# Acoustic Behavior of Dolphins in the Pacific Ocean: Implications for Using Passive Acoustic Methods for Population Studies

**Shannon Rankin[1], Julie N. Oswald[2], and Jay Barlow[1]**
[1]Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, California 92037
[2]Scripps Institution of Oceanography, University of California San Diego, La Jolla, California, 92038

## ABSTRACT

The Southwest Fisheries Science Center has been conducting shipboard visual line-transect cetacean surveys for over 30 years, and combined visual and acoustic surveys for seven years. Full incorporation of passive acoustics as a tool for population assessment requires an understanding of the acoustic behavior of cetaceans as well as the limitations of the methods used in these surveys. Our research summarizes data collected during seven years of combined visual and acoustic surveys throughout the central and eastern North Pacific Ocean, ranging from the Aleutian Island chain in the north, to Peru in the south. Phonations from 2,034 dolphin schools were examined to better understand the acoustic behavior of cetaceans. Equally important are the cetacean schools that were seen but not heard, and this analysis includes an examination of these groups by species, group size, geographic location, and time of day. The results of this analysis allow us to take the first steps to incorporate passive acoustics into line-transect cetacean surveys.

## RÉSUMÉ

Le Southwest Fisheries Science Center a étudié les cétacés à bord de navires en utilisant des transects linéaires pour des données visuelles depuis plus de 30 ans, et une combinaison des méthodes visuelles et acoustiques depuis seulement sept ans. L'incorporation complète de l'acoustique passif comme outil d'évaluation de la population exige une bonne compréhension du comportement vocal des cétacés, ainsi que de connaître les limites des méthodes utilisées dans ces études. La présente recherche résume les données provenant de sept années d'études visuelles et acoustiques tout au long de la partie centrale et orientale du Pacifique Nord, depuis les îles septentrionales d'Aleutian, jusqu'au Pérou, au sud. Les vocalisations des dauphins, à partir de 2034 groupes suivis, ont été examinées afin de mieux comprendre le comportement vocal des cétacés. Les groupes de cétacés qui ont été vus mais non entendus, sont également importants ; cette analyse examine ces groupes par espèce, taille du groupe, position géographique et heure du jour. Les résultats nous permettent de prendre en compte les premières mesures pour incorporer l'acoustique passif dans un transect linéaire dans l'étude des cétacés.

## 1. INTRODUCTION

Population studies of cetaceans in offshore waters have typically relied on shipboard visual observations, which are limited to daylight hours and must be suspended when poor weather conditions prohibit reasonable visual detection of animals. In recent years, passive acoustic detection of cetacean phonations using towed hydrophone arrays has been used to complement visual shipboard surveys (Thomas *et al.* 1986, Gordon *et al.* 2000, Oswald *et al.* 2007a). Acoustic detection of cetacean phonations is not limited by time of day, nor is it affected by most weather conditions. The primary limitation of acoustic methods is that the animals must be producing sounds within the frequency range of the equipment.

Dolphin phonations have been grouped into three categories: whistles, burst pulses, and echolocation clicks. Whistles are tonal, frequency-modulated signals used for communication (Janik and Slater 1998, Herzing 2000, Lammers *et al.* 2003). Most dolphin species produce whistles, which typically have fundamental frequencies between 2 and 30 kHz (Lammers *et al.* 2003, Oswald *et al.* 2004). Burst pulses are broadband click trains that have very short inter-pulse intervals. These sounds are also thought to be used for communication, although they may also be for echolocation (Herzing 2000). Echolocation clicks are short, broadband, pulsed sounds used for navigation and object detection. Echolocation clicks have peak frequencies ranging from tens of kilohertz to well over 100 kHz (Au 1980, Au 1993). Basic descriptions of acoustic repertoire exist for many species; however, little is known of the acoustic behavior of most species in their natural habitat.

The Southwest Fisheries Science Center (SWFSC) has been conducting visual observations of cetaceans during shipboard line-transect surveys for over thirty years. In 2000-2006, a towed hydrophone array was added to examine the potential for the use of passive acoustics during these surveys. In this paper we present a preliminary examination of the acoustic behavior of dolphins in the

Pacific Ocean and our ability to detect their phonations using a towed hydrophone array with a limited bandwidth (2 - 24 kHz).

## 2. METHODS

We conducted cetacean surveys in the Pacific Ocean from 2000 to 2006 using simultaneous visual and acoustic line-transect methods. The acoustic effort during these surveys is shown in Figure 1. The dates, study area, and effort for each survey varied, and a summary of this information is given in Table 1.

