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Interpreting the acoustic pulse emissions of a wild bottlenose dolphin (*Tursiops truncatus*)

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Summary

This paper presents an analysis of sonar pulses from a wild dolphin, recorded at sea in conditions of low underwater visibility. The use of a recently developed, very high resolution, speech spectrograph to examine the recorded data has enabled the structure of the dolphin echolocating pulses to be analysed in some detail. The authors identify several modes of dolphin pulse emission and have endeavoured to relate these to observed behaviour. The conclusions support the hypothesis of very sophisticated signal processing in the dolphin's acoustic sensory mechanism.

Introduction

Between April 1984 and December 1985 a young male dolphin (*Tursiops truncatus*) was resident in the sea off Solva, West Wales (Lockyer & Morris, 1987*a*,*b*), permitting a series of studies of natural dolphin behaviour in the wild. In this paper we report the results of some acoustic recordings made of the dolphin in October 1985, during a period of bad weather, when underwater visibility was very poor, as a result of aeration and a high suspended particle load. Under such conditions it seemed likely that acoustic perception would be the dolphin's dominant sensory faculty.

Experimental conditions

The study boat was moored near the outer harbour entrance of Solva, between the cliffs but inshore of a small rocky islet (Black Rock), which provided limited protection from the high sea state. The water depth, tide dependent, varied between 3 and 8 metres. The bottom is believed to be generally hard sand, but rock strewn, especially near the cliffs. Weather conditions for these recordings were particularly bad, between severe gales, with a residual sea state of Beaufort 5/6 between the cliffs. To summarise, reverberant acoustic conditions with a high ambient sea noise and very poor underwater visibility prevailed. The animal's movements and behaviour were monitored by four surface observers, and a diver was in the water close to the boat with a submersible housing containing a Panasonic video camera. The camera housing comprised a stainless steel cylinder with transparent polycarbonate end windows. Hydrophones were hanging in the water next to the boat at depths of one to two metres. Signals from these were continuously recorded while the dolphin was in attendance, and a voice logging channel left open for commentary.

Behaviour patterns were generalised under the following headings.

i) Fast approaches from a distance (30 to 100 metres), usually slowing down on approach to the observers' boat, the swimmer or equipment.
ii) Slow approach to a target, usually leading to (iii).
iii) Lying stationary in the water whilst 'examining' a target.

Tape recording and analysis

The underwater recordings were all made on Nagra IV-S and IV-SJ recorders running at 7.5 and 15 ips. (The 15 ips recordings were utilised primarily for the spectrographic analysis. The Nagra IV-S − 3dB frequency response extends from 25 Hz to 35 KHz at 15 ips.) The hydrophones utilised included a Bruel & Kjaer 8104, with a QSJA-BK 40 dB preamplifier and a Universal Sonar D1/70 ball, with additional amplification from a 60 dB low noise preamplifier (wide band LUTEE design).

Detailed tape analysis was made possible with an LSI Sound Spectrograph. Some very loud dolphin emissions at close range overloaded the tape and were distorted; however, significant sections of tape remained with a satisfactory signal to noise ratio for analysis. The spectrographic analysis was made at the equipment manufacturer's premises (Loughborough Sound Images Ltd., LSI). The technique applied

FIG.1a: SOLVA DOLPHIN - CLICK TRAIN DURING APPROACH TO BOAT - V.Scale 4 kHz/cm (0-32 kHz); H.Scale 40 ms/cm.

