EARTHJUSTICE

June 5, 2017

Via Federal eRulemaking Portal

Jolie Harrison
Chief, Permits and Conservation Division
Office of Protected Resources
National Marine Fisheries Service
http://www.regulations.gov

Re: Proposed Regulations re: Takes of Marine Mammals Incidental to the U.S. Air Force 86 Fighter Weapons Squadron Conducting Long Range Strike Weapons System Evaluation Program at the Pacific Missile Range Facility at Kauai, Hawaii, 82 Fed. Reg. 21,156 (May 5, 2017)

Dear Ms. Harrison:

Earthjustice submits these comments on behalf of the Animal Welfare Institute, Center for Biological Diversity, Conservation Council for Hawaiʻi, Natural Resources Defense Council and the Ocean Mammal Institute in response to the National Marine Fisheries Service's (NMFS's) request for public input on NMFS's proposal to issue regulations granting the U.S. Air Force 86 Fighter Weapons Squadron's request for authorization to take marine mammals incidental to Long Range Strike Weapons System Evaluation Program (WSEP) activities at the Pacific Missile Range Facility (PMRF) off Kauaʻi, Hawaiʻi, for the period of August 23, 2017, through August 22, 2022. *See* 82 Fed. Reg. 21,156 (May 5, 2017). As discussed below, the regulations, as currently proposed, would violate the Marine Mammal Protection Act's (MMPA's) mandate to effect "the least practicable adverse impact" on the various marine mammal stocks threatened by WSEP activities. 16 U.S.C. § 1371(a)(5)(A)(i)(II)(aa). Moreover, the proposed regulations would fail to require adequate monitoring to ensure the Air Force's compliance with the levels of take NMFS proposes to authorize. *See id.* § 1371(a)(5)(A)(i)(II)(bb).

Violation of Marine Mammal Protection Act: Failure to Minimize Impacts

The MMPA seeks to prevent marine mammal species and population stocks from "diminish[ing] beyond the point at which they cease to be a significant functioning element in the ecosystem of which they are a part." *Id.* § 1361(2). To achieve this goal, Congress mandated that, when NMFS issues regulations authorizing incidental take of marine mammals, the agency must prescribe the "means of effecting the least practicable adverse impact" on marine mammal species or stocks. *Id.* § 1371(a)(5)(A)(i)(II)(aa). That requirement applies equally to all activities that incidentally harm marine mammals, including "military readiness activity" such as the Air

Force's proposed WSEP activities off Kauaʻi. *Id.* § 1371(a)(5)(A)(ii); see also Natural Resources Defense Council, Inc. v. Pritzker, 828 F.3d 1125, 1134-35 (9th Cir. 2016).

The proposed regulation's reliance on aerial surveys as the primary measure to minimize impacts on marine mammals falls far short of satisfying Congress's command to effect the least practicable adverse impact. As discussed in the comments on the proposed regulations submitted by Dr. Robin Baird of Cascadia Research Collective and by the Marine Mammal Commission (both of which are attached hereto and incorporated by reference), aerial surveys will have an extremely low probability of detecting marine mammals that are present in the target area, even under the best conditions, with the probability of detection declining precipitously in rougher ocean conditions and/or as aircraft speed increases. These views are entirely consistent with the best available scientific literature. *See, e.g.*, Barlow (2015) (*g*(0) decreases as Beaufort state increases, even for visually conspicuous species); Dawson, *et al.* (2008) (*g*(0) from aircraft lower than for ships because aircraft's field of view is almost instantaneous); Barlow (1999) (*g*(0) decreases with speed of observer vessel).

NMFS is well-aware that aircraft scanning the ocean for marine mammals are likely to miss far more animals than they will find. The final environmental impact statement for the U.S. Navy's Hawaii-Southern California Training and Testing (August 2013) – which NMFS adopted – calculates the *g*(0) for "Aircraft Sightability" for various species that NMFS proposes to authorize the Air Force to take incidentally. *See* HSTT EIS at 3.4-152. For Dwarf sperm whales – the marine mammal for which NMFS proposes to authorize the highest take levels from WSEP activities, including nearly two-thirds of Level A harassment – the *g*(0) aircraft value is only 0.074. *Id.*

Given the poor track record of aerial surveys to locate the marine mammals that are most likely to be present in the target area during WSEP activities, there is no justification for NMFS's failure to mandate the use of the PMRF hydrophone range to carry out real-time acoustic monitoring to detect additional marine mammals, to ensure they are kept out of harm's way. As Dr. Baird details in his comments, "[t]he instrumented hydrophone range at PMRF has frequently been used for real-time detection, classification and localization (DCL) of marine mammals on the range as part of research activities." *See, e.g.*, Baird *et al.* (2016).[1] To comply

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[1] This report, which Cascadia Research Collective jointly authored with the Naval Undersea Warfare Center, describes how PMRF's Marine Mammal Monitoring on Navy Ranges (M3R) system has been successfully deployed to secure "real-time results … to isolate animal vocalizations on the range" and "confirm species classification." *Id.* at 5; *see also id.* at 13 (M3R system detected three groups of marine mammals that had not been detected visually). The report specifies that "marine mammal monitoring does not interfere with range use," belying any possible claim that requiring real-time acoustic monitoring would not be practicable. *Id.* at

with the MMPA's command to achieve "the least practicable adverse impact" on marine mammals, NMFS must require the use of this proven technology, which would supplement aerial surveys to permit the detection of marine mammals that may be present in the impact area and are either not at the surface to be observed visually or overlooked due to rough seas, other adverse conditions, or the inherent limitations of visual detection by aircraft. *See* 82 Fed. Reg. at 21,175 ("NMFS prescribes mitigation measures that accomplish, have a reasonable likelihood of accomplishing (based on current science), or contribute to the accomplishment of … an increase in the probability of detecting marine mammals, thus allowing for more effective implementation of the mitigation").

Violation of Marine Mammal Protection Act: Failure to Require Adequate Monitoring of Take

The MMPA mandates that NMFS require adequate monitoring to ensure that the Air Force complies with the specified limits on incidental take for WSEP activities and also does not take any species for which take is not authorized. *See* 16 U.S.C. § 1371(a)(5)(A)(i)(II)(bb). The proposed regulation's reliance on post-mission aerial visual surveys to scan the ocean for marine mammals fails to comply with this mandate. *See id.* at 21,176.

The proposed regulations would not authorize any mortality, serious injury or even slight lung injury or gastrointestinal tract injury. *See id.* at 21,180. Rather, the only take to be authorized would consist of hearing loss (permanent or temporary) and behavioral disturbance. *See id.* at 21,181-82. Accordingly, while the sighting from an aircraft of a dead or seriously injured marine mammal in the vicinity of WSEP activities would indicate that unauthorized take has likely occurred, the absence of such observed harm would provide no meaningful information about whether the Air Force is complying with the limits on take consisting of permanent or temporary threshold shifts or behavioral disturbance. Indeed, the Federal Register notice discussing NMFS's proposed regulations is conspicuously silent regarding how post-mission aerial visual surveys could possibly detect whether any animals that might be observed in the vicinity of the test site have suffered either hearing loss or behavioral disturbance, much less (given that aerial surveys will fail to detect most animals exposed to sound or detonations associated with WSEP activities) whether authorized levels of take have been exceeded.

The types of take NMFS proposes to authorize are determined based on the distance of a marine mammal from the location where a weapon detonates in the ocean. *See id.* at 21,176-78. At the time that weapons are released into the ocean, all aerial survey personnel will – for safety reasons – have already vacated the impact area. *See id.* at 21,173. Accordingly, the only way to

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5; *see also* 82 Fed. Reg. at 21,157 (hydrophones will be operating "to collect data before, during, and after LRS WSEP missions").

determine whether, at the time of impact, a marine mammal likely is close enough to the sound/detonation source to be injured, as well as to assess the nature and extent of likely injury, is to review the information gathered by the PMRF hydrophone array. *See* Baird *et al.* (2016) (discussing use of M3R system to locate marine mammals for at-sea research).[2] The hydrophone array also provides invaluable information to determine if a marine mammal for which no take was authorized – such as sperm whales, which, as Dr. Baird observes, are present in the target area in densities greater than many species for which NMFS proposes to authorize take – was near enough to a detonation to have been harmed.

As the Marine Mammal Commission explained in its comment letter, PMRF's M3R system "can be used to provide in-situ measurements of the detonations and data on impacts to marine mammals in the vicinity prior to, during, and after the detonations." Meaningful monitoring of the authorized take limits requires not only that passive acoustic monitoring (PAM) data be collected and stored, but also that those data actually be analyzed. *See* 82 Fed. Reg. at 21,176. Particularly in light of the astronomic sums the Air Force will expend on the training itself, NMFS's suggestion that the Air Force might lack sufficient funds also to analyze the PAM data is, frankly, absurd. Ensuring that authorized take levels are respected is vital to achieving the MMPA's goals. Accordingly, NMFS must require the Air Force to analyze the PAM data to determine the nature and extent of injury to any marine mammal that PMRF's hydrophone array system detects in the vicinity of WSEP activities.

Thank you for your consideration of these comments. Please feel free to contact me via email (dhenkin@earthjustice.org) or telephone (808-599-2436, ext. 6614) if you would like to discuss our concerns.

Sincerely,

David L. Henkin
Staff Attorney

DLH/tt
Attachments

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[2] While the hydrophone array may not detect all marine mammals that are present (*e.g.*, animals that are not vocalizing prior to weapons detonation), as the Marine Mammal Commission noted, "[b]eing able to localize certain species (or genuses) provides more effective [monitoring] than localizing none at all."

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May 23, 2017

Jolie Harrison, Chief
Permits and Conservation Division
Office of Protected Resources
1315 East West Highway
Silver Spring, MD
20910

Dear Jolie,

I am writing to provide comments on the proposed rule authorizing takes of marine mammals incidental to the U.S. Air Force 86 Fighter Weapons Squadron conducting the Long Range Strike Weapons System Evaluation Program (WSEP) at the Pacific Missile Range Facility (PMRF) on Kaua'i, Hawai'i. These comments address inadequacies with the proposed mitigation measures, note some issues with estimation of takes and the selection of which species are considered for Section 7 consultation, and provide suggestions for improved mitigation and monitoring.

The primary mitigation measure proposed (aerial surveys) is insufficient to minimize impacts on marine mammals for several reasons, including inappropriate sea states for detection of marine mammals, as well as potentially using an inappropriate aerial survey platform. Detection probability on surveys decreases with an increase in both sea state[1] and survey speed. The impact site is not in the lee of the island and typically is subjected to wind speeds in excess of 15 knots, equivalent to a Beaufort 4 sea state, at which point the probability of detecting the two species with the highest number of takes (dwarf and pygmy sperm whales) is approximately 0.3% of what it is in Beaufort 0 conditions[1]. While the preamble to the proposed rule notes that operations will be delayed "if daytime weather and/or sea conditions preclude adequate monitoring for detecting marine mammals", "adequate" sea conditions are not defined, and during the October 2016 WSEP[2] wind speeds were in the 17-20 mph range, equivalent to Beaufort 4 or 5 sea state[3]. Thus the likelihood of detecting animals that are present would be extremely low, even with a survey platform that was covering the area relatively slowly[4]. The

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[1] Barlow, J. 2015. Inferring trackline detection probabilities, *g*(0), for cetaceans from apparent densities in different survey conditions. Marine Mammal Science doi 10.1111/mms.12205

[2] Department of the Air Force. 2016. Protected species monitoring and mitigation results for 2016 Long Range Strike Weapon System Evaluation Program operational testing, Pacific Missile Range Facility, Kaua'i, HI.

[3] Sustained wind speed at Lihue, Kaua'i during the October 2016 WSEP was between 17 and 20 mph, equivalent to Beaufort 4 or 5 sea state.

[4] Expected trackline detection probability (*g*(0)) values for a fast moving survey platform would be substantially lower than reported by Barlow 2015.

aerial surveys would be conducted for 30 minutes around the target site prior to the first impact, ending at some point prior to the estimated impact to allow the aerial survey platform to safely leave the area. If any marine mammals are observed in a ~13-mile radius around the impact site the launch would be delayed. It is unclear from the proposed rule whether helicopters will be used for the aerial survey, or if some other platform will be used. The impact site is approximately 90 km from the air field at PMRF. The FR notice states that "when missions are located farther offshore, surveys may be conducted by mission aircraft (typically jet aircraft such as F-15E, F-16, or F-22) or a U.S. Coast Guard C-130 aircraft", rather than by a helicopter or by a C-62 aircraft. Normal marine mammal aerial surveys (for research purposes) are flown at ~100 mph, while the cruising speed of a C-130 is approximately 336 mph. Cruising speeds of mission aircraft are presumably much faster. Since the impact location is known, the Air Force should be able to specify whether the surveys will be done with a helicopter or some other less suitable survey platform.

Given that the proposed aerial surveys will have an extremely low probability of detecting marine mammals that are present, real-time acoustic monitoring of the PMRF hydrophone range should be used as a supplemental mitigation measure. The final report for protected species monitoring and mitigation for the October 2016 WSEP[2] noted that "the engineer monitoring the hydrophones listened for any signs of marine mammal life post [aerial] survey and leading up to weapon impact", demonstrating that some form of acoustic monitoring is already being undertaken during Air Force operations. The instrumented hydrophone range at PMRF has frequently been used for real-time detection, classification and localization (DCL) of marine mammals on the range as part of research activities[5]. Cascadia Research Collective (CRC) has participated in 10 different field efforts off PMRF working in conjunction with the Navy to respond to marine mammals that are detected acoustically through the hydrophone system. While there are acknowledged limitations to using the system for DCL, just as there are with aerial surveys, the Navy has successfully directed a CRC small vessel to a variety of species of marine mammals on the range, including sperm whales, short-finned pilot whales, false killer whales, Blainville's beaked whales, bottlenose dolphins, and rough-toothed dolphins, demonstrating that groups can be successfully localized and classified as to species using this method[5,6]. Given that recordings from the hydrophones will be made, and thus presence (and potential take) of some species may be detected after the fact, using the hydrophones for real-time mitigation would also decrease the likelihood of the Air Force exceeding authorized takes or the taking of species (e.g., sperm whales or false killer whales) where no takes have been authorized.

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[5] Baird, R.W., D.L. Webster, S. Watwood, R. Morrissey, B.K. Rone, S.D. Mahaffy, A.M. Gorgone, D.B. Anderson and D.J. Moretti. 2016. Odontocete studies on the Pacific Missile Range Facility in February 2015: satellite-tagging, photo-identification, and passive acoustic monitoring. Prepared for Commander, U.S. Pacific Fleet. Also - Baird, R.W., A.N. Dilley, D.L. Webster, R. Morrissey, B.K. Rone, S.M. Jarvis, S.D. Mahaffy, A.M. Gorgone and D.J. Moretti. 2015. Odontocete studies on the Pacific Missile Range Facility in February 2014: satellite-tagging, photo-identification, and passive acoustic monitoring. Prepared for Commander, U.S. Pacific Fleet, submitted to Naval Facilities Engineering Command, Pacific by HDR Environmental, Operations and Construction, Inc.

[6] Baird, R.W., D.L. Webster, J.M. Aschettino, D. Verbeck and S.D. Mahaffy. 2012. Odontocete movements off the island of Kaua'i: results of satellite tagging and photo-identification efforts in January 2012. Prepared for U.S. Pacific Fleet, submitted to NAVFAC PAC by HDR Environmental, Operations and Construction, Inc.

The FR notice mentions that "mobile marine mammal[s]… are expect[ed] to exhibit avoidance behavior to loud sounds within the BSURE area" (page 21180) and "levels [of PTS] would be slight/mild because research shows that most cetaceans exhibit relatively high levels of avoidance" (page 21181). However, CRC research on cetaceans off Kauaʻi, the area where WSEP activities would take place, has shown that individuals of four different species of odontocetes (rough-toothed dolphins, false killer whales, short-finned pilot whales, and bottlenose dolphins) exposed to relatively high source levels of MFA sonar are not leaving the area[7,8]. Thus assuming that the responsive behaviors of animals moving away from an initial sound source will reduce the likelihood of repeated exposure or repeated TTS leading to PTS may not be correct for all species in this area.

Based on relative densities and the potential ranges of impacts, it is unclear why no takes of ESA-listed sperm whales were requested (or authorized) and why no Section 7 consultation was initiated regarding sperm whales. The FR notice states that sperm whales were not included "because of the low density of this species and the short duration of mission activities." However, the listed density for sperm whales (0.00156, Table 6[9]) is 9.75 times higher than the density of sei whales (0.00016), another ESA-listed species that is included both for authorized takes and for Section 7 consultation under the ESA. It is possible the reason sperm whales were left out from Section 7 consultation (and requested takes) was because of the reduced distances estimated for either Level A or Level B harassment (Table 5), which means density would have to be substantially higher than for sei whales in order for sperm whales to surpass some probability threshold of being inside the zone of influence. However, the magnitude of the difference in the area encompassed for Level B harassment (based on SPL distances given in Table 5) is less than the magnitude of differences in density (8.8 times vs. 9.75 times), even using the lower value (0.00156) rather than the one presented in Bradford et al. (0.00186)[9]. Thus it seems inconsistent to engage in Section 7 consultation and authorize takes for sei whales but not to do so for sperm whales.

There is a potential for Air Force activities to overlap spatially and temporally with research activities off Kauaʻi conducted both by NMFS and by other researchers, and as such the Air Force should provide the NMFS Pacific Islands Regional Office (PIRO) and any researchers who may be undertaking research activities in the area (i.e., those authorized by NMFS to conduct research around Kauaʻi) advance notification of the planned activities. This would allow for PIRO to ensure that stranding response network staff are notified/available, and in the case of researchers (both NMFS and non-NMFS), allow for the de-conflicting of any research activities.

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[7] Baird, R.W., S.W. Martin, D.L. Webster, and B.L. Southall. 2014. Assessment of modeled received sound pressure levels and movements of satellite-tagged odontocetes exposed to mid-frequency active sonar at the Pacific Missile Range Facility: February 2011 through February 2013. Prepared for U.S. Pacific Fleet, submitted to NAVFAC PAC by HDR Environmental, Operations and Construction, Inc

[8] Baird, R.W., S.W. Martin, R. Manzano-Roth, D.L. Webster and B.L. Southall. 2017. Assessing exposure and response of satellite-tagged odontocetes to MFA sonar during Submarine Commanders Courses at PMRF. Presentation to the Pacific Marine Sciences Monitoring Program Review, Seattle, April 27, 2017.

[9] Densities used for almost every species in Table 6 (including sei whales) match what are presented in Bradford et al. (2017), but the density used for sperm whales (0.00156) is lower than what is presented in Bradford et al. (0.00186). If the value from Bradford et al. (2017) is used, sperm whale density is 11.62 times higher than sei whale density. Bradford, A.L., K.A. Forney, E.M. Oleson and J. Barlow. 2017. Abundance estimates of cetaceans from a line-transect survey within the U.S. Hawaiian Islands exclusive economic zone. Fishery Bulletin 115:129-142.

For example, if we are attempting to do a project off Kaua'i, knowing of planned range closures would help ensure that we are not excluded from our study area unexpectedly.

Lastly, NMFS should consider additional monitoring requirements other than the collection of acoustic data through the PMRF hydrophone range. CRC has previously worked with the Navy to deploy satellite tags on cetaceans on PMRF prior to Submarine Commanders Courses in order to utilize tag data to examine exposure[5,6] to acoustic impacts (in this case from mid-frequency active sonar) and to examine the potential responses[7,8] of these species. This approach, in additional to proposed monitoring efforts, would provide additional information on the exposure and potential responses to WSEP activities that would help inform both estimation of takes and potential mitigation and monitoring for future WSEP activities.

I hope these comments are useful,

Sincerely,

Robin W. Baird, Ph.D.
Research Biologist
rwbaird@cascadiaresearch.org

MARINE MAMMAL COMMISSION

16 May 2017

Ms. Jolie Harrison, Chief
Permits and Conservation Division
Office of Protected Resources
National Marine Fisheries Service
1315 East-West Highway
Silver Spring, MD 20910-3225

Dear Ms. Harrison:

The Marine Mammal Commission (the Commission), in consultation with its Committee of Scientific Advisors on Marine Mammals, has reviewed the National Marine Fisheries Service's (NMFS) 5 May 2017 notice (82 Fed. Reg. 21156) and the letter of authorization (LOA) application submitted by the U.S. Air Force (the Air Force) seeking issuance of regulations under section 101(a)(5)(A) of the Marine Mammal Protection Act. The taking would be incidental to conducting long range strike weapon systems evaluation program (WSEP) activities at the Pacific Missile Range Facility (PMRF), off Kauai, Hawaii. The proposed activities would occur from August 2017 to August 2022.

Background

The Air Force plans to conduct its WSEP activities on the Barking Sands Underwater Range Expansion (BSURE) at PMRF. The purpose of those activities is to evaluate the maneuvers and performance of various munitions. Those activities involve the use of missiles and bombs[1] (ranging from a 10 kg bomb to a 136 kg missile). The Air Force would conduct all WSEP activities in waters approximately 4,645 m in depth and at a distance of approximately 81 km from the coast. The activities generally would occur on five consecutive days in summer or fall[2] of each year.

NMFS preliminarily has determined that the proposed activities could cause both Level A harassment of 4 marine mammal species and Level B harassment of 16 marine mammal species but anticipates that any impact on the affected species and stocks would be negligible. NMFS does not anticipate any take of marine mammals by serious injury or death and believes the proposed mitigation measures provide the means of effecting the least practicable impact on marine mammal species or stocks and their habitat. The proposed mitigation, monitoring, and reporting measures include—

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[1] Approximately 106 munitions could be detonated either at the surface or at 3 m in depth.

[2] NMFS indicated in the *Federal Register* notice that activities would not occur from January through May of each year. However, that was an error. The Commission understands that activities would not occur from December through May, during winter and spring.

- conducting activities only during daylight hours and on weekdays;
- conducting aerial monitoring for approximately 30 minutes both 1 hour before and 30 minutes after the proposed activities;
- using delay and shut-down procedures;
- using the PMRF hydrophones to collect acoustic data before, during, and after WSEP activities[3], which would be analyzed as funding allows;
- reporting injured and dead marine mammals immediately to NMFS's Office of Protected Resources and the Pacific Islands regional stranding coordinator; and
- submitting a final report.

Ranges to effects

As indicated in previous Commission letters, the methods used by the Air Force to estimate range to effects[4] for the various thresholds and the numbers of marine mammal takes have been inconsistent and imprecise, resulting in overly conservative estimates. The Commission understands that the Air Force estimated the range to effects based on the longest radial of any of the depth bins for the representative scenario[5], which appears to include a cumulative metric rather than adding the ranges of the multiple munitions. However, the ranges to those thresholds are quite large. For sound exposure level (SEL) thresholds, some of the estimated ranges are 7 to 11 times larger[6] than comparable munitions analyzed under the Navy's Draft Environmental Impact Statement/Overseas Environmental Impact Statement (DEIS) and Letter of Authorization application for training and research, development, test, and evaluation within the Hawaii-Southern California Fleet Training and Testing study area (HSTT) for Phase II. While the Commission has advocated being precautionary, that should not be confused with being overly conservative and inaccurate.

The Commission understands that the Phase III HSTT DEIS will be provided to the public for comment in the coming months. Given the discrepancies noted in ranges to effects for similar munitions being detonated in the same general area in Hawaii, the Commission believes NMFS should investigate the issue further. Therefore, the Commission recommends that NMFS review the Air Force's and Navy's modeling of range to effects to ensure that the results are comparable for similar munitions at the various thresholds, including the same trends in range to effects. A similar trend should be evident between the Air Force and Navy documents for the dual criteria of SEL and peak sound pressure level (SPL_{peak}) metrics for PTS and temporary threshold shift (TTS) thresholds—that is, the range to effects should be based on the same metric. It would be inconsistent for the Air Force to be basing the PTS and TTS ranges on the SEL metric and the Navy on SPL_{peak} metric. In addition, the Commission recommends that NMFS require the Air Force to revise the estimated numbers of takes based on any changes to the range to effects, and thus impact areas, after comparison with the Navy ranges.

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[3] In support of monitoring rather than mitigation requirements under the MMPA.

[4] i.e., distance to the various thresholds or radii.

[5] Three missiles and 18 bombs detonating within a given area in a 4-hour timeframe.

[6] The Commission acknowledges the slight difference in thresholds and weighting function shapes between the two documents, but those likely would not explain such large differences in the ranges.

Mitigation and monitoring measures

In previous Commission letters regarding the Air Force's activities at Eglin Air Force Base (Eglin) off Florida and at the Navy's PMRF, the Commission has recommended that NMFS require the Air Force to determine the effectiveness of its mitigation measures and to supplement those measures with the use of passive acoustic monitoring (PAM) devices, which in this case already are in place at PMRF[7] and would be used to collect acoustic data to be analyzed at a later date. For the proposed authorization, the mission area would be determined to be clear of marine mammals at least 30 minutes, and likely longer, before the munitions are detonated. The monitoring aircraft typically would move to the periphery of the human safety zone, which appears to be at least 13 km. Given that distance, the Commission is not convinced that the Air Force would be able to monitor effectively for marine mammals entering the mortality and injury zones after the area has been cleared and during the timeframe prior to detonation (see Table 5 of the *Federal Register* notice for sizes of the relevant zones).

NMFS described multiple limitations regarding using the PMRF hydrophones for real-time mitigation in the *Federal Register* notice based on information provided by the Navy (82 Fed. Reg. 21174). Those limitations include (1) the inability to detect, classify, and localize individual marine mammals and (2) animals that are present either aren't vocalizing or are vocalizing at frequencies beyond the hydrophone detection range. However, the Commission understands that the Navy is quite adept at detecting, classifying, and localizing individual marine mammals on PMRF[8]. For example, Helble et al. (2015) indicated that they were able to track multiple animals on PMRF hydrophones in real time, including humpback whales, a species that can be problematic to localize. Multiple animals were localized simultaneously with a localization error rate of 2 percent or less. Similar methods can be used for other species. Baird et al. (2015) also indicated that the PMRF hydrophones allow the PAM analyst to isolate animal vocalizations on the range, confirm species classification, and localize groups of animals in real time. Multiple detectors can be used for sperm whales, delphinids, beaked whales, and baleen whales. Similar to Helble et al. (2016), Baird et al. (2015) indicated that localization algorithms could determine an animal's position. In the case of bottlenose dolphins, that location was within approximately 100 m of the vocalizing animal. Similar localizations have been used to direct researchers to groups of vocalizing odonotocetes to deploy satellite tags as well (Baird et al. 2014).

The *Federal Register* notice indicated that the detection ranges are generally larger than current mitigation zones for many activities, which according to the Navy would delay the activities unnecessarily due to uncertainty in the animal's location. However, the range to mortality is more than 300 m, slight lung injury is more than 600 m, and permanent threshold shift (PTS) is more than 20 km depending on the species. Therefore, the Commission is not convinced that the inability to detect, classify, and localize vocalizing marine mammals on PMRF is the limiting factor.

Regarding the second limitation, the Commission does not follow the Navy's logic regarding animals that are present and may not be vocalizing. That phenomenon is no different than that of visual monitoring when an animal may be present but not at the surface to be observed. This does not preclude visual monitoring from being used as a primary means of mitigation for nearly all

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[7] PMRF has 199 bottom-mounted hydrophones for PAM capabilities.

[8] Via the Marine Mammal Monitoring on Navy Ranges (M3R) program.

activities, including WSEP activities. The Navy expressed the view that, if an activity were to be moved based upon low-confidence localizations, it may be moved inadvertently to an area where non-vocalizing animals of endangered/threatened species are present. However, the Commission has not advocated physically moving an activity, but rather delaying an activity. In addition, the Navy's rationale is similar to moving an activity from an area in which a few animals may have been sighted to an area where other animals could be below the surface but has been deemed clear during range clearance procedures. This issue is further compounded by the area being swept during range clearance procedures up to an hour or more before the activity begins—a circumstance that likely has occurred in the past.