Visual observation methods followed standard SWFSC protocol that has been used since the 1980s (Kinzey *et al.* 2000). A team of three experienced visual observers rotated between two 'big-eye' 25x150 binoculars and one data-recording position. Visual observation occurred during daylight hours in Beaufort sea states 0-5. When animals were sighted by the visual observation team, they were approached for species identification and group size estimation.

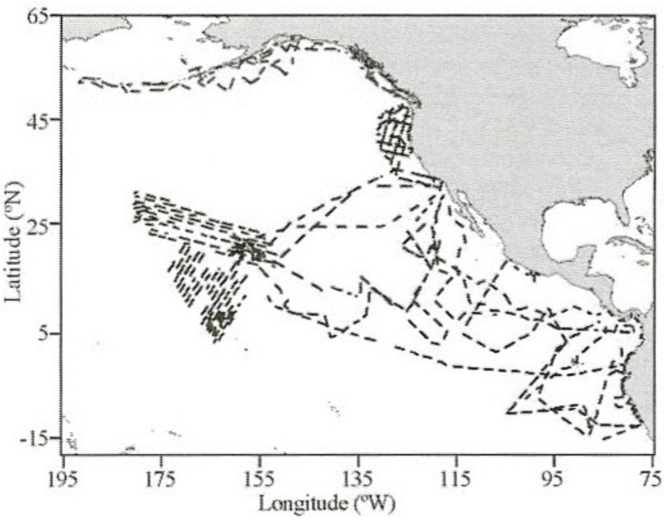


**Figure 1. Map of survey area and tracklines with passive acoustic effort using a towed hydrophone array shown as dashed lines.**

A towed hydrophone array was used for acoustic detection of cetacean phonations. The array was typically towed 200-300 m behind the ship during daylight hours and in sea states less than Beaufort 7. Several array configurations were used, each with its own specifications. The five-element 'Sonatech' array (Sonatech, Inc., Santa Barbara) had a flat frequency response from 2 kHz to 45 kHz (± 4 dB at -132 dB re 1 V/μPa), the three-element high-frequency 'HF' array (Sonatech, Inc., Santa Barbara) had a flat frequency response from 2 kHz to 120 kHz (± 3 dB at -164 dB *re* 1V/μPa), and the 'SWFSC' array had a flat frequency response from 500 Hz to 30 kHz (± 5 dB at -155 dB re 1V/μPa). The specific arrays used during each survey are shown in Table 1.

Signals from the array were equalized using a Mackie CR1604-VLZ mixer and recorded using a Tascam DA-38 eight-channel digital recorder (sample rate 48 kHz). Sounds were monitored by an acoustic technician both aurally, using headphones, and visually, using real-time scrolling spectrographic software (ISHMAEL, Mellinger 2001). Acoustic localization of dolphin schools was performed based on the convergence of bearing angles plotted on Whaltrak, a custom-written plotting program. Bearing angles to phonating dolphin schools were calculated using the phone-pair bearing algorithm in ISHMAEL (Mellinger 2001). All data presented here are based on monitoring within the limitations of the hydrophones and recording equipment; only sounds detected between 2 kHz and 24 kHz were included in the analyses.

**Table 1. Summary information for seven cetacean surveys conducted by the Southwest Fisheries Science Center, including the cruise name, dates, region surveyed, survey vessel, hydrophone arrays used, and the number of acoustic detections. Three surveys were conducted in the eastern tropical Pacific Ocean (ETP).**

| Cruise Name | Dates | Region Surveyed | Survey Vessel | Array | # Detections |
|---|---|---|---|---|---|
| STAR | 28 July - 9 Dec, 2000 | ETP | *McArthur* | Sonatech, HF | 374 |
| ORCAWALE | 30 July - 9 Nov, 2001 | US West Coast | *Jordan* | Sonatech, HF | 132 |
| HICEAS | 27 July - 8 Dec, 2002 | Hawai'i | *Jordan* | SWFSC | 273 |
| STAR | 6 Oct - 9 Dec, 2003 | ETP | *McArthur II* | SWFSC | 260 |
| SPLASH | 29 June - 20 Oct, 2004 | Alaska | *McArthur II* | SWFSC | 35 |
| PICEAS | 29 July - 14 Nov, 2005 | Pacific Islands | *McArthur II* | SWFSC | 229 |
| STAR | 30 July - 6 Dec, 2006 | ETP | *McArthur II* | SWFSC | 731 |

Acoustic activity (presence/absence of phonations) within the limits of our monitoring bandwidth was compared among species. The acoustic detection distance, or the greatest distance at which phonations could be confidently matched to a known dolphin sighting, was compared for each species. Variation in acoustic activity was examined using Classification and Regression Tree analysis (CART) to determine which factors influenced the detection of dolphin schools (latitude, longitude, group size, sea state).