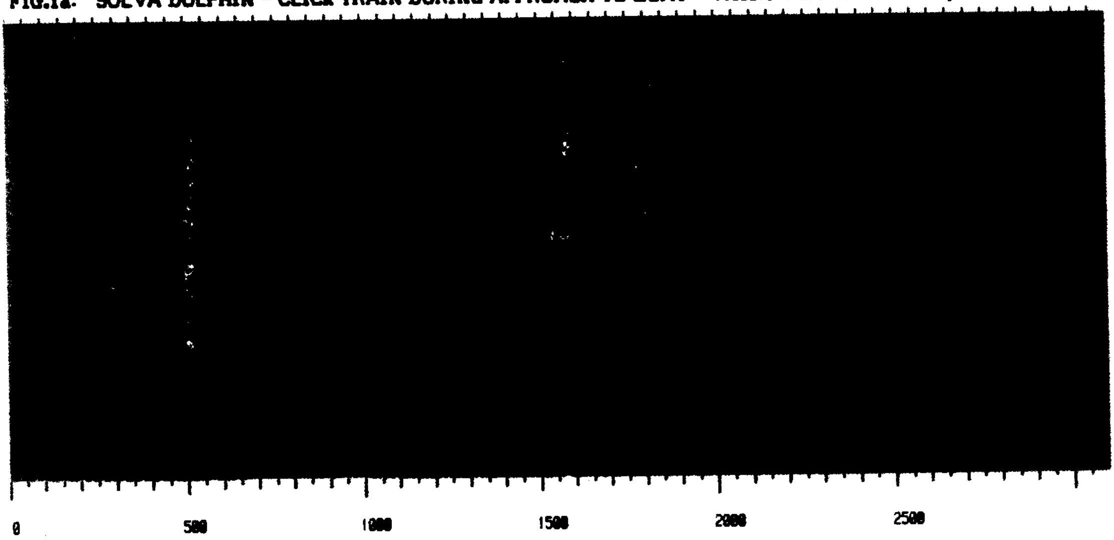


FIG.1b: EXPANDED CLICK TRAIN from scale 450 - V.Scale 4 kHz/cm (0-32 kHz); H.Scale 2.5 ms/cm.

