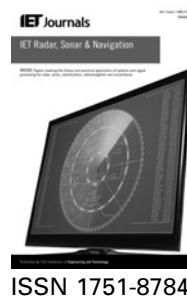


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Review of the occurrence of multiple pulse echolocation clicks in recordings from small odontocetes

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Abstract: This study investigates the extent of the possible correlation between small odontocetes that predominantly inhabit littoral waters, and those which have been associated with the detection of echolocation clicks that consist of multiple pulses. The echolocation clicks discussed are primarily characterised as short, high frequency (>100 kHz) and narrow band. There are many sources that report clicks that contain multiple pulses and there is more than one structure associated with such pulses. A review of the literature provides a list of odontocetes which have been associated with such sounds and the structure of those reported clicks. The competing hypotheses regarding the origins of such multiple pulses in recordings are discussed. Regardless of the mechanism by which multiple pulse clicks occur, there are potential competitive advantages which may arise from them, and these are highlighted.

1 Introduction

The acoustical challenges of the near-shore environment have perplexed sonar operators throughout the modern era, although these issues remained largely ignored by engineers until the end of the Cold War [1]. Several factors contribute to these challenges, including time-varying surface undulations [2], suspended sediment [3, 4], ambient noise issues and especially bubbles [5–7]. Odontocetes (toothed whales) rely upon echolocation to survive [8–10]. Despite the apparent physical difficulties of employing sonar in shallow water, many species of odontocetes exploit an evolutionary niche within the littoral zone.

Almost no published work exists which explores the impact on biosonar of these factors that hinder sonar in littoral water. One exception is the anecdotal account of Fasick [11], an animal trainer at a Beluga whale tank. Beluga whales echolocate using clicks with a peak frequency that is usually in the range of 100–115 kHz [8]. Fasick described how a plumbing malfunction resulted in the presence of large numbers of microbubbles in the tank water. These bubbles caused the whales' biosonar to deteriorate to the point where they could no longer entertain the public in their task of collecting rings in the water, for which they had been successfully trained in normal (i.e. nominally bubble-free) conditions. In littoral water, oceanic bubble clouds are easily generated, for example, by ship wakes, breaking waves or biogenic and geophysical activities, and they are very strong scatterers and absorbers of sound waves [5, 6]. Hence, they can contribute a significant amount of signal clutter in such water. In the discussion of potential competitive advantages of using multiple pulse

echolocation, as a form of simplification, only clutter in the form of bubble clouds is considered here.

This paper will first review observations of multiple pulse structures in the echolocation clicks of small odontocetes that primarily reside in littoral waters. These are predominantly animals from the genera *Cephalorhynchus* and *Phocaena*. Animals in these genera produce echolocation clicks for foraging and communication that which are characterised as being narrow-band and high-frequency (NBHF), with centre frequencies in the range of 100–140 kHz [12–15]. These animals typically inhabit coastal, near-coastal, estuarine or riverine regions, where an individual's survival critically depends on its ability to echolocate in some of the most challenging acoustical environments. Using bubble clouds as the source of clutter, this paper will discuss how multiple pulse clicks might assist echolocation in these environments. It will also explore competing hypotheses surrounding the observation of multiple pulse structures. These hypotheses are that the observed additional pulses are the result of reflections or they arise directly from the animal.

2 Observations of multiple pulse clicks from small odontocetes

The terminology commonly used to describe the echolocation signals of interest to this paper is as follows: during echolocation animals usually emit a series of clicks, referred to as a click train, and each one of the echolocation clicks may contain multiple components referred to as pulses. It is well established that some species employ echolocation clicks that contain multiple pulses. Other species are not commonly thought to produce such clicks.

The most widely studied example of an odontocete whose echolocation click has a multiple pulse structure is the sperm whale (*Physeter macrocephalus*). Although these animals are not directly relevant to the present discussion, being a deep water large species, we intend to adapt the convention used to label their pulse structure for our purposes, so it is appropriate to give a brief overview of that structure. The multiple pulse structures in sperm whale echolocation clicks can be explained using a widely accepted model: the so-called ‘bent horn’ model [16]. Each sperm whale echolocation click consists of a series of pulses, which are the result of reflections within the large anatomical complex that these animals use to generate the clicks. The pulses in a click typically decay in time and occur at regular intervals. In some instances, a precursor pulse prior to the dominant pulse can be observed. The exact structure of pulses making up the click depends on the orientation of the whale relative to the observer.

In the study of sperm whales, the pulses making up a click are conventionally referred to as P_1, P_2 etc. with the dominant on-axis pulse being labelled P_1 . Note that in the case of sperm whales this notation is further refined to include labels like P_0 (the precursor pulse) and $P_{1/2}$ (a pulse observed off-axis

occurring between P_1 and P_2). This more refined labelling presumes a level of understanding about the generation mechanism which is not appropriate to the work here. The pulse labelling convention applied in this work follows the simple form of labelling for sperm whale clicks, specifically P_1, P_2, \dots (as shown in Fig. 1), representing the individual pulse components in the order they are received. (The adoption of the sperm whale pulse notation is not intended to imply a similarity in the physical pulse/click generation mechanisms.)

The following sections review observation of multiple pulses in small odontocetes. Table 1 provides a list of the species which are the focus of discussion in this paper along with the habitats they inhabit and Table 2 details the acoustic parameters associated with the echolocation clicks these species. This consideration of the vocalisation behaviours common to near-shore marine mammals begins with a historical discussion of the observations of the genus *Cephalorhynchus*. All the members of this genus have habitats that are confined or nearly confined to shallow waters [17]. This genus comprised the following animals: Commerson’s dolphin (*Cephalorhynchus commersonii*), Hector’s dolphin (*Cephalorhynchus hectori*), the Chilean/