## 3. RESULTS

This analysis includes 2,034 acoustic detections of dolphin schools made during seven years of combined visual-acoustic line-transect surveys of cetaceans in the Pacific Ocean. A total of 971 single species schools were identified to species by experienced visual observers and included: *Stenella attenuata*, *S. coeruleoalba*, *S. longirostris*, *Delphinus* spp., *Tursiops truncatus*, *Steno bredanensis*, *Pseudorca crassidens*, *Globicephala* spp., *Lagenorhynchus obliquidens*, *L. obscurus*, *Lissodelphis borealis*, *Grampus griseus*, *Orcinus orca*, *Berardius bairdii*, and *Feresa attenuata*. Phonations produced by *Delphinus delphis* and *Delphinus capensis* were grouped together as *Delphinus* spp., as were detections produced by *Globicephala macrorhynchus* and *Globicephala melas* (*Globicephala* spp.). In addition, mixed-species schools of *S. attenuata* and *S. longirostris* were included in some analyses.

Overall, 73% of sighted dolphin schools were also detected acoustically. The percentage of sighted schools that were detected both visually and acoustically ranged from 28% for *Berardius bairdii* to 100% for *Pseudorca crassidens* (Table 2). Dolphin species that had a high acoustic detection rate (> 80% of schools) were found in significantly larger schools than species with a low acoustic detection rate (Mann-Whitney $U$, $p<0.001$). The mean group size of schools detected acoustically was significantly (Mann-Whitney $U$, $\alpha = 0.05$) greater than the mean group size of schools not detected acoustically for most species (Table 2). The CART analysis showed that group size was the most important factor associated with the acoustic detection of dolphin schools, both overall and for each species individually.

Most dolphin species found in our study areas are known to produce whistles within the acoustic detection bandwidth of the equipment used during these surveys (Table 3). Whistles were evident in 93% of the 2,034 acoustic detections; however, not all species produced whistles. No whistles were detected from schools of *Lissodelphis borealis*, *Lagenorhynchus obliquidens*, *L. obscurus*, or *Berardius bairdii*. Maximum acoustic detection distance varied from 1.5 nmi for *Lissodephis borealis* to 10 nmi for *Stenella coeruleoalba* (Table 3). Dolphin species in which most schools were found to produce whistles were generally detected at greater distances (Table 3).

Many dolphin groups were detected and localized using acoustic methods but were not seen by visual observers. Species was not known with certainty for groups that were not seen. These data were not examined for this study.

## 4. DISCUSSION

This study provides the largest dataset of simultaneous visual and acoustic observations of cetaceans during shipboard line-transect surveys published to date. The limited frequency bandwidth of our acoustic system did not allow for an examination of the full frequency range of dolphin phonations, however, for the purposes of population surveys, detection of the school is of greater importance than detection of the full acoustic repertoire.

Nearly two-thirds of sighted dolphin schools were detected acoustically; however, acoustic detection of dolphin schools was not equal among species. Of the variables included in the analysis, group size was found to be the single most important factor influencing the acoustic detection of dolphin schools, both among and within species. Most dolphin schools that were not detected by the acoustic team contained fewer than 20 animals. Species that were consistently detected acoustically had large mean group sizes. For example, 85% of *S. attenuata* schools were detected acoustically and this species had an average school size of 93.1. There are exceptions to this trend, however. All *P. crassidens* schools and 96.8% of *Steno bredanensis* schools were detected acoustically, but these species had small mean group sizes (10.7 and 15.3, respectively). In the case of *P. crassidens*, individual group sizes were small, but encounters included a large number of these small groups spread out over large areas. *Steno bredanensis*, on the other hand, are found in small isolated groups, and there is no clear explanation for their high level of acoustic activity.

