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ISBN 91-87272-23-7

Produktion: Swede Publishing AB

Sätter: TextOmsorgen AB

Tryckeri: Östertälje Tryckeri AB

Stockholm 1991

SPERM WHALE CLICKS: PULSE INTERVAL IN CLICKS FROM A 21 M SPECIMEN.

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ABSTRACT

Clicks from a large sperm whale, *Physeter catodon*, were recorded intermittently over a period of 34 hours in Skálafjörður, in the Faroes. Clicks consisted of series of pulses with constant intervals of 7.6 msec. Previously reported intervals have been in the range of 2 to 4.8 msec.

The present findings support a theory on sperm whale sound production (Norris, K.S. and Harvey, G.W. (1972): "A theory for the function of the spermaceti organ of the sperm whale", NASA SP-262, USA), predicting a simple relationship between the size of the animal and the pulse intervals in the clicks. Measurements of pulse intervals may consequently allow remote determination of sperm whale size.

INTRODUCTION

Sperm whale, *Physeter catodon*, clicks have been recorded and described a number of times, most detailed by Backus and Schevill (1966). Generally, the clicks are emitted in trains, with repetition rates of less than 50 clicks per second. Each click, which sounds like a hammer blow on a nail, can be resolved into a series of regularly spaced pulses of decreasing amplitude (cf fig 2 and 3). Pulse duration has been reported in the order of 1 msec, while the range of interpulse interval has not been explored. In one particular click, Backus and Schevill (1966) found intervals of 2-4 msec between pulses. In addition to a pulse interval of 2 msec from one of their own sperm whale click recordings, Norris and Harvey (1972) cited 4.8 msec as the largest interval reported. Backus and Schevill used interval in the sense of pulse spacing, while Norris and Harvey use interval and interpulse interval in the sense of pulse spacing plus duration. We will use the term pulse interval in accordance with Norris and Harvey (1972) for the time lapse from one particular event in a pulse to the homologue event in the following pulse.

The monstrous shape and complex anatomy of the sperm whale forehead, which can occupy more than 1/3 of the total body length have incited a number of diverse speculations about its function. Norris and Harvey (1972) reviewed those deduced on anatomical evidence and added a number of their own observations on the forehead structure. They proposed a sound producing and focussing function of the forehead complex as a whole.

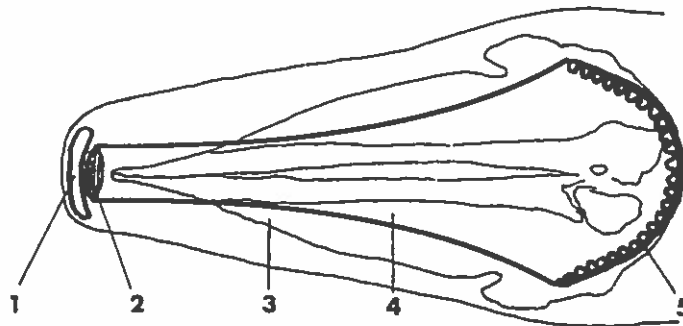


FIG 1. Schematic drawing of the relative positions of the anatomical structures with a proposed acoustic function in the sperm whale forehead. 1. Distal air sac. 2. Mousseau du singe. 3. Skull. 4. Spermaceti case. 5. Parabolic frontal air sac.

The crucial structure (see fig 1, and fig VII.4 in the Appendix) is the spermaceti organ, which is an elongated bag containing a liquid wax, that will transmit sound at the remarkably high velocity of 2.6 km/sec (Diercks, cited in Norris and Harvey 1972). The spermaceti organ is located between two air sacs, which function as sound reflecting mirrors. The nearly parabolic frontal air sac borders against the skull, while the distal air sac is situated at the tip of the snout, anterior of the spermaceti "case". Between the distal