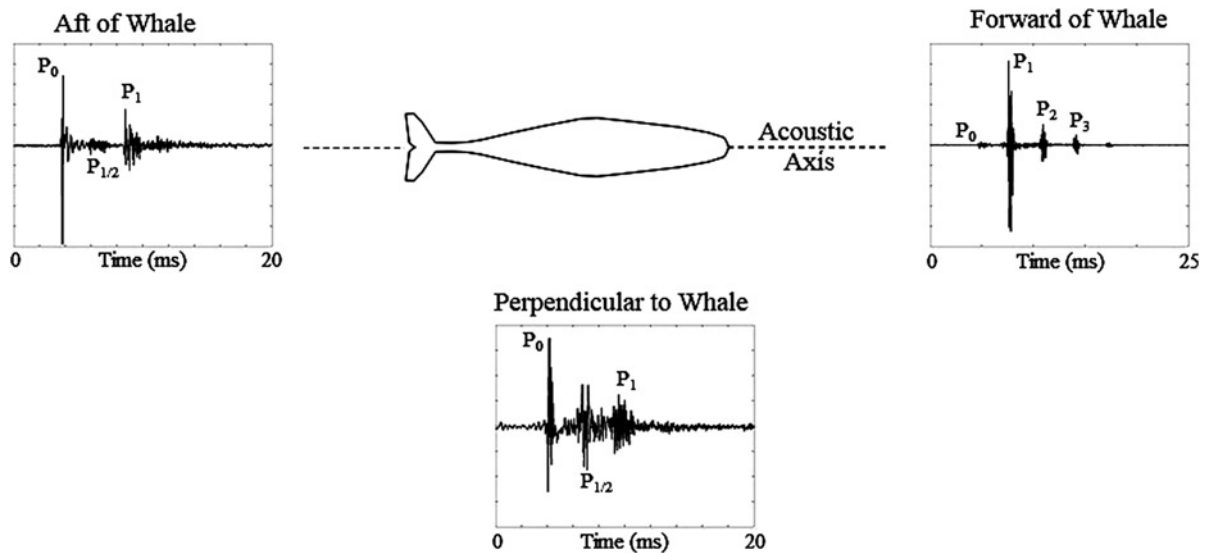


Fig. 1 Typical waveform shapes for clicks received on a hydrophone at different orientations to a sperm whale. Pulses making up the clicks are labelled using the conventional labelling scheme

Table 1 Small cetaceans for which detection of multiple pulses has been reported

Genus	Species	Primary habitat	References	
Cephalorhynchus	Commerson’s dolphin, <i>Cephalorhynchus commersonii</i>	coastal east Argentina, south Chile and Indian Ocean	Goodall <i>et al.</i> [19]; Kamminga and Wiersma [20]; Evans <i>et al.</i> [21]; Kyhn <i>et al.</i> [22]	I
	Hector’s dolphin, <i>Cephalorhynchus hectori</i>	coastal New Zealand, often in estuaries	Dawson [23]	
	Chilean black dolphin, <i>Cephalorhynchus eutropia</i>	coastal Chile	Watkins and Schevill [24]; Götz and Heinrich [25]	
Phocoenidae	Finless porpoise, <i>Neophocaena phocaena</i>	coastal Asia	Li <i>et al.</i> [12]	II
	Dall’s porpoise, <i>Phocoena dalli</i>	coastal and non-coastal, warm temperate to sub-arctic waters of the Northern Pacific Ocean	Evans <i>et al.</i> [21]; Awbrey <i>et al.</i> [26]; Bassett <i>et al.</i> [27]	

Group I: Have been recorded (single hydrophone) sustained sets of equal-amplitude pulses with constant separation times

Group II: Equal amplitude phase inverted pulses, attributed to surface reflections

Table 2 Acoustical parameters of echolocation pulses for species which may be capable of generating multiple pulses

Species	Pulse duration, μs	Centre frequency, kHz	3 dB bandwidth, kHz	Apparent source level, dB peak-to-peak re 1 μPa	Reference
Commerson's dolphin	52–138	133	21	177	[22]
Hector's dolphin	140	112–130	14	151	[23]
Chilean dolphin	82.6	126	18	165	[28]
Dall's porpoise	60 [29]	140 [29]	5 [21]	170 [29]	[21, 29]
Finless porpoise	80 [13]	121 [13]	17.5 [13]	129–157 [14]	[13, 14]

black dolphin (*Cephalorhynchus eutropia*) and Heaviside's dolphin (*Cephalorhynchus heavisidii*). All of these animals are restricted to the southern hemisphere [18]. The other species that are discussed in this paper are northern hemisphere members of the family *Phocoenidae* which includes the finless porpoise (*Neophocoena phocaena*) and Dall's porpoise (*Phocoena dalli*).

The literature concerning the acoustic activity of these odontocetes in the littoral zone is comparatively sparse. This deficit of knowledge is partly because few of these species are kept in captivity. Compared with field studies (which study odontocetes in the wild), studies of captive odontocetes in laboratory settings are able to provide a higher level of control over experimental variables and offer the opportunity to investigate the foundations and mechanisms of acoustic behaviour like echolocation. These complement field studies, which can provide insights into how certain mechanisms revealed in the laboratories are expressed in natural settings, leading to improved understanding of the odontocete [30, 31]. Coupled with the highly flexible nature of the echolocation ability of odontocetes, both laboratory and field studies are necessary to determine whether results from any study are indicative of the species. For example, field studies of wild harbour porpoise (*Phocoena phocoena*) have recorded source levels of emitted signals [32] to be at least an order of magnitude higher than reported for those in captivity [30]. Field recordings of other species of odontocetes have also confirmed that this is not unique for this species [8, 9]. Numerous echolocation trials have also shown changes in the signals produced related to the context of the trials [8, 33].

There are two forms of multiple pulse structure that must be distinguished from one another. These will be referred to as overlapping and non-overlapping pulse structures. In the overlapping form, the main pulse and subsequent pulses overlap in time, that is the delay between the pulses is shorter than the duration of the first pulse.

Typical delays in these cases are in the order of 10 μs , corresponding to path length differences in water in the order of centimetre. The non-overlapping form of pulse structure occurs when there is a clear gap between the individual pulses. In this instance, time delays are typically in the order of 100 μs , corresponding to path length differences in the order of 10 cm. Evidently this distinction has the potential (in theory at least) for ambiguity, but in the examples considered here the distinction is always clear. In both cases the pulses are labelled according to the P_1, P_2, \dots convention.

In some cases a combined structure exists wherein the non-overlapping multiple pulses exist and each of the individual pulses also exhibits an overlapping multiple pulse structure. In those instances the labelling of pulses will generally be performed according to the non-overlapping structure, that is only non-overlapping pulses are labelled. A hierarchical

labelling scheme can be adopted to label the overlapping pulses in each non-overlapping pulse, but this level of complexity is unnecessary for this study.

