d = -2V_r/\lambda$ , where  $\lambda = c/f$  is spectral line wavelength ( $c$  is sound velocity in water,  $f$  is spectral line frequency), and  $V_r$  is relative sonar–target radial velocity. Therefore, it may be supposed that the Doppler shift of echo frequencies ( $f_d$ ) will be “measured by the dolphin” even more accurately from the line spectra of direct and reflected coherent pulse packs than from the continuous spectra of whistles (since continuous spectra suffer greater uncertainty in frequency than discrete ones). To add, the varied contour of interpulse intervals in coherent pulse packs may perhaps be used by the dolphin as an operative label on each of its “own” packs to distinguish their echoes from the signals of its kin (and from one another).

At high repetition rates, in packs of coherent pulses the duty factor reached 20–40% (Fig. 6, Tables 2, 3). In echolocation technology, a pulse sequence with more than 10% occupancy is called quasicontinuous. Such an emission regime combines the advantages of pulsed and continuous modes of echolocation. With increasing number of pulses, there is a gain in energy of the probing signal and of its echo. For instance, after the end of pack  $p_8$  (Fig. 5, channel II) sent by Yasha it is clearly seen that the SPL of its echoes (Fig. 5, channel I) is not much lower than that of the direct signal. Judging from the delays (interval from 30.283 to 30.293 s), these may be reflections from the front pool wall (7 in Fig. 1), left (6) and right sidewalls and bottom (8); and then (30.293–30.303 s) arrive the echoes from the distal wall opposite to 7.

The time-bandwidth product ( $B = \Delta t \cdot \Delta f$ ) calculated from mean duration ( $\Delta t$ ) and mean spectral width ( $\Delta f$ ) of recorded dolphin signals proved to be type-specific (Table 5), and for the signals discussed here substantially exceeded that of simple signals (e.g., for a tonal radio pulse,  $B = 1$ ). This suggests complexity and functional specialization of dolphin sounds as probing signals in different types of sonar. Moreover, the noncoherent pulses, along with the echolocation function, appear to be conversational elements [27] and for this reason have the largest  $B$  among dolphin’s pulse signals; yet here we consider them only in terms of echolocation.

The spatial damping of sound in water steeply increases with rising frequency. The spatial damping factor ( $\beta$ ) below 20 kHz is insignificant,  $\sim 1$  dB/km, but about 100 kHz  $\beta > 33$  dB/km and at 1 MHz,  $\beta > 330$  dB/km. Therefore, the spectral width of dolphin signals (up to 150 kHz) does not allow using a higher carrier frequency to increase the sonar range. Thus it appears that Nature had to provide dolphins with different specialized probing signals (clicks, packs of coherent, noncoherent and versatile pulses, whistles) and corresponding echo-processing mechanisms, each optimized to a particular echolocation task.

Noncoherent and versatile pulses appear to originate from the same putative organ, they cover the same frequency band and have close SPLs; and at first glance should better not be classed separately. However, the distinctions in other structural and dynamic features considered above are indicative of their functional specialization, whereby they must be regarded as distinct types of pulse signals.