Lastly, the Navy indicated that, since large baleen species vocalize at frequencies well below 1 kHz, there are few broadband hydrophones with low-frequency capabilities at PMRF. The Navy asserts that those hydrophones are widely spaced, especially on the southern portion of the PMRF range, which makes estimating the positions of low-frequency baleen whales difficult in that area. A review of published information indicates otherwise. Martin and Matsuyama (2015) noted that 41 of the BSURE hydrophones were replaced in 2010[9] with a high pass filter at 50 Hz with roll-off characteristics that enable detection of signals down to approximately 12 Hz—those enable call detection for fin, sei, and Bryde's whales. Further, in Figure 8 of Martin and Matsuyama (2015), it appears the spacing of the hydrophones is similar or even closer at the southern portion of the PMRF range[10]. In fact, Martin and Matsuyama (2015) provide tracks of Bryde's whales[11] based on multiple BSURE hydrophones, both those in the north and south (see Figure 7 as an example).

In short, the Commission doesn't agree with the Navy's, and thus NMFS's, rationale regarding the PMRF hydrophone limitations. The PMRF hydrophones appear to be capable of localizing animals and as such, they should be used to supplement visual monitoring, which itself has yet to be deemed effective. Being able to localize certain species (or genuses) provides more effective mitigation than localizing none at all. Further, USAF activities would only occur on five consecutive days each year, thus requesting that the Navy's M3R analysts be on site for those few days should be neither impractical nor overly expensive. For these reasons, the Commission again recommends that NMFS require the Air Force to supplement its mitigation measures with the use of real-time PAM using the PMRF hydrophones and M3R analysts and to delay WSEP activities if vocalizing animals are localized within the relevant mortality or injury zones. The injury zones would include the PTS zones for those species for which Level A harassment takes are not authorized.

In addition to supplementing mitigation, PAM devices also can be used to provide in-situ measurements[12] of the detonations and data on impacts to marine mammals in the vicinity prior to, during, and after the detonations. NMFS indicated that USAF would archive the PAM recordings for analysis when funding is available at a later time. Fulfilling the monitoring requirements under section 101(a)(5) of the MMPA should be made a priority in addition to real-time mitigation implementation.

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[9] Which were expanded to 62 hydrophones in 2012 to support localization of whale calls.

[10] USAF indicated it would be operating in the northern not southern portion of the PMRF range (Figure 2–2 in the LOA application). Thus, the point may be moot.

[11] That vocalize at 21 to 37 Hz.

[12] Including sound propagation.

The Commission trusts you will find its letter helpful. Please contact me if you have questions regarding the Commission's comments and recommendations.

Sincerely,

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Inferring trackline detection probabilities, g(0), for cetaceans from apparent densities in different survey conditions

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Abstract

Visual line-transect surveys are commonly used to estimate cetacean abundance. A key parameter in such studies is *g*(0), the probability of detecting an animal that is directly on the transect line. This is typically considered to be constant for a species across survey conditions. A method is developed to estimate the relative values of *g*(0) in different survey conditions (Beaufort state) by comparing Beaufort-specific density estimates. The approach is based on fitting generalized additive models, with the presence of a sighting on a survey segment as the dependent variable, Beaufort state as the key explanatory variable, and year, latitude, and longitude as nuisance variables to control for real differences in density over time and space. Values of relative *g*(0) are estimated for 20 cetacean taxa using 175,000 km of line-transect survey data from the eastern and central Pacific Ocean from 1986 to 2010. Results show that *g*(0) decreases as Beaufort state increases, even for visually conspicuous species. This effect is greatest for the least conspicuous species (rough-toothed dolphins, beaked whales, minke whales, and dwarf and pygmy sperm whales). Ignoring these large effects results in a nontrivial bias in cetacean abundance estimates.

Key words: abundance, cetacean, detection probability, density, dolphin, *g*(0), line-transect, porpoise, survey, visual, whale.

Line-transect methods are often used to estimate the density and abundance of cetacean species (whales, dolphins, and porpoises) based on visual sighting surveys conducted from ships. A defined study area is surveyed with systematic or random transect lines, and cetacean density is calculated using either conventional distance sampling or multiple-covariate distance sampling methods (Buckland *et al.* 2001, 2004). One common assumption of both methods is that all animals directly on the transect line are seen or that the fraction of detected animals (the trackline detection probability or *g*(0) in distance sampling terminology) can be estimated. Cetacean species are typically seen only when some portion of their body is above the water's surface or, for larger cetaceans, when their exhalations are visible as a distinct blow. Cetaceans are typically not visible from surface vessels when diving, which would result in an underestimate of density if corrections were not applied for missed animals. This is referred to as availability bias. An additional bias,

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perception bias, can occur if animals surface within the visual range of observers but are not seen. This can result because the visual observers were not looking in the right direction, because the surfacing was obscured by waves, or a wide variety of other factors. Perception bias is strongly affected by weather and other conditions that affect search effectiveness, especially for inconspicuous cetacean species. The concept of perception and availability bias (as conceived by Marsh and Sinclair 1989) is helpful, but in reality the two can be convolved. Visual observers on ships typically search in a 180° arc in front of the survey vessel and out to the horizon. The probability of detecting a surfacing cetacean declines with its distance from the survey vessel, and there is no distance at which an animal suddenly becomes unavailable to being seen. At larger distances, the probability of detection becomes essentially zero, but that distance depends on sighting conditions. As noted by Laake and Borchers (2004), the distinction between availability and perception can be fuzzy, but clearly the net effect of both depends on sighting conditions. Laake and Borchers (2004) reviewed many methods that have been developed to estimate availability bias, perception bias, or the combined effect of both for line-transect surveys. This subject continues to be an area of active research as shown by several recent publications (Okamura *et al.* 2012, Borchers *et al.* 2013, Langrock *et al.* 2013).

Despite recent advances in methods to estimate availability bias, perception bias, and trackline detection probability for cetacean surveys, these quantities have not been estimated for most cetacean surveys, and available estimates often pertain to a narrow range of sighting conditions. Estimation of $g(0)$ is not robust to pooling (Buckland *et al.* 2001), and abundance estimates can be biased if the effects of sighting conditions on $g(0)$ are not explicitly considered. For inconspicuous species like beaked whales and dwarf and pygmy sperm whales (*Kogia simus* and *K. breviceps*, respectively), trackline detection probabilities may be especially dependent on sighting conditions, but values for different sea states have typically not been estimated (Barlow 1999, Okamura *et al.* 2012, Borchers *et al.* 2013). Dual-platform methods are expensive to implement and require a separate independent team of observers, which is often logistically infeasible. For long-diving whales, it is not practical to use methods that require observations from multiple surfacings. The methods developed recently by Okamura *et al.* (2012) and Borchers *et al.* (2013) require diving data to quantify intermittent availability, and these data should ideally be collected at the same time and location as the line-transect data are collected. Such data requirements are seldom met. Methods are needed that can be applied more generally to a wide variety of species to estimate trackline detection probabilities in a variety of sighting conditions.

Here I present a method to estimate trackline detection probabilities for cetacean surveys based on the simple concept that true density does not change with sighting conditions. If density is estimated for a given study area in a variety of sighting conditions, the estimates made in the best conditions will be less biased than estimates made in poorer conditions. The degree to which estimates differ in differing survey conditions can be used to infer relative difference in trackline detection probabilities. If trackline detection is certain, $g(0) = 1.0$ in the best survey conditions, absolute estimates of detection probability can be made for all other conditions from the ratio of density estimates. If some individuals are missed even in the best survey conditions, but trackline detection probabilities can be estimated for those conditions (*e.g.*, Barlow 1999), this method allows extrapolation of those estimates to poorer survey conditions. This method is intended to complement rather than replace more traditional methods of estimating *g*(0), and every effort should be made to incorporate *g*(0) estimation into the design of any cetacean survey. However, the premise of this analysis is that estimating *g*(0) for a range of species across varying sighting conditions within a single survey is almost never feasible; thus a model-based approach drawing on data from numerous surveys is useful for obtaining such estimates.

This method is applied to estimate relative *g*(0) values for 20 cetacean species groups in the eastern and central Pacific Ocean. A generalized additive model (GAM) is used to statistically tease apart the effect of sighting conditions from other factors that influence cetacean densities, such as geographical variation and temporal changes in density. A similar GAM is used to determine whether changes in group size with sighting conditions might compensate for changes in group density. Parameters for both models are fit using a large compilation of 175,000 km of cetacean line-transect survey data collected by the Southwest Fisheries Science Center (SWFSC) on ship-based surveys conducted from 1986 to 2010.

METHODS

Field Methods

The SWFSC has conducted ship-based line-transect surveys for cetaceans in the eastern Pacific Ocean using consistent methods from 1986 to 2010. Survey methods are described in detail by Kinzey *et al.* (2000) and Barlow and Forney (2007). In brief, two experienced marine mammal observers searched with 25× pedestal-mounted binoculars from the flying bridge deck of 51–65 m research vessels. A third observer searched using unaided eyes and (occasionally) 7× binoculars and acted as data recorder. Survey conditions (Beaufort sea state, swell height, and visibility) were recorded every 30–40 min or whenever conditions changed. When cetaceans were seen within 3 nmi of the transect line, survey effort was typically halted, and the ship was maneuvered to approach the animals so that the observers could better determine the species present and estimate the group size. Vessels covered predetermined transect lines that representatively sampled the defined study area. Survey effort was greatest in the eastern tropical Pacific, along the U.S. West Coast, and in the central North Pacific (including waters around the Hawaiian Islands, and Palmyra and Johnston Atolls) (Table 1).

Trackline detection probabilities, *g*(0) are estimated here for 20 species or mixed-species categories (Table 2). Some similar-looking species are difficult to identify at sea. If a cetacean sighting could not be identified to species with certainty, higher-level taxonomic categories were used to classify a sighting. If these higher-level categories comprised an appreciable number of sightings, these categories are used in all analyses. All beaked whales in the genus *Mesoplodon* are combined as *Mesoplodon* spp. Similarly, dwarf and pygmy sperm whales are combined as *Kogia* spp., short-beaked and long-beaked common dolphins (*Delphinus delphis* and *D. capensis*, respectively) are combined as *Delphinus* spp., and sei whales (*Balaenoptera borealis*) and Bryde's whales (*Balaenoptera edeni*) are combined as a category called Sei/Bryde's. Some subspecies of spotted dolphin (*Stenella attenuata*) and spinner dolphin (*Stenella longirostris*) are identified at sea based on external morphology, but subspecies categories are not used here.

Table 1. Areas surveyed, years surveyed, total transect length, and proportions of survey effort stratified by Beaufort state. Study area boundaries for these regions are illustrated in Barlow (2013, fig. 1).

Survey region	Survey years	Transect length (km)	Proportion of survey effort by Beaufort state							Average Beaufort state
			0	1	2	3	4	5	6	
Eastern Tropical Pacific, inner core area	1986, 1987, 1988, 1989, 1990, 1992, 1993, 1995, 1998, 1999, 2000, 2003, 2006, 2007	164,369	0.006	0.046	0.153	0.257	0.353	0.177	0.008	3.5
Eastern Tropical Pacific, western and southern areas	1986, 1987, 1988, 1989, 1990, 1992, 1993, 1995, 1998, 1999, 2000, 2003, 2006, 2007	150,873	0.002	0.015	0.057	0.015	0.453	0.306	0.020	4.0
U.S. West Coast	1991, 1993, 1996, 2001, 2005, 2008	65,476	0.005	0.038	0.119	0.196	0.394	0.237	0.012	3.7
Central North Pacific	1997, 2002, 2005, 2010	65,297	0.002	0.008	0.046	0.106	0.445	0.330	0.064	4.2
Alaska/British Columbia	1994, 2004	16,149	0.013	0.066	0.218	0.200	0.295	0.160	0.047	3.4
Gulf of California	1993, 1995	9,064	0.014	0.119	0.262	0.263	0.262	0.079	0.000	2.9
Total		471,228	0.004	0.032	0.107	0.191	0.400	0.245	0.021	3.8

Table 2. Beaufort-specific estimates of effective strip width (*ESW*) for species included in this study. The *mcds* method was used with Beaufort as the only covariate and with the indicated truncation distance. Standard errors from the jackknife method are given in italics. Note that *ESW* decreases with Beaufort for all species except three (bold).

Species	Truncation distance (km)	Beaufort state						
		0	1	2	3	4	5	6
Ziphius cavirostris	4.0	2.40	2.07	1.75	1.47	1.22	1.02	0.85
		0.25	*0.18*	*0.14*	*0.14*	*0.17*	*0.18*	*0.19*
Mesoplodon spp.	4.0	3.23	2.81	2.30	1.78	1.34	1.00	0.75
		0.35	*0.38*	*0.32*	*0.21*	*0.13*	*0.11*	*0.11*
Kogia spp.	4.0	2.13	1.89	1.66	1.46	1.28	1.12	0.98
		0.38	*0.21*	*0.09*	*0.13*	*0.22*	*0.30*	*0.35*
Balaenoptera acutorostrata	4.0	2.52	2.13	1.75	1.42	1.15	0.92	0.75
		0.89	*0.52*	*0.19*	*0.31*	*0.47*	*0.56*	*0.60*
Delphinus spp.	5.5	4.10	3.84	3.54	3.24	2.92	2.62	2.33
		0.23	*0.19*	*0.13*	*0.08*	*0.08*	*0.13*	*0.19*
Stenella coeruleoalba	5.5	3.75	3.54	3.31	3.08	2.84	2.62	2.40
		0.45	*0.30*	*0.15*	*0.06*	*0.20*	*0.36*	*0.50*
Stenella longirostris	5.5	4.14	3.98	3.81	3.63	3.44	3.25	3.06
		0.37	*0.29*	*0.19*	*0.09*	*0.10*	*0.22*	*0.34*
Stenella attenuata	5.5	3.63	3.56	3.48	3.41	3.33	3.25	3.18
		0.41	*0.30*	*0.19*	*0.09*	*0.11*	*0.21*	*0.33*
Steno bredanensis	**5.5**	**2.04**	**2.08**	**2.13**	**2.18**	**2.23**	**2.28**	**2.33**
		0.21	*0.16*	*0.12*	*0.11*	*0.14*	*0.19*	*0.26*
Lagenorhynchus obliquidens	5.5	5.13	4.64	3.73	2.55	1.60	1.00	0.63
		0.06	*0.23*	*0.79*	*1.68*	*0.46*	*0.26*	*0.22*
Tursiops truncatus	5.5	3.27	3.09	2.90	2.72	2.55	2.38	2.22
		0.12	*0.10*	*0.09*	*0.09*	*0.10*	*0.12*	*0.14*
Grampus griseus	5.5	3.60	3.14	2.68	2.26	1.89	1.58	1.31
		0.24	*0.19*	*0.14*	*0.09*	*0.08*	*0.09*	*0.10*
Globicephala macrorhynchus	5.5	4.64	4.25	3.76	3.19	2.61	2.09	1.66
		0.49	*0.48*	*0.39*	*0.21*	*0.09*	*0.21*	*0.30*
Orcinus orca	5.5	4.85	4.62	4.34	3.99	3.59	3.17	2.73
		2.57	*0.67*	*1.00*	*1.37*	*1.75*	*2.22*	*2.71*
Phocoenoides dalli	4.0	2.35	2.04	1.74	1.47	1.25	1.05	0.89
		0.16	*0.11*	*0.07*	*0.06*	*0.08*	*0.09*	*0.09*
Physeter macrocephalus	5.5	4.74	4.57	4.37	4.14	3.88	3.59	3.29
		0.54	*0.50*	*0.43*	*0.31*	*0.20*	*0.24*	*0.44*
Balaenoptera musculus	**5.5**	**2.81**	**2.88**	**2.94**	**3.01**	**3.07**	**3.14**	**3.21**
		0.38	*0.31*	*0.25*	*0.20*	*0.21*	*0.28*	*0.37*
Balaenoptera physalus	**5.5**	**3.32**	**3.36**	**3.41**	**3.45**	**3.49**	**3.54**	**3.58**
		0.38	*0.26*	*0.15*	*0.08*	*0.16*	*0.27*	*0.39*
Balaenoptera borealis/edeni	5.5	2.94	2.91	2.88	2.85	2.82	2.79	2.76
		0.40	*0.28*	*0.18*	*0.10*	*0.13*	*0.23*	*0.33*
Megaptera novaeangliae	5.5	4.57	4.38	4.17	3.94	3.68	3.41	3.13
		3.19	*1.93*	*1.66*	*1.41*	*1.37*	*1.58*	*1.95*

Analytical Methods

Assuming that the true density of whales does not vary with sighting conditions, the ratio of density estimates for poorer survey conditions to those for good conditions provides an estimate of the proportional differences in $g(0)$ values (given that a constant $g(0)$ value was used initially to obtain the estimates for all conditions). If $g(0) = 1.0$ in excellent conditions, these relative estimates of $g(0)$ are also absolute estimates. If $g(0) < 1.0$ in excellent conditions but can be estimated (*e.g.*, Barlow 1999), absolute $g(0)$ for other conditions can be scaled using the relative estimates. Beaufort state is a subjective measure of wind speed as perceived by visual appraisal of the effect of wind on the water's surface and is the most frequently used measure of sighting conditions on visual line-transect surveys for cetaceans. Previous analyses of the SWFSC cetacean survey data have shown a measurable effect of Beaufort state on mean perpendicular sighting distances (Barlow *et al.* 2001) and on effective strip widths (Barlow *et al.* 2011) for all species, so Beaufort state is used here as a general measure of sighting conditions. Averaged values for Beaufort state vary geographically within the study area (Fig. 1), but calm and rough seas have been observed in all parts of the study area (Table 1).

The density, D_i, of groups of whales (number of groups per square kilometer) of species group i can be estimated using a conventional line-transect approach (Buckland *et al.* 2001):

$$D_i = \frac{n_i \cdot f_i(0)}{2 \cdot L \cdot g_i(0)}, \qquad (1)$$

where L = the length of "on-effort" transect lines, $f_i(0)$ = the probability density of the detection function evaluated at zero perpendicular distance, $g_i(0)$ = the trackline detection probability, and n_i = the number of sightings.

Density D is expected to vary spatially and temporally, whereas $f(0)$ and $g(0)$ are expected to vary with sighting conditions. A statistical approach is used to differentiate between real differences in density and "apparent" differences caused by the effect of sighting conditions and to quantify the effect of sighting conditions on $g(0)$.

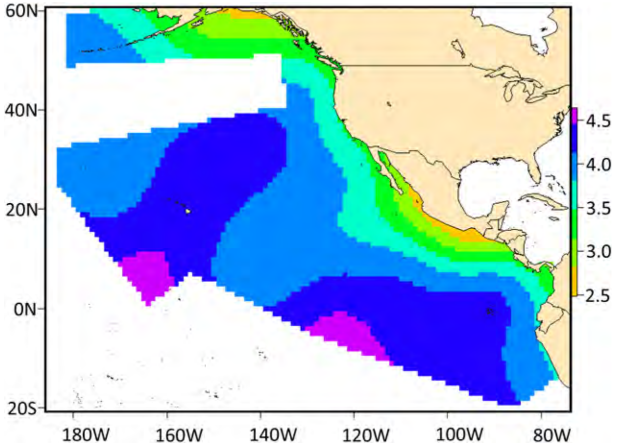

Figure 1. Smoothed contours of average Beaufort state in the eastern and central Pacific study area for the cetacean survey data used in this paper. Beaufort states are smoothed using a 2-D thin-plate spline regression model with a Gaussian link function. Gridded values are displayed on a 1° × 1° scale using *predict.gam* in R package *mgcv*. Unsurveyed areas are masked.

Substituting effective strip width (ESW_i) for $1/f_i(0)$ and rearranging the terms, Equation 1 can be expressed as

$$n_i = D_i \cdot g_i(0) \cdot (2 \cdot L \cdot ESW_i). \tag{2}$$

Beaufort conditions change frequently, often several times within a single survey day, so density is modeled using short segments of search effort (~10 km) with relatively constant survey conditions. The majority of these short segments contain at most a single sighting of a single species. Therefore, we can model group density as presence/absence on a survey segment. Statistically, the probability of seeing a species on a survey segment is modeled as continuous smoothed functions of space (latitude and longitude), time (year), and sighting conditions (Beaufort state) (all treated as fixed effects) using a general additive model (GAM) with a logit link function (Wood 2006) in R 12.2.0 (R Development Core Team 2010). The logit-probability of detecting a group on a survey segment is assumed to be proportionate to the area effectively searched (2•*L*•*ESW*), so this effective search area (*ESA*) is used as an offset in the GAM. Beaufort-specific values of *ESW* are estimated using the multiple-covariate distance-sampling (*mcds*) model (Thomas *et al.* 2010) in the R package *mrds*. Penalized thin-plate regression spline functions, *s*, (Wood 2003) as implemented in the program *gam* in the R package *mgcv* are used for the smoothed terms. The observation of a species, *p*, on a survey segment is modeled as a Bernoulli-distributed variate using the following GAM model specification:

$$\text{Logit}(p) \sim s(\text{Beaufort}) + s(\text{Latitude} \times \text{Longitude}) + s(\text{Year}) + \ \text{offset}(ESA). \tag{3}$$

To prevent model over-fitting, the maximum degrees of freedom for the univariate terms (year and Beaufort) is limited (*mgcv* parameter $k = 4$) and the overall penalty for model complexity is inflated (*mgcv* parameter *gamma* = 1.4) (Kim and Gu 2004, Wood 2006).

To fit this statistical model, survey effort was subdivided into sequential segments of at least 10 km. A new segment was created when a recorded location indicated that 10 km had been surveyed since the last segment was created. Because positions are not recorded continuously, actual segments were typically greater than 10 km (mean = 11.8 km, 1st and 3rd quartiles = 10.58 and 12.38 km). Shorter segments (<10 km) were generated at the end of each survey day and when a ship passed from one geographic stratum to another. When survey effort stopped during a day (due to weather or a sighting), an incomplete survey segment was continued when survey effort resumed that day, so survey effort within a segment is not necessarily continuous. Overall, 26% of effort segments include one or more cetacean sightings.

In interpreting the results of the statistical model, we assume that true variations in cetacean densities are effectively modeled by year, latitude and longitude, and that the residual modeled by Beaufort state represents differences in apparent density due to the effect of sighting conditions on $g(0)$. Values of $g(0)$ at Beaufort states 1–6 are estimated relative to its value at Beaufort state 0 (excellent sighting conditions) as the ratio of predicted probabilities from the GAM. Because there are no interaction terms in the above model, the Beaufort effect estimated by the model is the same for every position in space and every point in time; therefore, there is no need to average results over space or time to estimate the Beaufort effect on $g(0)$. The R routine *predict.gam* is used to predict the probability of a sighting per unit area searched, p_b, for

Beaufort states, b, ranging from 0 to 6 at a single fixed point in time (year) and space (latitude and longitude). Relative $g(0)$ values, ${}_{R}g_{b}(0)$, are thus given by:

$${}_{R}g_{b}(0) = \frac{p_b}{p_0}. \tag{4}$$

Coefficients of variation (CVs) for estimates of ${}_{R}g(0)$ were calculated using a jackknife procedure (Efron and Gong 1983). The GAM was fit to 10 subsets of the original data, each leaving out a sequential 10% of the survey segments. Standard errors (SEs) and CVs are calculated from the jackknife subsamples using standard methods (Efron and Gong 1983). Because *ESW* was estimated for each of the jackknife samples, variation in this component of the overall $g(0)$ estimation is accounted for in the overall CV for ${}_{R}g(0)$. $g(0)$ is expected to decrease with poorer survey conditions, but in some preliminary analyses, estimates of $g(0)$ increased slightly between Beaufort 0 and Beaufort 1. Since $g(0)$ values are relative to the best survey conditions, this resulted in implausible $g(0)$ values that were >1. Only 0.4% of survey effort was in Beaufort 0 and 3.2% in Beaufort 1, and this unusual increase in $g(0)$ with Beaufort was likely due to random chance and very small sample of sightings in low Beaufort conditions. Monotonicity constraints were applied by pooling data from the lower Beaufort states as needed to achieve a monotonic decline in $g(0)$ values. This approach generally resulted in lower AIC values as well.

Absolute $g(0)$ values for Beaufort 0–2 (excellent to good sighting conditions) were previously estimated for *Ziphius*, *Mesoplodon*, and *Kogia* using a model that accounts for both perception and availability bias (Barlow 1999). The model requires a large sample of sightings and therefore cannot be applied to estimate $g(0)$ for rougher Beaufort states, for which there are few sightings. The same model is fit here to the larger set of 1986–2010 data for the single Beaufort state with the greatest number of sightings (Beaufort 0 for *Kogia* spp. and Beaufort 1 for the beaked whales). These new estimates of absolute $g_i(0)$ for a single Beaufort state b are scaled by the relative values estimated here (Eq. 4) to yield absolute $g(0)$ values for other Beaufort states. For example, absolute $g_b(0)$ values for other sea states are estimated from estimates in Beaufort 1, $g_1(0)$, as:

$$g_b(0) = g_1(0)\ {}_{R}g_b(0)/{}_{R}g_1(0). \tag{5}$$

Group sizes are also modeled as functions of sighting conditions (Beaufort state) to evaluate whether differences in group size estimates might be the cause for differences in group density estimates. If a species forms larger groups in rougher conditions, this could explain an apparent decrease in group density with Beaufort state. Mean group sizes of each species for each survey segment is used as the dependent variable, and GAMs are fit to mean group size with a log-normal link function using the *mgcv* package in R. Again, location (latitude × longitude) and time (year) are included as explanatory variables to control for real differences in group size that might be correlated with sighting conditions. Again, the risk of over-fitting is reduced by limiting the degrees of freedom for the univariate terms (*mgcv* parameter $k = 4$) and the overall penalty for model complexity is inflated (*mgcv* parameter $gamma = 1.4$) (Kim and Gu 2004, Wood 2006).

RESULTS

Estimates of effective strip widths generally decrease with increasing Beaufort states for most species (Table 2), as is expected if the animals are harder to see when sighting conditions are worse. Similarly, estimated *g*(0) values generally decline with increasing Beaufort sea states (Fig. 2, Table 3). The Beaufort term was significant ($P < 0.05$, 2-tailed) in the GAM regressions for all species except humpback whales (*Megaptera novaeangliae*). The decline in modeled probability with Beaufort is greatest for less conspicuous species such as small whales (Fig 2C). For *Kogia* spp., the trackline detection probability is close to zero, $g(0) < 0.03$ in Beaufort state 3 and above (Table 3). Even for the most conspicuous species (*e.g.*, blue whales, *Balaenoptera musculus*), the estimates of *g*(0) for Beaufort 6 is less than half that for Beaufort zero (Table 3).

Modeled detection probability also varies significantly ($P < 0.05$) with the geographic component (latitude × longitude) of the GAM regression model (Fig. 3) for all species except minke whales (*Balaenoptera acutorostrata*) and Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) (Table 4). The year effect is significant ($P < 0.05$, two-tailed) for 12 of 20 species categories, and significant increases in abundance were indicated for 10 of these 12 (Table 4).

Results of the group size GAM (Table 5) show significant effects of Beaufort state for 10 of 20 species categories, and estimated group size decreases with increasing Beaufort state in 8 of these 10 of these cases. A significant trend in group size over time is seen for 11 species categories, with 6 showing a decreasing trend and five showing an increasing trend. Significant spatial variation in group size is seen for 9 species categories.

Absolute *g*(0) values for *Kogia*, *Mesoplodon*, and *Ziphius* are estimated by fitting a model (Barlow 1999) to 1986–2010 survey data for a single Beaufort state, and these values are extrapolated to other Beaufort states by scaling by relative *g*(0) values (Table 6). Results show that the *g*(0) values for Beaufort 0 range from 0.5 to 0.81 for these species, showing that the assumption of $g(0) = 1.0$ does not hold even in the best survey conditions.