2.1 Commerson's dolphin (*C. commersonii*)

Commerson's dolphin was the first member of *Cephalorhynchus* for which acoustical observations were made [34]. This species is distributed in two locations: the east coast of South America, and the Kerguelen Islands. Commerson's dolphin tend to occupy only near-shore waters, although at least one (presumed vagrant) dolphin of this species has been observed off the African continental shelf ~ 4000 km from the nearest distribution limits [35]. Despite the fact that several individuals of this species exist in captivity [36], very little has been published concerning their acoustic vocalisations. Watkins *et al.* [34] reported having made acoustical observations of this species in 1966 (published 1977) using equipment capable of recording frequencies from 60 Hz to 10 kHz. In 1980, Watkins and Schevill [24] re-studied vocalisations of Commerson's dolphins and recognised that the sounds generated by this species contain significant energy up to at least 100 kHz. Kamminga and Wiersma in 1980 [20] studied captive Commerson's dolphins at the Duisburg Zoo, Germany, and noticed that the presence of several multiple-pulse trains [21]. A series of overlapped multiple pulses, with energy centred on 120 kHz, observed by Kamminga and Wiersma has been reproduced and shown in Fig. 2. The figure shows eight clicks, the multiple pulse structure is seen as the sequence of decaying pulses; in the figure one click has been labelled with the approximate locations of the first three pulses. The multiple pulse structure in this case is classed as being of the overlapped variety.

The most obvious explanation of the data collected by Kamminga and Wiersma is that the secondary pulses are caused by reflection–boundary interactions within the propagation path. Reflections from the air–sea interface would be 180° out of phase with the direct signal, whereas bottom reflections would be expected to be more closely in-phase with the direct signal. If the multiple pulses were generated by reflections from the top or bottom of the water column, the inter-pulse times within individual pulse-sets would vary as the source-boundary-receiver geometry altered (perhaps as a result of motion by the vocalising dolphin) [37]. Kamminga and Wiersma [20] stated that the multiple pulse structures they recorded appeared to be temporally steady for a given animal during a given pulse sequence, suggesting that the inter-pulse rate did not change over multiple pulses. On the basis of those data, the authors concluded these multiple pulse resulted from reverberation within the animal's head.

One conclusive way to determine the source of these clicks (e.g. to determine whether the second pulse appeared to

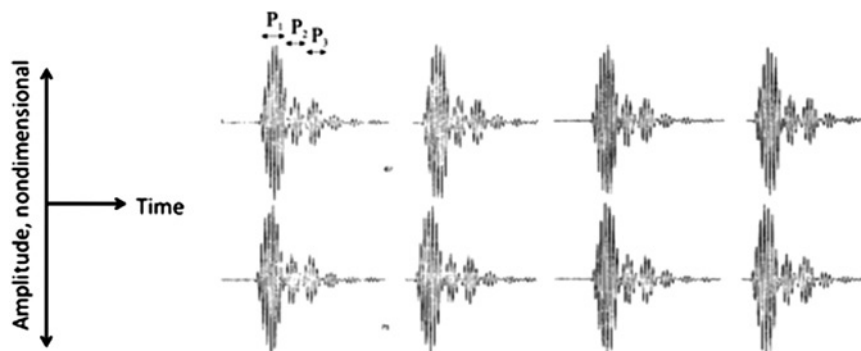


Fig. 2 Small portion taken from a sequence of successive clicks, adapted with permission from Kamminga and Wiersma [20]. Time samples all $\sim 300 \mu\text{s}$ in length

Table 3 Comparison of the conditions under which Aubauer *et al.* [37] and Li *et al.* [41] recorded their data

Mammal under study (author)	Depth of transducer (measured), m	Depth of phonating animals (calculated)	Approximate range to phonating animals, m
Spinner dolphin (Aubauer <i>et al.</i> [37])	3	0.8–3.0	61–67
Finless porpoise (Li <i>et al.</i> [41])	0.7/1.4	0.5–2.5	~ 50

originate from an ‘image’ source above the water surface [2]) would have been through the use of multiple receivers, and subsequent analysis of the relative temporal arrival delays [38].

It should also be noted that Evans *et al.* [21] stated that Commerson’s dolphins produce double pulses, but did not provide details.

Dziedzic and De Bueffrenil [39] studied the sounds produced by Commerson’s dolphins of the Kerguelen Islands. They attempted to measure the emissions of free-ranging dolphins in a fjord, but the vocalisations were masked by ambient noise. Two animals were captured and placed in a secluded creek within a $6 \times 6 \times 2.6 \text{ m}^3$ cage built with a $10 \text{ cm} \times 10 \text{ cm}$ mesh. These specimens were kept there for 65 h, during which time their acoustic emissions below 130 kHz were monitored continuously. The sounds reported were similar to reports for other populations [39], the centre frequency for tone packets being 116 kHz. There was no report of any production of multiple pulse echolocation clicks by the animals observed in that study.

In a more recent study, Kyhn *et al.* [22] used a six-element vertical array in field studies of vocalisations of both Commerson’s dolphin and Peale’s dolphin *Lagenorhynchus australis* (the classification for Peale’s dolphin is disputed, but recent work closely links Peale’s dolphin and *Cephalorhynchus* [40]). Guided by the assertion of Li *et al.* [41] that non-overlapping multiple pulses were the result of boundary reflections, Kyhn *et al.* [22] rejected from their analysis all clicks that contained non-overlapping multiple pulses on the assumption that none of these sounds were source generated.

2.2 Hector’s dolphin (*C. hectori*)

Hector’s dolphin is endemic to New Zealand waters, and is fragmented into at least three genetically distinct subpopulations [42]. Two of the subspecies inhabit the South Island, while the third inhabits the North Island. This third set is now recognised as a distinct subspecies, Maui’s dolphin (*C. hectori maui*). Oliver noted in 1922 that this

species is never seen far from the coast [43]. More recent work has confirmed that Hector’s dolphins have a marked preference for inshore waters, and are rarely seen more than four nautical miles offshore [44].

Digitally captured acoustic recordings of Hector’s dolphin vocalisations recorded by Steve Dawson [45] were sent to the authors for study. The data (which were taken on 27 and 30 January 2003 in Flea Bay on Banks Peninsula, New Zealand in 12 m of water) were examined for the presence of multiple pulses. The recordings were made using an analogue instrumentation recorder (Racal Store 4 DS with -1 dB bandwidth of 150 Hz–160 kHz) and a Sonatech 8178 hydrophone (with -3 dB bandwidth of 100 Hz–160 kHz) at a nominal depth of 10 m. The sounds were digitised at 16 bits with a sampling rate of 353 kHz.