For some species, fewer than 70% of sighted schools were detected using acoustic methods, including: *G. griseus*, *Lagenorhynchus* spp., *O. orca*, *Lissodelphis borealis*, *F. attenuata*, and *B. bairdii*. With the exception of three sightings of *Lagenorhynchus obscurus*, all of these were relatively small schools. Also, with the exception of *F. attenuata,* whistles were detected from fewer than half of the schools of these species. It is possible that these species mainly produce high frequency clicks and that the limited bandwidth of our equipment prevented the detection of these sounds.

Given that 93% of the groups that were detected acoustically produced whistles, the use of whistle sounds for detection would allow most schools to be picked up. Whistles tend to be lower in frequency than most click sounds, and can therefore be detected using less expensive, lower bandwidth systems than would be necessary for click detection and identification. In addition, lower frequencies propagate further than higher frequencies, suggesting that whistles can be detected over greater distances than clicks. It is possible that whistles play an important role in communication over the large areas occupied by these groups.

From our analysis of the acoustic detection of dolphin schools during these surveys, we define two detection categories: dolphin species with a high rate of acoustic detection (>80%) and dolphin species with a low rate of acoustic detection (<80%). Dolphin species with a high rate of acoustic detection were typically found in large schools and frequently produced whistles. Most of these species were found in the tropical study areas (Hawai'i, Pacific Islands, eastern Tropical Pacific Ocean). The species with a low rate of acoustic detection were typically found in smaller schools and produced few, if any, whistles. These species were more common in the temperate study areas off the west coast of the United States, Canada, and Alaska.

**Table 2. Mean group size for dolphin schools detected (1) both visually and acoustically, and (2) only visually. For all detections, the percent vocal indicates the percentage of sighted schools that were detected using acoustic methods. For acoustic detections, the percentage of detections that included whistles is given. Species are arranged according to the percentage of schools detected acoustically (percent vocal). A statistical comparison was made of the group sizes for acoustic/visual detections and for visual-only detections (Mann-Whitney U test).**

| | Acoustic/Visual Detections | | Visual-Only Detections | | Mann-Whitney U Test | All Acoustic Detections | All Detections |
|---|---|---|---|---|---|---|---|
| Species | Sample Size | Group Size | Sample Size | Group Size | Significance | % with whistles | % vocal |
| *P. crassidens* | 19 | 10.7 | - | - | - | 100.0% | 100.0% |
| *S. bredanensis* | 30 | 15.3 | 1 | 7.3 | 0.434 | 90.3% | 96.8% |
| *S. attenuata, S. longirostris* | 71 | 351.5 | 4 | 131.5 | 0.122 | 100.0% | 94.7% |
| *Delphinus* spp. | 134 | 192 | 23 | 62 | 0.001 | 98.5% | 85.4% |
| *S. attenuata* | 81 | 93.1 | 14 | 41.9 | 0.012 | 97.4% | 85.3% |
| *T. truncatus* | 62 | 78.1 | 13 | 10.1 | 0.020 | 96.7% | 82.7% |
| *S. longirostris* | 37 | 116.4 | 9 | 38.1 | 0.008 | 100.0% | 80.4% |
| *S. coeruleoalba* | 149 | 60.4 | 37 | 48.3 | 0.047 | 100.0% | 80.1% |
| *Globicephala* spp. | 55 | 21.2 | 21 | 14.4 | 0.064 | 92.6% | 72.4% |
| *L. obscurus* | 3 | 280 | 2 | 9.5 | 0.083 | 0.0% | 60.0% |
| *G. griseus* | 28 | 21.2 | 30 | 9.8 | 0.021 | 44.8% | 48.3% |
| *L. obliquidens* | 4 | 19.5 | 5 | 11.5 | 0.712 | 0.0% | 44.4% |
| *O. orca* | 21 | 11.9 | 28 | 5.6 | 0.011 | 50.0% | 42.9% |
| *L. borealis* | 7 | 27.3 | 13 | 7.8 | 0.021 | 0.0% | 35.0% |
| *F. attenuata* | 2 | 23.9 | 4 | 7.9 | 0.064 | 100.0% | 33.3% |
| *B. bairdii* | 2 | 16 | 5 | 7.6 | 0.245 | 0.0% | 28.6% |

In general, the limited bandwidth of the acoustic equipment used during these surveys was sufficient for the detection of dolphin schools encountered in tropical and sub-tropical study areas (*P. crassidens*, *Steno bredanensis*, *Delphinus* spp., *Stenella* spp., *T. truncatus*). Further examination of the data may provide a better understanding of why some tropical dolphin schools were not detected using these acoustic methods.