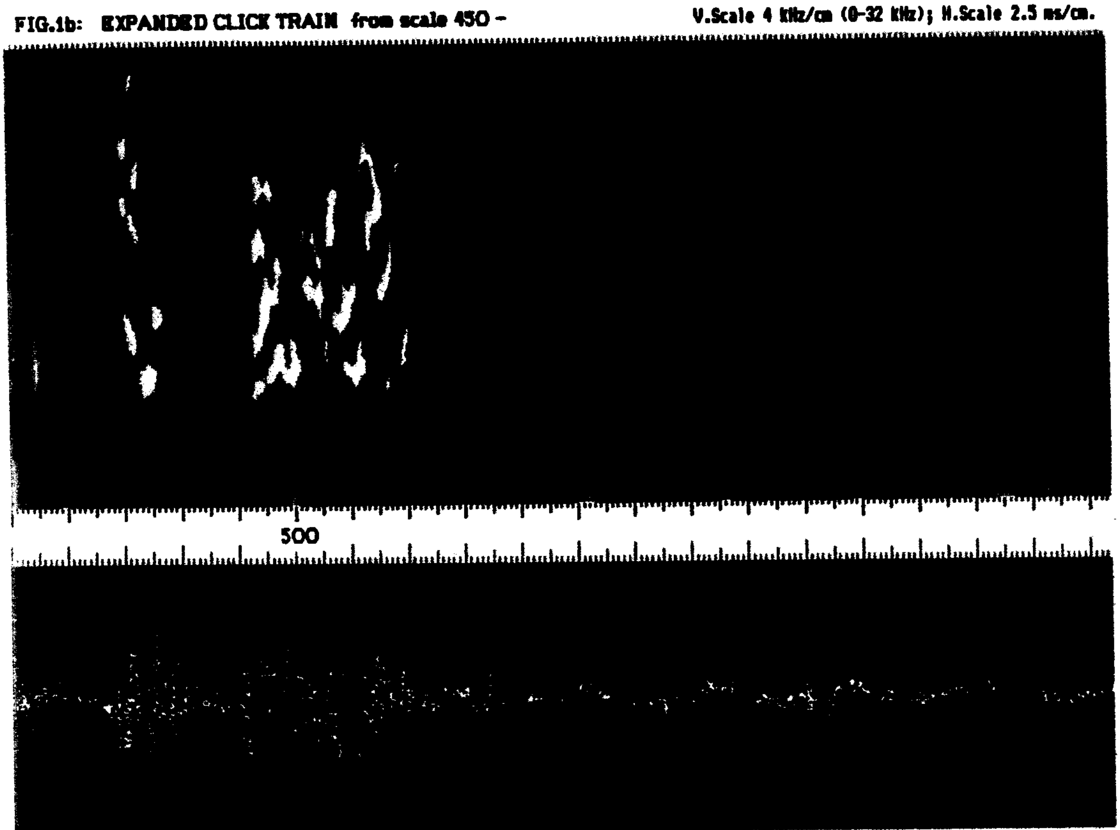


FIG.1c: EXPANDED CLICK TRAIN - WAVEFORM SOURCE from scale 450 - B.W. 1.6 kHz; H.Scale 2.5 ms/cm.

0 dB SIGNAL AMPLITUDE COLOUR SCALE : 40 dB DYNAMIC RANGE in 2.5 dB STEPS. -40dB

required several passes of the tape to screen for matching sound patterns, and to reject signals where tape overload, or very poor signal to noise, invalidated the recording. The sections selected were then digitised by the spectrograph in six second blocks. The analyser was set for 20 kHz sampling but, as this imposed a maximum frequency analysis of 8 kHz, tape speed frequency transposition techniques were applied. Most sections were played back at 1/4 speed, effectively increasing the analysis limit to 32 kHz, which coincidentally matched the tape recorders upper frequency response. Preliminary investigations indicated little significant signal content below 100 Hz. The partial loss of the low frequency fundamentals below 100 Hz, due to tape speed transposition, was thus judged acceptable. The digitised sections were then processed unweighted, initially with 50 Hz narrow band filtering (in effect 200 Hz filters), to determine the spectral distribution within the signals.

Since the diver in the sea with the video camera became a 'target' of the dolphin's interest it was necessary to determine the natural frequency/echo characteristics of the camera housing; this was subsequently done in the sonar acoustic test tank at Loughborough University. To stimulate resonances in the housing, 100 µsec gated pulses of 40 kHz (4 cycles duration) were transmitted, to simulate a dolphin 'click'. Mechanical shock excitation of the housing was also investigated. Responses were recorded, from a contact hydrophone (Raychem Vibetec PVdF) taped to the camera housing and from several midwater hydrophones at different ranges, for later spectral analysis.

It is important to note that the portable recording equipment and the spectrograph used for analysis have only sampled the lower 32 kHz of the dolphin's pulsed sound spectra.

Results and Discussion

The bulk of the recorded dolphin emissions exhibit the established wide band sharp 'click' characteristic of this species (eg. Popper, 1980; Kamminga, 1982; Kamminga & Van der Ree, 1976; Hohl & Kamminga, 1974) (Fig. 1). The ability of the LSI Spectrograph to expand the resolution was exploited to examine pulse structures in more detail, (Figs. 1a and 1b). Fig. 1a shows both 'loud clicks' (ref. scale 500 and 1500) and 'ranging clicks' (ref. scale 0 to 2000). The expansion of an individual 'loud click' pulse (Fig. 1b), reveals a complex, well structured, doubled pulse linked by a brief burst of a pure tone. The visual correlation between the starting edges of the pulse pairs is evident. The period between the loud clicks (Fig. 1a) suggests a listening radius of some 200 metres, which would include the acoustic horizon between the cliffs. The double pulse structure is such that autocorrelation techniques could be applied to give improved detection capability for weak signals in high ambient noise.

The 'loud click' signals are interposed between faster and simpler pulse trains, 'ranging clicks'. This buzzing sound was observed during the dolphin's approach phase. These signals exhibit a regular decreasing interval, corresponding to the reducing range as the dolphin approaches it's target (which is not the hydrophone) (Murchison, 1980).