An initial visual inspection of the Hector’s dolphin data revealed several possible candidates for multiple pulses. A single example is shown here in Fig. 3.

This is a clear example of non-overlapping pulses, although it has not been established whether this was generated by the animal or by boundaries in the water column. The auto-correlation for the signal shown in Fig. 3 shows that P_1 is very nearly the inverse of P_2 [2]. Note that both pulses P_1

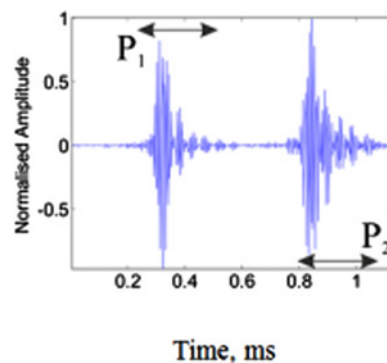


Fig. 3 Double non-overlapping pulse extracted from a segment of a recording of Hector’s dolphin vocalisations

Labels indicate the approximate locations of the pulses

and P_2 each consist of a series of overlapping pulses and this highlights the need for clarity regarding the form of pulse structure being considered, that is whether it is an overlapping or non-overlapping pulse structure. A review of a single 6-s recording contained 214 echolocation pulses, 132 of which were identified as consisting of non-overlapping multiple pulses. The data set analysed, although adequate for documenting basic features of sounds generated by Hector's dolphin, was not well suited for phase analysis.

2.3 Chilean dolphin (*C. eutropia*)

The final member of *Cephalorhynchus* considered in this review is the Chilean dolphin. The Chilean dolphin was labelled in 2002 by Folkens and Reeves [46] as one of the 'most poorly studied cetaceans'. Consistent with this observation, very little is known about the vocal repertoire of this species [47]. This lack of information is presumably a result of the fact that the Chilean dolphin lives only in waters that are difficult to navigate, and so comes into contact with humans only rarely compared with the other more visible members of the genus.

Watkins *et al.* [34] attempted in 1977 to record the sounds of Chilean dolphins, but heard only very low-level sounds described as 'a series of rapid pulses, up to 500/s, produced in a somewhat stereotyped sequence. The sound varied in duration from 0.4 to 2.0 s'. The equipment used by Watkins *et al.*, however, had an upper limit near 30 kHz. As Goodall *et al.* [19] pointed out, if the operating frequency used by Chilean dolphin is similar to that used by Commerson's and Hector's dolphin (120–150 kHz), it would be unsurprising that the low-frequency recording equipment used by Watkins *et al.* [34] captured only low-level signals.

In 2005, Götz and Heinrich [25] made recordings of free-ranging Chilean dolphins using a two-element vertical array. A second publication on the topic by Götz *et al.* [28] discussed the observation of multiple pulses within the Chilean dolphin recordings, but attributed these to being off-axis merged waveforms, wherein the second pulse is presumed to be the result of a reflection. The structure of these pulses appears to be non-overlapping.

2.4 Dall's porpoise (*P. dalli*)

Some evidence exists that suggests that Dall's porpoise is capable of generating double pulses. Evans *et al.* [21] clearly imply that Dall's porpoise produce double pulses, and Bassett *et al.* [27] state that 'Dall's porpoise produce multiple click types'. The habitat of this mammal is not restricted to the near-shore zone, unlike the animals in the previous sections. Dall's porpoise is found over the continental shelf and in offshore waters from approximately the US – Mexico border (32°N) and central Japan (35°N) north to the Bering and Okhotsk seas; but not in the shallow north-eastern Bering Sea [46]. In oceanic waters, Dall's porpoise can be found in the central North Pacific north of 41°N. In general, this animal has a preference for deep (>180 m), cool (<17°C) waters. Some Dall's porpoises shift seasonally from north and offshore in summer to south and inshore in winter [46].

Evans *et al.* [21] used only a single hydrophone, and observed a non-overlapping pulse structure. They state that 'Each component of a double pulse is only about half as long as a single pulse and may show considerable amplitude

modulation. The first component shows more spectral broadening above the dominant frequency of 139 kHz than the second component because of its more pronounced frequency modulation and higher harmonics at the beginning'. The only other work to support the theory that Dall's porpoises are capable of producing double clicks was conducted by Bassett *et al.* [27], but the only publication so far associated with that work is in the form of an abstract.

2.5 Finless porpoise (*N. phocaena*)

The Yangtze finless porpoise is one of three subspecies of finless porpoise, and is endemic to the Yangtze River and shallow waters surrounding China. The finless porpoise has been studied extensively [12, 14, 41] and there are no known reports of finless porpoise sightings in deep water in the literature. Within recordings of Yangtze finless porpoise vocalisations, Li *et al.* [12] observed NBHF signals and a non-overlapping multiple pulse structure [41].

After reporting the sounds emitted by the finless porpoise, Li *et al.* [12] noted the inverted phase relation between successive pulses, and published a second paper [41] based on a hypothesis concerning the origin of the clicks. They observed that that finless porpoises would emit echolocation pulses, which would be subsequently received by their hydrophones. They then hypothesised that the second pulses, P_2 , are the result of reflections off the sea-air interface. By calculating the delay between the initial and subsequent pulses τ_{delay} they estimate the distance between the porpoise and the hydrophone using the method demonstrated with the vocalisations of spinner dolphins (*Stenella longirostris*) by Lammers [48] and Aubauer *et al.* [37]. In the case of pulse structures where there are three or more distinct acoustic pulses, the third pulse, P_3 , was generally observed to be in phase with the first. Li *et al.* [41] suggest that these pulses are the result of bottom reflections. Attributing phase-inverted pulses to surface reflections and in-phase pulses to bottom reflections is an entirely reasonable approach, given the extent to which such multipaths are used in, say, geophysical surveying [49].