**Table 3. Acoustic detection distance and whistle frequency range for each species. The maximum acoustic detection distance (nmi) provides the range at which our equipment detected sounds from each species. Frequency ranges (kHz) of whistles were obtained from the literature, and all fall within the 2-24 kHz detection range of our equipment (note: the authors have detected whistles in the presence of *F. attenuata*, but there are no published descriptions of whistles for this species). Species are labeled from highest acoustic detection rate to the least (Table 2).**

| | Detection Distance | | Whistle Range | | |
|---|---|---|---|---|---|
| Species | Mean (St. Dev) | Maximum | Low Frequency | High Frequency | Reference |
| *P. crassidens* | 2.87 (1.64) | 6 | 1.8 | 18 | Oswald *et al*. (2007b) |
| *S. bredanensis* | 1.53 (1.19) | 4.5 | 4 | 9.5 | Oswald *et al*. (2007b) |
| *Delphinus* spp. | 2.22 (1.6) | 6 | 3.5 | 23.5 | Oswald *et al*. (2007b) |
| *S. attenuata* | 1.88 (1.54) | 6 | 3 | 21 | Oswald *et al*. (2007b) |
| *T. truncatus* | 1.75 (1.31) | 6 | 1.9 | 21.6 | Ding, *et al*. (1995) |
| *S. longirostris* | 2.57 (1.56) | 6 | 4 | 25 | Oswald *et al*. (2007b) |
| *S. coeruleoalba* | 2.61 (1.83) | 10 | 1 | 23 | Oswald *et al*. (2007b) |
| *Globicephala* spp. | 2.58 (1.79) | 8.5 | 0.3 | 23.6 | Oswald *et al*. (2007b) |
| *L. obscurus* | 0.98 (1.33) | 2.5 | 1 | 27 | Ding, *et al*. (1995) |
| *G. griseus* | 0.93 (0.7) | 2.3 | 2 | 24 | Rendell *et al*. (1999) |
| *L. obliquidens* | 0.71 (0.87) | 2 | 2 | 20 | Caldwell and Caldwell (1971) |
| *L. hosei* | 2 | 2 | 4.3 | 24 | Oswald *et al*. (2007a) |
| *O. orca* | 0.73 (0.71) | 2.3 | 1.5 | 18 | Thomsen *et al*. (2001) |
| *L. borealis* | 0.58 (0.67) | 1.5 | - | - | Rankin, *et al*. (2007) |
| *F. attenuata* | 1 (1.05) | 1.75 | - | - | * |
| *B. bairdii* | 1.1 (0.84) | 1.7 | 4 | 8 | Dawson, *et al*. (1998) |

Many of the species encountered in the temperate study areas (*Lagenorhynhus* spp., *G. griseus*, *O. orca*, *Lissodelphis borealis*, and *B. bairdii*) had low rates of acoustic detection. It is possible that the limited bandwidth of our acoustic equipment prevented the detection of many of these dolphin schools. Acoustic studies conducted in these areas should be carried out using broadband equipment to guarantee the detection of higher-frequency click sounds produced by these species. An increased bandwidth (over 100 kHz) for cetacean studies in the temperate regions would also allow for detection of porpoise species, which could not be included in this study. Despite our bandwidth limitations, we detected both clicks and click bursts from many groups and were able to describe the sounds produced by *L. borealis* (Rankin *et al.* 2007).

## 5. CONCLUSION

The Southwest Fisheries Science Center has been using a standard protocol for combined visual and acoustic shipboard line-transect cetacean surveys for seven years. Using this standard protocol, we have been able to detect and localize odontocete groups in situations in which the visual team was unable to work due to weather or darkness. Our ability to detect dolphin schools varies by species, group size, and acoustic behavior. These results highlight the variation in acoustic behavior within and among species, and the need for a more rigorous examination of the acoustic behavior of each species. Nonetheless, the high rate of acoustic detection of dolphin schools in the tropical and sub-tropical Pacific Ocean justifies the use of acoustic methods for the detection of most dolphin schools within these areas.

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## ACKNOWLEDGEMENTS


This work could not have been accomplished without the assistance and cooperation of the scientists, officers and crew of the *McArthur*, *McArthur II*, and the *David Starr Jordan*. Special thanks to Liz Zele and the many acousticians who helped in the field. Funding for this research was provided by the Southwest Fisheries Science Center and the U. S. Navy.