The changing rate of the 'ranging clicks' in Fig. 1a between scale ref. 0 and 1500 (375 milliseconds duration real time), demonstrates an approach speed of about 7 metres/sec, typical of several approaches observed. These fast click trains appear, when expanded, in many cases to be 'click pairs' (Fig. 1c). However it appears (Fig. 1b) that while one edge is characteristic of the pulse series, the second edge, separated from the first by approximately 1 millisecond, may lead or trail it. This second edge contains distinctly different frequency components in succeeding pulses, which could be interpreted as a pulse 'coding' technique to permit the detection of approaching 'over range' targets. This theory is supported to some extent by the absence of randomly timed pulses, which would indicate multiple target sampling.

Change of interest to a new target appears to occur as a sudden change in pulse rate: Fig. 2a, ref. scale 800

Figure 1a: Solva Dolphin—click train during approach to boat. This spectrogram typifies the dolphin's transmissions during the last stage of approach toward the hydrophone and passing by it. At the same time the animal emits two 'loud clicks' in order to monitor the wider environment. Note: The time axis is stretched by the tape speed: Scale 3000/4 = 750 milliseconds real time.

Figure 1b: Expanded click train from scale 450. Expanded 'Loud Click' Orientation pulse (Fig. 1a Scale 500). These are very broad band and contain most energy between 6 and 24 KHz, although it is evident that energy in the pulse extends well above this. The 268 millisecond period between the loud clicks suggests interest in an acoustic range of approximately 200 metres. The equivalent oscillogram trace of the expanded signal amplitude is shown in Fig. 1c. Note the structure of the 'Loud Click' from which even simple signal processing could usefully enhance target echoes buried in background noise. Linking the pulse edges at approximately 18 KHz is a pure tone of a frequency which is significantly absent from the background noise in this example.

Figure 1c: Expanded click train—waveform source from scale 450. This displays the same data as Fig. 1b in the conventional 'A Scan' mode as on an oscilloscope.

FIG.2a: CLICK TRAIN DURING APPROACH TO BOAT & DIVER - V.Scale 8 kHz/cm (0-32 kHz); H.Scale 40 ms/cm.

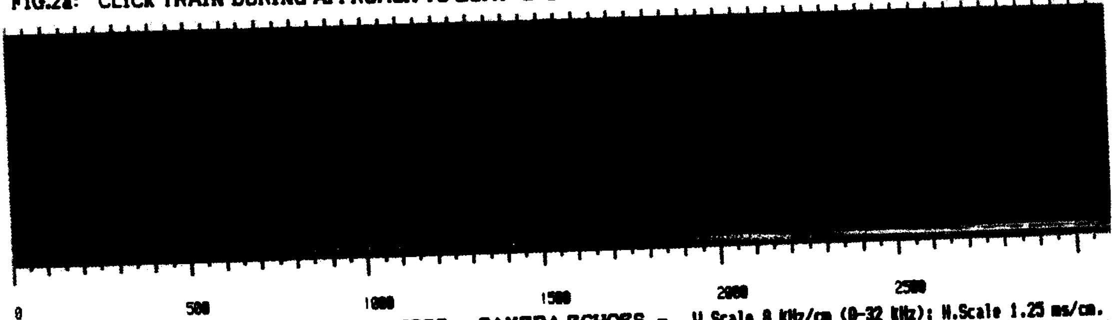


FIG.2b: EXPANDED CLICKS from scale 2500 - CAMERA ECHOES - V.Scale 8 kHz/cm (0-32 kHz); H.Scale 1.25 ms/cm.

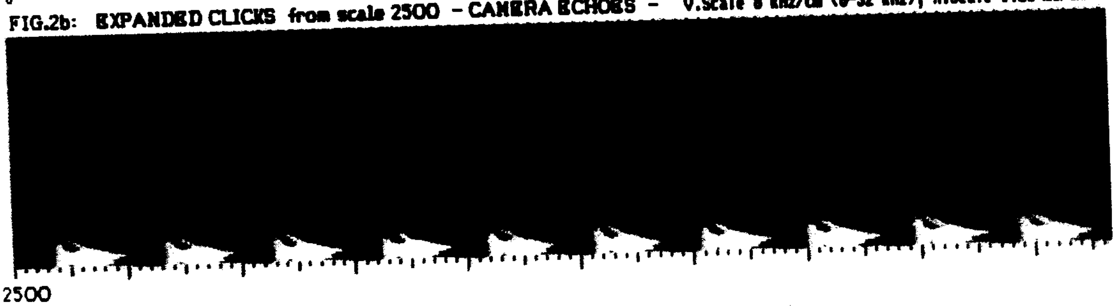


Fig.2c: SYNTHESISED 'CLICK' ECHOES - HOUSING RESONANCES - V.Scale 8 kHz/cm (0-32 kHz); H.Scale 40 ms/cm.