Although the analysis by Li *et al.* [41] is expertly done, it does raise some questions. In the 20 pulse trains (of which eight pulse trains are reproduced in Fig. 4) shown in Li *et al.*'s [12] study, the amplitude of the second pulse is at least equal to that of the first pulse in all of the examples. A multi-pulse structure would cause surface bounces, and the second pulse is usually of lower amplitude, because it has followed a longer propagation path than the direct pulse, and undergone a reflection from a surface which, at the acoustic wavelength of the pulses they measured (~1.5 cm), might be considered to be rough (depending on the surface waves). Indeed Medwin [50] found significant fall-off with amplitude (exceeding inverse square losses because of the surface roughness) of even normal incidence reflections from an upward-looking sonar directed from below at the air/water interface while significant variation in these reflections attributed to surface waves was also found by Tindle *et al.* [51]. A study of the propagation loss of porpoise-like clicks by DeRuiter *et al.* [52] also found large variability in transmission loss that can be partly attributed to surface waves. Although a reduction in amplitude for rough scattering would be expected as the norm, transient focusing of reflections by surface waves is of course possible (as anyone who has seen sunlight scattering from ripples on water will know), but for the amplitude of the

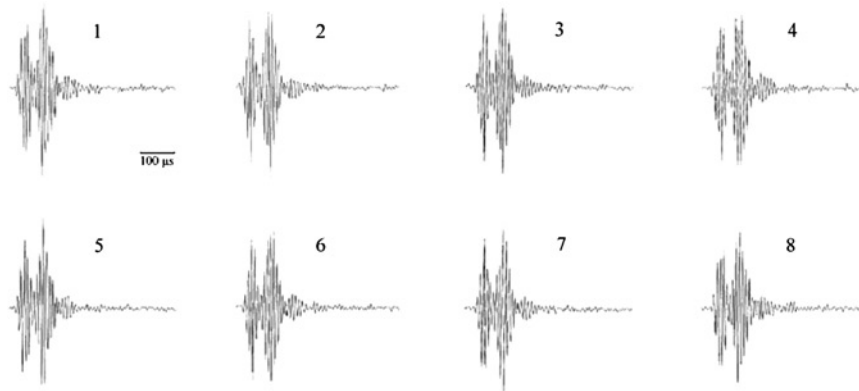


Fig. 4 Pulse pairs shown in Li *et al.* [12] of which eight pairs are presented here. Adapted with permission from Li *et al.* [12]

second pulse to equal or exceed that of the first pulse in all 20 pulse trains presented by Li *et al.* [41] would be remarkable. Li *et al.* [41] acknowledge this problem with their hypothesis and suggest it might be the consequence of the direct path corresponding to an off-axis measurement and the reflected path being closer to the main axis. However, for such a mechanism to operate with such consistency over all 20 pulse trains requires a high level of stability in the measurement configuration.

Working with Spinner dolphins (an animal which is not known to produce multiple pulses directly), Aubauer *et al.* [37] pioneered the use of a single hydrophone for the estimation of source–distance estimates based on the time gap between an initial arrival and the subsequent arrival of its reflection by the surface. In that paper, the source–receiver geometry was similar to that used in Li *et al.* [41] as shown in Table 3. However, despite the relative similarity in geometry between the two setups, Aubauer *et al.* [37] make no mention of reflections (late-arrival pulses) having amplitude near that of the incident pulse. In fact, in a published sample pulse train, the reflections are very small indeed when compared with their corresponding direct signals as shown in Fig. 5.

The hypothesis of Li *et al.* [41] that in this case the double- and multi-pulse artefacts observed were the result of surface reflection is certainly plausible. However, the experimental result of Aubauer *et al.* [37] does suggest that their conclusions might not be definitive.

2.6 Beluga whales (*Delphinapterus leucas*)

Beluga whales are often found in circumpolar shallow coastal waters and brackish riverine estuaries, but in the course of migration they are encountered in deeper waters. They are distinct from the other genera discussed here but are included to highlight how high-frequency echolocation clicks can be formed from multiple pulses. Recently, it was shown by Lammers and Castellote [53] that Beluga whales' echolocation pulses consist of two distinct components. Careful examination of clicks recorded simultaneously at a variety of angles revealed that off-axis an overlapping two pulse character for the clicks can be observed (Fig. 6). In contrast, when observed on-axis each echolocation click appears as a single pulse. The separation between pulses is $\sim 300 \mu\text{s}$ at 90° to the whale's main lobe. Lammers and Castellote suggest this multiple pulse structure arises because the animals use both phonic lips to generate echolocation clicks. It is further suggested that by independently controlling these sources the animal obtains a greater degree of control over the beam pattern of the echolocation click emitted.

2.7 Hypotheses as to the generation mechanism for multiple pulses

There are two basic hypotheses that explain the mechanism by which multiple pulse echolocation clicks can be generated. These are that they are the result of a dual source

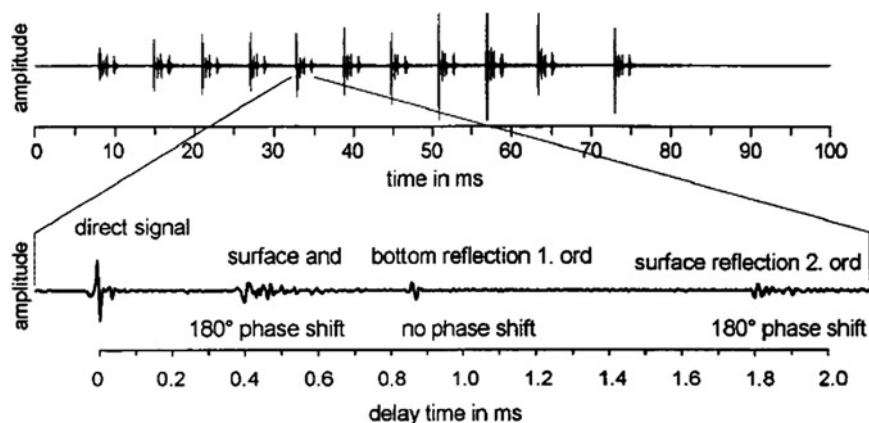


Fig. 5 Spinner dolphin burst pulse signal with multipath propagation recorded in shallow waters along the Waianae Coast of Oahu. Adapted with permission from Aubauer *et al.* [37]

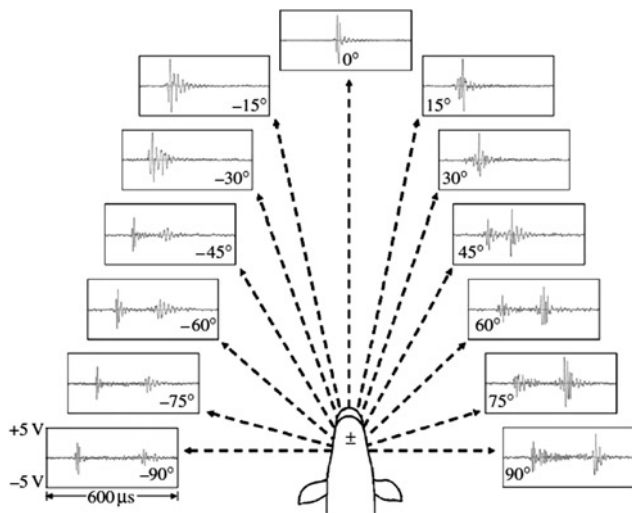


Fig. 6 Sonar pulses produced by the beluga whale as recorded at 15° angular interval in a 180° arc along the horizontal plane of the animal. Reproduced with permission from Lammers and Castellote [53]

mechanism, for example both phonic lips being used, or they are generated through reflections, be that internal reflections within the animal or externally from interfaces in the environment.