DISCUSSION

In analyses of cetacean survey data, trackline detection probability, *g*(0), is often assumed to be 1.0 in all sighting conditions (Gunnlaugsson and Sigurjónsson 1990, Wade and Gerrodette 1993, Fulling *et al.* 2003, Mullin and Fulling 2004, Kaschner *et al.* 2012) if only because estimates of true *g*(0) are often not available. It is widely recognized that this assumption is violated for surveys of species that are either hard to see or that dive for long periods of time (Barlow 1999, Hammond *et al.* 2002), but the assumption that all groups on the trackline are seen has often been considered reasonable for conspicuous species like dolphins that occur in large groups or baleen whales with large blows. Hammond *et al.* (2002) found that detection probability was not significantly affected by Beaufort state in ship surveys for minke whales and white-beaked dolphins (*Lagenorhynchus albirostris*), but the Beaufort effect was significant for harbor porpoises (*Phocoena phocoena*), which are smaller and occur singly or in small groups. Barlow (1995) presented evidence that *g*(0) equals 1.0 for larger groups of delphinids (>20 individuals) and for larger groups of large whales (>3 individuals), but not for smaller groups of those species. Based on a much larger sample size than any of these previous studies, the current results

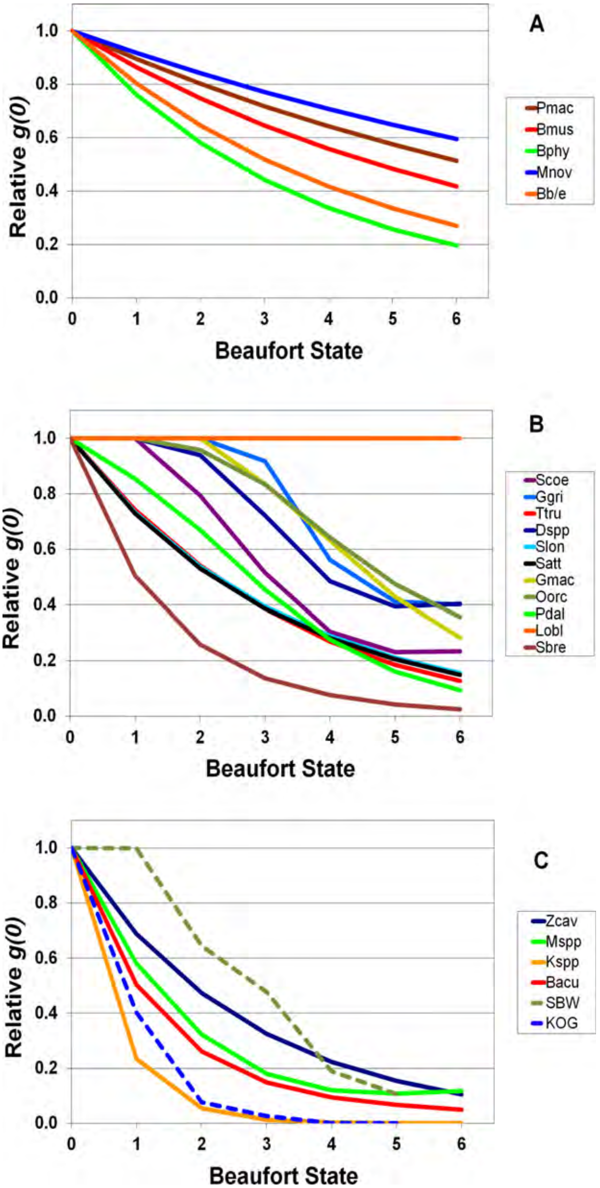

Figure 2. Estimated values of *g*(0) in Beaufort states 1–6 relative to Beaufort zero for (A) large whales, (B) delphinoids (dolphins and porpoises), and (C) small whales. KOG (*Kogia*) and SBW (small beaked whale) estimates are from Barlow (2013). Other abbreviations are based on the first letter of the genus name and the first three letters of the species name (or "spp" to indicate all species in that genus).

show that the estimated number of cetacean groups per unit area declines in rougher sea conditions and that mean group sizes do not increase to compensate (in fact, group size estimates were more likely to decrease in rougher seas). Therefore, the

Table 3. Estimated values of *g*(0) for sightings conditions in Beaufort states 1–6 relative to Beaufort zero and total number of sightings used for these estimates. Coefficients of variation (CV) from jackknife method are in italics, and *g*(0) values significantly different from 1.0 (*z*-test) are in bold.

Species	Number of sightings	Beaufort state						
		0	1	2	3	4	5	6
Ziphius cavirostris	262	1	**0.688**	**0.473**	**0.325**	**0.224**	**0.154**	**0.106**
			0.10	*0.19*	*0.26*	*0.30*	*0.34*	*0.37*
Mesoplodon spp.	322	1	**0.581**	**0.323**	**0.179**	**0.120**	**0.108**	**0.118**
			0.14	*0.21*	*0.25*	*0.29*	*0.39*	*0.66*
Kogia spp.	249	1	**0.234**	**0.055**	**0.013**	**0.003**	**0.001**	**0.0002**
			0.08	*0.16*	*0.25*	*0.33*	*0.41*	*0.49*
Balaenoptera acutorostrata	43	1	**0.503**	**0.262**	**0.148**	**0.094**	**0.067**	**0.050**
			0.36	*0.70*	*0.88*	*0.82*	*0.71*	*0.91*
Delphinus spp.	1,247	1	1	0.940	0.722	**0.485**	**0.394**	**0.404**
				0.25	*0.25*	*0.14*	*0.20*	*0.50*
Stenella coeruleoalba	1,621	1	1	**0.794**	**0.516**	**0.303**	**0.231**	**0.234**
				0.11	*0.14*	*0.11*	*0.16*	*0.31*
Stenella longirostris	969	1	**0.733**	**0.537**	**0.394**	**0.289**	**0.212**	**0.155**
			0.03	*0.06*	*0.09*	*0.13*	*0.16*	*0.19*
Stenella attenuata	1,653	1	**0.728**	**0.531**	**0.386**	**0.282**	**0.205**	**0.149**
			0.03	*0.06*	*0.09*	*0.12*	*0.15*	*0.18*
Steno bredanensis	379	1	**0.505**	**0.259**	**0.137**	**0.076**	**0.043**	**0.024**
			0.18	*0.33*	*0.41*	*0.43*	*0.41*	*0.41*
Lagenorhynchus obliquidens	78	1	1	1	1	1	1	1
Tursiops truncatus	1,076	1	**0.742**	**0.542**	**0.386**	**0.269**	**0.185**	**0.127**
			0.16	*0.27*	*0.30*	*0.26*	*0.24*	*0.26*
Grampus griseus	616	1	1	1	0.917	**0.561**	**0.412**	**0.401**
					0.14	*0.09*	*0.20*	*0.48*
Globicephala macrorhynchus	494	1	1	1	**0.835**	**0.631**	**0.430**	**0.283**
					0.08	*0.15*	*0.24*	*0.35*
Orcinus orca	190	1	1	0.958	0.834	0.642	**0.475**	**0.356**
				0.35	*0.48*	*0.44*	*0.48*	*0.63*
Phocoenoides dalli	314	1	0.854	0.670	**0.455**	**0.276**	**0.161**	**0.094**
			0.32	*0.54*	*0.59*	*0.56*	*0.55*	*0.58*
Physeter macrocephalus	367	1	0.896	0.802	0.718	0.643	**0.575**	0.514
			0.11	*0.20*	*0.26*	*0.31*	*0.38*	*0.50*
Balaenoptera musculus	171	1	0.865	0.748	0.646	**0.559**	**0.483**	**0.418**
			0.10	0.19	0.28	0.36	0.44	0.51
Balaenoptera physalus	200	1	**0.762**	**0.581**	**0.442**	**0.337**	**0.257**	**0.196**
			0.08	0.16	0.23	0.30	0.35	0.40
Balaenoptera borealis/edeni	431	1	**0.804**	**0.646**	**0.520**	**0.418**	**0.336**	**0.270**
			0.05	*0.10*	*0.15*	*0.20*	*0.25*	*0.30*
Megaptera novaeangliae	116	1	0.917	0.841	0.772	0.708	0.649	0.595
			0.09	0.17	0.25	0.32	0.39	0.45

density of all cetaceans is likely underestimated for rough sea conditions (high Beaufort states) unless *g*(0) corrections are used.

The primary assumption of the method used here to estimate relative *g*(0) is that true group densities do not vary with Beaufort state. The most likely violation of this

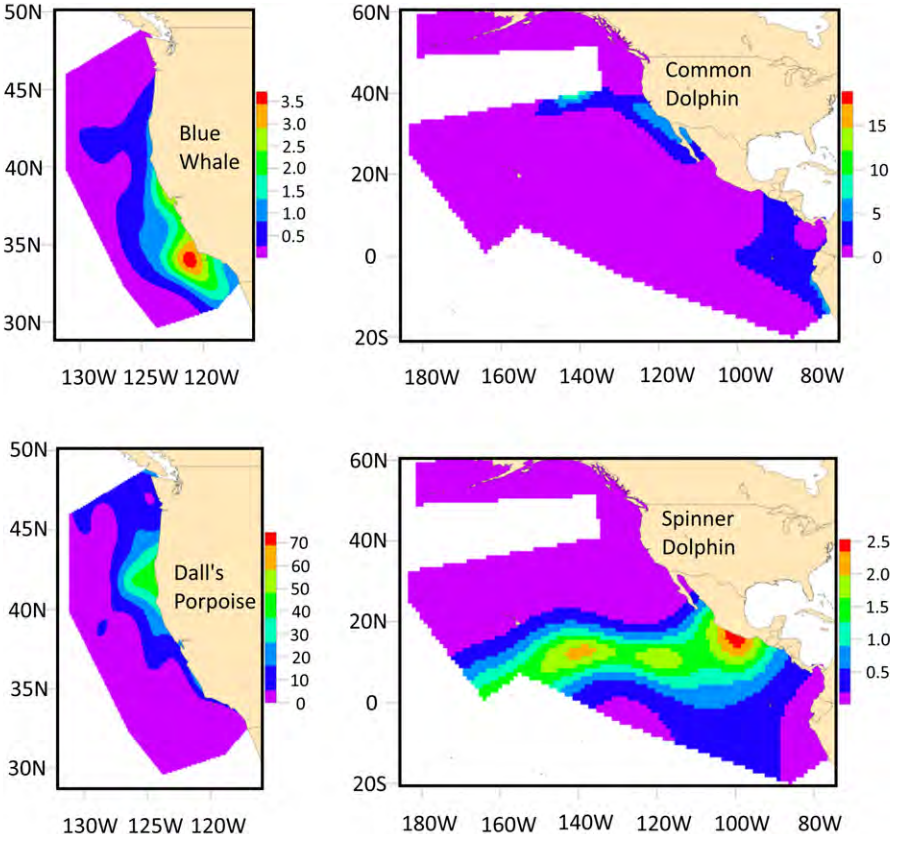

Figure 3. Geographic components of group encounter rate models that also included Beaufort sea state and year as covariates in a GAM framework for several example species (see Fig. S1 for all species). The geographic effect was modeled with latitude and longitude as a 2-D thin-plate spline in the R package *mgcv*. Predicted group densities (groups per 1,000 km^2) were obtained with *predict.gam* for Beaufort 0 and a mid-point year (1998). Gridded values are displayed on a 1° × 1° scale for the entire Pacific and on a 0.1° × 0.1° scale for species that were modeled using only U.S. West Coast data. Unsurveyed areas are masked.

assumption would occur if all cetacean species in our study were more likely to occur in windy or calm areas. Primary production is correlated with wind-driven upwelling in some oceanographic areas, and cetacean abundance can be correlated with primary production (Jaquet *et al.* 1996). Different study areas have different distributions of Beaufort state (Table 1). The broad-scale correlation between Beaufort state and cetacean density should, however, be captured with the geographic term in the GAM analysis. Although average Beaufort varies geographically, daily values in all areas vary from very calm to very rough with daily changes in weather. There should, therefore, be sufficient contrast within these data to tease apart geographic and Beaufort state variations in apparent cetacean density. Moreover, not all species would be expected to be similarly distributed with respect to sea conditions; some species could be more likely to occur in calmer areas (*e.g.*, near-coast species) while others could be

Table 4. Summary of general additive models of probability of detecting a group on a segment of survey effort as functions of Beaufort state, year, and location (latitude × longitude). The effective degrees of freedom and approximate significance levels (from *mgcv* package) are given for each predictor in the GAM model. All Beaufort trends showed a decrease with increasing Beaufort except for *L. obliquidens*. The year trend (increase or decrease) is given for models with a significant year term based on whether the final estimate is greater or less than the initial. Significance levels are coded as $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***).

		GAM model terms						
		Beaufort state		Year		Latitude × longitude		
Species group	Species/genus name	e.d.f.	sig.	e.d.f.	sig.	e.d.f.	sig.	Year trend
Small whales								
	Ziphius cavirostris	1.0	***	1.0		18.1	***	
	Mesoplodon spp.	2.5	***	2.4		18.8	***	
	Kogia spp.	1.0	***	1.0		23.3	***	
	Balaenoptera acutorostrata	1.4	***	1.0		19.6		
Delphinoids								
	Delphinus spp.	2.7	***	2.7	***	28.8	***	increase
	Stenella coeruleoalba	2.9	***	1.0	*	27.6	***	increase
	Stenella longirostris	1.0	***	1.0	**	22.4	***	increase
	Stenella attenuata	1.0	***	1.4	***	21.7	***	increase
	Steno bredanensis	1.4	***	1.0	***	19.5	***	increase
	Lagenorhynchus obliquidens	1.0	*	2.4		9.8		
	Tursiops truncatus	1.4	***	1.6	***	23.1	***	increase
	Grampus griseus	2.4	***	1.0		18.7	***	
	Globicephala macrorhynchus	2.0	***	1.7	***	26.3	***	increase
	Orcinus orca	1.7	**	1.0		10.7	***	
	Phocoenoides dalli	1.8	***	1.0		28.6	***	
Large whales								
	Physeter macrocephalus	1.0	*	2.1	***	19.6	***	decrease
	Balaenoptera musculus	1.0	*	1.0	**	19.0	***	decrease
	Balaenoptera physalus	1.0	***	1.0	***	19.6	***	increase
	Balaenoptera borealis/edeni	1.0	***	1.4	***	25.3	***	increase
	Megaptera novaeangliae	1.0		1.4	***	12.7	***	increase

more likely to occur in rougher areas (*e.g.*, offshore deepwater species). The nearly ubiquitous pattern in our analysis of lower density estimates in rougher sea conditions seems to provide additional evidence that the effect of sighting conditions on $g(0)$ is not merely an artifact of a geographic bias in the data.

Differences in relative $g(0)$ values estimated here for different Beaufort states may not be due entirely to difference in trackline detection probabilities near the vessel. Estimates of cetacean density can be biased by undetected movement of animals

Table 5. Summary of general additive models of group sizes as functions of Beaufort state, year, and location (latitude × longitude). The effective degrees of freedom (e.d.f.) and approximate significance levels (from *mgcv* package) are given for each predictor in the GAM model. The Beaufort and year trends (increase or decrease) is given for models with a significant year term based on whether the final estimate is greater or less than the initial. Significance levels are coded as $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***).

		GAM model terms							
		Beaufort state		Year		Latitude × longitude			
Species group	Species/genus name	e.d.f.	sig.	e.d.f.	sig.	e.d.f.	sig.	Beaufort trend	Year trend
Small whales									
	Ziphius cavirostris	1.7		1.0		3.5			
	Mesoplodon spp.	1.0	***	1.9	*	6.2		decrease	decrease
	Kogia spp.	1.0		1.4		2.0			
	Balaenoptera acutorostrata	1.4		1.0		2.0			
Delphinoids									
	Delphinus spp.	1.6		1.8	*	18.4	***		decrease
	Stenella coeruleoalba	1.7		2.9	*	21.8	***		increase
	Stenella longirostris	2.3	***	2.9	***	28.6	***	increase	increase
	Stenella attenuata	2.9	***	2.8	*	16.4	***	decrease	decrease
	Steno bredanensis	2.9	***	3.0	***	15.1	***	decrease	decrease
	Lagenorhynchus obliquidens	1.0	*	1.0	***	19.5	***	decrease	increase
	Tursiops truncatus	2.8	**	1.0		28.9	***	increase	
	Grampus griseus	1.3	**	2.9	*	10.7		decrease	decrease
	Globicephala macrorhynchus	1.0	**	1.0	***	16.4		decrease	increase
	Orcinus orca	3.0	***	1.0		17.5		decrease	
	Phocoenoides dalli	1.4		1.0		2.0			
Large whales									
	Physeter macrocephalus	1.8		1.0		8.5			
	Balaenoptera musculus	1.0		2.6	**	2.1	**		increase
	Balaenoptera physalus	1.0		1.0		2.0			
	Balaenoptera borealis/edeni	3.0	***	1.0	***	19.5	***	decrease	decrease
	Megaptera novaeangliae	1.0		2.4		14.2			

Table 6. Absolute values of $g(0)$ for *Ziphius, Mesoplodon*, and *Kogia* estimated using a model (Barlow 1999) fitted to the 1986–2010 survey data for the single Beaufort state with the greatest number of observations (Beaufort 0 for *Kogia*, and Beaufort 1 for the beaked whales). Absolute estimates are scaled by the relative estimates from Table 3 to give absolute values for Beaufort states 0–6.

Genus/species	Beaufort state	Absolute $g(0)$ estimates	Relative $g(0)$ estimates	Scaled absolute $g(0)$ estimates
Ziphius cavirostris	0		1.000	0.584
	1	0.402	0.688	0.402
	2		0.473	0.276
	3		0.325	0.190
	4		0.224	0.131
	5		0.154	0.090
	6		0.106	0.062
Mesoplodon spp.	0		1.000	0.813
	1	0.472	0.581	0.472
	2		0.323	0.262
	3		0.179	0.146
	4		0.120	0.097
	5		0.108	0.088
	6		0.118	0.096
Kogia spp.	0	0.495	1.000	0.495
	1		0.234	0.116
	2		0.055	0.027
	3		0.013	0.006
	4		0.003	0.001
	5		0.001	0.000
	6		0.000	0.000

either towards or away from the transect line in response to the ship (Buckland *et al.* 2001). Because animals can be detected at greater distances in good conditions, this bias is likely to depend on survey conditions. The methods used here cannot truly distinguish between bias due to differences in trackline detection probability and bias caused by responsive movement. The relative values of $g(0)$ presented here should be considered general factors that can be used to account for a variety of factors that might bias estimates of cetacean group density as functions of Beaufort state. It should be noted, however, that the pattern of declining relative $g(0)$ values with Beaufort state is seen both for species that avoid vessels (*e.g.*, the *Stenella* spp.) and species that are attracted to vessels (*e.g.*, *T. truncatus*) within the study area.

The observed decreases in estimates of group density with increasing Beaufort state would not necessarily lead to decreased estimates of animal density if it were caused by a real increase in characteristic group sizes. Here we show that estimated group sizes actually decrease with increasing Beaufort state for most species with a significant Beaufort term in their group size model. This could result in an additional negative bias in estimates of individual density. The general pattern of decreasing group sizes with Beaufort may, however, be perceptual. Group size is certainly more difficult to estimate in rougher seas and group sizes are likely to be underestimated if fewer individuals can be seen at the surface. Additional research is needed to determine whether real group sizes change with Beaufort or whether the observed decline is only due to estimation error. Additional corrections may be needed for the effect of Beaufort state on group size estimation and hence on cetacean density estimation.

A nearly exponential decline in detection probability with Beaufort state is seen for most species (Fig. 2), which resulted from a nearly linear fit of log-transformed values (e.d.f. < 1.5, Table 4). Overall, less than 4% of survey effort was conducted in Beaufort 0 and 1 (Table 1), and the fraction of sightings in these calm conditions is very low for some species. Because there is so little data in calm conditions, there is some danger of extrapolating the trend seen for apparent densities in other sea states to values at Beaufort 0 and 1. When relative $g(0)$ values were estimated for small beaked whales using a stratified density approach instead of a model-based approach (SBW in Fig. 2C), values for relative densities in Beaufort 0 and 1 were similar (Barlow 2013). If trackline detection probability in Beaufort 0 is really not greater than in Beaufort 1, all values of relative $g(0)$ could be biased downward.

The expectation of monotonically decreasing $g(0)$ values with increasing Beaufort states was achieved by pooling lower Beaufort states (which had low sample sizes) for six species (all delphinids). This could be done more elegantly using shape constrained additive models such as implemented the R package *scam* (Pya and Wood 2014). In practice, that approach was not favored by AIC model selection, as it required many more parameters (knots) and resulted in greater decreases in $g(0)$ with Beaufort than were supported by the data.

Small Whales

The grouping of small whales (Table 4) includes species which typically occur in small groups and which are difficult to see because they typically do not have a visual blow and do not splash or leap when they surface. This group includes small beaked whales and *Kogia* spp., which have relatively long dive times (Barlow 1999). It has long been recognized that the density of these species is likely underestimated even in calm conditions (Barlow 1999) due to availability bias. Sightings of these species are so rare in higher sea states that density is often estimated only from survey data collected in calm seas (Mullin *et al.* 2004, Barlow and Forney 2007). It is not surprising then that the relative $g(0)$ values for this group of small whales show the greatest decline with Beaufort state (Table 3, Fig. 2B). The rate of decline is nearly exponential and is greatest for *Kogia* spp.

Relative $g(0)$ values in different Beaufort states have been estimated previously using a slightly different method (Barlow 2013) and were used in an analysis of trends in beaked whale abundance (Moore and Barlow 2013). Barlow (2013) estimated density of small beaked whales (the genera *Ziphius* and *Mesoplodon*) and of *Kogia* spp. in two nonoverlapping study areas in the eastern tropical Pacific, stratified by Beaufort state. The study areas were defined to include relatively uniform distributions of average Beaufort state so as to reduce the confounding effect of different densities and Beaufort states. The 1986–2008 survey data in that study were largely overlapping with data used in the current study. Resulting estimates of relative $g(0)$ from that study (for Beaufort states 0–6, respectively, averaged for the two study areas) were 1.00, 1.00, 0.64, 0.48, 0.19, 0.11 for small beaked whales and 1.00, 0.40, 0.08, 0.03, 0.00, 0.00 for *Kogia* spp. (Barlow 2013). These values are very similar to estimates from the statistical approach used here for *Kogia* spp., and estimates for small beaked whales are very similar to estimates for *Z. cavirostris* in Beaufort 4 and 5 conditions (Fig. 2C). Relative $g(0)$ values for small beaked whales are higher in that study for Beaufort states 1–3. The methods used in this paper are likely to be more reliable than those in Barlow (2013) because they are based on a larger sample size and use a more robust estimation procedure.

Absolute *g*(0) values have been previously estimated for the genera *Ziphius, Mesoplodon,* and *Kogia* in a pooled category of Beaufort 0–2 (Barlow 1999). These values (0.23 for *Ziphius*, 0.45 for *Mesoplodon*, and 0.35 for *Kogia*) correct density estimates for both availability bias and perception bias. When this method is applied to estimated absolute *g*(0) for a single Beaufort state category, relative *g*(0) values can be used to scale this value to give absolute *g*(0) estimates for other Beaufort states. Results show that *g*(0) is appreciably less than 1.0 for these species even in the calmest seas and that values decrease rapidly with Beaufort state (Table 6), which emphasizes the need to collect dive data to allow *g*(0) estimation for these species using one of the other estimation methods.

Delphinoids

Estimates of *g*(0) decrease with Beaufort state and are <0.5 at Beaufort 6 for all delphinoid species except *L. obliquidens* (Fig 2B). Previously, Brandon *et al.* (2002) and Gerrodette and Forcada (2005) suggested that the assumption of *g*(0) = 1.0 is generally valid for large groups of dolphins. Data from independent observers generally have supported this assumption, at least for large groups (Barlow *et al.* 1995, Hammond *et al.* 2002). Although many porpoise species occur in small groups and surface without conspicuous splashes, the delphinids are typically very conspicuous, and it is hard to conceive of missing a large group on the transect line, even in rough conditions. Data presented here appear to contradict this commonly held perception.

Beaufort trends in *g*(0) for *L. obliquidens* and *S. bredanensis* appear as contrasting outliers among the other dolphins (Table 3, Fig. 2). For *L. obliquidens*, *g*(0) estimates increased with Beaufort and the decreasing monotonicity constraint resulted in values of 1.0 for all conditions. This is likely because ESW decreased with Beaufort much more rapidly for this species than for any other dolphin, possibly an artifact of the small sample size for this species (n = 78). *S. bredanensis* occurs in small groups and is difficult to see, which may help explain why *g*(0) decreases with Beaufort conditions much more rapidly for this species than for other dolphins. This does not help explain why ESW increases slightly with Beaufort state for *S. bredanensis* (Table 2).

Many delphinoids are attracted to bow ride on research vessels, including some of the species studied here. Buckland and Turnock (1992) analyzed the effect of vessel attraction on estimates of Dall's porpoise (*Phocoenoides dalli*) abundance and concluded that abundance can be overestimated by a factor of 4. The reactive movement (attraction or avoidance) will affect density estimation if it occurs before the group is seen, and this is most likely to occur in poor sighting conditions. This suggests that *g*(0), as estimated here, could either decrease or increase with Beaufort state depending on whether animals either avoid or are attracted towards the survey platform. It is surprising then, that apparent *g*(0) decreases with Beaufort state for virtually all delphinoid species, including ones that are strongly attracted to ships. Vessel attraction could, however, help explain the unusual results seen for *L. obliquidens*.

Large Whales

The blows of large whales are relatively conspicuous, even in rough seas. It is not surprising that the decline in *g*(0) with Beaufort state is smallest for these species (Fig. 2A). Nonetheless, *g*(0) decreases to below 0.6 in Beaufort 6 conditions for all species. Barlow and Forney (2007) estimated *g*(0) for large whales in the U.S. West Coast study area to be approximately 0.92 (CV = 0.02) using a conditionally independent observer method developed by Barlow (1995) and applied to Beaufort sea states 0–5. That method assumes that all whales are available to be seen and thus only corrects for perception bias. To compare the current estimates for individual Beaufort state to this earlier estimate for pooled Beaufort states, average *g*(0) values are calculated for each species weighted by the proportion of survey time at each Beaufort state for the U.S. West Coast (Table 1). Weighted average values are 0.67, 0.59, 0.39, 0.46, and 0.73 respectively for sperm whales, blue whales, fin whales, sei and Bryde's whales, and humpback whales. All weighted averages are considerably less than the *g* (0) value of 0.92 that was calculated by Barlow and Forney (2007) based on perception bias alone.

Relative *g*(0) values can be used as absolute *g*(0) estimates if all trackline whales are seen in the calmest sea states. Typical dive times for large whales range from several minutes (for Bryde's whales) to over an hour (for sperm whales). Availability bias in calm conditions is likely to vary considerably among these large whale species. Additional research is needed to determine absolute *g*(0) values in calm conditions. When this is done, these values can be scaled to other sea states using the relative *g*(0) values estimated here. Until then, however, relative *g*(0) values are minimum estimates and should be used in place of estimates that only include perception bias.

Future Directions

The approach presented here uses Beaufort state as the sole measure of sighting conditions. On most cetacean surveys, other measures of sighting conditions are often recorded, including swell height and the presence of rain, snow, fog, or haze. All of these might affect trackline detection probability for cetaceans. Additional covariates could be added in future analyses to obtain better estimates of relative *g*(0). This might improve precision by explaining more of the variation in apparent density but also might reduce bias by ensuring that absolute *g*(0) is closer to 1.0 for the best survey conditions. Additional research is needed to more effectively implement a monotonically decreasing constraint in estimating *g*(0) as a function of sighting conditions.

The empirical approach used here to estimate *g*(0) values relative to the best survey conditions could be integrated with more theoretical approaches that estimate absolute values for *g*(0). The application of other approaches to estimate Beaufort-specific estimates of *g*(0) are typically limited by sample size, especially for hard-to-see species in poor conditions. But a failure to explicitly consider sighting conditions can result in bias because pooling robustness does not generally apply to *g*(0) estimation. The relative approach used here uses additional information (apparent density in different conditions) to help inform the pattern of change in *g*(0) with Beaufort state.