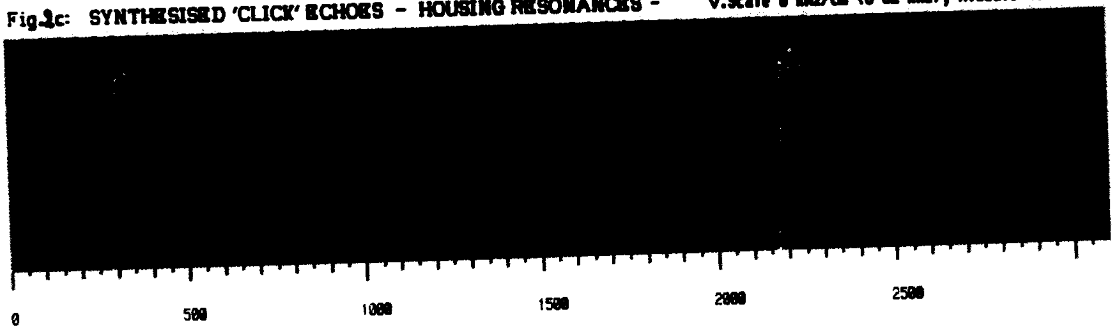
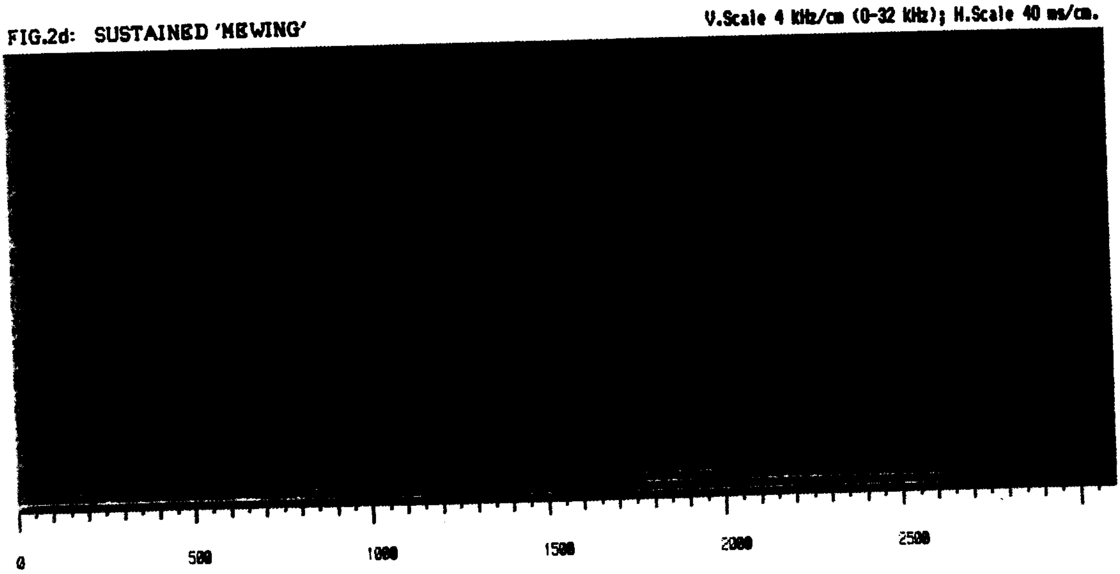


FIG.2d: SUSTAINED 'MEWING' V.Scale 4 kHz/cm (0-32 kHz); H.Scale 40 ms/cm.



demonstrates such a change of target interest during an approach towards the boat, diverting to the diver and camera housing.