In the case of overlapping multiple pulse structures, the short path length differences involved are suggestive of the cause being internal to the animal. The fact that in most instances the overlapping multiple pulse structure has more than two components indicates that it is unlikely to be solely because of the source, but it is certainly plausible that a combination of two sources and internal reflections causes this observed structure.

The source of the non-overlapping multiple pulse structure is a little more contentious. It is most commonly attributed to surface reflections, often from the air–water interface. This suggestion is certainly viable, although in that case the fact that the later pulses are commonly of similar amplitudes to the direct pulse requires further explanation. The possibility that the pulses derive from the animal has not been conclusively eliminated in many cases.

3 Competitive advantages

This paper has reviewed the detection of multiple pulses by small, littorally based cetaceans and has concluded that the evidence does not preclude the possibility that some animals are generating these at source. If they did so, it might be a collateral result of anatomy, or might have evolved as a deliberate technique to provide competitive advantages, which would be of significant interest given that there is a need for enhanced man-made sonar capability in littoral waters resembling those in which these animals compete. Note that advantages are conceivable even if the multiples are generated by reflections in the external environment.

There are several mechanisms by which multiple pulses could give potential sonar enhancement, whether produced by the animal or whether generated by surface bounces and processed as bistatic sonar. If the second pulse comes from a surface reflection, it insonifies the target at an angle which differs from the direct path, and so can provide information as to the directional nature of the scatter from the target.

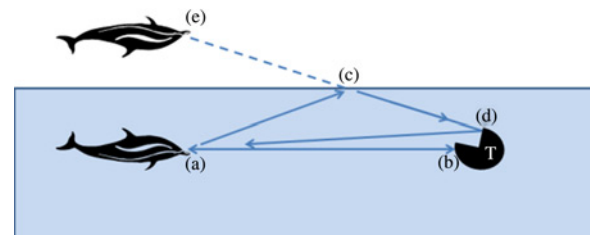


Fig. 7 Dolphin insonifies a target (T) directly (ray path (a)–(b)–(a)), but then obtains a later strong glint reflection of the emission along the path (a)–(c)

This echo indicates the presence of an appropriately angled facet (ray path (a)–(c)–(d)–(a)) where the calm flat surface generates an image source at (e). There are of course many other paths (e.g. (a)–(d)–(c)–(a)) which have not been included for simplicity

Fig. 7 shows an example scenario where a glint from a facet of a target may be observed via a surface reflection. By insonifying the target from multiple directions and by receiving echoes from multiple paths, more information regarding the scattering characteristics of a target is available. Albeit this information is encoded in the return signal which is complex in character, and may be affected by additional contributing factors, for example, surface roughness. However, these animals have evolved in these environments and it is feasible they can accurately extract information from such returns. One should note that the roughness of the water surface will typically give rise to temporal spreading of echoes arising from paths including reflections from surface. Conceivably, this temporal spreading can be used to help identify which echo components arise via this indirect path.

Although there is no conclusive evidence that any species of cetacean use Doppler processing, it is interesting to note the relationship between the frequency of a pulse with its pulse length for Doppler processing. In the simplest Doppler sonar system, a single pulse system, the target speed can be estimated from the frequency shift observed in backscatter from a single acoustic pulse using the relation, $f_d = (2f_t v/c)$, where f_d is the Doppler frequency shift, v is the relative speed of the target, f_t is the transmitted frequency and c is the speed of sound in water [54]. Using the pulses of the Hector's dolphin as an example, for a target (prey) moving at relative speed of 5 m s^{-1} , the maximum Doppler frequency shift will be $\sim 800 \text{ Hz}$ for a pulse with centre frequency of 121 kHz . To detect a Doppler shift on the basis of a single pulse of duration, τ , generally requires that there be at least one cycle of the Doppler frequency shift within the pulse, that is, that the product of f_d and τ is greater than unity [54], which implies a minimum pulse length of 1.25 ms . Hector's dolphin pulse durations are typically $100\text{--}200 \mu\text{s}$, approximately an order of magnitude shorter than required to detect Doppler shifts in a single pulse.

Some man-made systems exploit multiple pulses in order to overcome this limitation and are referred to as coherent Doppler systems and exploit a regular train of transmitted pulsed signals. For such a Doppler system, the relationship between the maximum unambiguous velocity, V_{max} , and t , the interval between pulses, is expressed as $V_{\text{max}} = c/(4ft)$ [55]. The use of a pulse train with a shorter time between multiple pulses increases the maximum unambiguous velocity. For the Hector's dolphin vocalisations studied here, the pulse interval between a pair of double pulses is about 50 ms with the pulse interval within the double pulse

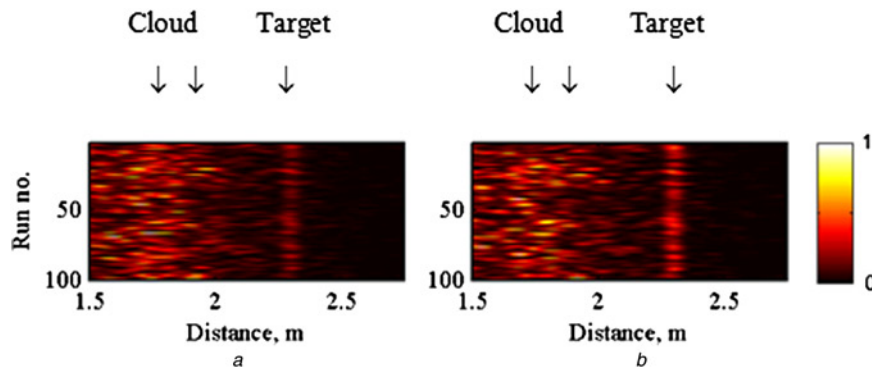


Fig. 8 Comparing the image plots of a target placed in bubbly water from 100 runs using Hector's dolphin-like pulses of peak-to-peak source level of 163 dB re 1 $\mu\text{Pa m}$

a With one pulse, and

b Coherent averaging of two pulses

Cloud is assumed to evolve between runs. The colour scale in both plots have been normalised to a value of 2.0×10^5

pair being $\sim 500 \mu\text{s}$: using these intervals the values of V_{max} are 0.06 m s^{-1} and 6 m s^{-1} , respectively. The presence of double pulses thus increases the possibility that some form of coherent Doppler processing can occur.