The approach presented here, using a Cartesian spatial model of variation in cetacean densities, could be easily extended to spatial models of cetacean density based habitat metrics instead of or in addition to latitude and longitude (Redfern *et al.* 2006). Beaufort state is often included in such habitat-based spatial models to account for non-habitat variation in apparent density, but predicted densities are typically based on average Beaufort conditions (Forney *et al.* 2012). Relative *g*(0) estimation can easily be extended to habitat-based spatial models if, instead, predictions are made for the best-case survey conditions (Beaufort 0) or (better yet) for the conditions for which absolute *g*(0) has been previously estimated. In this way, the effect of Beaufort on *g*(0) would implicit in the predicted density estimates.

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SUPPORTING INFORMATION

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Figure S1. Geographic components of group encounter rate models that also included Beaufort sea state and year as covariates in a GAM framework for all species. The geographic effect was modeled with latitude and longitude as a 2-D thin-plate spline in the R package *mgcv*. Predicted group densities (groups per 1,000 km^2) were obtained with *predict.gam* for Beaufort 0 and a mid-point year (1998). Gridded values are displayed on a 1° × 1° scale for the entire Pacific and on a 0.1° × 0.1° scale for species that were modeled using only U.S. West Coast data. Unsurveyed areas are masked.

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Design and field methods for sighting surveys of cetaceans in coastal and riverine habitats

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ABSTRACT

1. Dolphins and porpoises in coastal and/or riverine habitats face serious conservation threats, yet surveys of their abundance are often especially difficult due to the challenges imposed by the habitats. Because many of these species occur in developing countries, lack of resources imposes a further set of challenges.
2. We offer advice on designing and conducting line-transect surveys with a focus on sound, practical, design rather than analytical sophistication, and we attempt, where possible, to offer simple, inexpensive solutions.
3. We guide the reader through the questions of what kind of survey should be done, whether by boat or aircraft, and we discuss ways to avoid bias and increase precision.
4. Our treatment of field methods focuses especially on robust, but low-cost, approaches. We provide two case studies to illustrate the implementation of these ideas.

Keywords: abundance, aerial, boat, dolphin, porpoise, trends

INTRODUCTION

Data on abundance are among the most basic in ecology and conservation biology. Unfortunately, the simple question of ‘how many are there?’ can be difficult to answer robustly. That challenge is particularly great for cetaceans in coastal and riverine habitats. Abundance data for these species are sorely needed, for our coasts and rivers suffer greater human impact than any other marine mammal habitat. Several coastal and riverine species are seriously threatened, and one, the Baiji *Lipotes vexillifer* of China’s Yangtze River, is now probably extinct (Turvey *et al*., 2007). All of the river dolphins suffer from by-catch and habitat loss and fragmentation (Smith & Smith, 1998). All coastal cetaceans suffer from by-catch in fishing gear (IWC, 1994). Some are seriously impacted by pollution (e.g. beluga *Delphinapterus leucas*; Muir *et al*., 1996). Some suffer from direct hunting for bait or human consumption (e.g. dusky dolphins *Lagenorhynchus obscurus*, Burmeister’s porpoise *Phocoena spinipinnis*; Vidal, 1993; Van Waerebeek *et al*., 1999), and some suffer from habitat loss due to coastal development (e.g. Indo-Pacific humpback dolphins *Sousa chinensis*; Jefferson & Hung, 2004). Impacts of these threats cannot be assessed quantitatively without robust abundance data.

Additionally, abundance data form part of the scientific basis of conservation planning. The need for such data was clearly demonstrated at the January, 2007 IUCN workshop held

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to update and revise the Redlist status of cetaceans. Ten of 21 odontocetes that could be considered coastal or riverine were provisionally classified as 'Data Deficient' – chiefly for lack of abundance or trend data.

While the need for high-quality abundance data is clear, the means of getting them is not. Coastal and riverine habitats are complex and impose many constraints on survey design. Further, because many of these species are found in countries without large budgets for conservation, it would help enormously if survey methods were as inexpensive as possible (Aragones, Jefferson & Marsh, 1997).

There are two major classes of methods for assessing cetacean abundance: mark–recapture methods in which re-sightings of naturally or artificially marked individuals are used to calculate abundance, and sighting surveys in which animals are counted in order to assess their density (Seber, 1982). Mark–recapture analysis of photo-ID data can provide highly precise estimates of abundance, and has two important advantages over line-transect surveys; photo-ID generally has meagre boat requirements (e.g. no need for a raised sighting platform) and can provide data on a wealth of other biological parameters (Hammond, Mizroch & Donovan, 1990). In practice, most mark–recapture studies of cetaceans have quantified local populations on relatively small geographical scales (e.g. Gormley *et al.*, 2005). However, several studies have used systematic wide-ranging surveys to estimate abundance for a species using line-transect methods, and then have combined photo-ID data from those surveys with localized photo-ID data collected from small boats to estimate abundance using mark–recapture methods. Examples include humpback whale *Megaptera novaeangliae* and blue whale *Balaenoptera musculus* (Calambokidis & Barlow, 2004) and killer whales *Orcinus orca* (Zerbini *et al.*, 2007; P. Wade, unpublished data). Mark–recapture methods are, however, less generally applicable than line-transect methods, because they rely on individuals being distinctive and easily photographed. Mark–recapture methods are thus not suitable for many species of coastal and riverine cetaceans.

Here we focus on sighting surveys (Barlow, 1988). General issues relating to line-transect surveys are covered in the new edition of *Distance Sampling* (Buckland *et al.*, 2001). Further developments in the field can be found in a second volume, *Advanced Distance Sampling* (Buckland *et al.*, 2004). Our intention is not to cover that ground again, but to concentrate on issues which specifically relate to designing and conducting surveys of inshore or riverine cetaceans. We assume that the reader is familiar with the basics of line-transect sampling. Aragones *et al.* (1997) provide a useful overview of a variety of marine mammal survey techniques that are applicable in developing countries, including boat and aerial surveys. We focus here on details of design and field methods not covered in that paper.

In this contribution, we emphasize the use of proper survey design to obtain unbiased estimates of cetacean abundance. Recent developments in line-transect theory have allowed analysis of data from poor sampling designs (without equal coverage probability) (Hedley, Buckland & Borchers, 1999; Buckland *et al.*, 2004) by using spatial modelling methods to develop a model of marine mammal densities within the study area. We do not discuss this advanced topic in detail. Typically, such methods have been applied to data collected from platforms of opportunity (e.g. Williams, Hedley & Hammond, 2006), from which it was not possible to conduct a well-designed survey. Using data from an aerial sighting survey, Gómez de Segura *et al.* (2007) compared standard line-transect analysis with an analysis via spatial modelling, finding similar density and variance estimates for both methods. Clearly, model-based estimation is useful if an equal coverage sighting survey is not possible but detailed environmental data are available, and may have a useful role in analysing data where a good design was intended, but not achieved, perhaps due to environmental factors such as fog, rough weather or ice. But it is not a substitute for good survey design. No amount of analytical sophistication can fully compensate for inadequate sampling.

The software package Distance 5.0 has a design module that implements many aspects of good survey design automatically (Strindberg, Buckland & Thomas, 2004). This excellent feature is not a replacement for understanding the principles of line-transect survey design, and requires a fair amount of sophistication from the user. Distance's design module can be very helpful in evaluating different candidate designs (see Thomas, Sandilands & Williams, 2007).

Our experience has been that surveys are often designed poorly. We have seen many survey designs that had no chance of providing unbiased, reasonably precise population estimates. We are familiar with many of the pitfalls, having ourselves fallen into them or narrowly missed doing so. In this paper, we aim to help researchers design surveys and avoid fundamental flaws.

WHAT IS THE QUESTION: ABUNDANCE OR TRENDS?

For any survey it will be important to start by clearly identifying an appropriate major objective, and by prioritizing any additional objectives. A crucial question is whether the need is for an absolute abundance estimate, or an assessment of population trend. Surveys for the former are more difficult to do, as they require quantitative assessment of the 'fraction missed' on the track line (i.e. the proportion of animals not available to, or not counted by, the survey method). Estimates of absolute abundance have the advantage that they facilitate direct calculation of what level of take should be sustainable (e.g. by-catch limits; e.g. Potential Biological Removal [PBR], Wade, 1998). Estimation of trends usually do not involve assessment of the fraction missed, on the assumption that if survey methods are kept constant, the fraction missed should not change systematically (Caughley, 1977). This assumes, however, that the fraction missed does not change due to factors beyond the control of the survey team, which is often unrealistic. For example, cetacean distributions can change substantially in El Niño years (e.g. Gardner & Chávez-Rosales, 2000). If the fraction missed varies with measurable factors (like Beaufort sea state or cloud cover), a trend analysis can use these covariates to correct for some of the sources of variation in fraction missed (Forney, Hanan & Barlow, 1991).

Obviously, assessments of trends require repeated surveys. In order to increase the statistical power to detect change, and depending on the expected rate of change, it is often better to conduct intensive surveys at several-year intervals, rather than less survey effort annually. Issues of detecting trends are dealt with in Holt, Gerrodette & Cologne (1987), Gerrodette (1987), Forney *et al.* (1991) and Wade & DeMaster (1999). While there are cases in which surveys have detected declines in abundance, and the detected decline led to conservation actions (e.g. Cook Inlet beluga whale; Hobbs, Rugh & DeMaster, 2000), it is important to note that the power to detect trends from repeated abundance surveys, even if they were carefully designed, is likely to be very low (Taylor *et al.*, 2007). Very rare species may actually go extinct before a statistically significant trend can be detected (Taylor & Gerrodette, 1993).

In many cases, the most realistic aim is to obtain a good estimate of absolute abundance and use it to assess the level of human impact on the population using Population Viability Analysis or the PBR approach (Wade, 1998). This approach was taken by Slooten *et al.* (2006) who showed that there are so few Maui's dolphins *Cephalorhynchus hectori maui* (111, cv = 44%) that a PBR calculation results in an 'allowable' by-catch of fewer than one dolphin per year. In other words, this abundance survey showed that any by-catch from this population would likely be unsustainable.

LINE-TRANSECT OR STRIP-TRANSECT?

Line-transect surveys require measurement of the perpendicular distance from the track line to each sighting. Particularly in small boats, this can be difficult. In strip-transect surveys, animals are counted within a specific distance either side of the track line. Probability of detection is assumed to be one, or at least constant, from the track line out to the edge of the strip. These assumptions are not realistic in most surveys of marine mammals. In analysis of line-transect surveys, a curve is fitted to the observed detection distances in order to estimate effective strip width (Buckland *et al.*, 2001). Hence, in line-transect surveys strip width is not assumed, but empirically estimated from the sighting data. Line-transect techniques have the further advantage of maximizing sample size, because sightings outside the strip width are not ignored (as they are in strip-transect surveys). For these reasons, line-transect methodology is considered superior for cetacean surveys, and strip-transect methods are recommended only in special cases. For example, strip-transects were used to supplement a line-transect survey of river dolphins in the Amazon because of stratification of a very narrow strip along the river banks (see case study 2; Vidal *et al.*, 1997).

SURVEY PLATFORM – AIRCRAFT OR BOAT?

Coastal line-transect surveys can be carried out using aircraft or boats. Aircraft, because of their speed [typically but not necessarily 90–100 knots (167–185 km/h)], can cover large areas in a short period, and for this reason might be favoured in regions with short periods of suitable weather. They are not prone to causing responsive movement in the animals surveyed (Buckland *et al.*, 2001). Also, the steeper angles to sightings allow for more accurate measurement of sighting distances than is usually possible from boats. Due to limited seating in aircraft, there is usually less opportunity to rotate or rest observers in order to combat fatigue. Boats, because they travel more slowly (typically ≤10 knots) allow more time for an animal to surface, and therefore boat surveys typically count a much larger proportion of the population. Additionally, boats more easily facilitate collection of other data (e.g. oceanographic, photo-ID and genetic data) while the survey is in progress. Boat surveys are usually less expensive per unit time, but because they take longer for the same amount of coverage, they can work out to be considerably more expensive overall, especially for larger boats or ships. Also, they often cause responsive movement (see below). Issues of survey design are similar for both.

Choice of boat

A very wide range of boats can be used for line-transect surveys, though some are much more suitable than others. Increasing observer height increases the resolution with which observers can measure the downward angle to sightings, allows observers to see animals further away (lessening the chance of responsive movement) and increases the sightability of the animals (less chance of a sighting being hidden by a wave). For these reasons, boats used for line-transect surveys should have an elevated sighting platform. A ‘tuna tower’ or similar platform is ideal, and can be designed to be temporary and/or collapsible. For example, we have used a sighting platform on a sailing vessel that could be erected or dismantled (to allow the boat to sail) in less than 10 min (Fig. 1). Platform height needs to be a compromise: if too high, platform movement due to sea conditions will make it difficult for observers to measure distances, especially if they use binoculars. To minimize effects of pitching, the ideal platform would be mounted towards the stern, rather than amidships, assuming that visibility forward is not obstructed.

Open ocean line-transect surveys typically use ships of between 50- and 70-m length. Due to the damping effect of size, they offer greater inherent stability than smaller vessels. For

Fig. 1. Examples of small vessels used in coastal and riverine line-transect surveys. Note the raised sighting platforms, which give eye heights between 4.5 and 6 m.

many surveys, however, large vessels are prohibitively expensive to run, and because of their draught and limited maneuverability, they are unsuitable for many inshore surveys. Depending on sea conditions, high-quality line-transect data can be collected from vessels as small as 6–8 m, though the 10- to 20-m size range is probably ideal. Because of their resistance to rolling motion, catamarans can be very suitable. Catamarans are capable of higher cruising speeds with less horsepower than typical displacement monohulls of similar length, and this makes them economical survey platforms. The narrowness of the hulls can make catamarans more sensitive to pitching, but in practice this can be minimized by steaming survey lines down-swell. This was done whenever necessary in line-transect surveys of Hector's dolphin *Cephalorhynchus hectori* (Dawson *et al.*, 2004).

Most line-transect surveys from boats are conducted at between 8 and 10 knots (15–18.5 km/ h). The upper end of this range is usually governed by the boat's capability. Boat speed should be at least 2–3 times faster than the typical average speed of the animals, or a positive bias may result (Hiby, 1982). Travelling too fast will result in fewer sightings as there will be less time for animals to surface within viewing range. We are not aware of successful cetacean boat surveys carried out at speeds greater than ~14 knots.

Vessel cost is a very important criterion, because several of the most threatened small cetaceans occur in countries without generous funding for marine mammal research. In addition to facilitating survey work with limited budgets, low-cost vessels allow (i) much more survey effort to be expended for the same cost; (ii) surveys to be conducted in better sighting conditions (since vessel costs are low, you can afford to wait); and (iii) a significant amount of vessel time to be spent on observer training. The probability of detecting an animal of interest on the track line, which in line-transect jargon is known as g(0), combines both availability bias and perception bias. Various methods are used to correct for these biases, including the use of an independent observer team on the same platform. The method(s) chosen will necessarily influence the selection of an appropriate aircraft or boat.

Choice of aircraft

The primary aircraft requirements for line-transect surveys have to do with visibility, safety and running cost. Because observers must have an unobstructed view of the water, high-wing aircraft are inherently suitable. Additionally, it is very important that observers can see the track line (i.e. directly under the aircraft). Bubble windows, which can be fitted to many aircraft, are sometimes sufficient for this, but a belly window is a better option if available (ideally one would have both). Many line-transect surveys have been done without the ability to see the track line. For this to work, the sighting data must be left-truncated (Buckland *et al.*, 2001) by deciding on a distance at which detection is believed to be maximal and fitting the detection function only to data beyond that distance. This process is necessarily arbitrary, and should be avoided if possible by choosing aircraft from which the track line can be seen.

Safety during aerial surveys is a crucial requirement. We are aware of several fatal crashes on aerial surveys. Causes have included water in the fuel, running out of fuel, and gross handling errors by the pilot. While we are not aware of any aerial survey crashes caused by engine failure, we prefer to use twin-engine aircraft to minimize the consequences of engine malfunction. If survey plans call for occasional circling over sightings (e.g. for species identification), an aircraft with a relatively slow stall speed is desirable. It is worthwhile remembering that key requirements of aerial surveys, specifically the need to fly at low altitude (500 feet is typical) and at relatively slow airspeeds (90–100 knots), inevitably involve some risk and leave little margin for error. All observers need to understand this.

Twin engine aircraft that meet these requirements, and which are often used on aerial surveys, include the six seater Partenavia P-68 (especially the Observer model with an unrestricted view forward), Aero Commander (including the standard model, Shrike and Turbo Commander), Cessna Skymaster and the much larger Dehavilland Twin Otter. Helicopters can be extremely useful, particularly for helping to assess the fraction of sightings missed on the track line (see later). They are, however, usually too expensive to use as a primary survey platform.

Methods for assessing the fraction missed are covered later, but it is worth pointing out that some methods impose specific aircraft requirements. For example, a belly window is required to assess perception bias (the proportion of sightings that were available to be seen but missed due to fatigue, momentary inattention, glare, etc.) via independent observation of the track line (e.g. Forney, Barlow & Carretta, 1995). A six-seater aircraft is required if perception bias is to be assessed via comparison of sightings made by two independent teams of observers (e.g. Slooten, Dawson & Rayment, 2004).

SURVEY DESIGNS

Two recent papers by Strindberg *et al*. (2004) and Thomas *et al*. (2007) have provided much more guidance on survey design issues than was available previously. Inevitably, some of what is below is also covered by them. Here we focus particularly on issues we see as being important for surveys of inshore and riverine cetaceans.

Before starting a survey, it is crucial to *define* the study area. The abundance estimate derived will apply only to the study area, so it is important to delineate this area precisely. In addition, we should ensure that:

- The area chosen is relevant to any management goals, e.g. the location and size of a proposed or existing protected area.
- The area is biologically relevant, containing the typical movement range of the population at that time of year, or a substantial part of it.
- Practicalities are considered; for example, the study area is not too large to cover within the time available, and the vessel choice suits the area to be surveyed.

LAYING OUT TRANSECT LINES

The transect lines must represent a random sample of all the habitat area in the survey block. An important principle to bear in mind is that any patch of water within the survey block should have an equal chance of being surveyed – this is termed ‘equal coverage probability’. Transect lines could be fully randomized with respect to location and orientation, but this will rarely be practical, because it will result in a large amount of travel time between transects and will often lead to directions of travel that are impractical because of glare or swell direction. Even in a parallel line survey, lines could be spaced at random distances apart to achieve fully random sampling. Recent simulation studies, overlaying different survey designs on a spatially realistic model of an inshore dolphin population, showed that random line spacing had no clear advantage in reducing bias, and systematic line spacing resulted in better precision (DuFresne, Fletcher & Dawson, 2006).

It is important to remember that the transect lines only have to be random with respect to the animal’s distribution and to provide equal coverage probability. Practically, it is useful to combine a random start with regular line spacing within survey blocks. One way to do this is to draw an imaginary baseline along the coast, and plot the start of the first transect at a random point along that baseline (Fig. 2, also see Appendix for details). Thereafter, the other transect lines can be spaced at regular intervals according to the sampling intensity required. The subsequent lines could be described as pseudo-random, but this is only likely to be a problem if the spatial aggregation of animals, by bad luck, coincides with the transect spacing. Therefore, in most cases it will be most practical to lay out a regular pattern of transect lines, but with a randomized starting location.

Regular spacing of lines (whether parallel or zigzag) offers several other advantages over random line spacing. Visual interpretation of spatial distribution is easier, and the data are ideal for contouring density, as long as the sampling intensity and sighting rate are

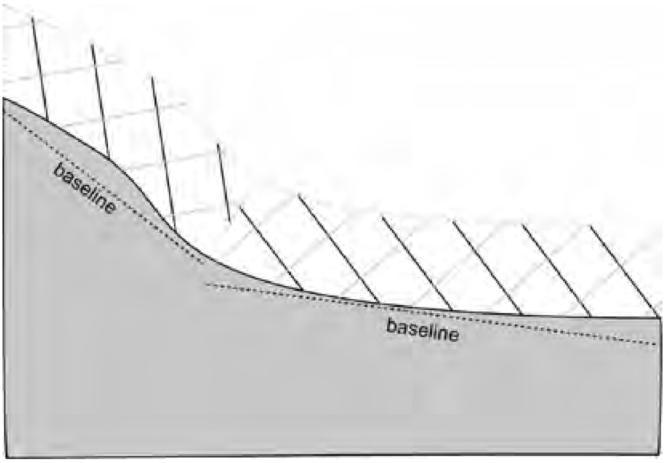

Fig. 2. Where there are gradients in offshore and alongshore distribution, transects at 45° can be a good solution. In this case, the coast is divided into blocks, a baseline is drawn approximately parallel to the coastline in each block, and equally spaced lines drawn at 45° to the baseline. The first line in each block is drawn at a random point along the baseline, and the others drawn at a constant spacing with respect to it. The grey 45° lines are an alternate set that would be used if conditions (e.g. swell, glare) favoured them.

appropriate to the scale of the contours. Also, it is easier to post-stratify the data into particular areas, and hence calculate abundance in a particular sub-area. Regular spacing may also make it easier to examine distribution in relation to shore or depth or other correlates.

Orientation of lines relative to density gradients

Sampling theory suggests that transect lines should be orientated perpendicular to the contour lines of any known gradients. This is done to avoid bias and to minimize the variance in encounter rate, which will be high if many transects have no or few sightings, while a few transects have many sightings. In particular, this is crucial if the gradient in the density of animals changes more rapidly than the distance between transect lines. Many coastal cetaceans show a density gradient from high density nearshore to low density offshore, so transect lines perpendicular to shore will be preferred over lines parallel to shore. Many cetaceans also show a density gradient alongshore, so transect lines at a 45° angle to shore will be a good scheme for sampling distributions that vary both alongshore and inshore/offshore (Fig. 2).

Zigzags or parallel transects?

Boat surveys are usually affected by glare and swell. Boat motion will be most stable running down-swell, and observers will be ineffective looking into glare. For this reason, zigzag designs, while they minimize travel time between transects, may be impractical (especially in small boats). Surveys using small fast boats can minimize travel time between transects by increasing speed. Glare is only really a problem if it is close to the track line. However, zigzag designs mean that the swell and glare conditions may be very different on the different legs of the survey and may compromise observer efficiency for a substantial part of the survey. A survey design that avoids this problem involves laying out two sets of parallel lines at 45° to the shore, each set at 90° to each other within each survey block (e.g. Fig. 2). Each survey day, you can choose which set to do, in which direction, so as to minimize effects of swell and glare. In this approach, it is helpful to set block size so that the whole block can be completed

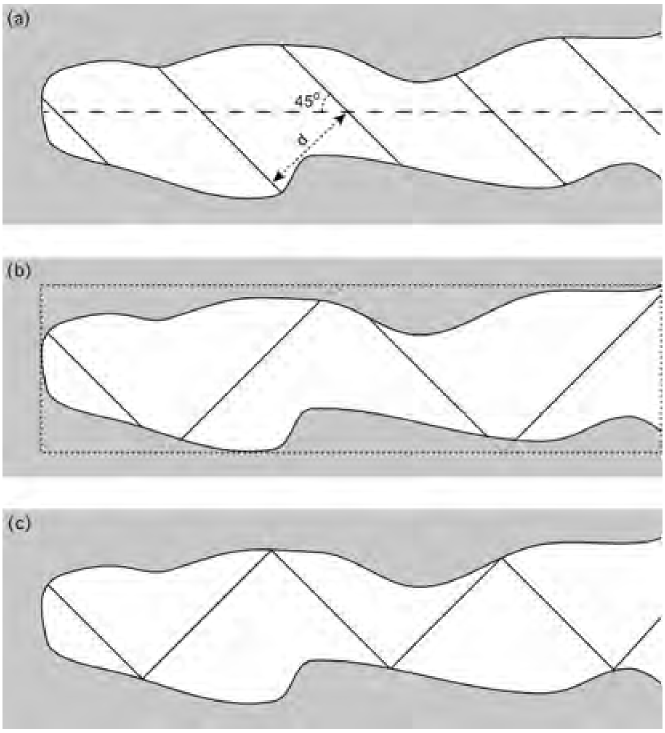

Fig. 3. Two alternate (a & b), equal coverage schemes for laying out transect lines in a long, narrow inlet. In (a) equally spaced lines are drawn at 45° to a line down the centre of the inlet. In (b) zigzags are drawn within a box bounding the inlet. As drawn (a) and (b) represent approximately equivalent survey effort. Designs in which the zigzags reflect off the coast (c) are undesirable (see text).

in a sampling day. Changing line orientation after a block is partly covered will result in unequal coverage.

Surveys in very confined waters pose special difficulties. While it might be efficient to travel down the centre of a harbour, fiord or channel, doing so is usually inappropriate as it will almost always result in unequal coverage probability of all the confined waters. If the animals of interest are concentrated in the centre or at the edges, the sampling can be particularly biased. A better approach is to draw an imaginary line down the channel's centre, and place transect lines at 45° to that centre line (Fig. 3a).

It can be more difficult to achieve equal coverage probability in a zigzag design. An alternative that we recommend is to draw zigzags bounded by a box outside the shoreline (see Fig. 3b), rather than reflecting off the shore itself (Fig. 3c). This approach is relatively easy to design and implement, and provides equal coverage probability. It leaves gaps between transect lines, but these gaps can be beneficial in avoiding problems that can occur at the apexes of zigzag surveys (see discussion below). A design with a constant angle (Fig. 3c), though commonly used, is flawed. Unless the shores are parallel, the coverage will be non-uniform. Other zigzag sampling schemes, and related issues, are described in more detail in Strindberg & Buckland (2004), Buckland *et al.* (2004) and Thomas *et al.* (2007).

In their layout, both schemes a and b (Fig. 3) should have random start points. In (a), an easy way to do this is to randomly select a point on the imaginary line down the centre of the inlet, and draw the first line crossing this point. The other lines are then regularly spaced from

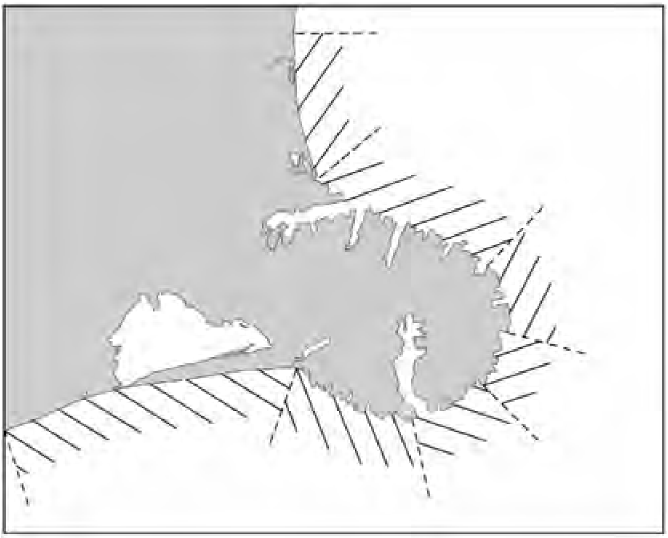

Fig. 4. An example of using survey blocks and randomised 45° lines to achieve an equal coverage survey design for Hector's dolphins at Banks Peninsula, New Zealand. The transect lines extend to 4 n mile offshore and, within each block, are 2 n mile apart.

this line. In (b) the zigzag lines could be drawn starting from a random point on a line drawn across the entrance of the inlet. In either design, there is no reason why they should not be replicated (ideally with different lines) to increase sample size and precision.