Interestingly, versatile pulses through the pack  $p_1$  (Fig. 2, channel II) assumed an almost uniform shape when their SPL was maximal (intervals 0.75–1.3, 2.35–2.65, 3.85–4.2, 4.9–5.25 s). Spectral analysis of such sequences reveals substantial attenuation of high-frequency components and a corresponding downshift in the frequency of the energy peak with declining pulse amplitudes (Table 2, Fig. 4, packs  $p_3$ – $p_7$ ). Also, noncoherent pulses in packs 1–5, 9 (Fig. 2) as well as versatile pulses in packs  $p_1$ – $p_9$  (Fig. 2) exhibit a smooth pulse-to-pulse variation in amplitude. The law by which amplitudes change in channels I and II can be similar among noncoherent packs (2, 3 and 9) as well as among versatile ones ( $p_2$ ,  $p_4$ ,  $p_5$ – $p_8$ ), but can also differ for packs of pulses of the same type (noncoherent 1, 4, 5; versatile  $p_1$ ,  $p_3$ ,  $p_9$ ). Furthermore, the pulse amplitude at the proximal hydrophone is often higher than at the distal hydrophone (packs 1–3, 6, 8–11 of noncoherent and  $p_1$ ,  $p_2$ ,  $p_5$ – $p_8$  of versatile pulses) but can also be lower than that (noncoherent 4, 5, 7; versatile  $p_3$ ,  $p_4$ ,  $p_9$ ). These facts in the aggregate are again indicative of signal modification and oscillation of the beam pattern taking place as the dolphin emits noncoherent and versatile pulses without changing its body position. The beam pattern in  $p_1$  when the pulses have

maximal amplitude and nearly identical shape (Fig. 2, channel II) appears to most closely match the direction onto hydrophone 2 (Fig. 1).

It is noteworthy that the dolphin can modify the pulse shape (Figs. 2, 3, 4) to the extent of producing packs of versatile pulses of constant shape with constant interpulse interval (Fig. 5), i.e., of coherent ones; yet in this case the pulses are broader-band and have higher SPL than the coherent pulses generated by another (also unknown yet) organ (Fig. 6). The characteristics of noncoherent and versatile pulses imply their echo processing in different modes (equivalent to MTI, pulsed-Doppler sonar, incoherent sonar, and maybe others yet unknown to us). A sonar using such pulses can perform a broad range of tasks, so it may indeed be called universal.

Probing signals similar to dolphin's noncoherent and versatile pulses are employed in echolocation technology—these are concatenated signals with chopper modulation. They consist of discrete subpulses, such that

$$\begin{aligned} f(t) &= f_1(t) & 0 < t < T_1, \\ f(t) &= f_2(t - T_1) & T_1 < t < T_2, \\ &\dots \\ f(t) &= f_n(t - T_{n-1}) & T_{n-1} < t < T_n. \end{aligned}$$

Individual subpulse intervals  $T_{i+1} - T_i$  may be identical or not, while subpulse functions may be partially zeroed so that the signal becomes a chain of separate pulses with different interpulse intervals. Subpulses may have different modulation function. Such signals can provide an ambiguity function with one sharp lobe.

The characteristics and possibilities of the dolphin sonar based on noncoherent and versatile pulses present special interest and demand special future study. Considering that noncoherent pulses are elements of dolphin language as well as echolocation signals [27], the results reported here corroborate the dual purpose (previously referred to as “bimodality” [27]) of versatile as well as noncoherent pulses.

As to the coherent pulses, their features (Figs. 2, 6, Tables 3, 5) are consistent with the data on free-ranging Hawaiian spinner dolphin (*Stenella longirostris*) and Atlantic spotted dolphin (*Stenella frontalis*) [28, 29]. That is, the Black Sea bottlenose dolphins use packs of coherent pulses (Fig. 2) just as Hawaiian and Atlantic dolphins, supposedly in a pulsed-Doppler sonar [27]. Along with that, coherent pulse packs  $n_1 - n_5$ ,  $n_7 - n_8$  display smooth pulse-to-pulse changes in amplitude and interpulse interval (Fig. 2). It is not always possible to compare the changes in levels at the two hydrophones because signals at the distal one are masked by noise ( $n_1 - n_5$ ,  $n_8$ ,  $n_{12}$ ,  $n_{14}$ ,  $n_{15}$ ). However, the pulse amplitude in pack  $n_8$  at the proximal hydrophone was greater than at the distal one by almost 14 dB (i.e. 5 dB higher than expected for an undi-