Other competitive advantages of using multiple pulses can be illustrated using a theoretical pulse, based on the echolocation pulse of the Hector's dolphin, in a theoretical bubble cloud model as described in [56]. The Hector's dolphin-like pulse used here has a duration of $\sim 141 \mu\text{s}$, and a centre frequency of 121 kHz. A peak-to-peak source level of 163 dB re 1 $\mu\text{Pa m}$ obtained by Dawson and Thorpe [57] is used. The size distribution of the bubble cloud is similar to that used in [56] but with a higher void fraction of order of $10^{-4}\%$. In the hypothetical scenario, the main bulk of the bubble cloud is assumed to be in front of a linear target of target strength of -32 dB . This value of -32 dB is within the typical range of target strength of some species of fish (for fish length of $\sim 15\text{--}30 \text{ cm}$) [58].

A number of pulses emitted in succession might allow coherent averaging. Fig. 8 shows the image plots of the smoothed envelope of the match-filtered return signal of one pulse together and that of two pulses with coherent averaging for a target placed behind a bubble cloud. The interval between the two pulses is assumed to be large enough for the cloud to evolve between pulses. A hundred

separate runs are stacked (with amplitude represented by colour as defined in the colour bar), forming the image plots shown. With coherent averaging of two pulses (Fig. 8b) in such a scenario, the overall scatters from the cloud is reduced and the presence of the target is observed to be enhanced with respect to the cloud as seen in the image plot. A target enhancement ratio, $10\log_{10}(E_{\text{target}}/E_{\text{cloud}})$, is calculated where E_{target} is the 'energy' associated with scattering from the target, taken to be between 2.2 and 2.4 m and E_{cloud} is the 'energy' associated with scattering from the bubble cloud taken to be between 1.5 and 2.0 m. This target enhancement ratio is found to increase from -8.0 to -6.1 dB as the number of pings is increased from one to two. When the number of coherent averaged pings increases to four, the target enhancement ratio is found to increase to approximately -3.7 dB (figure not shown)

In scenarios where a number of pulses are emitted in quick succession such that the cloud does not evolve between pulses, coherent averaging of two or more pulses will only have competitive advantage if the ambient noise is high such that the scatters from the bubble cloud is not the main source of interference. To highlight the advantage of coherent averaging in such scenarios, the ambient noise spectrum level is increased to 60 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ where coherent averaging of two pulses were carried out and shown in Fig. 9b. This is compared with Fig. 9a where no

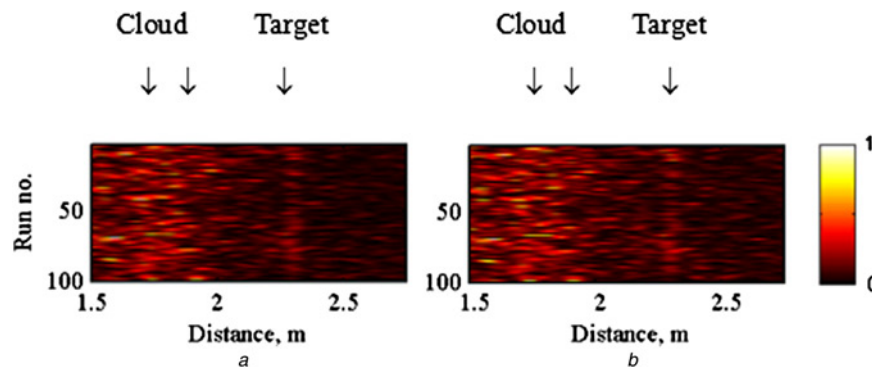


Fig. 9 Comparing the image plots of a target placed in bubbly water from 100 runs using Hector's dolphin-like pulses of peak-to-peak source level of 163 dB re 1 $\mu\text{Pa m}$

a With one pulse, and

b Coherent averaging of two pulses

It is assumed the cloud does not evolve between runs. The ambient-noise spectrum level used is 60 dB re 1 $\mu\text{Pa}^2/\text{Hz}$. The colour scale in both plots have been normalised to a value of 2.8×10^5

coherent averaging is carried out. In Fig. 9b, both the bubble cloud and target are enhanced by coherent averaging as the overall ambient noise is reduced with coherent averaging. The target enhancement ratio is calculated to increase by only 0.4 dB with coherent averaging of two pulses. This suggests that the main clutter is from the bubble cloud.

The potential for sonar enhancement when using pairs of pulses, the second of which is inverted with respect to the first, has been shown in littoral waters by Leighton *et al.* [59, 60], who demonstrated enhanced target detection and clutter suppression using twin inverted pulse sonar (TWIPS) operating at 6–12 kHz. This method, however, requires the signals to be of sufficiently high amplitude to cause non-linear scattering by bubbles in the water column [61, 62]. The compilation of sound levels associated with NBHF species published by Morisaka *et al.* [63] suggests that none of the relevant species are capable of producing sounds much louder than peak-to-peak source level of 180 dB re 1 μPa m. Although such levels can generate a non-linear response in individual bubbles [64, 65], they are insufficiently high to result in significant non-linear scatter from the wide size distribution [66–68], which characterises ocean bubbles in littoral populations [69]. On axis measurements of wild animals challenged by bubble presence are required, but unless these indicate levels which

can generate TWIPS enhancement (noting that the required level generally increases with frequency), the use of TWIPS by these species seems unlikely.

To illustrate this, using the same theoretical bubble cloud model as above, two source levels of the Hector's dolphin-like pulses were used: a peak-to-peak source level of 163 dB re 1 μPa m and a hypothetical higher peak-to-peak source level of 205 dB re 1 μPa m to illustrate the competitive advantage as well as limitations of TWIPS. In TWIPS processing, the return signals from a pair of the dolphin-like pulses (one of which is the opposite polarity of the other), are first match-filtered and subtracted from each other and the smoothed envelope of this subtraction is then obtained. This will be denoted as P_- . Similarly, the addition of match-filtered signals will be denoted as P_+ . The TWIPS processing is compared with 'standard sonar' processing technique. In standard sonar processing technique, the smoothed envelope of the match-filtered return signal from each pulse is obtained. To ensure a fair comparison, the average of the standard sonar processed return signals from each pulse pair is computed [59, 60].