Zigzag survey designs are efficient, as they allow the survey to be more continuously 'on effort', but are most practical along relatively straight coasts or in open water. Line layout on curved or convoluted coasts should not follow the coast. If a zigzag design were laid out around a peninsula, for example, the outer apexes of the zigzags would be further apart than the inner ones. This would result in less effort offshore than inshore, and would be a biased design. This problem is even more obvious in designs using lines orientated directly offshore – these would splay out like the spokes of a wheel. Using parallel lines helps avoid the problem, but better still is to break the curved coastline into several blocks, and draw the parallel lines within the blocks (Fig. 4). In any scheme using parallel lines, it can be advantageous to allow a certain amount of course deviation on any one line (e.g. 10°) to minimize rolling, pitching and/or glare. Ideally, this course change would be applied to all the lines within a sample block.

The apexes of zigzags present some potential problems. Sightings made at the end of one leg may be made again at the start of the next. Additionally, having recently made a sighting near an apex, an observer might subconsciously bias his/her sighting effort on the next leg. Apexes also present opportunities for responsive movement (if the target species either is attracted to or avoids the survey vessel) to bias encounter rates on the start of the next leg. Scheme (b) (Fig. 3) minimizes these problems because the apexes are not surveyed. Another important issue with zigzags is that if there is any significant swell or glare, one leg or the other will have very different sighting conditions. Therefore, it is preferable to steam in one direction only. In many small boat surveys, zigzag survey routes are not practical.

Survey blocks

Often, it is useful to break the study area into smaller survey blocks. Blocks are not necessarily the same as strata – they are usually smaller. Advantages of blocking include:

1. To make laying out transect lines easier or more efficient and to ensure even coverage of sampling effort within strata.
2. To deal with complex shorelines (e.g. peninsulas, bays, harbours, fiords) so that oversampling or under-sampling part of the area is avoided.
3. To better accommodate environmental conditions. For example, in an area where bathymetry or coastal topography create localized swell or wind effects, the orientation of lines can be adjusted within this block to minimize the problem, yet retained at a standard orientation elsewhere.
4. To allow for estimation of separate detection functions if part of the study area involves enclosed waters where land prevents the full detection width from being available.
5. To accommodate an offshore boundary that is determined by distance from shore, or depth.
6. To facilitate calculation of an abundance/density estimate for a sub-area of special management or scientific interest (e.g. for Akaroa Harbour in Dawson *et al*., 2004).

Blocks surveyed at the same intensity of effort (equal effort per unit area) can be pooled for analysis (methods for accomplishing this are summarized in the Appendix). If blocks are surveyed at different intensities, the survey will have a stratified design, and density estimates must be computed for each stratum. The pros and cons of stratification are considered later.

The size of the study area, and of any strata used, must be measured. Usually, this is done using a planimeter or grid system on high-resolution charts or, increasingly, via GIS or other software[1]. This facility is also available in Distance 5.0. Areas that cannot be surveyed (too shallow, etc.) should be excluded from the area measurement.

STRATIFICATION (DIFFERENT INTENSITY OF EFFORT FOR DIFFERENT SURVEY BLOCKS)

There are three main reasons to consider stratifying a survey. The first is that if one knows ahead of time that there are more animals in one part of the study area, and fewer animals in another, one can achieve greater precision in the total abundance estimate by allocating more effort per unit area to the high-density zone. Second, stratification can allow for areas that have different sighting conditions. For example, if the surveyed area includes protected bays/inlets as well as open coasts, the sighting conditions between these two types of habitat are likely to be different. If so, it may be most appropriate to estimate a separate detection function for each of the two major habitat types (e.g. Dawson *et al*., 2004). Additionally, if in confined waters the land cuts off the full potential detection width, this will narrow the detection function; this is acceptable if a separate detection function is calculated for that area. Third, stratification can more easily allow generation of abundance estimates for particular areas for management interest (e.g. to match areas used in fisheries management in order to allow easier comparison with fishing effort data), although this can also be accomplished through the creation of separate survey blocks, as discussed above.

A simple, unstratified design is probably favoured when uncertain about future areas of interest (e.g. stock boundaries, future protected areas), or when differences in density are small (DuFresne *et al*., 2006).

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[1] Software for this purpose is freely available for Linux, Mac OS (9 and X) and Windows. e.g. *ImageJ* (http://rsb.info.nih.gov/ij/) can import a map on which a study area is drawn. Following a simple calibration process, area can be calculated automatically. See also Table 1. Be aware that different projections in GIS software can affect area calculations.

Table 1. Free software for recording data on line-transect surveys, designing surveys and analysing line-transect data

Name	Operating system	Functions	Available from
Distance	Windows 95, 98, 2000, NT	Survey design, analysing data	http://www.ruwpa.st-and.ac.uk/distance/
Wintrak	Windows 95, 98, 2000, NT	Designing cruise tracks, calculating coverage	http://swfsc.noaa.gov/prd.aspx
GeoArea	Windows 95, 98, 2000, NT	Calculating study areas	http://swfsc.noaa.gov/prd.aspx
WinCruz	Windows 95, 98, 2000, NT	Data entry and track recording for boat surveys	http://swfsc.noaa.gov/prd.aspx
Logger, 2000	Windows 95, 98, 2000, NT	Data entry and track recording. Customisable for manual data input	http://www.ifaw.org/ifaw/general/default.aspx?oid=25653
Airtrack	DOS	Data entry and track recording for aerial surveys	http://www.otago.ac.nz/marinescience/
L-Tsurv	DOS	Data entry and track recording for boat surveys	http://www.otago.ac.nz/marinescience/

For software available from SWFSC, follow the 'Data portal and software' link (several other useful programmes are also available here). *Airtrack* and *L-Tsurv* are optimized for HP200LX palmtop computers.

Coastal habitats are much more complex than the open ocean, and may have areas with very different sighting conditions, or areas of particular management significance. Hence, while open ocean surveys are often unstratified, using randomly generated transect lines, allocating survey effort according to a geographical stratification scheme is often desirable in coastal or riverine surveys. Even coverage within strata is crucial, and helps minimize biases due to patchiness or geographical trends in distribution.

The principal cost of stratification is that if it does not match patterns in the target species' density, the variance of the abundance estimate may be higher than in an unstratified design, perhaps considerably so. This would be likely only if effort levels within strata were in the wrong rank order of true density, which could be avoided by conducting a pilot study first.

Pilot surveys can provide valuable guidance on survey design. The practical constraints on a survey in that habitat will become clear, and the pilot survey could generate sufficient density data to facilitate good stratification of effort in the main survey. The person who is going to analyse the data from the main survey should be involved in the pilot survey at least, so that s/he understands the constraints on data collection, and has input into designing the main survey.

A useful way to retain flexibility in stratification, and to avoid the possibility of poor stratification, is to use lines at spacings that can be evenly divided. An example would be a stratification scheme that has parallel lines at 4 n mile intervals at the lowest level of survey effort, lines at 2 n mile intervals at the middle level of effort, and for the most intensive level has lines at 1 n mile (e.g. Jefferson, 2000; Slooten *et al.*, 2006). In this scheme, if an area with a low level of effort produces an unexpectedly high number of sightings, inserting the intervening lines could be done to bring the effort up to the next stratification level. Such increases in effort must cover the entire stratum and strata must be designated prior to the survey. This is, in effect, a two-phase sampling scheme. The first phase of sampling is used to decide the intensity of the second phase.

A further development is adaptive sampling, in which a base level of effort is applied, and more effort added, e.g. by starting to zigzag, when encounter rates reach a trigger value (Pollard, Palka & Buckland, 2002: Pollard, Buckland & Borchers, 2004). Such designs can produce gains in precision, but are potentially biased (Francis, 1984). A key factor is the amount of extra effort added in the adaptive phase (Francis pers. comm.). For example, if most of the total effort is at the base level, bias will probably be small. As this level decreases, at some point the level of information on density will become insufficient for good ‘decisions’ on when to start adding more effort. Whether and when the trigger level will be reached become increasingly dependent on chance. Such surveys also need a trigger level for resuming the base level of effort. Adaptive surveys are most practical when there is a relatively high density in some areas and high variance in density. They are difficult to optimize in multi-species surveys (Thomas *et al.*, 2007). Palka & Pollard (1999) conducted an aerial survey in which they compared standard and adaptive approaches; the adaptive approach did result in more sightings but only gave a slight improvement in precision. In the context of most cetacean surveys, we believe that a simpler approach is preferred.

In data analysis, it is possible to post-stratify data by factors that affect the probability of seeing distant groups. Such factors include group size, sea state and (for aerial surveys) cloud cover. Line-transect analysis methods are typically robust to pooling data from different conditions, so it may not be necessary to stratify by such factors when estimating effective strip width (Buckland *et al.*, 2001). Methods are available within the program Distance to adjust for situations when larger groups have a greater probability of being seen at distance than smaller groups. Post-stratification is, however, desirable if the probability of detecting animals on the transect line [g(0)] is found to vary with survey conditions or group size. This is especially important if different geographical strata have different sighting conditions but are (because of small sample size) pooled for estimating Effective Strip Width (ESW). For these reasons, factors that affect sighting conditions should be recorded frequently throughout a survey. A new development in the field is multiple covariate distance sampling, in which the effects of covariates of sighting conditions (such as group size, Beaufort state or sighting platform) are explicitly modelled as part of the detection function. This advanced analysis technique is available in program Distance 5.0 and a description of the technique can be found in Buckland *et al.* (2004). One advantage of this technique is that it avoids the potential problem of stratifying data into bins with inadequate sample sizes. An example applied to fin whale *Balaenoptera physalus*, humpback and minke whale *B. acutorostrata* can be found in Zerbini, Waite & Wade (2006).

Adding extra lines to estimate ESW robustly

Estimating effective strip width is a process of fitting models to observed sighting distances. Usually, the fit (and hence the variance associated with ESW) will improve with more data. Buckland *et al.* (2001) recommend that 60–80 sightings are usually required to achieve a good fit and that 20–30 sightings should be considered a minimum. If there are sufficient existing data on density, it is sometimes possible to design a survey so that this number of sightings will be achieved. In low-density areas, however, unrealistic effort levels might be required to reach this target. In that case, a good solution is to run extra lines in an area with higher densities but the same sighting conditions (and same boat or aircraft and observers), and use these sightings to improve estimation of ESW (e.g. Dawson *et al.*, 2004; Slooten *et al.*, 2006). If the extra sightings are allocated within the study area, that area should be post-stratified so that extra sightings contribute not only to improving estimation of ESW, but also to estimation of group size and encounter rate within that stratum. If the extra lines are allocated outside the study area, the sightings can be used only to improve estimation of ESW.

SURVEY MODE – PASSING OR CLOSING?

Two modes are commonly used for cetacean line-transect surveys. In *passing mode*, the survey vessel continues to travel along the established transect line after a group of marine mammals is seen. Group size and species composition are estimated from the transect line while survey effort continues. In *closing mode*, the vessel leaves the transect line when a sighting is made and approaches ('closes on') the group of animals in order to estimate group size and species composition. Additional sampling can occur on closing mode surveys, including photo-identification and genetic sampling. In closing mode, the vessel can either resume survey effort by returning to the transect line at the same point it left that line, or resume survey effort immediately after all data are collected from a given group. The former approach is preferred to minimize potential biases (see below).

Closing mode has a potential for generating biased estimates of group density by a variety of different mechanisms. If effort is resumed without returning to the track line, the survey vessel may be drawn into areas with higher density, thus resulting in abundance estimates being biased high. If the vessel does return to the track line and the same group is re-sighted and is inadvertently recorded as a new sighting, abundance will again be overestimated. Conversely, if the survey is designed to fill a certain amount of time (e.g. 20 days of ship time) rather than a given number of transect lines, closing mode can act to underestimate abundance because time spent in closing mode cannot be spent running lines and making new sightings. Hence, the vessel spends a smaller fraction of each survey day searching for cetaceans in high-density areas, and therefore, such areas may be underestimated in the overall survey. The biases associated with closing mode can be minimized by (i) keeping track of the previously sighted group while returning to the transect line in order to guard against double counting; and (ii) preventing the vessel from being drawn into high-density areas by setting limits on the distance from the transect line that the survey vessel can stray.

Passing mode also has potential for generating biased estimates of group size and incorrect species determinations. Often, group size of cetaceans can only be estimated accurately if the observer is in close proximity to the group and is underestimated at greater distances. For example, in one survey post-encounter estimates of group size of 'transient' killer whales were 26% higher than initial group size estimates (Zerbini *et al.*, 2007). Also, identifying species can be very difficult at distances of more than a few hundred metres. For multi-species groups of cetaceans, species composition may be even more difficult to estimate than group size and may require several passes in close proximity to the group. Species identification and group size estimation in passing mode can often be improved by using higher-power binoculars than are normally used to search for groups. If species identification at distance is difficult and samples sizes are sufficient, it is reasonable to truncate the perpendicular distance data to eliminate most or all sightings that cannot be identified to species.

Clearly, there is no perfect survey mode for cetaceans. The choice between passing mode and closing mode typically depends on whether group size and species can be accurately determined from the transect line. This is often a judgement call, but experiments can be done during a pilot survey wherein observers are required to make group size estimates and species determinations from the transect line and then are asked to update their estimates after the group is approached. If species composition and group size cannot be accurately determined from the transect line, closing mode is recommended. Every effort should be made to reduce the potential biases associated with closing mode (see above). For surveys in which group sizes are relatively small and easily determined, multiple groups can be in sight simultaneously, and if it is difficult to track individuals from one surfacing series to the next, passing mode is recommended. As examples, passing mode has been used for harbour porpoises *Phocoena phocoena* and minke whales, two species which occur in small groups and which are difficult to track from one surfacing series to the next if multiple groups are in the same area.

FIELD METHODS AND PROTOCOLS

From an observer's point of view, the key assumptions of distance sampling are that: (i) the probability of detecting an animal of interest on the track line [g(0)] is one (or can be estimated); (ii) the animals of interest do not move in response to the survey platform before detection (or the extent to which they do can be estimated); (iii) the species are identified correctly; and (iv) the distance to the sightings is accurately estimated, as is (v) group size. Meeting these assumptions requires substantial skill on the observer's part. Additionally, good observers have long attention spans, can tolerate long periods of discomfort and are not prone to motion sickness.

Training of observers is extremely important. If possible, we recommend training in an area with a high density of the target species and running transects there until each observer has reached a minimum number of sightings (e.g. 20), and is totally familiar with scanning and recording procedures (e.g. Dawson *et al*., 2004). These data are not used in the subsequent abundance analysis. For very rare target species, training on other species that provide similar sighting cues may be appropriate. This training period is also very important for the aircraft pilot or boat captain. Navigating transect lines precisely is a skilled task, and a poorly trained pilot or captain can cause unnecessary delays and increase the cost of a survey. Familiarity with the GPS system to be used is very important.

To address the first two assumptions above, it is important that observers scan as far ahead of the vessel as they reasonably can. In this way, an animal on the track line has more time to be detected, and has the greatest chance of being detected before it reacts to the survey vessel. For these reasons, as well as being able to measure angles to sightings, using binoculars is strongly encouraged. Scanning behaviour, i.e. how much time observers should spend looking in different sectors, should be concentrated near the track line, and this should be discussed and practised. For example, if one observer is used on each side, each should probably spend about twice as much time scanning from dead ahead to 45° than from 45° to 90°. Additionally, it is good practice for two observers to overlap their scans on the track line. Observers often feel a temptation to try to make sightings as far away to the side of the survey platform as they can, and are often competitive. This should be strongly discouraged, as it potentially violates assumptions 1 and 2 above, and creates a distribution of sightings that is difficult to model for the purposes of fitting the detection function. On the other hand, if observers focus too closely on the track line (e.g. 10° either side of the track line), this can create too narrow a 'shoulder' in the distance data, and make estimation of the detection function unreliable. To maximize consistency, it is helpful to write a brief observer manual, and ask observers to reread it regularly throughout the survey.

Correct species identification is obviously important, as is accurate estimation of group size. Both should be addressed in the training period. Assessing group size is often less of a problem on coastal and riverine surveys than it is on oceanic surveys, because coastal and riverine species typically have much smaller group sizes. If observers are not confident about the size of a particular group, breaking off the transect to approach the group (closing mode) can be used to improve estimation.

MEASURING DISTANCES TO SIGHTINGS

Line-transect surveys require data on the perpendicular distances of sightings to the track line. In surveys using binoculars, the vertical angle is usually measured by counting the number of reticle divisions from the horizon down to the sighting (Lerczak & Hobbs, 1998). In coastal surveys, the horizon is often obscured by land. In this case, the observer measures the declination from the shoreline to the sighting (using binocular reticles) while the vessel's captain simultaneously measures the distance to the shoreline in the same direction via RADAR (a laser-range finder can also be used if close to shore). In analysis, you can add the expected declination (in reticles) from the horizon to the shoreline given its distance to your observed declination, and then convert this total declination to a true distance to the animals (e.g. Barlow, 1995; Lerczak & Hobbs, 1998). Distance to land can also be measured from the boat position (if that is known accurately, e.g. via GPS) using accurate paper or digital charts. Even inexpensive, hand-held GPS units are accurate enough for this purpose without differential correction (e.g. Garmin eTrex; over 48 hours 50% of fixes were <3.8 m of the true position, and 95% were <6.7 m; Wilson, 2007).

Distances to sightings can also be measured photogrammetrically (Leaper & Gordon, 2001). A video camera is used to gain images which show the object of interest, and the horizon simultaneously. Provided that camera height and lens focal length are known, these images provide measurements of sighting distance via the same trigonometry used to calculate vertical angles from binocular reticles. When used from a large survey vessel, Williams *et al.* (2007) found this method to be unbiased and more reliable than measurement via reticles. For both of these measurement methods, accuracy increases with increasing platform height.

The 25-power binoculars used on some shipboard surveys allow sightings to be made at great distances (e.g. Wade & Gerrodette, 1993), but are large, require pedestal mounting, and their utility is compromised by vessel movement and vibration. Hence, they are seldom useful on vessels smaller than *c.* 30 m (smaller in calm conditions). Hand-held (typically 7-power) binoculars offer a practical alternative for smaller survey vessels. Several brands offer reticule scales that allow measurement of vertical angles (Kinzey & Gerrodette, 2001), along with built-in compasses to measure horizontal angles (by taking the compass bearing to the sighting, and another of the vessel's course). Compasses are susceptible to deviation caused by magnetic fields or ferrous metals, and may be unusable on steel vessels. If deviation is not excessive, each binocular should be assigned to a particular observer position, and a deviation card made for that binocular/position combination. Our experience, and that of Jefferson (2000), is that such binoculars work better than angle boards (see below). It should be noted that in-built compasses intended for use in the Northern Hemisphere may not be accurate in the Southern Hemisphere (and *vice versa*) as the 'dip' of the card will be wrong, and may prevent it from moving freely.

Horizontal angles can also be estimated using an angle board, which resembles a large protractor equipped with a pointer at its centre (Buckland *et al.*, 2001). The observer aligns the pointer with the sighting, and then reads off the angle on the board. In our experience, observers using angle boards are more prone to 'rounding' their sighting angles (e.g. record a sighting at 3° as either 0° or 5°) than those using binocular compasses. To avoid this, the correct procedure is to line up the pointer first, without looking at the angle scale, and then read the corresponding measurement.

In closing mode surveys, GPS can be used to measure distances directly, by recording a fix when the animals are first seen, then again when the animals are reached (Dolar *et al.*, 2006). This approach will tend to overestimate ranges unless the target animals are stationary, and is not generally recommended. It is probably most appropriate in surveys from small boats where the 'closing' can be done at reasonably high speed in order to limit the effect of animal movement.

Laser rangefinders are now readily available, relatively inexpensive (e.g. US$ 200–400), and highly accurate (typically ± 1 m). However, except in the case of large targets (i.e. whales) at close range (<200 m), they seldom receive enough reflected energy to measure distances to sightings. They are, however, extremely useful for measuring distances to land where land is close (<1 km), and for practice in estimating distances.

If the survey vessel is too small to have a raised platform, observers will probably not be able to estimate distances via reticle-equipped binoculars, and may have to estimate distances by eye. With training, observers can make reasonably accurate judgements of sighting distance (e.g. Dolar *et al*., 2006; Williams *et al*., 2007), and some surveys use estimations 'by eye' for at least some (or all) of their distance data (e.g. Hammond *et al*., 2002). Observers differ in their ability to estimate distances, and so must be calibrated (in this process a laser range finder is very useful; Smith *et al*., 2004). Additionally, because each observer's ability may drift with time, training must be ongoing throughout the survey. Observers must consciously avoid rounding their estimates to convenient values. Even with thorough training, the accuracy of estimates done 'by eye' will always be open to question. Since accuracy of sighting distances is a key assumption in distance sampling, it is always better to measure rather than 'guesstimate' distances.

Whatever methods are used to estimate distances to sightings, we recommend daily inspection of the data in order to detect problems which can make fitting a detection function much more difficult. This is especially important during the training period and over the first few days of a survey. A histogram of distance data should have a 'broad shoulder' – the first few distance bins should be of reasonably similar height (Burnham, Anderson & Laake, 1980). A spike in the first bin, caused by excessive focus on the track line, or rounding small angles to zero, is a particular problem (see Hiby & Hammond, 1989; for several examples). Likewise, plotting the distribution of horizontal sighting angles can indicate whether observers are rounding angles to particular values (e.g. are there peaks at 5, 10, 20 degrees with few intermediate values?).

Starting and stopping transect lines

If the target species is most common close to the shore or riverbank, starting and finishing transects as close to that edge as possible is important to avoid bias. For navigational reasons, the vessel's captain might wish to turn early away from the shore near a transect's end, potentially lowering sighting rates. While vessel safety is the captain's responsibility, s/he should be encouraged to avoid doing this if possible. Also, when nearing the start of a transect line, we instruct observers to look away from the intended path until actually 'on effort'. The reason for this is that if observers have made a sighting while 'off effort' soon before a transect is begun, their attention might be diverted to this zone, and this can bias sighting rate.

DATA RECORDING SYSTEMS FOR SMALL BOATS

The accuracy and affordability of GPS navigation has made it indispensable in line-transect surveys. Virtually all GPS navigation units allow input of waypoints that allow precise and easy navigation of transect lines. Most units have NMEA output that can be routed to the serial port of a computer for storage and/or have in-built memory that can store the track surveyed[2]. Recording of track is important because actual track may be significantly longer than the straight-line distance between the start and end point, due to current, wind or course-keeping difficulty. Several free or inexpensive applications are available for downloading GPS track files[3], and these can be extremely useful to provide a preliminary look at the survey track, and hence show whether course keeping was adequate, or lines were missed.

If the track is to be recorded on a computer, the same computer program might as well be used to record sightings. Most such programs record GPS position, date and time and prompt the user to input sighting information. At a minimum, this information includes sighting angles (vertical and horizontal angle in boat surveys), group size, species and sea conditions. Software developed to record data on line-transect surveys is freely available for both DOS and Windows operating systems (Table 1). A palmtop computer in a splash-proof housing, with a silicone membrane over the keyboard, is a practical solution on a small boat. Whatever recording system is used, it is important that the data can be recorded and corrected quickly and that a system is in place for recording simultaneous sightings. During a sighting, the recorder cannot observe. So, in areas where sightings are very frequent, it might be best to use a dedicated recorder. An even less complex recording system might comprise only a GPS with internal track recording, and a dictaphone for each observer. Each dictated sighting must record the exact time (synchronized to the GPS).

DATA RECORDING SYSTEMS FOR AIRCRAFT

GPS is, if anything, even more important on aerial surveys. We have been surprised to find that commercially qualified pilots are often not trained in GPS use, and need training and practice in order to navigate the lines properly. If using a new pilot, we sometimes send him/her our GPS unit before we arrive for a survey, and usually spend the first flight practising transect starts in addition to training observers. We have found that 'moving map' GPS plotters are easier for most pilots to use.

Because of the speed of the aircraft, data from sightings must be recorded instantly. There may be no time for a recorder to enter sightings s/he has been relayed by observers (there is often no space for a dedicated recorder either). A simple data-recording system has a central GPS which is used by the pilot and which feeds NMEA data to a computer. This computer logs the aircraft's track, and is used to record which transect is being flown, weather conditions, and start and stop points. Each observer is equipped with a dictaphone, inclinometer and a digital clock. At the start of each flight, the clocks are synchronized to the GPS, and velcroed near the bottom of each observer's window – ideally so s/he can see a clock without looking away from the sighting. On making a sighting, the observer starts his/her dictaphone, and dictates the sighting data, along with the precise time (to the second) that the sighting passes abeam. On returning from a flight, each observer transcribes their own dictaphone tape into a spreadsheet. Via later comparison with the GPS tracking file, the sighting times are used to locate where each sighting was made. When there is space for a dedicated recorder, another technique that has been employed is to use software that can instantly store multiple sighting positions with a single keystroke for each sighting, and allows the filling in

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[2] We have noted a several second error in the time stamps of the track recorded internally in some Garmin GPS units (e.g. Garmin GPS II+, 12XL). This error is constant and can be adjusted for, and arises from the time stamps not accounting for leap seconds (T. Thomas, pers. comm). In boat surveys, this error will probably be inconsequential, but it can be important in aerial surveys. The error is not present in the NMEA data sent from the GPS unit's serial port.

[3] Examples are: DOS, mac, unix, http://www.gpsbabel.orgGPSBabel; Windows, http://www.gpstm.com; Mac, http://www.macgpspro.com/.

of details directly afterwards. Observers can communicate their sighting information to the recorder over voice-activated headsets, while the recorder is still able to log the position of any new sighting detected in the meantime.

It is important that observers conducting independent observer studies do not communicate with each other while on effort but can still receive instructions from the survey leader. Noise within the aircraft, and the fact that observers are jammed against their windows, usually prevents an observer noticing when another has a sighting. We have found that dictaphones work surprisingly well despite the noisy environment.

Various other recording systems have been developed. Some use a central multi-track recording device, such as a hard-disk recorder. The advantage of a multi-track recorder is that the individual records are precisely synchronized in time which aids in the detection of duplicate sightings when observers are working independently. Given the expense of obtaining survey data, a redundant system should be considered as insurance against lost data.

ESTIMATING THE FRACTION MISSED ON THE TRACK LINE

No cetacean survey can reasonably expect to see all the animals present within the area surveyed. Line-transect methods, when properly applied, appropriately correct for animals missed as a function of their distance from the track line. As previously mentioned, though, one key assumption of line-transect methods is that the probability of detection on the track line is certain [i.e. $g(0) = 1.0$]. This assumption will often be violated. For example, some animals will probably be underwater and not available for counting ('availability bias'; *sensu* Marsh & Sinclair, 1989). Also, for a variety of reasons including glare, fatigue and momentary inattention, no observer will see all of the dolphins that are available at the surface ('perception bias'; *sensu* Marsh & Sinclair, 1989). In some cases, the combined effect of these, often termed the 'fraction missed' on the track line, is very large. For surveys of absolute abundance, estimating the fraction missed is vital.

For cetaceans, the potential bias from availability bias is a function of dive time and the relative speed of the survey platform. For aerial surveys, because of their speed over the water, the proportion of time that the target species spends at the surface is important for all species. Hence, aerial surveys using single aircraft need additional data to assess availability bias. On boat or ship surveys, availability bias is potentially the largest problem for long-diving species that spend little time at the surface; these species generally occur in deep water and will likely not be the target of inshore surveys. For very long divers, it may be necessary to model diving behaviour to adequately estimate availability bias (e.g. Barlow, 1999). For boat surveys of small cetaceans, typical vessel speeds are slow enough to ensure that small cetaceans surface within visual range at least once before the survey vessel passes; hence, a track line detection probability of less than 1.0 would be largely caused by perception bias. Perception bias is potentially largest for species that occur as single animals or in small groups and do not show much of their body when surfacing, such as harbour porpoise and minke whale. Estimates of perception bias have usually been >0.9 for dolphins that occur in large schools, for whales with large blows, and for larger delphinids that occur in groups and have relatively large dorsal fins (e.g. killer whale) (e.g. Barlow & Forney, 2007).