air sac and the anterior end of the spermaceti organ there is a peculiar, lip-shaped structure on connective tissue, termed the "museau du singe", which Norris and Harvey considered the most likely organ for the generation of clicks. They suggested that a single, intense pulse is emitted at the anterior end of the spermaceti organ, and "that the first pulse probably represents this initial signal transmitted directly into the water ahead of the whale, while the remaining pulses in the click represent reverberations of the backwardly directed portion of the signal, between the two air mirrors that bound the ends of the spermaceti organ". Accordingly, the pulse interval represents the transit time of two traverses of a pulse down the length of the spermaceti organ between the bounding sound mirrors. Since the distance between the mirrors is a function of the size of the whale, the theory predicts brief pulse intervals in the clicks from small specimens and long intervals from large specimens. The pulse interval is hence fixed by anatomical characteristics and no control over its duration should be possible by the individual.

Norris and Harvey were able to measure the pulse intervals in clicks recorded from a sperm whale, and used this to calculate its total body length according to their theory. An independent body length estimate was obtained by comparing the whale with the length of the boat used for the recordings. Both estimates turned out to be 9 meters. So far no further experimental evidence, testing their theory, has been reported, not surprising, considering the enormous size and elusive habits of this fascinating species.

Unusual circumstances, however, provided an opportunity for the acquisition of additional information. During a period of 4 weeks in April 1975 a single sperm whale was confined to a fiord named Skálafjordur at Esteróy in the Faroes. We were able to record the clicks from this specimen on two consecutive days. For comparison with the acoustical estimates, the size of the animal was estimated from air photographs. The present paper deals with pulse intervals in the clicks from this animal, in an attempt to answer two questions, and thereby testing the predictive power of the Norris and Harvey theory: 1. Is the pulse interval constant, when measured over a long period of time? 2. Is the recorded pulse interval related to total body length?

MATERIALS AND METHODS

Skálafjordur is approximately 14 km long, 1 km wide and has a greatest depth of 80 meters. The brinks are gently sloping towards the middle. Two kilometers from the mouth of the fiord the bottom raises gradually to a threshold with only 30 of water. The part of the threshold facing inwards is almost vertical. No discontinuities in temperature or salinity are found (Bogi Hansen, Academia Faeroensis, pers. comm.). When the small fishing vessels, ferries and traffic to ship building industries, which were the main noise sources in the fiord, were inactive, the fiord was very quiet, compared to the open sea.

The sperm whale was first observed on April 1. It swam quietly about, dived and surfaced at irregular intervals. It appeared undisturbed by the local boat traffic. It is an open question whether the whale was trapped in the fiord, discouraged from returning to

open sea by the sound reflecting properties of the threshold (cf Dudock van Heel 1962), or it stayed by preference. On April 29 a fisheries research vessel, using its horizontal sonar, was actively driving the whale out of the fiord (Kjartan Hoydal, Fiskirannsoknastuin, pers. comm.).

The length of the whale was estimated by throwing a 1.2 meter wooden rod alongside it from a helicopter, and subsequently photographing both from a height of approximately 100 meters. One photograph was taken almost vertically above the whale when the rod was only 6 meters away. With a resolution of 0.8 meters, this resulted in an estimate of the total body length of 21 meters. Another photograph, taken at an angle and with the rod located about 100 meters from the animal, gave a total body length estimate of 23 meters (resolution 2 meters). Thus this was indeed a very large whale. The largest previous record in modern times was 20.7 m (Tomilin 1957). Several "eye ball" estimates by persons passing by the whale at close range varied between 10 and 18 meters. The present authors feel entirely incapable of producing a realistic estimate in this way without extensive training.

Only male sperm whales have been observed at latitudes as far north as that of the Faroes (Bruyns 1971). Moreover, the size of the Skálafjordur specimen was about twice the maximum for female sperm whales (Matthews 1938). Thus, most likely the Skálafjordur whale was a male.

Sound recordings were obtained at 6 stations, spread over a distance of 7 km. A Brüel & Kjaer 8100 hydrophone, suspended to a depth of 6 meters, was used for 32 of the 36 click trains recorded. The remaining 4 click trains were obtained using a specially built hydrophone and amplifier set-up. The response of the latter combination was flat within 6 dB from 0.35 to 11 kHz. This hydrophone was operated at 3 meters depth.