Fig. 10 shows how a pulse pair of higher source level of the Hector's dolphin-like pulses can be used with TWIPS. Figs. 10a, c and e show the plots of standard sonar

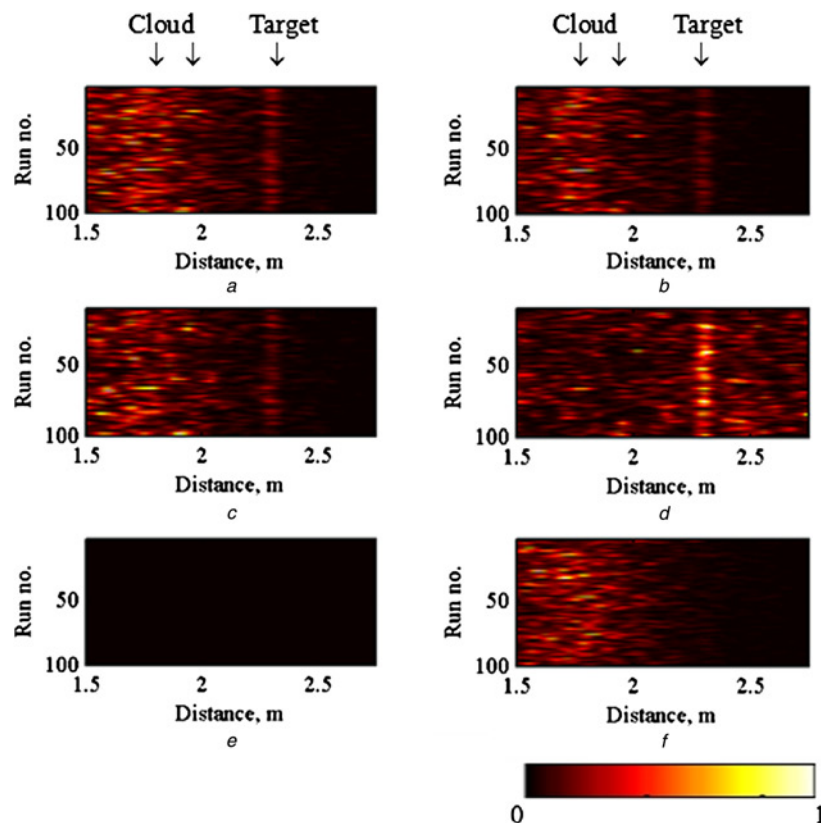


Fig. 10 Comparing the image plots with TWIPS enhancements from a target placed in bubbly water using Hector's dolphin-like pulses of different source level for 100 runs which for

a Is standard sonar

c P_-/P_+ and

e P_+ at peak-to-peak source level of 163 dB re 1 μPa m

b Standard sonar

d P_-/P_+ and

f P_+ at peak-to-peak source level of 205 dB re 1 μPa m

Each colour scale has been normalised to the following value in each plot, which for a is 2.0×10^5 , b 4.4×10^9 , c 1.3×10^5 , d 1.0×10^3 , e 2.5×10^8 , f 2.5×10^8

processing and TWIPS functions when pulse pairs of lower amplitude are used. With a higher amplitude pulse pairs, it can be observed that the bubble cloud is driven to a higher degree of non-linearity, and separate identification of the bubble cloud and target can take place by comparing which items are enhanced and suppressed in the plots of P_-/P_+ and P_+ (Figs. 10d and e, respectively). By using standard sonar processing only, backscatters from the bubble cloud and target cannot be distinguished from each other (see Figs. 10a and b).

Figure 8 demonstrates that applying coherent averaging to data when the cloud is evolving in between pulses can increase the detectability of the target, whereas when it is applied to data in which the cloud remains unchanged the detectability of both the target and the cloud is increased (Figure 9). TWIPS, as shown in Figure 10, can discriminate between the two by processing the same echoes in different ways, selectively enhancing the target and suppressing the cloud (using P_-/P_+), or vice versa (using P_+). When a low-amplitude pair of pulses is used, it is insufficiently high to result in significant non-linear scatters from the wide size distribution cloud (Fig. 10b). To allow a comparison of the non-linear scatters when a higher source level is used, Figs. 10b and d have been scaled to the same maximum value. Fig. 10d shows the position of the bubble cloud (between 1.5 and 2 m) when P_+ is used. This cannot be achieved using a low-amplitude pulse that has levels similar to those recorded to date from species associated with the detection of such pairs of inverted pulses. The target enhancement ratio calculated is also found to increase by ~ 7.5 dB with TWIPS processing (Fig. 10d) over standard sonar processing (Fig. 10b). Although the use of low output level has also been suggested as a possible competitive advantage to help reduce clutter [70], there is no simple correspondence between pulse amplitude and level of clutter from oceanic bubble clouds [62].

4 Conclusions

This paper has focused on the occurrence (in recordings of littoral-based acoustically active odontocetes) of multiple pulse structures. Several species all have been associated with multiple pulses: Commerson's dolphin, Hector's dolphin, the finless porpoise and Dall's porpoise. The Beluga whale produces closely spaced pulses at source. This paper has demonstrated that although man-made dual pulse sonar systems can yield performance advantages, the equivalent advantage will not arise from NBHF odontocete clicks. The potential advantages in terms of pulsed sonar are considered and the opportunities offered for exploitation of insonification close to a boundary explored. However, the data are insufficient to resolve a number of key questions, including whether all the non-overlapping pulses are the result of surface reflections, or whether in some cases animals can generate these pulses themselves; if the pulses are produced by the animal, whether this is done deliberately for sonar enhancement or whether it is the by-product of anatomy; if the pulses are produced by the animal, whether the trend observed in Beluga whales (where multiple pulses are only seen off-axis) occur in other species, or whether these others can produce on-axis multiples. The paucity of information concerning the echolocation emissions of littoral-based odontocetes (and in particular, the absence of published work addressing controlled tests on wild dolphin biosonar involving

challenging near-shore conditions) contrasts sharply with the current scientific interest in shallow-water acoustics.

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