Perception bias can be estimated using two independent teams of observers who can (*post hoc*) determine whether they detected the same groups of animals or not. The observer teams can be on the same platform, but need to be arranged so they do not give clues to each other about groups that have been detected. Alternatively, the two teams can be on separate platforms surveying simultaneously. A combination of perception and availability bias can be estimated through tracking methods, where an individual group of cetaceans is tracked by one observer or team and it is determined whether the sighting team detects that group or not. The tracking team can be on a separate platform, such as a helicopter (e.g. Buckland & Turnock, 1992), on land (e.g. Laake *et al.*, 1997) or even on the same platform. The key to estimating g(0) where availability bias is accounted for lies in having a separation in time between when a group begins to be tracked, and when the observer team has a chance to detect them. If the tracker is on the same platform, s/he have to be able to look well ahead of the observer team. For example, in some cetacean surveys, this has been accomplished by having a tracker using 25x binoculars to look only for sightings well ahead of the ship (Hammond *et al.*, 2002). This can also be done having a tracker using 25x binoculars in combination with an observer team using 7x binoculars.

Platform choice (boat or aircraft) may restrict methods available for bias assessment. Two independent teams of observers, on separate observation platforms but on the same vessel, have been used to quantify perception bias (as well as correct for reactive movement; see below) for harbour porpoise (Palka, 1995). Dual, independent, observer teams, however, are not likely to be practical on vessels less than, 20 m long. An independent observer looking through a belly window was used to assess perception bias on an aerial survey for multiple species of cetaceans (Forney *et al.*, 1995). Sightings made by two independent teams of observers have been used to quantify perception bias in aerial surveys of dugongs (Marsh & Sinclair, 1989) and Hector's dolphins (Slooten *et al.*, 2004). Availability bias has been estimated in an aerial survey of dugongs using helicopter observations of dugong *Dugong dugon* models at various depths, and data from animals tagged with time-depth recorders (TDR) (Pollock *et al.*, 2006). TDR data alone cannot answer the key question, i.e. what proportion of the time is the target species *visible* from the survey height? If one assumes that the animal is only visible when the tag is at the surface, this will underestimate the proportion of time the animal is visible from the air, and therefore overestimate abundance.

Tandem aerial surveys (the dual-platform approach), using two observer teams in independent aircraft, were used to estimate the fraction missed during surveys for bottlenose dolphins *Tursiops truncatus* off the Californian coast (Carretta, Forney & Laake, 1998) and for harbour porpoise in the North Sea (Borchers *et al.*, 1998). This sophisticated approach is probably beyond the resources of most research teams. Barlow *et al.* (1988) used shore and helicopter observations to estimate what proportion of the time harbour porpoise were visible near the surface, and hence available to be counted.

For small cetaceans found very close to shore, it is possible to estimate g(0) via repeated trials in which a theodolite is used on shore to track nearby groups, while a survey comes through the area. Laake *et al.* (1997) used this approach for an aerial survey of harbour porpoise, but the method could likely be applied to a vessel survey as well. Provided suitable observation points are available, this approach is much more affordable than using a helicopter. Such trials would have to be done over many days to dilute any effect of the same cetaceans being repeatedly exposed to the survey vessel. The crucial assumption would be that g(0) measured in such locations was representative of the rest of the survey area. This same approach could equally well be used to measure the effect of reactive movement.

In some habitats, availability bias can vary geographically. For example, small-scale differences in turbidy affect the sightability of submerged dugongs (Pollock *et al.*, 2006). Ways to mitigate this problem include: (i) stratifying sampling for availability bias over the range of conditions experienced in the actual survey; (ii) recording water colour as a proxy for turbidity, and using it as a covariate in analyses; and (iii) recording whether sightings are made at or under the surface and examine the ratio of these two types of sightings across different habitats for evidence of bias.

With good, well-trained observers on an appropriate platform, 'perception bias' will be small for most species. Nevertheless, ideally each survey should attempt to empirically estimate it. The topic of estimating g(0) is covered elsewhere in more detail (e.g. Buckland & Turnock, 1992; Palka, 1995; Barlow, 1999; Palka & Hammond, 2001; Buckland *et al.*, 2004).

THE EFFECT OF REACTIVE MOVEMENT

Responsive movement by the target species either towards or away from the survey platform will bias abundance estimates positively or negatively, respectively, and often occurs on cetacean surveys. The effect of reactive movement may be particularly important in coastal surveys from small boats. Because sightings are typically made at closer ranges, the animals sighted are more likely to have reacted to the survey vessel. Observed densities may be artificially lowered by avoidance (e.g. harbour porpoise, Palka & Hammond, 2001) or raised by attraction (Dall's porpoise *Phocoenides dalli*, Turnock, Buckland & Boucher, 1995; Hector's dolphins, Dawson *et al.*, 2004). From a conservation perspective, the latter is worse, because it could result in impacts being judged as sustainable when they are not. At a minimum, observers should collect data on the orientation of animals when they are first seen. If disproportionately many were heading towards the boat when first seen, this could be evidence of attraction.

The effect of reactive movement on abundance estimates can be minimized by using higher sighting platforms and/or binoculars to detect animals at greater distances, before they react to the vessel. This may require limiting survey conditions to those which allow animals to be seen before they react. For example, Barlow (1995) showed that very few Dall's porpoises were approaching the vessel when first seen if they were seen in calm seas, so he estimated their abundance only from data collected in Beaufort sea states of two or less. Alternatively, the effect of reactive movement can be quantitatively assessed. Often, this has involved a two-platform approach (e.g. Palka, 1995) in which the topmost team looks far ahead. In general, dual platform tracking methods (described above for correcting for availability bias) can be used to correct simultaneously for both availability bias and responsive movement. For example, Buckland & Turnock (1992) proposed methodology using a helicopter combined with a ship survey to correct for both biases for Dall's porpoise. Any approach can work if sightings can be made far enough ahead to justify the assumption that the animals have not yet responded to the survey vessel before being seen by the observer team. It is obviously better if the second team of observers is not on the boat that the animals are responding to.

Boat/helicopter studies are an excellent way to accomplish this. Helicopters are expensive, but this cost can be minimized by conducting the studies in an area where sightings are very frequent. It is also worthwhile remembering that only one observer is needed in the helicopter (see Hector's dolphin case study below), so small, relatively inexpensive, two-person helicopters can be used. Also, using an expensive tool for a short time can be cheaper than using a less expensive tool for longer. Some surveys have managed to get helicopter time supplied by the military [e.g. Jefferson *et al.* (2002)]. As above, if the species of interest is found very close to shore, simultaneous boat survey/cliff-top observations could be used to quantify reactive movement.

CASE STUDIES

Example 1: Hector's dolphin survey around Banks Peninsula

Dawson *et al.* (2004) carried out a line-transect survey of Hector's dolphin abundance in New Zealand waters. They chose to use a catamaran for reasons of cost and practicality. Hector's dolphins are found very close to shore, and sometimes occur in very shallow water, making it impractical to use a large vessel. In addition, chartering a large research vessel was well beyond the available research funding, which came from levies imposed on gill-net fisheries with demonstrated dolphin by-catch.

Having decided on a relatively small vessel, a catamaran was chosen for its greater lateral stability. The vessel used for this particular survey was the 15-m sailing catamaran *Catalyst*, which could cruise under power at 10 knots (18.5 km/ h). A collapsible observation platform was built, giving three crew (two observers and one recorder) an eye height of about 6 m, which was sufficient to use binoculars with reticles to estimate the distance to each sighting. Non-ferrous construction of the platfom and vessel allowed compasses in the binoculars to be used to estimate the horizontal angle to each sighting.

Transect lines were placed at a 45° angle to the shoreline to ensure the survey sampled across alongshore and offshore gradients in dolphin density. The primary area surveyed was from the coast out to 4 n mile offshore. Peninsulas and bays were challenges for survey design. Along relatively straight sections of coastline, all that was needed was to start with a random starting point and plot lines at a constant distance (e.g. 2 nautical miles) apart. On curved coasts, the survey area was divided into blocks, and lines placed at 45° to the coastline within each block (Fig. 4). Long harbours (e.g. Akaroa and Lyttelton harbours, Flea Bay) were surveyed according to the scheme shown in Fig. 3a, using transects spaced 1 nautical mile apart. Because sighting conditions differed systematically between the open coast and harbours (inlets), separate detection functions were computed for each habitat type. In harbours, sets of transect lines as shown in Fig. 3a, each with different randomized start points, were replicated until the target of 60–80 sightings was achieved. On the open coast, this target number of sightings was achieved without replicate sets of lines.

A major challenge was that Hector's dolphins are strongly attracted to survey vessels, which has the effect of increasing the apparent density. On the first survey, we noted the direction dolphins were facing or travelling when first sighted. Analysis of these data showed that a far greater proportion than expected by chance were facing in the direction of the survey vessel. On the second survey, we therefore used a relatively inexpensive two-person helicopter (Robinson R22) which was flown in front of the survey vessel. Sightings made by one observer in the helicopter were compared with sightings made by the observers on the vessel to estimate the proportion of dolphin groups that were missed, and to determine whether the dolphins had moved towards the vessel before they were detected by the observers (Buckland & Turnock, 1992; Dawson *et al.*, 2004).

The vessel's RADAR was used to measure the helicopter's position while it briefly hovered over a sighting. The observer on the helicopter communicated with a crew member in the wheelhouse of the vessel, but not with the crew on the observation platform. The flying height of the helicopter (500 feet) made it impossible for the observers to see the helicopter while they were using their binoculars. They could, of course, hear the helicopter and see it with the naked eye. The observers were strongly encouraged to ignore the helicopter and to stick to their normal scanning and sighting routine. Further, the helicopter pilot was instructed to sometimes behave as if on a sighting when not, further encouraging the observers to ignore the helicopter.

The joint boat-helicopter surveys described above resulted in a correction factor of 0.5. In other words, without correction for attraction to the survey vessel, the above surveys would have overestimated abundance by a factor of 2.

Example 2: Amazon River dolphin survey

Riverine habitats pose some of the greatest challenges for cetacean surveys. However, many river dolphin and porpoise populations are endangered, and there is a lack of abundance information for most. Some of the challenges include:

1. Complicated topography – river channels are long, narrow and often convoluted. River levels may vary by tens of meters between wet and dry seasons and may flood adjacent forests for much of the year. Many parts of the river system may not be navigable by large vessels due to shifting sand bars.

2. Currents – river currents are relatively fast compared with most ocean currents, and they vary throughout the river. Typically, currents are faster in the centre of rivers and are slow at the margins. Consequently, in order to navigate a zigzag transect across a river, the course heading needs to vary with the current speed. Eddies, particularly at the confluence of rivers or downstream from islands add complexity to the habitat. Currents can cause a patchwork of ripples or standing waves which can make cetaceans harder to see but which cannot easily be quantified as a covariate in line-transect analyses.

3. Navigation – most riverboat pilots navigate by visual landmarks. They are typically unfamiliar with GPS or with navigation by compass. They have no experience navigating a straight course to follow defined transect lines. Nonetheless, local knowledge is essential in navigating most rivers. Upriver navigation may be necessarily slower than downriver navigation due to the effects of currents.

4. Animal distribution – river dolphins are not distributed uniformly in their environment. Some species appear to be most abundant along the banks and others favour the centre of large channels. Survey vessels are constrained by the navigable depth of the river, thus given the non-uniform distribution of the animals, it may not be possible to meet the line-transect assumption that animals are uniformly distributed with respect to the distance from the survey vessel (within the search distance).

In 1993, Omar Vidal and colleagues organized one of the first line-transect surveys for river dolphins. The survey estimated the abundance of the Amazon River dolphin *Inia geoffrensis* and tucuxi *Sotalia fluviatilis* in a section of the Amazon River bordering Columbia and Peru (Vidal *et al.*, 1997). They used a local 17.5-m riverboat with a one-cylinder diesel engine, and they built an observation platform on the top of the wheelhouse (Fig. 1). Due to currents and direction of travel, vessel speed varied between 5 and 15 km/h. The survey was conducted in the low-water season when the dolphins are concentrated in the channels and are not in the flooded forests.

From prior work, they knew that the density of dolphins was much higher near the riverbanks, around islands and in the small tributaries and lakes associated with the Amazon. For this reason, they designed a stratified survey, with more intensive survey efforts in the areas of higher expected density. However, because the near-bank regions and the small tributaries were so narrow and because dolphins are not uniformly distributed with respect to distance from the bank[4], a line-transect survey design was deemed impractical for these areas. Their compromise design included strip transects along the banks and around the islands in the main channels and in the smaller channels (<200-m width) and included zigzag line-transects in the centre of the large channels (>300 m but typically over 1 km in width; Fig. 5). In the main channels, the strip transects were conducted at a distance of 100 m from the riverbanks and included 100 m on each side of the vessel. This strip width was defined to be

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[4] One of the line-transect assumptions is that animals are uniformly distributed with respect to distance from the survey vessel.

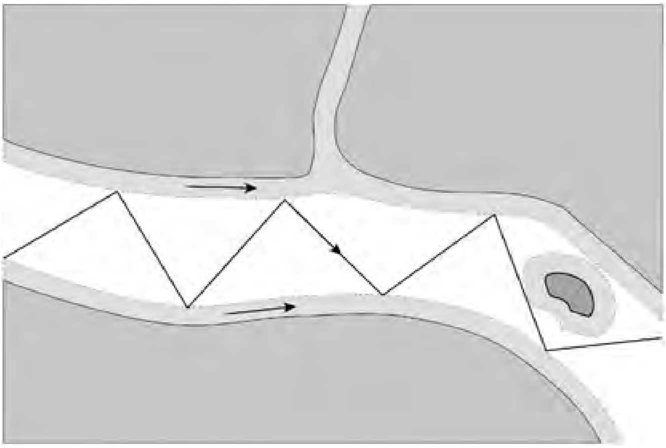

Fig. 5. Schematic representation of the survey design used in the Amazon river. A 17.5-m river boat surveyed the zigzags using line-transect methods, while a small outboard-powered open boat surveyed the light shaded area using strip-transect methods. For practicality, the zigzags followed the course of the river, rather than being drawn to a bounding box outside it (see Fig. 3); hence, this is not an ideal equal-coverage design.

conservatively narrow to increase the likelihood that the strip transect assumption (that all animals are seen within the defined strip) would be met; analysis of the line-transect data justified this by showing that the detection probability was relatively flat out to 200 m on each side of the ship (Vidal *et al*., 1997). The line-transect densities of *Inia* and *Sotalia* in the centre of the large channels were 0.57 and 0.89 dolphins/km^2 (respectively) and the strip-transect densities along the main banks of the same channels were 2.02 and 2.78 dolphins/km^2 (respectively). Given this three- to fourfold difference density in the two habitats for both species, the precision of the survey undoubtedly benefited from the stratified survey design.

Analysis of the above survey required more data than is typically recorded during ship surveys at sea. During the survey, the width of the channels was recorded frequently and proved to be essential in the analysis. An optical rangefinder was used to measure distance to the riverbank up to approximately 1 km. Because the animals were only visible for a few seconds and because the optical rangefinder did not work on the ripple left behind after a surfacing, distances to dolphins were estimated by eye[5]. Given the uncertainty in using distances estimated by eye, observers were frequently calibrated during the survey by asking them to estimate the distance to a floating object (typically a clump of reed grass). Estimates from each observer were recorded and they were then told the distance measured via an optical rangefinder. Data from the distance calibrations showed that observers can be trained to make unbiased estimates of distance by eye out to a distance of approximately 450 m (Anonymous, 1993). Unlike most strip transects, perpendicular sighting distances were recorded for all sightings to allow for *post hoc* adjustment of the strip width if necessary. Water turbulence was recorded as a categorical variable to account for the effect of river currents on the observers' ability to see dolphins.

In general, all aspects of the survey worked well as described above. The major shortfall of the Amazon survey was that no attempt was made to estimate fraction of animals missed by

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[5] Reticules in binoculars could not be used because the horizon was obscured by trees and the ship did not have a radar to estimate the actual distance to the bank.

the observers [g(0)]. Vidal *et al.* (1997) suggested the use of one or more rear-looking observers to act as quasi-independent sighting platform.

CONCLUDING REMARKS

In summary, line-transect survey methods provide a well-understood and powerful set of tools to gain robust estimates of abundance, which are often a precursor for conservation action. In several cases, the methods have been adapted to work well from small boats, making them much more affordable and hence more suitable for developing countries. Irrespective of whether a boat or aerial survey platform is chosen, adherence to relatively straightforward design principles will dramatically increase the robustness of results. Here we have tried to concisely and pragmatically summarize issues of design and methodology that relate directly to surveys of cetaceans in inshore and riverine waters. We have also tried to suggest less expensive options, when available, as we recognize that many of the inshore and riverine species of cetaceans that face substantial human threats occur in developing countries. As we have pointed out, platform choice (with no other resources available) may preclude some of the methods used for correcting for the fraction of sightings missed on the track line. If bias assessment is not feasible (we think it usually is), conducting properly designed surveys without such assessment is still much better than doing nothing. The resulting abundance estimates will usually be underestimates, but at least they will facilitate preliminary assessment of conservation status. Where quantitative abundance surveys cannot yet be conducted due to a lack of funds, important preliminary information can be obtained via interviews, land-based monitoring and carcass analysis (Aragones *et al.*, 1997). These data may help design a robust abundance survey, but they should not be seen as an alternative to one.

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APPENDIX. USEFUL CALCULATIONS FOR DESIGNING SURVEYS

An Excel file containing these formulae is available at http://nmml.afsc.noaa.gov/Software/software.htm. Also available at that site is another Excel file (Geofunc.xla) that provides Excel geometry functions that are useful in survey analysis.

1. Calculation of effort per unit area

Sampling effort per unit area represents the sampling intensity of a given survey. As discussed in the text, in a non-stratified survey, different survey blocks should have equal effort per unit area. In a stratified survey, different survey blocks can have unequal effort per unit area. In either case, it is useful to be able to calculate effort per unit area for a given design.

Survey block and transect definitions.

Let (see Fig. 6)

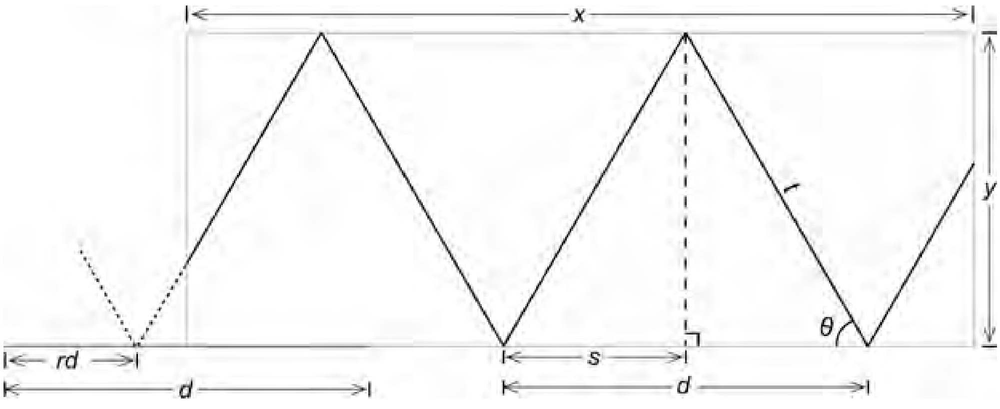

Fig. 6. Figure illustrating terminology used for designing zigzag surveys (see Appendix).

a = distance between transect lines in a parallel line survey design
d = distance between two apexes in a zigzag survey design
rd = random distance between s and $-s$
$s = 0.5d$, or half the distance between two apexes in a zigzag survey design
t = length of a given transect line (usually spanning the survey block)
y = width of the survey block
x = length of the survey block

a. Parallel lines layout.

For a given spacing between transect lines (a), the effort per unit area is simply the inverse of the distance between the lines:

$$\frac{Effort}{Area} = \frac{1}{a} \tag{1}$$

(b) Zigzag layout.

For a given zigzag pattern, with survey block of width y, with a given distance between the apexes of the zigzag of d (where $s = 0.5d$), the effort per unit area is given by:

$$\frac{Effort}{Area} = \frac{t}{s \times y} = \frac{\sqrt{s^2 + y^2}}{s \times y} \tag{2}$$

Note that there is this relationship between t, s, and y:

$$t = \sqrt{s^2 + y^2} \tag{3}$$

2. Calculations of zigzag patterns to meet specified targets.

Although survey effort per unit area can be specified from statistical calculations to achieve a desired precision (see below), survey design will often be driven by how much boat time is available. In that situation, one can multiply the number of days available for the survey by the survey speed to estimate the amount of track line that can be covered. However, one also has to be realistic about the amount of time that will be lost due to weather or other problems, as well as time spent around animals on closing mode surveys. For example, we have often found it the case that on a survey with 12 hours of daylight, cruising at 10 knots (and thus potentially covering 120 n mile), one can realistically expect to between 60 and 80 n mile per day over the course of a survey. From the predicted total track line that is hoped to be covered with search effort (z), the effort per unit area is simply calculated as total effort divided by the size of the survey block:

$$\frac{Effort}{Area} = \frac{z}{x \times y} \tag{4}$$

To calculate the correct zigzag pattern from the size of the survey block and the total expected search effort (z), the distance between the apexes (d) can be calculated from:

$$d = 2 \times \sqrt{\frac{y^2 \times x^2}{z^2 - x^2}} \tag{5}$$

In this way, once d is calculated, the zigzag pattern can then be laid out that will result in a given effort per unit area.

The angle that the transect line is orientated away from shore (where zero degrees would be running parallel to shore) is found by:

$$\theta = \arctan\left(\frac{y}{s}\right) \tag{6}$$

To replicate the same effort per unit area in a different sized block, some additional calculations must be made. If the second block is the same width but a different length, the transect lines can be laid out with the same distance between apexes (and will have the same length transects); all that will differ will be the number of individual transects. If the second block has a different width, the following equations can be used to lay out zigzag transect lines that will have the same pre-pecified effort per unit area.

Let the width and length of the 2nd block be designated y_2 and x_2, respectively. First, calculate the total transect line needed in the 2nd block (z_2) to create a specified effort per unit area:

$$z_2 = y_2 \times x_2 \times \left(\frac{effort}{area}\right) \tag{7}$$

Then calculate the distance between apexes in the 2nd block (d_2) as:

$$d_2 = 2 \times \sqrt{\frac{x_2^2 \times y_2^2}{z_2^2 - x_2^2}} \tag{8}$$

3. Estimating the amount of effort needed to achieve a given level of precision.

The precision of abundance surveys is often expressed as the coefficient of variation (CV), which is the abundance estimate divided by its estimated standard error. Note that for cetacean line-transect surveys, a rough rule of thumb would be that a CV of 0.10 would be outstanding, 0.30 good, 0.50 fair, and values higher than 0.50 considered poor. If a pilot survey or a similar previous survey has been conducted one can predict the precision of a future survey for a given level of expected sightings or survey effort. This assumes that the future survey will use a similar platform and be conducted in a similar way. If only a small-scale pilot study has been conducted, one can use the number of sightings (n_0) and the total transect length ($L0$) to calculate the transect length (L_{target}) needed to achieve a target coefficient of variation (CV_{target}) (Buckland *et al.*, 1993, p. 303):

$$L_{target} = \left(\frac{b}{CV_{target}^2}\right) \times \left(\frac{L_0}{n_0}\right) \tag{9}$$

Buckland *et al.*'s (1993) summary of the literature suggests the value of *b* is fairly stable across surveys, and recommend for planning purposes using a value of 3.0 for *b* in this equation to be conservative; a value of 2.5 would be more optimistic.

If the CV of abundance (or density) has been calculated from a pilot survey or a similar previous survey, one can estimate *b* from that previous survey as:

$$b = n_0 \times CV^2 \tag{10}$$

Then that value of b would be used in Equation 9 rather than an assumed value of 3.0.

If the amount of transect line to be surveyed is prespecified, Equation 9 can be re-arranged to allow one to predict the precision of the future survey for the given level of survey effort using this equation (Buckland *et al.*, 1993):

$$CV_{expected} = \left(\frac{b}{L \times \left(\frac{n_0}{L_0}\right)}\right)^{1/2} \tag{11}$$

Buckland *et al*. (1993) show this relationship broken down into components of variance from both the number of sightings and from cluster size (e.g. schools of dolphins), but 11 can be used under the assumption that the distribution of cluster sizes will be the same in future surveys as in the previous survey.

4. Randomizing the start of a transect line

It is important that the location of the first transect line within a survey block be randomized. Specifically, the transect line should not start in the corner of the survey block (unless randomly picked to start there). One relatively simple way to randomize the first transect line of a zigzag design is to choose a random distance between *s* and –*s*, and locate the first apex of the zigzag this distance from the corner of the study block. If positive, the first apex is within the survey block. If negative, the first apex is not within the survey block, but simply serves as the starting location of a transect line that will extend into the survey block. Only the portion of the first transect line within the survey block is surveyed. Another way of expressing this is to extend the line representing the length side of the survey block back a distance of s from the corner of the survey block, then choose a random distance between 0.0 and *d* ($2 \times s$) to locate the first apex. In Excel, a function statement to accomplish this, where rd is the random distance between 0.0 and *d*, would be:

$$rd = d \times RAND(\,) \tag{12}$$

Note that RAND() generates a random number between 0.0 and 1.0.

5. Useful geometry functions

Many useful geometry functions (written by J. Laake) can also be found at: http://nmml.afsc.noaa.gov/Software/software.htm in the Excel add-in file geofunc.xla. These include routines for angle and distance measurements (such as calculating a new position a known distance from a given position), geographical position unit conversions, and survey distance measurements (such as calculating distance from reticules in a binocular).

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Trackline detection probability for long-diving whales

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ABSTRACT: Long-diving whales such as dwarf and pygmy sperm whales (*Kogia* spp.) and beaked whales (*Mesoplodon* spp., *Ziphius cavirostris*, and *Berardius bairdii*) are often missed on visual line-transect surveys because they do not always surface within an observer's field-of-view. I develop a simulation model to estimate the probability of detecting these species. This model differs from similar models in that it more completely considers parameter uncertainty. Search parameters are estimated from data that were collected on the behavior of observers using 25x binoculars during cetacean surveys. Whale dive times were estimated from visual observations. Conditional detection probabilities (given that a previously undetected animal is at the surface within an observer's field-of-view) were fitted to observed distributions of radial sighting distances. The probability of detecting a whale on the trackline, g_0, was estimated from the simulation model. For the given methods (>50 m ship, 25x binoculars, etc.), the estimates of g_0 are 0.35 (CV=0.29) for *Kogia* spp., 0.45 (CV=0.23) for *Mesoplodon* spp., 0.23 (CV=0.35) for *Ziphius cavirostris*, and 0.96 (CV=0.23) for *Berardius bairdii*. These estimates are most sensitive to estimates of vessel speed and the duration of long dives.

Key words: abundance, beaked whale, *Berardius bairdii*, detection model, detection probability, diving model, dwarf sperm whale, g_0, *Kogia*, line transect, marine mammal, *Mesoplodon*, pygmy sperm whale, search model, survey, whale, *Ziphius cavirostris*.

1 INTRODUCTION

Line-transect survey methods require either that all animals directly on the transect line are seen or that the fraction seen can be estimated (Buckland et al. 1993). For whales that spend a large proportion of their time submerged, trackline animals can easily be missed as a survey platform (either aircraft or ship) passes over them. Many methods have been proposed and tested to estimate the fraction of trackline cetaceans seen, generally referred to as g_0 (see review by Buckland et al. 1993). Recent estimates of g_0 have been based on methods which use two independent teams of observers, either on the same survey platform or on different platforms (e.g. parallel ships). These independent observer methods can only estimate the probability of being seen given that the animals are available to be seen by at least one team. Independent observer methods cannot estimate the fraction missed for those animals that do not surface within the visual range of either team.