The signal from the 8100 hydrophone was amplified by a Brüel & Kjaer 2425 amplifier or alternatively using a specially built amplifier system, and then recorded on a Nagra IV-D tape recorder. 7 click trains were recorded on a Uher 4200 tape recorder. Recorder input was monitored on a Sony Tektronix 323 oscilloscope. The overall response of any B&K 8100 combination was essentially determined by the tape recorders, the frequency response of which was 3 dB down at 21 and 18 kHz, respectively.

The unit chosen for analysis was the click train, which was considered to be terminated when the click interval exceeded the preceding interval by a factor of 10. The 36 recorded click trains contained 1864 recognizable clicks, emitted in 1764 seconds. The recordings were obtained between 11 am and 3 pm on April 10, and between 3 pm and 9 pm on the following day.

Clicks selected for analysis were played back at reduced speed, digitized to 8 bit at an effective rate of 40 kHz, and then stored in the memory of a Nova 1200 minicomputer. The digital sample was plotted and the first, main pulse (P1 in fig 2) was identified, isolated and cross-correlated with the entire click. The correlogram was plotted (see fig 3b) and the positive peaks above a chosen level identified by the software with a time resolution of 25 μ sec. Finally, the time of occurrence and magnitude of each peak was printed out. Spectrum analysis was performed on a limited number of pulses digitized at a rate of 160

kHz, and repetitively applied to a slowly scanning, narrow band wave analyser (Brüel and Kjaer 2010), via a D/A converter and a low pass filter, according to the method of Broch and Olesen (1970).

RESULTS

The sampling strategy chosen was as follows: The number of clicks in a train were counted and the first, middle and terminal clicks were selected for analysis, irrespective of train duration, click rate and recording quality. If the tape recorder had been switched on after the onset of a train, the first click occurring after 2 seconds was chosen.

A. Description of the click

The overall waveform of the clicks from the Skálafjordur specimen were highly variable in terms of periodicity of cycles, pulse duration and number of pulses in each click. The concept of signature (Backus and Schevill 1966) seemed to apply only to clicks within a train or even part of a train. Consequently, a description of the clicks can only treat some general features of relevance to pulse intervals. These features applied to most, but not all clicks recorded. Fig 2 illustrates the general pattern of the click waveform. The first event, labelled P0, was usually more than 30 dB below the peak intensity of the next following pulse, and consequently only recognizable at increased amplification (fig 2, lower part). The waveform of P0 showed no characteristic features and no apparent resemblance to the later events in the click, as shown by the absence of prominent peaks in the correlograms. The onset of P0 was estimated to occur 6.5 msec ($n=13$, $SD=0.19$) ahead of the main pulse P1.

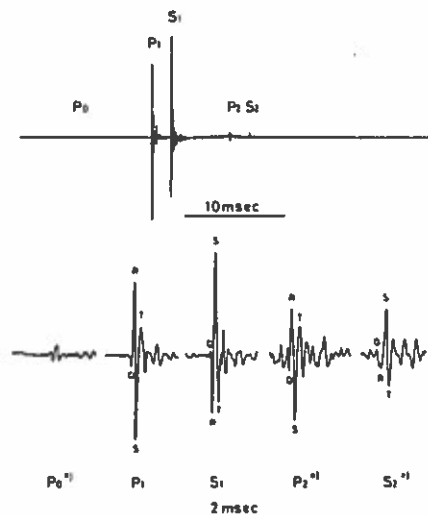


FIG 2. Waveform of a sperm whale click with simple pulses. Upper part: continuous record. Labelled events are discussed in text. Lower part: expanded views of segments covering the labelled events. Those marked x) have been amplified 20 dB relative to the upper part. Homologous peaks of the various pulses are identified by letters.