rected signal). When the pulse amplitude substantially exceeded the noise level, one could see the profile of amplitudes in channels I and II: it could be similar ( $n_6$ ,  $n_{11}$ ) or different ( $n_7$ ); in packs  $n_6$  and  $n_7$  the pulses at the distal hydrophone were even stronger than at the proximal one, almost by 4 dB (Fig. 2). To add, spectral analysis revealed a decay of high-frequency components with decreasing pulse amplitude (usually at the start or end of pack). Thus, coherent pulses do not appear to be definitely directed. Anyway, directionality is markedly less pronounced than for noncoherent and versatile pulses or whistles. Consequently, the echoes of coherent pulses would arrive over a broad space around the dolphin. As dolphins emit coherent pulses over distances of 3–14 m [29], such signals have the lowest SPL (1–10 Pa) among all those registered (Figs. 2, 6). Perhaps dolphins use coherent pulses near obstacles (underwater rocks, bottom) or water surface, or near each other, when it is important to monitor the relative movement and velocity without using vision, in order to avoid collisions. Moreover, at high repetition rates (0.3–1.25 kHz) in coherent pulse packs and target distances within 2.5–0.6 m (when  $t_{mi} > t_{2w}$ ), the dolphin can, along with the Doppler shift, accurately assess the distance to target. This is suggested both by the high enough level of echoes from the pool sidewall, Fig. 6b, and the high temporal resolution of dolphin hearing, ~0.02 ms [30–33], which allows the dolphin to process short echoes coming from such small distances.

Regarding the recorded whistles, their fundamental contours and the number of harmonics (Figs. 2, 4, 7, Table 4) are generally consistent with other data [16–26]. However, Yasha produced whistles  $w_6$ ,  $w_7$ ,  $w_{11}$ ,  $w_{13}$  and  $w_{14}$  with fundamentals from 3.8–5.5 up to 35–42 kHz, which is somewhat higher than in the cited works (within 20–35 kHz). To add, for the first time we have recorded two broadband noise-like whistles  $w_8$  and  $w_{10}$ , with SPL up to 10 Pa (Fig. 4, Table 4) and >50 and >28 harmonics respectively. These signals carry enough energy in the human audio range, so during playback they are well heard as noise pulses. On aggregate evidence, they originate from the same organ as common whistles, but are distinguished by shape and spectrum (Figs. 4, 7). Neither high-fundamental nor noise-like whistles have earlier been noted in dolphins, which might be explained by limitations of that recording equipment. Remarkably, high-fundamental  $w_6$ ,  $w_7$ ,  $w_{11}$ ,  $w_{13}$ ,  $w_{14}$  had complicated contours, with sharp inflections attended by broadband noise-like splashes conspicuous in the sonogram (Fig. 4).

It should be noted that practically all whistles were produced by Yasha (Fig. 2); Yana emitted only  $w_9$  (at 27.76–28.13 s). At about the same time Yasha emitted a noise-like  $w_8$  and a versatile pulse pack  $p_7$  (Fig. 4). Intriguingly, earlier [27] in the same conditions the whistles of the same dolphins were shaped differently, and their fundamental did not exceed 28 kHz.

Signals like dolphin whistles are used in echolocation technology. In a general form, they are described by one or several functions of equal duration. When these are tones, the signal is called a simultone. The ambiguity function for equispaced tones is multilobed. A simultone has strong amplitude modulation, increasing with the number of harmonics. If the number of harmonics in the given frequency band is large, the signal resembles banded noise, like  $w_8$  and  $w_{10}$  (Figs. 2, 4). A dolphin's whistle, along with harmonics, may bear amplitude, frequency, and phase modulation. Technically, such are the probing signals of a Doppler sonar. It appears that the dolphin can also use them in an FM Doppler sonar; the echo is perhaps processed in Doppler filters tuned to determine the frequency shift not only for the basic tone but also for harmonics, which should substantially enhance sonar sensitivity at low radial velocities [27]. Therewith the varied contour of each whistle may be an operative label distinguishing the echoes of own whistles from whistles of other dolphins (and from one another).