For species that dive for long periods, many individuals may not surface within the visual range of observers on a ship conducting line-transect surveys. This is of particular concern for species of small beaked whales (*Mesoplodon* spp. and *Ziphius cavirostris*) and dwarf and pygmy sperm whales (*Kogia simus* and *K. breviceps*) which cannot be seen at great distances (because they surface inconspicuously without a visible blow or splash) and which dive for relatively long periods. It is also true for larger beaked whales (*Berardius* spp. and *Hyperoodon* spp.) and sperm whales (*Physeter macrocephalus*) which are conspicuous at the surface but which can dive for extraordinarily long periods (>60 minutes, Leatherwood et al. 1982a, Kasuya 1986, Hobson & Martin 1996). For such species, independent observer methods will underestimate the fraction missed.

A model-based approach of estimating g_0 (Doi 1971) allows estimation of the fraction of animals that are seen even if some animals are never available to be seen. This approach is based on detailed analytical (Doi 1971, 1974) or simulation (Doi et al. 1982, 1983) models of: 1) the search behavior of the observers, 2) the probabilities of whale detection as a function of distance from the ship, and 3) the diving behavior of the whales. The model-based approach has been faulted and has fallen into disuse, largely because its results were sensitive to model assumptions (Best & Butterworth 1980, Doi et al. 1982, 1983, Buckland et al. 1993). This approach is, however, the only approach that has been used for long-diving whales such as beaked whales (Kasamatsu & Joyce 1995) and may be the only practical method for such species.

In this paper, I use simulation modeling to estimate g_0 for long-diving whale species. My approach is similar to the simulation models of Doi et al. (1982, 1983). However, in past implementations of this approach, different assumptions lead to appreciably different results (Doi et al. 1982, 1983) and estimates of statistical precision for g_0 did not incorporate these structural uncertainties in the model. I eliminate assumptions about the sighting process and recast them as parameters within the model. By doing so, I ensure that uncertainty about the structure of the model is reflected in the estimates of uncertainty for g_0. I use data collected on cetacean surveys to estimate parameters describing the search behavior of marine mammal observers using 25x binoculars. I develop a new approach to fit a conditional detection probability for long-diving whales as a function of sighting distance. Data on the duration of dive and surface periods for *Mesoplodon*, *Ziphius*, *Kogia*, and *Berardius* are used to formulate a model of diving behavior for the species in these genera. Finally, I use the simulation model to estimate g_0 for these species and investigate the sensitivity of these results to a range of feasible parameters.

2 METHODS

2.1 *Survey methods*

The simulation model is based on the method of conducting visual sighting surveys for cetaceans which has been used by the Southwest Fisheries Science Center (SWFSC) since 1979 (Holt 1987, Wade & Gerrodette 1993, Barlow & Lee 1994, Barlow 1995) and which has been adopted for cetacean surveys by the Southeast Fisheries Science Center and Texas A&M University. This method (referred to here as the SWFSC Method) uses three observers located on the flying bridge deck of a >50 m research vessel. Two observers search with 25x pedestal-mounted binoculars and a data recorder searches with unaided eyes (and occasionally a 7x binocular). Searching in this mode continues until a marine mammal sighting is confirmed. At that time, the bearing to the animal(s) (relative to the bow) is measured using a calibrated collar on the 25x binoculars (or, rarely, "by eye" if not seen through a 25x binocular), and the distance to the animal(s) is estimated using a reticle scale in the oculars of both the 25x and 7x binoculars (Barlow & Lee 1994). Search effort is typically discontinued if the animal(s) is within 3 nmi of the trackline, and the vessel is directed towards the animal(s) to identify species and to estimate group size. After group size is estimated, the vessel typically resumes its course, and observers resume searching.

SWFSC observers have been given little guidance on how to conduct their search using 25x binoculars. They have been told that they are responsible for searching from 10° on the opposite side of the bow to just abeam of the ship on their side. [The region of overlap at the bow was to reduce the probability of missing trackline animals.] There has been no attempt to tell the observers at what speed they should swing the binoculars or whether they should swing the binoculars from the bow towards abeam or vice versa. New observers have, however, watched and picked up tips from the more experienced observers, and most observers have converged on a similar approach. Many observers search while swinging the binoculars from the bow towards abeam; when binoculars have swung to the abeam position (or just slightly aft of abeam), the observers swing the binoculars rapidly (without searching) to their starting position (Figure 1a). The observers who do not use this approach generally use the opposite (starting abeam and

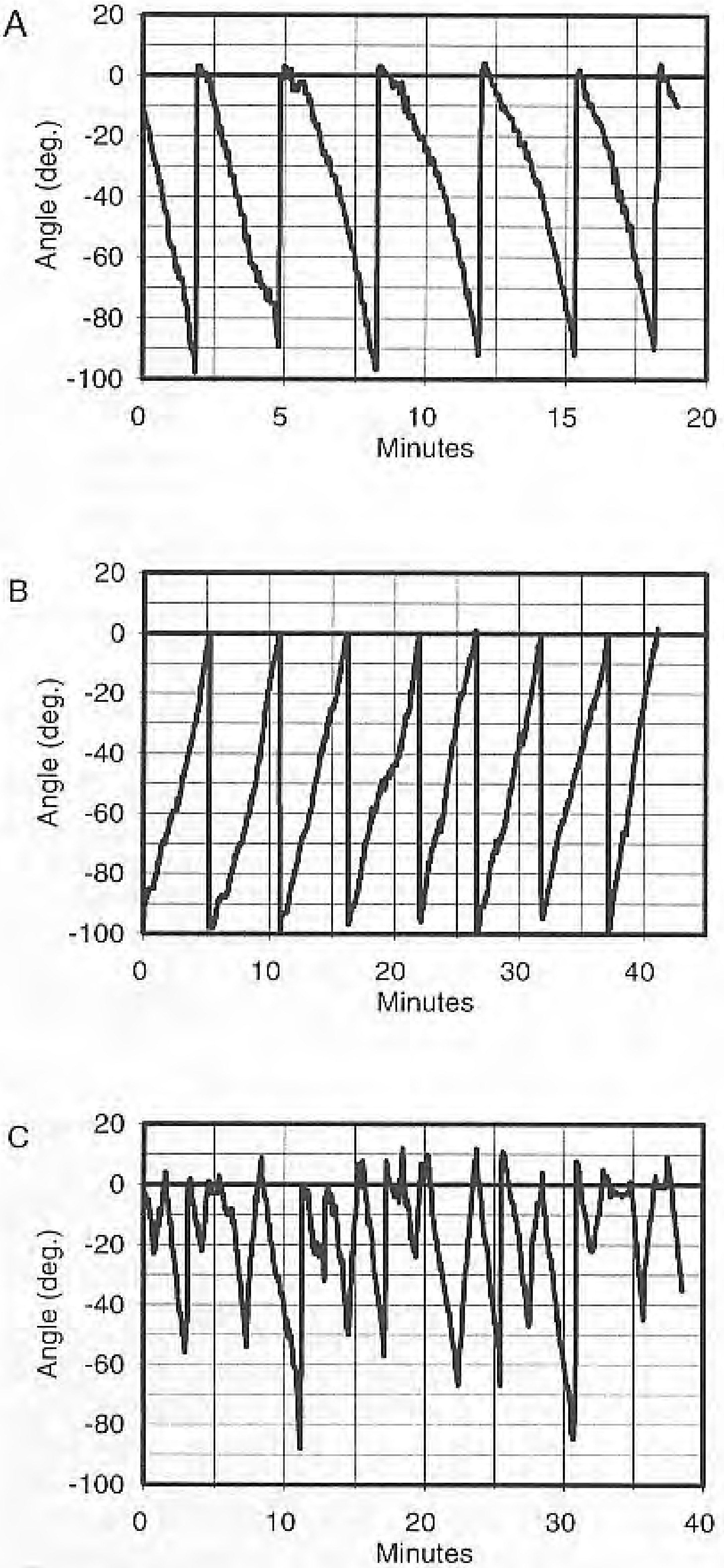

Figure 1. Typical search patterns for 3 observers using the 25X port binocular: A) sweeps from bow towards abeam, B) sweeps from abeam toward bow, and C) irregular sweeps in both directions. Negative angles are left of bow.

scanning forward only, Figure 1b). A few observers use a more random search pattern, scanning in both directions (Figure 1c).

The data recorder is instructed to search at shorter distances to ensure that animals which surface close to the ship (under the visual range of the 25x binoculars) are detected. Most searching by the data recorder is in the forward quadrant by unaided eyes; a 7x binocular is typically used only to verify objects seen by eye. In practice, the vast majority of sightings (>90%) are made by the observers using 25x binoculars.

Table 1. Parameters used in a model to simulate observer searching behavior, whale diving behavior, and whale-detection probabilities. Angles to the left of the bow are negative. The SWFSC Method uses two observers searching with 25x binoculars and one observer searching with unaided eyes. Measured parameters are estimated from field data independent of the simulation model. Fitted parameters are estimated by fitting simulation output to field observations.

Variables	Number of Parameters	Nominal Values	Estimation Method
Search Model	13		
Vessel speed	1	10 kts	Measured
25x Binocular field-of-view	1	2.5°	Measured
Right 25x Binocular search sector	1	90° to -10°	Measured
Left 25x Binocular search sector	1	10° to -90°	Measured
25x Binocular scan rates		(Left, Right)	
0-10°		-0.31, -0.38°/s	Measured
10-20°	1	-0.28, -0.35°/s	Measured
20-30°	1	-0.35, -0.43°/s	Measured
30-40°	1	-0.43, -0.52°/s	Measured
40-50°	1	-0.46, -0.57°/s	Measured
50-60°	1	-0.49, -0.59°/s	Measured
60-70°	1	-0.53, -0.65°/s	Measured
70-80°	1	-0.62, -0.76°/s	Measured
80-90°	1	-0.74, -0.90°/s	Measured
Diving Model	4		
Duration of long dives (min.)	1	[a]	Measured
Duration of surfacing series (sec.)	1	[a]	Measured
Number of surfacings per series	1	[a]	Measured
Duration of a surfacing event (sec.)	1	[a]	Measured
Detection Model	2		
σ, 25x binocular	1	[a]	Fitted
α, 25x binocular	1	[a]	Fitted
TOTAL 19			

[a] All values are species-specific; see Table 3.

2.2 *Overview of the simulation model*

The simulation model was structured to closely mimic the actual search process: virtual animals are generated as fixed points on a Cartesian coordinate grid; animals surface and dive at their fixed points according to a model of their diving behavior; a virtual vessel approaches these animals while two virtual observers search the grid ahead of the vessel; and the program keeps track of which animals are detected as a function of their distance from the vessel's trackline. The time step of the model is one second. The approach is identical in most regards to that of Doi et al. (1982), but to save computer time, each simulation begins with animals distributed uniformly at trackline distances between 6 nmi (just over the horizon) and 12 nmi ahead of the vessel (instead of distributing the animals along a 120 nmi transect line). In reality, a "sighting" often represents a group of animals. For simplicity in the following description, I will use the term "group" to refer to either a group or an individual.

2.3 *Search model*

The "searching" component of the simulation model includes 13 parameters (Table 1) which determine changes in the location of the ship and the angles being scanned by the observers. The fields-of-view of each of the two observers are represented as two independently scanning sectors whose angular widths are equal to the field-of-view for binoculars (2.5° for 25x binoculars). Scan rates are allowed to vary between 10° strata. Insufficient information is available to quantify search behavior for the data recorder (who searched with unaided eyes). Because so few sightings are made by unaided eyes, the bias in estimating g_0 caused by not including this

Table 2. Scan rates (degrees per sec) and standard deviations (S.D.) measured for 13 individuals. Sample size (n) is the number of completed scans used for this measurement.

Observer	n	Scan Rate	S.D.
1	15	0.65	0.10
2	13	0.53	0.13
3	7	0.30	0.04
4	8	0.25	0.04
5	2	0.15	0.04
6	12	0.24	0.04
7	2	0.23	0.01
8	3	0.68	0.07
9	8	0.36	0.04
10	7	0.95	0.13
11	10	0.51	0.06
12	13	0.51	0.09
13	8	0.35	0.07

observer is likely to be small (see Discussion).

Information on the angular distribution of searching effort for observers using 25x binoculars was collected in 1987, 1989, and 1996. In 1996, search angle was recorded every second for six observers using the port 25X binocular, allowing a detailed look at search behavior (Figure 1). In 1987 and 1989, the distribution of angular search effort in ~5° bins was only recorded for teams of 3 observers for both the port and starboard 25X binoculars pooled (Barlow & Sexton 1996). The cumulative distribution of search angles for all three years showed a similar pattern (Figure 2) with a concentration of effort along the trackline.

The mean rate at which observers scan with 25x binoculars was measured on a 1996 dolphin survey in the Gulf of Mexico (R. Pitman, unpubl. data) and on a 1996 SWFSC survey off the U.S. west coast. The observers included a variety of experience levels from beginner (first survey using 25x binoculars) to very experienced (more than 20 years using 25x binoculars). Mean scan rates were estimated independently for thirteen individuals based on complete scans covering at least 60° (Table 2). Mean rates (°/sec) varied among individuals but were fairly constant within these individuals. Here I use the average of the thirteen individuals (0.438°/s, coefficient of variation CV=0.14) to represent the scan rate for observers using 25x binoculars.

Based on these empirical measurements of searching behavior, I create a simplified model of this behavior to be used in the overall simulation model. In this model I assume that, when using 25x binoculars, observers search continuously between 10° on the opposite side of the vessel and abeam (90° left or right) on their side of the vessel. To simulate the two most commonly observed search patterns (Figure 1 a,b), one virtual observer searches from the bow towards abeam and the other searches from abeam towards the bow. The observed non-uniform angular distribution of search effort (Figure 2) is achieved by making scan rate a function of bearing angle (using scan rates that are constant within ten 10° bins but which vary between bins) (Table 1). The mean duration of a scan is estimated from the total number of degrees scanned (100°) divided by the mean scan rate (0.438°/s), or 228 s (3.8 min). To avoid the artificial situation caused by an exact synchronization of the two 25x binoculars, I use mean scan durations of -10% for one binocular (205 s) and +10% for the other (251 s).

2.4 *Whale diving model*

A typical whale diving pattern consists of a long dive, followed by a period of frequent surfacings to breathe, followed by another long dive. Periods of submergence during a surfacing series are typically much shorter than those between surfacing series. I use four parameters to model this behavior: 1) the duration of a long dive, 2) the duration of a surfacing series, 3) the number of surfacings within a series, and 4) the time actually spent at the surface during one surfacing (Table 1). Surfacings are distributed uniformly within a surfacing series. In the model, the time

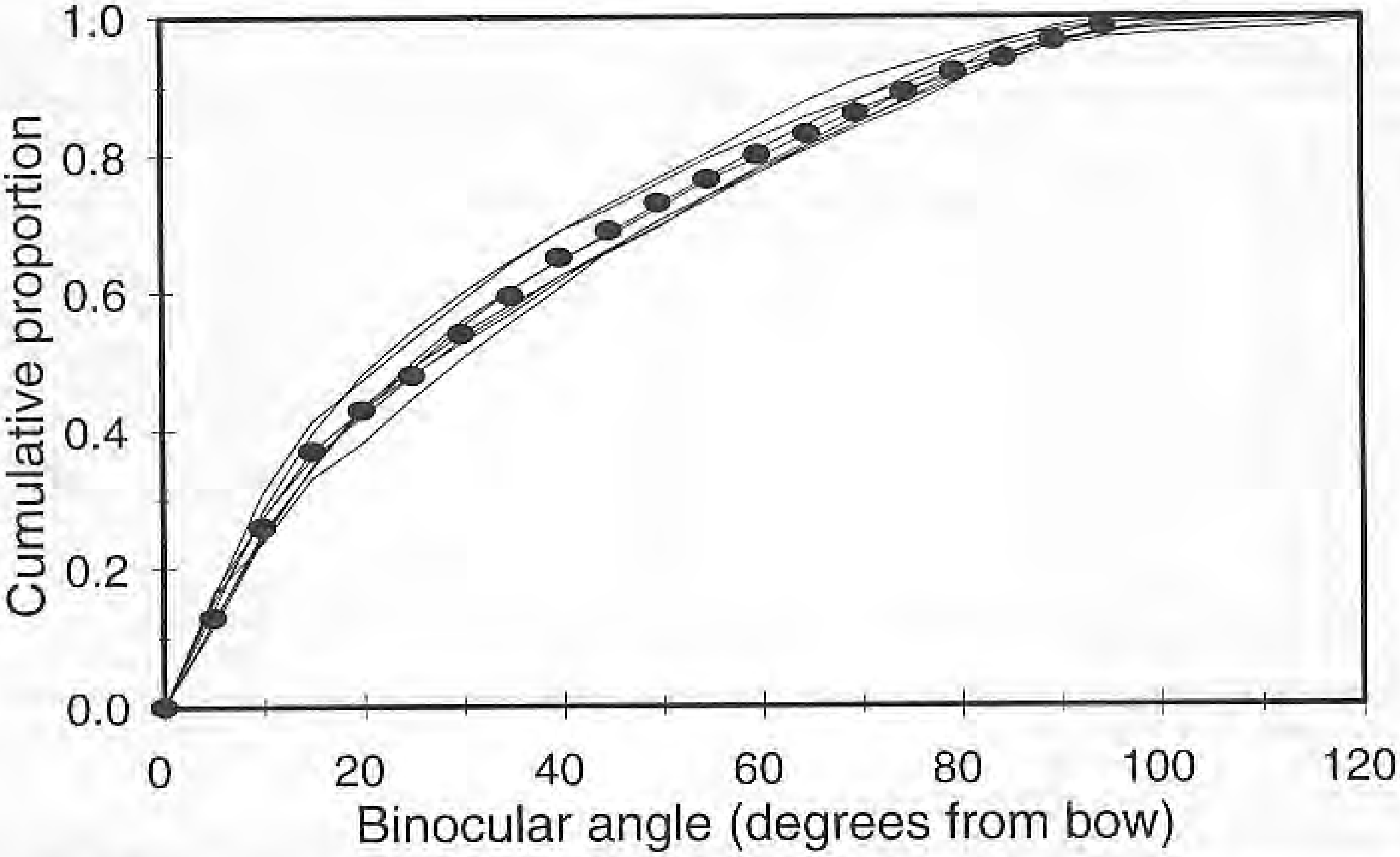

Figure 2. Cumulative proportion of angles searched using 25x binoculars on actual surveys (lines) and from the simulation model using parameters given in Table 1 (black dots). Survey data include eight observer teams in 1987/89 and six individual observers in 1996.

until the next surfacing is recorded for each group and is updated at each time step. All groups are assumed to have the same dive patterns, but their dive times are staggered by initializing each group at a random time in this dive cycle.

Very few quantitative observations of dive patterns have been recorded for beaked whales or dwarf and pygmy sperm whales. Most of the available data were collected during 1993 and 1995 SWFSC research cruises in the Gulf of California (Barlow et al. 1997) with a few additional observations in 1992 in the Gulf of Mexico (R. Pitman & K. Mullin, unpubl. data) and in 1993 and 1996 off California (Barlow 1997). In all cases, observations were made from a ship at distances of greater than 0.5 nmi to avoid affecting their behavior (see Barlow et al. 1997 for methods). Forty-two dive cycles (each including the duration of one surfacing series and one long dive) were recorded for *Ziphius cavirostris*, 59 cycles were recorded for *Kogia* spp. [most were identified as *Kogia simus* and the remainder could not be identified to species], 27 dive cycles were recorded for *Mesoplodon* spp. [species included *Mesoplodon peruvianus*, *Mesoplodon densirostris*, a yet unnamed *Mesoplodon* sp. (Pitman et al. 1987), and an unidentified *Mesoplodon* sp. (probably *Mesoplodon europaeus*)], and 23 dive cycles were recorded for *Berardius bairdii*. Dive cycles were measured for a mix of individuals and synchronously diving groups. Median durations of long dives (Table 3) are a better estimate of expected dive time than are mean dive times because medians are less affected by extreme outliers (that may represent errors). Observed dives include observations which are more than twice the median values (Figure 17 in Barlow et al. 1997) and may represent two dives with an unobserved surfacing between. Median durations of surfacing series (Table 3) are also likely to be less biased than mean surface times when outliers represent errors (in this case, because the first surfacings in a series may be missed).

For the vast majority of the surfacing series, the number of surfacings could not be counted (either because the swells were too high to reliably see every surfacing or because the animals occurred in groups and surfacing rates of individuals could not be discriminated). On two occasions, however, the number of surfacings per series were measured: once for a group of two *Ziphius cavirostris* and once for a group of three *Mesoplodon peruvianus*. For both species, the number of surfacings is strongly correlated with the length of the surfacing series. Based on these surfacing rates and the median lengths of surfacing series (2.1 min. and 2.5 min), Barlow & Sexton (1996) estimated that the expected numbers of surfacings are approximately 17 and 18

Table 3. Estimates of g_0 and its precision based on given parameters used to simulate whale diving behavior and detection probabilities for *Kogia*, *Mesoplodon*, *Ziphius cavirostris*, and *Berardius bairdii*. Precision of parameters is represented as CVs and ranges. Surfacing series for *Kogia* and *Berardius* are modeled as one continuous period of time at the surface, hence the CV of the number of surfacings per series is not applicable (N/A). Parameters describing search behavior are given in Table 1. Estimates of g_0' are based on simulations with the binoculars fixed on the trackline.

Variables	*Kogia* spp.	*Mesoplodon* spp.	*Ziphius cavirostris*	*Berardius bairdii*
Diving Model				
Duration of long dives (min.)	10.9	20.4	28.6	15.5
(CV)	(0.19)	(0.08)	(0.07)	(0.13)
Duration of surfacing series (sec.)	78	150	126	210
(CV)	(0.12)	(0.11)	(0.07)	(0.10)
Number of surfacings per series	1	18	17	1
(CV)	(N/A)	(0.20)	(0.20)	(N/A)
Duration of a surfacing event (sec.)	78	3	3	210
(Range)	(N/A)	(2-4)	(2-4)	(N/A)
Detection Model				
α, 25x binocular	0.771	1.244	0.94	4.78
(CV)	(0.20)	(0.21)	(0.23)	(0.37)
σ, 25x binocular	2.45	0.891	1.50	0.00129
(CV)	(0.13)	(0.11)	(0.22)	(0.56)
g_0	0.35	0.45	0.23	0.96
(CV)	(0.29)	(0.23)	(0.35)	(0.23)
95% C.I.	0.17-0.57	0.23-0.62	0.09-0.41	0.20-1.00
g_0'	0.99	0.98	0.75	1.00

(respectively, for *Ziphius* and *Mesoplodon*) . I use these surfacing parameters in the simulation model for these beaked whales (Table 3). Typically, *Kogia* and *Berardius* are observed resting at the surface almost continuously during their surfacing series (Leatherwood et al. 1982b, Kasuya 1986). I modeled the diving pattern of these species as a long dive followed by a continuous surface period (1.2 min. for *Kogia* and 3.5 min. for *Berardius*) (Table 3).

The duration of a single surfacing event has not been measured for small beaked whales. For large whales, the time that an animal or its blow is visible to an observer has been measured to range from 2.7 sec for sperm whales to 5.1 sec for blue whales (Doi 1974). Because small beaked whales do not typically have a visible blow, the visible surface period of an individual will be less than these values. Roughly, I estimate that some part of the whale will be visible above water for approximately 2 sec. However, because small beaked whales are often found in cohesive, synchronously surfacing groups of 2-5 individuals and because surfacings are not precisely synchronous, I estimate that at least one member of a group will be visible for up to 4 sec. I use an estimate of 3 sec to model the duration of a single surfacing event for *Ziphius* and *Mesoplodon* (for a "typical" group of 1-5 individuals), but I consider the range of 2-4 sec to be as likely.

2.5 *Detection model*

A group can be detected only if, within a time step of the model, it falls within a sector being scanned by one of the observers and is at the surface. If these conditions are met, the probability that a group will be detected within one time step is calculated as a function of its distance from the ship:

$$Pr(seen) = e^{-\sigma \cdot d^{\alpha}} \tag{1}$$

where d = straight-line (radial) distance to the group. The probability of being seen is always

1.0 at zero distance. This is a generalization of the same hazard-rate formulation used by Doi et al. (1982, 1983) with $\alpha=2$. To simulate detection probability, a number is drawn randomly from a uniform distribution between 0 and 1, and the group is considered to be detected if the random number is less than *Pr(Seen)*. The Detection Model is specified by the parameters α and σ.

The detection function (Eq. 1) represents the conditional probability that a group will be detected if it is within the visual line-of-sight of one observer for one time step of the model (1 sec). Previously, the parameters of the detection function were estimated by fitting the function to the cumulative distribution of radial sighting distances for groups that were seen close to the transect line (Doi et al. 1982, 1983; Kasamatsu & Joyce 1991). This ad-hoc approach is not appropriate to estimate parameters for my model because it ignores the time-dependence of these parameters. The probability of seeing a group is evaluated each time a group is within the field-of-view of an observer. A group may remain within an observer's field-of-view for several time steps of the model or may reappear on a later binocular sweep, and each time, the probability of detection will be evaluated. The realized distribution of radial sighting distances from the model will depend on the time step used, the scan rates, the duration of surfacing cues, etc. The detection parameters must be estimated within the context of the other parameters of the model. I estimated the detection parameters (α and σ, Eq. 1) by finding the values that give the best fit of the predicted distribution of radial sighting distances from the simulation model to the observed distribution of radial sighting distances measured during actual surveys. To estimate the predicted distribution of radial sighting distances for a given α and σ, I initialized a simulation with 10,000 groups distributed uniformly at perpendicular distances up to 6 nmi from the trackline. Values of α and σ were varied, and the Simplex algorithm was used to find the values that gave the best fit to the observed distribution of radial sighting distances for a given species (Figure 3). When fitting Eq. 1, a transformation was used to reduce the correlation between the parameters and to improve the convergence to a stable solution (Barlow & Sexton 1996). A Kolmogorov/Smirnov 2-sample test statistic was used as a measure of similarity between the observed and predicted distributions of radial sighting distance. Radial sighting distances for observers searching with 25x binoculars were taken from two similar vessels (R/V *David Starr Jordan* and R/V *McArthur*) on SWFSC surveys in the eastern Pacific from 1986 to 1996. I limited observation to those sea state conditions that are considered to be "acceptable" for abundance estimation (Beaufort 0 to 2 for *Kogia, Mesoplodon,* and *Ziphius*; Beaufort 0-5 for *Berardius*). Observations included 124 sightings of *Kogia* spp., 55 sightings of *Mesoplodon* spp., 50 sightings of *Ziphius cavirostris*, and 12 sightings of *Berardius*.

2.6 g_0 *estimation*

I estimated g_0 from the simulation model using my best estimates of the parameters of the Search Model, the Dive Model, and the Detection Model (Tables 1 & 3). I initialized a simulation with 10,000 groups directly on the trackline and estimated g_0 as the fraction of those that were "seen". To estimate the fraction of groups that surface within the visual range of the observers, I fixed the binocular scan angles to continuously cover the trackline (-1° to 1°) and repeated the simulation with 10,000 trackline groups. I found that a sample size of 10,000 groups is sufficient to reduce the stochastic variation in repeated estimates of g_0 so that its coefficient of variation is less than 1%.

2.7 *Model sensitivity studies*

The sensitivity of estimates of g_0 to error in the input parameters was measured by varying the parameters (one at a time) and measuring the change in g_0. I used a quantity known as "elasticity" (Caswell 1984) to measure the proportional change in g_0 caused by a proportional change in one of the input parameters:

$$Elasticity = \frac{\Delta g_0}{g_0} / \frac{\Delta p}{p} \qquad (2)$$

where p is the parameter being changed. In sensitivity studies, I used +/-20% changes in the parameters given in Table 4. An elasticity value of 1.0 for dive time would indicate that a 20% change in dive time would cause a 20% change in g_0. Although the fit of the Detection Model is somewhat dependent on the other model parameters, I did not re-estimate the hazard-rate parameters α and σ after the change in each parameter because, when the elasticity is small, the differences in g_0 due to error in estimating these parameters was greater than the difference in g_0 due to the change in parameter p. I averaged the elasticities estimated from positive and negative changes in each parameter.