The main pulse, P1, consisted of from 1 to 5 or more high intensity cycles. Pulses with 2 or less regular cycles are labeled simple pulses, and they usually produced unambiguous pulse intervals. The duration of P1 at 10% of the peak amplitude ranged from 3 to several msec. The periodicity varied from 0.04 to 0.7 msec. The P1 was not representatively sampled, but in a sample of 22 consecutive clicks with simple P1 pulses, the peak energy was found to vary between 6.2 and 6.5 kHz with effective bandwidths (Albers 1965) from 4 to 8 kHz.

A phase inverted replica of P1, labelled S1, occurred after P1 at any delay between 1 and 3.5 msec. In the correlograms, S1 showed a high, negative correlation with P1. S1 is interpreted as an artefact, resulting from a reflection of P1 on the water surface.

The second proper pulse of the click is labelled P2. It was generally of much lower amplitude than P1 (ranging from -3 to -30 dB rel to P1). As a rule, simple, high intensity P1 pulses were followed by low intensity P2 pulses like the one shown in fig 2. In clicks with a more complicated P1 waveform, higher order pulses had less relative attenuation, giving a characteristic, exponentially decaying pattern (fig 3a). In clicks with simple pulses, and with favourable signal to noise (S/N) ratio, P2 always appeared to have the same phase polarity as P1, such as presented in the lower part of fig 2. This feature was more pronounced in the correlograms, where even highly complicated P1 pulses would correlate positively with P2.

Following P2, a phase inverted version, S2, appears. The P2-S2 interval was equal to the P1-S1 interval, and S2 was therefor considered to be the water surface reflected P2 event.

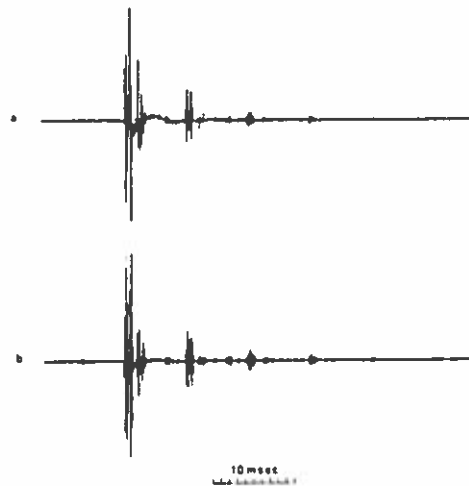


FIG 3a. Waveform of sperm whale click with slowly decaying amplitude of higher order pulses. P (true pulses) and S (surface reflections) segments are overlapping. Distortion through overloaded electronics is evident.

FIG 3b. Correlogram obtained by cross-correlating the P1 segment (from 10.05 to 10.60 msec relative to beginning of click sample) with the entire click in fig 3a. Note the change in relative amplitude and phase of the P-S events compared with the original waveform.

Depending on the attenuation of higher order pulses and S/N ratios, a number of later P and S pulse pairs could be detected, always having intervals identical to the P1-P2, S1-S2 complex. Also the phase relationships of higher order pulses, when identifiable, were identical to those of the P1-S1 event. In the entire set of data only eight P1-P3 estimates could be calculated.

In 18 click trains the pattern outlined above was additionally complicated by the presence of a complex pulse, C1, which occurred from 2 to 8 msec after P1. C1 usually had a waveform entirely dissimilar to that of P1. However, when the interval of this pulse could be detected, it was identical to that of the P-pulses.

B. The P1-P2 interpulse interval

The 108 selected clicks were placed in four hierarchially arranged groups, according to confidence in the identification of the P, S, and C components.

Group 1. Clicks with simple P1 waveforms (≤ 2 cycles), and components P and S (and C if present) clearly defined in time. The amplitude of the P2 correlation peak was twice as large or larger than any other peak between S1 and S2. Waveforms were not distorted in the recording process. The click in fig 2 exemplifies this group.

Group 2. Clicks with P and S components (and C if present) identifiable by waveform. The amplitude of the P2 correlation peak was at least as large as any event between S1 and S2. Moderately saturated recording electronics permitted.

Group 3. P, S and C ill defined. Correllograms showed either a single peak or a peak assembly 1.25 times the amplitude of any other peak in the 6-9 msec range. The click illustrated in fig 3 belongs to this group.