On the other hand, the broad frequency band of whistles (with harmonics, up to 100 kHz; and even 135 kHz in noise-like ones) suggests their possible use in a pulse-compression sonar [27]. In this case the echoes may be processed in the matched filter of dolphin hearing. The response time of such a filter is known to be inversely proportional to the spectral width and independent of the whistle duration or the fundamental contour shape. The echo compression factor will equal the signal time-bandwidth product, which amounts to 10251 even considering only the fundamental range, and 49000 with harmonics (Table 5); it is still greater for noise-like whistles, e.g.,  $w_8$ , about 108000. This means that dolphin whistles are nearly ideal as probing signals in the pulse-compression sonar. Thereby, long broadband signals provide high range resolution at greater distances to target, and require less peak power of the generating organ, because to put in more energy the dolphin can simply emit a longer whistle. The varied contour of each whistle may also serve as an operative label.

Notable are the changes in directivity of whistles emitted by quasi-stationary dolphins. In particular, the maximal SPL of  $w_4$  (Fig. 7) was  $-45$  dB in channel II but  $-61$  dB in channel I (a 16 dB difference), with only the fundamental seen in the channel I sonogram; for the next whistle  $w_5$  (in 180 ms) the interchannel difference in SPL was only 7 dB (as for an omnidirectional signal), with similar envelope shapes and harmonics well seen in both channels. Comparison of interchannel differences in SPL of  $w_2$ – $w_4$ ,  $w_7$ ,  $w_{11}$  and  $w_{14}$  (Table 4) testifies to dolphin's ability to rapidly and broadly vary the whistle beam patterns without body movement. Most plausibly, in our case the whistles were used for orientation.

Whistles are known to be used by dolphins in certain behavioral contexts [16, 17]: “signature whistles”

for personal identification [20], maintaining group cohesion or contacts between remote individuals [23] at distances up to 10.5 km [26]. Admittedly, sweeping of the beam would markedly complicate the task of determining the direction in which the whistling dolphin moves [8, 34], but clearly the functions just mentioned were not relevant to our sessions (Fig. 1). Thus the generally consistent idea is that whistles also have a dual purpose: communication and orientation (pulse-compression and FM Doppler sonars).

How does the dolphin perceive and sort out this multitude of acoustic signals and echoes? The area of maximal sensitivity of its “new external ear” (mental foramen and mandibular canal) [35–37] encompasses the nasal, ventral, and lateral directions. Moreover, the partial nasovertral overlap of the directionalities of the left and right ears gives rise to a complex spatial and frequency pattern of receptivity [35, 37, 38]; together with binaural features, this ensures detection and 3D location of conversation characters, echoes of own sonar probes [27] and actually any acoustical inputs.

Clearly, dolphin sonars, which have evolved over many million years, deserve further in-depth study, the more so that such research may be beneficial for technical echolocation and radiolocation.

## CONCLUSIONS

1. The echolocation system of the dolphin, and perhaps Odontoceti in general, is more complicated than earlier supposed, and involves at least four organs to independently produce acoustic signals of different types: whistles (simultones), packs of coherent, versatile and noncoherent pulses, and clicks (coherent ultra-broadband signals).

2. All acoustic signals of the dolphin are complex probing signals of its multiple sonar systems adapted to performing various echolocation tasks. Along with that, noncoherent pulses appear to be elements of the dolphin “spoken language.” Other signals in a varying degree can also serve the dual purpose: echolocation and (limited) communication.

3. The sonars using whistles, noncoherent and versatile pulses are distinguished by fast and broad variation of the beam patterns without body motion.

4. The commonly known probing signals and the new types considered here imply various regimes of echo processing by the dolphin that have equivalents in echolocation technology—moving target indication, pulsed-Doppler sonar, pulse compression sonar, FM Doppler sonar, incoherent sonar—and maybe others (versatile sonar).

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