Sonar activity close to a target changes and, if the dolphin slows or stops, a third type of signal sounding like a 'mew' (angry wasp) often occurred. For example, in Fig. 2a, the sequence of approach to the cameraman culminates in a high pulse repetition rate 'mewing' sound whilst the dolphin lay almost stationary in front of the camera. This hydrophone signal comprised a pulse train, the rate of which increased to 105 Hz. This pulse sequence does not exhibit the very broadband spectrum observed on other, otherwise similar, signals (e.g. Fig. 2d), but in this case the clicks appear to excite a strong target echo (Fig. 2b scale 2500) between 14–18 kHz (centred at 16 kHz). Resonance of the underwater camera housing is suspected as the echo source. The analysis of the recordings from the laboratory experiment with the underwater video housing confirmed that the target echo signature contained a series of resonances with a significant one occurring at 16 kHz (Fig. 2c)

Other examples of close range 'mewing' at targets are on tape, and in general comprise very broad band frequency sweeps, generated by rapid click rates approaching 1 kHz, usually with harmonic energy evenly distributed to well above the 32 kHz analysis limit. Fig. 2d demonstrates a sustained signal containing all the harmonics of a 620 Hz fundamental. (Note the weakening signal and lowering pulse rate at scale 3000.) These 'mew' signals are clearly audible to a swimmer listening underwater.

Conclusions

Our observations, combined with the spectrographic analysis of the recordings, identify three specific dolphin pulse emission modes.

1) 'Loud Click'

The 'loud click' is a complex structured broad band pulse containing sufficient information to imply that auto-correlation reception techniques are being used by the dolphin. Such signal processing would enhance target echoes otherwise lost in background noise. This type of pulse occurs at slow repetition rates, and is not always present when 'concentrating' on a close up target. The pulse is possibly used as an orientation mode to determine an acoustic horizon, permitting the dolphin to maintain an awareness of its environment and to determine the location of any new targets within that area.

2) 'Ranging Clicks'

A regular click rate, increasing steadily in frequency as the target range decreases, is a mode frequently utilised during the approach phase and the click rate at any one time appears to indicate the range at which interest is focussed (Au, 1980; Au & Moore, 1986). The pulse train is often constructed from click pairs (1 millisecond separation), the secondary edge of which could indicate a pseudo-random coding sequence, permitting target detection beyond the range indicated by the primary pulse repetition rate.

3) 'Mewing'

Mewing when close to a target probably assists visualisation of the target structure, ie. exciting a characteristic echo signature from the target. This may have partly evolved as a recognition technique for fish targets, because individual fish would exhibit a specific echo resonance, characteristic of swim bladder size etc. By transmitting signals closely matched to the target's echo signature, the dolphin can hunt a selected target without apparent distraction. Unmatched echoes would be partially suppressed, while a selected target would be enhanced: for example this would give the dolphin the ability to select a single fish within a shoal. This rejection of unmatched echoes may explain why dolphins occasionally collide with fishing nets, the presence of which they ought normally to be able to detect (Hembree & Hayward, 1986).

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Figure 2a: Click train during approach to boat and diver. Approach phase (scale 0 to 800), change of interest from scale 800 leading to 'camera target' resonance, scale 2500 plus.

Figure 2b: Expanded clicks from scale 2500—Camera Echoes. Expanded 'camera target' resonance, from scale 2500 in Fig. 2a. Between the click edges there appears to be a resonant echo centred at 16 kHz.

Figure 2c: Synthesised 'Click' Echoes—Housing Resonances. Camera Housing Resonance in Loughborough test tank. 100 μsec (40 kHz) synthesized dolphin click excitation. Echo received on D1/70 ball hydrophone.

Figure 2d: Sustained 'Mewing'. Sustained dolphin 'mew'. This examples demonstrates a very broad band signal with significant energy in the harmonics up to the 32 kHz analysis limit. The analysis displays the harmonics of fast repetition rate, 600 Hz, sharp clicks. Beyond scale 2500 the energy and pitch of the harmonics fall.

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