Group 4. Click unsuitable for interval analysis due to ill defined waveforms or masking of one component by another.

The results are summarized in Table I. In four trains all the three selected clicks had to be placed in group 4. In these trains higher order pulses generally were of such low amplitude, that the peak detecting procedure failed to recognize them. Fig 3 illustrates the invariance of the pulse spacing in a multi-pulse click.

TABLE I

Interval	Criteria	No of trains	No of clicks	Min msec	Max msec	Mean msec	S.D. msec
P1-P2	1	6	7	7.5	7.6	7.55	0.03
	2	11	21	7.5	7.6	7.55	0.04
	3	18	27	7.0	8.2	7.5	0.05
	4	20	53	-	-	-	-
P1-P3	1-4	7	8	14.6	15.2	15.01	0.20

DISCUSSION

The data on pulse intervals in Table I can be used in testing the hypothesis of interval constancy only if the following three conditions are met: The sampling must secure that no significant variability is missed. The recording and analyzing procedures must be accurate and sensitive enough to detect such variability, if present. Finally, the analyzing procedures must be insensitive to noise in the sense that intervals should be read between sets of proper pulses only, and not between true pulses and noise pulses. The trivial nature of these conditions is not reflected in the ease by which they can be met. In regard to sampling, pilot analysis showed a strong tendency of aberrant waveforms in leading and trailing clicks, relative to the bulk of clicks in a train. Consequently, the sampling strategy was designed to include such clicks, even though they contributed only little to the content of the high reliability groups in Table I. A sampling strategy based on waveform quality would have given a quantitatively higher yield, but a conclusion about interval constancy would then have been restricted to such clicks.

The accuracy of the recording and analyzing procedures was limited by wow, flutter and speed reduction errors, as well as bandwidth limitations and digitizing errors. The summed effect of these errors are estimated to be below 0.5%. The sensitivity was largely governed by the peak detecting procedure. Since peak detection was done by a routine operating on the output from the cross-correlator, the "reading" process had a resolution determined by the A/D sampling rate. i.e. 25 psec. It is important to realize that the peak of the correlogram was a measure of similarity between an entire pulse and a later event. Minor waveform distortions that seriously may have influenced the accuracy of peak detection by standard oscillographic analysis of the waveform would only reduce the height of the correlogram peak, but was unlikely to change its position on the time scale. As a consequence the procedure used was sensitive to changes in pulse interval of less than 1%.

The third condition (insusceptibility to noise) could only be met in part. Noise is regarded as anything that will tend to obscure the true pulse interval. Most seriously, noise may result in misinterpretation of the recorded pulses in a click. Besides the considerable number of pulses emitted by the whale itself, any reflecting body or boundary close to the direct path would have introduced its own set of pulses, as exemplified by the surface reflected pulses. Another source of noise is distortion of the waveform during propagation and recording, while noise from other sources than the whale appeared to be less of a problem. However, mistaking one pulse for something else is a very likely possibility, which has forced us to rank the sampled clicks according to confidence in the pulse identification.

The Table I shows that for the two highest reliability groups, including 1/4 of the entire sample, no variability in pulse interval beyond system inaccuracies was found. If the pulse interval was adjustable and under control by the whale, then a wide, continuous distribution of this interval would be expected. However, since not a single click in these two groups fall outside by as little as 0.1 msec, we find it unlikely that the Skálafjördur

sperm whale could exert any control over its pulse interval.

The analysis of clicks in group 3 showed that, even when the "anatomy" of a click could not be deciphered, usually due to complex, overlapping waveforms, an interval of 7.6 msec was still found in a substantial portion of the sample. The standard deviation in this group was slightly larger than for group 2. An analysis of variance showed that the interval in the group 3 was significantly different from an evenly distributed sample in the 6 to 9 msec range at the 0.01 level ($F=10$, $n=27$).

In the few cases, where the cross-correlation peak detecting process could determine the P3 pulse, the mean interval between P1 and P3 was exactly twice that of P1 and P2, as seen in Table I.

While alternative explanations are not ruled out, the double mirror hypothesis of Norris and Harvey (1972) seems very adequate for explaining the fixed interval, as well as the phase relations between the pulses.

In several details, however, the Skálafjörður results are not consistent with the original Norris and Harvey proposal. The observation of identical phase relationships in P1 and P2 is not easily explained if the first, powerful P1 pulse was emitted directly into the water, and the second P2 pulse has been reflected and phase inverted only once. Rather, we would like to think of P0 as the possible expression of the initial event. What was recorded of it was stray energy, as the main part of the power was directed inwards, through the spermaceti organ. When it reached the parabolic frontal air sac, it was reflected, phase inverted and then emitted as the P1 pulse. With an estimated aperture of 3 to 4 meters in this specimen, the frontal air sac mirror was likely to provide a highly directional gain. Higher order pulses were considered to result from stray energy that bounces back and forth in the system, rather than a useful feature. The reason for this conclusion is partly the very low amplitude of P2 dominating our records, and partly the improved sonar range discrimination and clutter rejection that can be expected on theoretical grounds from a single, Dirac-type of pulse (Angelari 1970). Accordingly, clicks with relatively small (i.e. <10 dB) attenuation of higher order pulses may represent samples outside the main beam.

Several observations remain unexplained by the original, as well as the modified theory on sperm whale sound generation. For instance, if the spermaceti case in fact is a sound guiding structure, what is then the functional significance of the unusually high velocity of sound in spermaceti? The problem is here, that a sound channel requires a low velocity core (Albers 1965). Furthermore, what is the functional significance of the enormously increased length of the sperm whale forehead? The focal point of the frontal air sac parabola, as inferred from the skull shape, lies far back in the head, above the bony nares, about 10 focal lengths posterior of the proposed sound source in the anterior end of the system. Simple geometric considerations show no correspondence between these observations and the idea of a highly directional sound emitting system, so strongly suggested by the symmetric, nearly parabolic skull surface, built from highly asymmetrical bones.

When the pulse interval of 7.6 msec is converted to distance, using the figure of 2.6

km/sec for the velocity of sound in spermaceti (Diercks, cited in Norris and Harvey 1972), the distance between the mirrors comes out as 9.9 meters. Using this as an estimate of the length of the head, and extrapolating the curve describing the relation between total body length and length of the head in male sperm whales (fig 3 in Nishiwaki et al 1963), a total body length of 22 meters is obtained. Behind this acoustic estimate of total body length lies a number of assumptions, the accuracy of which are not known (velocity of sound in the entire spermaceti case, the head and body length ratio outside its known range, and the double mirror hypothesis itself).

The direct estimate of body length of 21 meters, obtained photographically is subject to errors due to the limited resolution of the film negative and due to possible distortions of the image of the wooden rod, caused by refractions at the air-water interface. Also, the estimate requires that the whale was not bent in the vertical plane, a possibility that cannot be excluded.

However, the close agreement between the two independent measures of total body length is encouraging, even if the significance of the agreement cannot be fully evaluated. It seems to be a safe conclusion, though, that the large Skálafjörður whale produced a large pulse interval, whereas a small whale, as demonstrated by Norris and Harvey (1972), produced a small interval. Thus there is reason to believe that sperm whale size can be assessed remotely by measuring the pulse interval of clicks that can be recorded at ranges exceeding 3 km (Levenson 1974). This conclusion has two implications. First, since the relationship between age and size in sperm whales is fairly well known (Nishiwaki et al 1963), the pulse interval measurement may allow remote age determination of sperm whales, and thus become a new tool in the study of the biology of this species (Möhl et al 1981). Unfortunately, the Skálafjörður specimen was so far outside the known range of age and length relationship, that an age estimate was not possible. Secondly, if we can extract size information encoded in the click structure, sperm whales may also be able to do so, and use this information in social interactions.

ACKNOWLEDGMENTS

Logistic support was given by the staff of Academia Faeroensis, as well as by the commander and crew of "Vaedderen" of the Danish Navy. This work was supported by grants from the Danish Research Council for Natural Sciences.

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