2.8 *Quantifying uncertainty*

I used a non-parametric bootstrap to quantify uncertainty in estimating the hazard-rate parameters α and σ. The coefficients of variation for these parameters were estimated by repeating the fitting process for 30 bootstrap iterations; prior to each iteration I drew a new distribution of radial sighting distances from the observed distribution (with replacement). [A bootstrap sample size of 30 is generally considered small, but due to the complexity of the fitting process, each bootstrap simulation took approximately 15 hours on a 90 MHZ Pentium computer.]

I used a parametric bootstrap to estimate the effect of parameter uncertainty on the coefficients of variation for g_0. Each bootstrap estimate of g_0 was obtained by initializing a simulation with different values for seven of the input parameters: 25x binocular scan rate, dive duration, surfacing series duration, number of surfacings per series, the hazard-rate parameters α and σ, and the duration of a surfacing event. For the first six parameters, values were determined for each bootstrap simulation by adding a normally-distributed random number with a standard deviation equal to its standard error. The same normal random number was added to the scan rates of both 25x binoculars. For the duration of a surfacing event, I chose from three likely values (2 s, 3 s, and 4 s) with equal probability. I estimated the coefficient of variation and 95% confidence intervals of g_0 from 1,000 bootstrap estimates.

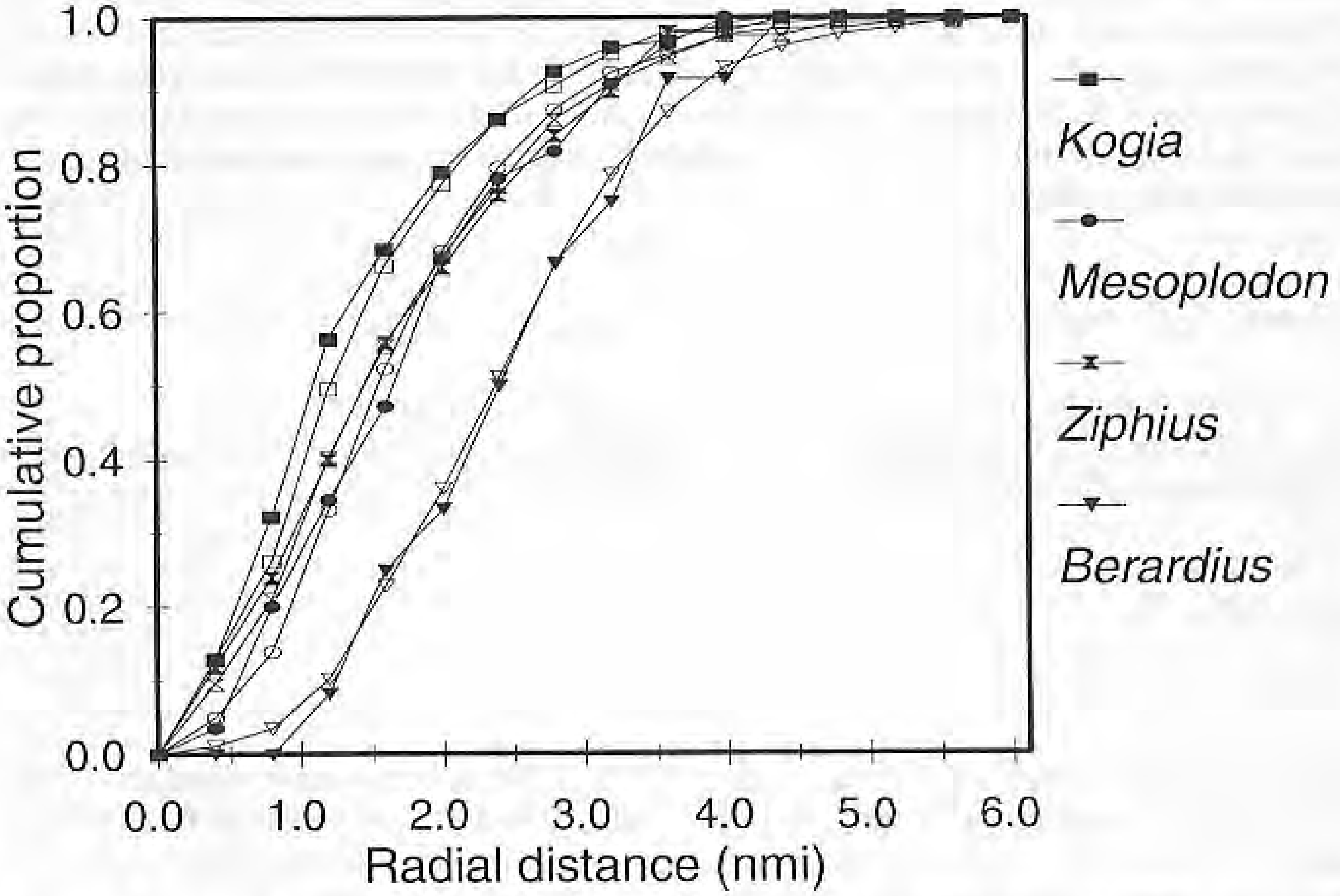

Figure 3. Cumulative distributions of radial distances of sightings made with 25x binoculars on surveys (solid symbols) and from the best-fit models (open symbols).

3 RESULTS

3.1 *Comparison with previous models*

To verify that the model was designed and programmed without significant errors, I tested the model using the same parameters as were used by previously by other authors (Doi et al. 1982, 1983; Kasamatsu & Joyce 1991). Some minor modifications of my model were necessary to facilitate this comparison; the actual parameters used and results are given by Barlow & Sexton (1996). Estimates of g_0 from my model were not statistically different from values estimated by these other authors.

3.2 *Fitting values to the detection model*

When the value for one of the hazard-rate parameters, α, is fixed and the other, σ, is fitted to the observed distribution of radial sighting distances, a wide range of values for the parameter α provided adequate fits ($p>0.1$) of the predicted to the observed distributions of radial sighting distances. These ranges varied from $\alpha = 0.5$ to 1.0 for *Kogia* and from $\alpha = 0.5$ to 1.5 for small beaked whales. The best fit for the other detection parameter, σ, was highly correlated with α (Barlow & Sexton 1996). Detection parameters were similar for two genera of beaked whale. The fitted distributions of radial distances from the simulations were very similar to those observed on surveys (Figure 3).

3.3 *Estimates of g_0*

Estimates of g_0 from my simulation model (Table 3) indicate that the abundance of small long-diving whales is greatly underestimated by visual surveys using 25x binoculars. Abundance corrected for g_0 would be approximately 2 to 4 times the uncorrected abundance estimates for *Kogia*, *Mesoplodon*, and *Ziphius* but would be only slightly greater for *Berardius bairdii*. The estimated coefficients of variation for g_0 are small compared to those of the abundance estimates for small whales in California (CVs≈ 0.7 to 1.0, Barlow 1995). When binoculars are only allowed to search along the trackline, estimates of g_0 for small whales increase dramatically (Table 3); this indicates that many trackline groups of small whales are missed because the binoculars do not happen to be pointing at the right direction at the right time and not because they were out of visual range.

3.4 *Sensitivity of g_0 to input parameters*

When estimates of g_0 are high (such as for *Berardius bairdii*), g_0 is not particularly sensitive to any of its input parameters (Table 4). In the other cases, however, g_0 is very sensitive to estimates of vessel speed and the duration of long dives (Table 4).

4 DISCUSSION

4.1 *Availability and perception*

In discussing biases in abundance estimation due to missed animals, Marsh & Sinclair (1989) distinguish between "availability" and "perception" bias. Availability bias results from groups that are never available to be seen, such as groups that never surface within the visible range of observers. Perception bias results from groups that are available but are not seen for some other reason. The distinction between these two sources of bias is not complete because the visual range of observers does not have a distinct edge. Nonetheless, this distinction is useful in understanding g_0.

Estimates of g_0 for availability bias (g_0') are much higher than estimates of total g_0 for small whales (Table 3). This indicates that trackline groups of small whales are available to be seen but are most frequently missed because they are not perceived. Because the surface times of small whales are so short (<3 min) compared to the scan rates of the binoculars (100° in >3 min), it is not surprising that trackline groups are missed even at close range. The lower g_0' for *Ziphius* helps explain why the total g_0 is so much less for *Ziphius* than for *Mesoplodon* or *Kogia*. Availability bias is small if dive times are less than 20 min because all groups are likely to surface at some time within the visual range of observers. Above this threshold, g_0' decreases sharply with increasing dive times.

4.2 *Previous estimates of* g_0

Based on a 1991 SWFSC survey, g_0 was estimated for the general categories of "small whales" (including *Ziphius* and *Mesoplodon*) and for "cryptic species" (including *Kogia*) (Barlow 1995). These estimates (0.79, 0.84, and 0.84 respectively for *Kogia*, *Mesoplodon*, and *Ziphius*) were based on data collected by independent observers who reported groups that were missed by the three primary observers. These values only account for perception bias; therefore, it is not surprising that they are larger than the values reported here (Table 3) which include both perception and availability bias.

4.3 *Diving behavior*

Because most of the dive-time data come from a study in the Gulf of California, I do not know to what extent my models of diving behavior can be extrapolated to other areas or to other species of *Kogia* and *Mesoplodon* found in other areas. Most (if not all) of the dive times for *Kogia* were for *Kogia simus*. The other species in this genus (*Kogia breviceps*) is slightly larger and might have longer dive times (and, perhaps, longer surface times). For *Mesoplodon*, most of the dive times are for *Mesoplodon peruvianus* (the smallest species of the genus) and a yet-undescribed *Mesoplodon* sp. A (an average-sized, 5-5.5 m *Mesoplodon*, Pitman et al. 1987). The few observations that have been made for other species of *Mesoplodon* have shown similar dive times. Prior observations of *Berardius bairdii* off Japan (Kasuya 1986) were nearly identical in mean dive and surface times as the observations I used, but a related species (*B. arnuxii*) showed much longer modal dive times (35-60 min., Hobson & Martin 1996). This modeling approach was applied to sperm whales (*Physeter macrocephalus*) in a preliminary paper (Barlow & Sexton 1996); however, large groups of sperm whales are typically composed of asynchronously diving subgroups which complicate the dive time model for this species. More information on diving behavior is needed for all the long-diving whale species.

Table 4. Relative sensitivity (elasticity) of g_0 to variation in the parameters used to estimate it. Relative sensitivity is estimated as the proportional change in g_0 divided by the proportional change in the input parameter. The proportional change in the parameters was 20% (except for duration of surface event which was 33% to maintain integer values) and the sensitivities of positive and negative changes were averaged. For *Kogia* and *Berardius*, animals are considered to be continuously at the surface during a surfacing series.

Variables	*Kogia*	*Mesoplodon*	*Ziphius*	*Berardius*
Search Model				
Vessel speed	0.86	0.92	0.88	0.61
25x Binocular scan rates	0.55	0.31	0.34	0.63
Whale Diving Model				
Duration of long dives (min.)	0.80	0.92	0.90	0.39
Duration of surfacing series (sec.)	0.61	0.24	0.30	0.49
Number of surfacings per series	N/A	0.65	0.46	N/A
Duration of a surfacing event (sec.)	N/A	0.40	0.46	N/A

4.4 *Sightings made by observers not using 25x binoculars*

The estimates of g_0 made in this paper are based only on a model of search by two observers using 25x binoculars. SWFSC surveys also include a third observer (the data recorder) who searches by unaided eye and occasionally a 7x binocular. The data recorder does make some sightings (usually close to the vessel), and in the past, abundance estimates have been based on sightings made by all observers. Of all groups that were seen close to the trackline (<0.4 nmi), the fractions made by the data recorder were 14% for *Mesoplodon*, 31% for *Ziphius*, and 0% for *Kogia*. Because the sighting distances by unaided eye are so much less than by 25x binoculars, many (or even most) of the groups seen first by the data recorder would have quickly passed behind the vessel and would therefore have been "missed" by the observers using 25x binoculars. Given my estimates of g_0, it is not surprising that this number of groups would have been missed by the observers using 25x binoculars. However, these data indicate that the value of g_0 for the entire team of three observers may be appreciably (10-30%) higher than the values of g_0 estimated for two observers using 25x binoculars.

These data show the importance of considering the effect of sightings by the data recorder on estimates of g_0. Information about the behavior of observers searching by unaided eyes is unavailable and is likely to be much more difficult to gather than information about the search behavior of observers using binoculars. It is difficult to measure where the eyes are pointing and what the "effective" field-of-view (field-of-acuity) of the human eye might be for seeing marine mammals. Rather than developing a separate model for observers searching with unaided eyes, a better solution might be to ignore those sightings and to estimate abundance based only on sightings made with 25x binoculars. If that were done, the estimates of g_0 presented here could be applied in a more straight-forward fashion.

4.5 *Generality of results*

Although the simulation method presented here should be widely applicable, it is important to recognize that my estimates of g_0 cannot be extrapolated to other survey methods. Using different binoculars or different observation heights would result in very different parameters for the Detection Model. The Detection Model also depends on sighting conditions so estimates of g_0 should only be applied to estimates of abundance that were made for similar conditions (e.g. Beaufort sea state 0-2 for small whales or 0-5 for *Berardius*).

4.6 *Future directions*

Although this paper makes some improvements in the simulation modeling approach to estimating g_0, it remains true that the simulation is based on a large number of measured and fitted parameters (approximately 20) and does not account for all statistical and biological uncertainties. I did not investigate the potential effect of animal movement; random movements are not likely to be a problem (because the ship travels 3-5 times faster than the animals), but directed movements may cause a significant bias. Group size almost certainly affects detection probabilities and estimates of g_0, a factor that could be investigated further. Perhaps the greatest challenge will be in reducing the number of measured parameters without introducing bias.

5 ACKNOWLEDGMENTS

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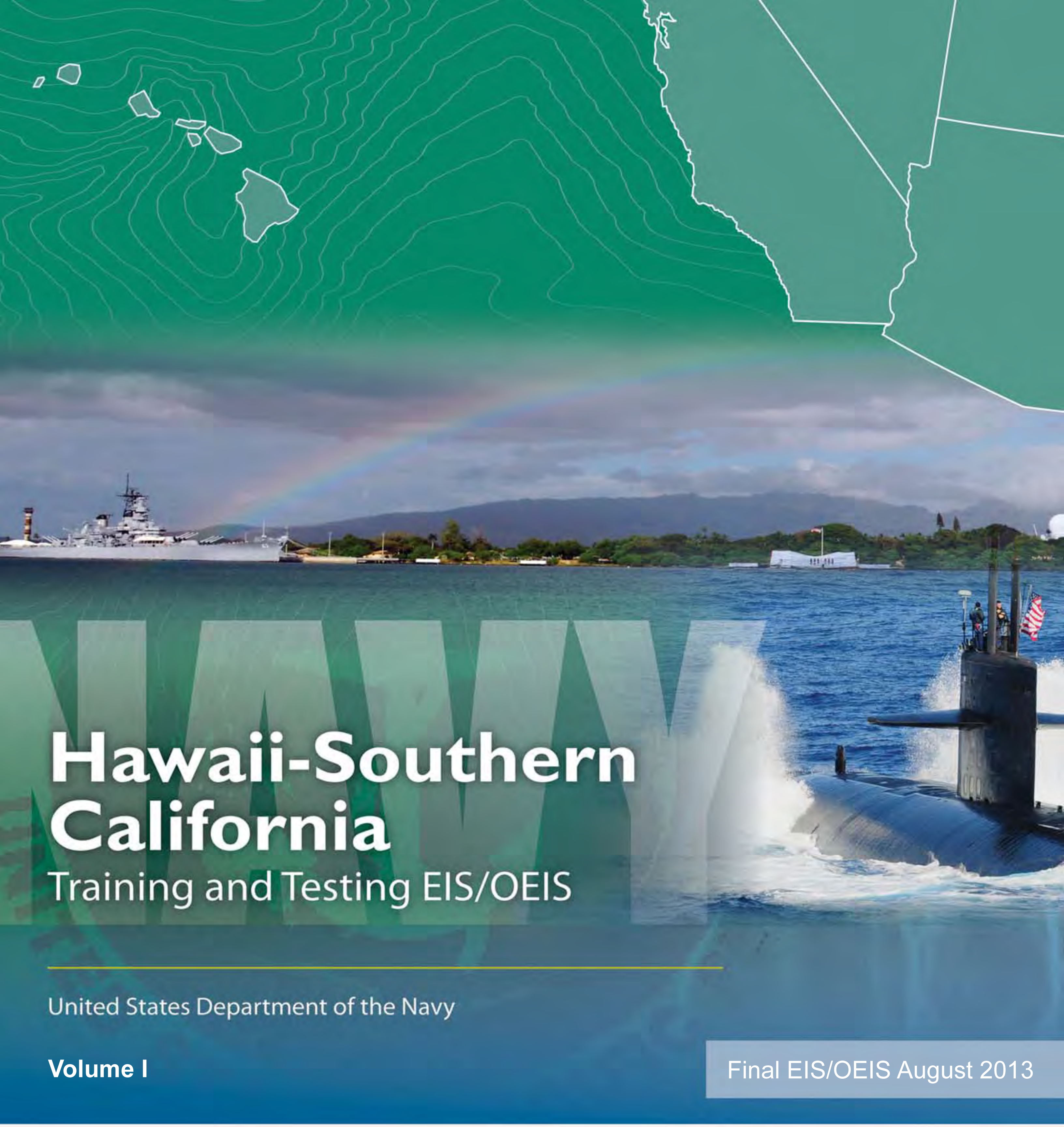

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effect and, to be consistent with prior actions and rulings (National Marine Fisheries Service 2001b, 2008b, 2008c) all injuries (except those serious enough to be expected to result in mortality) are considered MMPA Level A harassment.

Table 3.4-9: Sightability Based on g(0) Values for Marine Mammal Species in the Study Area

Species/Stocks	Family	Vessel Sightability	Aircraft Sightability
Baird's Beaked Whale	Ziphiidae	0.96	0.18
Blainville's Beaked Whale	Ziphiidae	0.40	0.074
Blue Whale, Fin Whale; Sei Whale	Balaenopteridae	0.921	0.407
Bottlenose Dolphin, Fraser’s Dolphin	Delphinidae	0.808	0.96
Bryde's Whale	Balaenopteridae	0.91	0.407
Cuvier's Beaked Whale	Ziphiidae	0.23	0.074
Dall's Porpoise	Phocoenidae	0.822	0.221
Dwarf Sperm Whale, Pygmy Sperm Whale, *Kogia* spp.	Kogiidae	0.35	0.074
False Killer Whale, Melon-headed Whale	Delphinidae	0.76	0.96
Gray Whale	Eschrichtiidae	0.921	0.482
Humpback Whale	Balaenopteridae	0.921	0.495
Killer Whale	Delphinidae	0.91	0.96
Long-Beaked/ Short-Beaked Common Dolphin	Delphinidae	0.97	0.99
Longman's Beaked Whale, Pygmy Killer Whale	Ziphiidae, Delphinidae	0.76	0.074
Mesoplodon spp.	Ziphiidae	0.34	0.11
Minke Whale	Balaenopteridae	0.856	0.386
Northern Right Whale Dolphin	Delphinidae	0.856	0.96
Pacific White-Sided Dolphin	Delphinidae	0.856	0.96
Pantropical Spotted/Risso’s/Rough Toothed/Spinner/Striped Dolphin	Delphinidae	0.76	0.96
Short-finned Pilot Whale	Delphinidae	0.76	0.96
Sperm Whale	Physeteridae	0.87	0.495

Note: For species having no data, the g(0) for Cuvier’s aircraft value (where g(0)=0.074) was used; or in cases where there was no value for vessels, the g(0) for aircraft was used as a conservative underestimate of sightability following the assumption that the availability bias from a slower moving vessel should result in a higher g(0). Some g(0) values in the table above are perception bias and others represent availability bias depending on the species and data that is currently available.
References: Barlow (2010); Barlow and Forney (2007); Barlow et al. (2006); Carretta et al.(2000); Laake et al. (1997).

PTS is non-recoverable and, by definition, results from the irreversible impacts to auditory sensory cells, supporting tissues, or neural structures within the auditory system. PTS therefore qualifies as an injury and is classified as Level A harassment under the wording of the MMPA. The smallest amount of PTS (onset- PTS) is taken to be the indicator for the smallest degree of injury that can be measured. The acoustic exposure associated with onset-PTS is used to define the outer limit of the MMPA Level A exposure zone. Model predicted slight lung injury, gastrointestinal tract injuries, and mortalities are also considered MMPA Level A harassment in this analysis.

Final Report

Odontocete Studies on the Pacific Missile Range Facility in February 2015: Satellite-Tagging, Photo-Identification, and Passive Acoustic Monitoring

Prepared for:

Commander, U.S. Pacific Fleet

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NAVFAC
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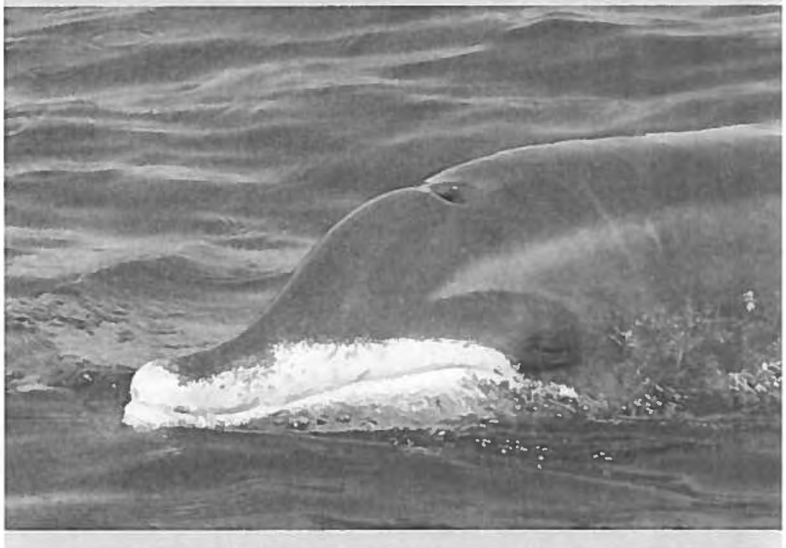

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Cover Photo Credits:

Rough-toothed dolphin (*Steno bredanensis*) off Kaua'i. Photo taken by Robin W. Baird under National Marine Fisheries Service permit no. 15330.

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Acronyms and Abbreviations

BARSTUR	Barking Sands Tactical Underwater Range
BSURE	Barking Sands Underwater Range Expansion
CRC	Cascadia Research Collective
FFT	Fast Fourier Transform
hr	hour(s)
Hz	Hertz
kHz	kilohertz
km	kilometer(s)
km^2	square kilometer(s)
m	meter(s)
M3R	Marine Mammal Monitoring on Navy Ranges
MFA	mid-frequency active
PAM	passive acoustic monitoring
PMRF	Pacific Missile Range Facility
RHIB	rigid-hulled inflatable boat
SWTR	Shallow Water Training Range

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Abstract

A joint project in February 2015 on and around the Pacific Missile Range Facility (PMRF) was carried out utilizing combined boat-based field efforts and passive acoustic monitoring from the Marine Mammal Monitoring on Navy Ranges (M3R) system. There were 1,132 kilometers (63.4 hours [hr]) of small-vessel survey effort over the course of the 13-day project. Weather conditions precluded field operations on 4 days, and strong westerly winds and/or range operations limited access to PMRF on seven additional days, with only 15.1 percent of search time (9.6 hr) spent within the range boundaries. Westerly winds resulted in effort off the east and southeast side of Kaua'i on 5 days, the first Cascadia Research Collective (CRC) small-boat effort off the east side of the island since 2005. A total of 10.5 hr of M3R acoustic monitoring was undertaken during the field effort. There were 35 sightings of at least five species of odontocetes and one species of mysticete other than humpback whales (*Megaptera novaeangliae*), three of which were directed by M3R acoustic detections. Bottlenose dolphins (*Tursiops truncatus*) were encountered on seven occasions, spinner dolphins (*Stenella longirostris*) on two, short-finned pilot whales (*Globicephala macrorhynchus*) on three, rough-toothed dolphins (*Steno bredanensis*) on 20, dwarf sperm whales (*Kogia sima*) once, unidentified odontocetes once, and fin whales (*Balaenoptera physalus*) once. These were the first dwarf sperm whales documented in CRC small-boat efforts off Kaua'i or Ni'ihau since 2003, and the first CRC sightings of fin whales off Kaua'i or Ni'ihau. Two dead whales were found floating offshore in advanced states of decay, one sperm whale (*Physeter macrocephalus*) and one humpback whale. During the encounters 17,740 photos were taken for individual identification, and nine satellite tags were deployed on three species—four short-finned pilot whales (from two different social groups), two bottlenose dolphins, and three rough-toothed dolphins, although data were only obtained from seven of the tags (all but one short-finned pilot whale and one rough-toothed dolphin). Both of the other tagged rough-toothed dolphins and both of the bottlenose dolphins remained associated with the island of Kaua'i, with bottlenose dolphins remaining in shallow depths (medians of 80 and 275 meters) and rough-toothed dolphins using slope waters (median depths of 1,450 and 1,680 meters). One of the tagged groups of short-finned pilot whales included re-sighted individuals known to be from the resident island-associated population. The other group had no re-sightings (of 21 distinctive individuals), and satellite-tag data suggest that they are part of the pelagic population. Probability density analyses of all tag-location data obtained for bottlenose dolphins and rough-toothed dolphins tagged off Kaua'i since 2011 indicate that core ranges (i.e., the 50 percent kernel density polygons) are relatively small (1,200 and 1,656 square kilometers [km^2]). Probability density analyses were undertaken separately for 13 resident short-finned pilot whales tagged off Kaua'i since 2008, and for five pilot whales tagged off Kaua'i and O'ahu thought to be from the pelagic population. Core range for the pelagic population was more than 20 times larger (122,119 km^2) than for the resident population (6,157 km^2), and the overall range (using the 99 percent kernel density isopleth) was an order of magnitude larger for the pelagic population (755,166 km^2). This suggests that the likelihood of exposure to mid-frequency active sonar on the PMRF varies substantially between the two populations. Continued collection of movement and habitat-use data from all species should allow for a better understanding of the use of the range as well as provide datasets that can be used to estimate received sound levels at animal locations and examine potential responses to exposure.

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1. Introduction

The U.S. Navy regularly undertakes training and testing activities on or around the Pacific Missile Range Facility (PMRF) between Kaua'i and Ni'ihau. Vessel-based field studies of odontocetes first began off Kaua'i and Ni'ihau in 2003 (Baird et al. 2003) as part of a long-term, multi-species assessment of odontocetes in the main Hawaiian Islands (Baird et al. 2013a) being undertaken by Cascadia Research Collective (CRC). In recent years most of the work off Kaua'i and Ni'ihau has been sponsored by the U.S. Navy. Initially using photo-identification of distinctive individuals and biopsy sampling for genetic analyses, surveys in 2003 and 2005 showed evidence of site fidelity for rough-toothed dolphins (*Steno bredanensis*), bottlenose dolphins (*Tursiops truncatus*) and short-finned pilot whales (*Globicephala macrorhynchus*), as well as provided information on relative sighting rates around the islands (Baird et al. 2006, 2008a, 2009). Studies using satellite tags to assess movements and behavior of individual toothed whales on and around the PMRF were first begun in June 2008 in association with the Rim-of-the-Pacific naval training event (Baird et al. 2008b). During that effort, three melon-headed whales (*Peponocephala electra*) and a short-finned pilot whale were tagged and tracked for periods ranging from 3.7 to 43.6 days (Baird et al. 2008b; Woodworth et al. 2011). While the melon-headed whales moved far offshore to the west, the short-finned pilot whale remained around Kaua'i and moved offshore of western O'ahu (Baird et al. 2008b). Since 2008 and prior to February 2015, there have been eight additional vessel-based field projects off Kaua'i (seven in conjunction with passive acoustic monitoring [PAM] through the Marine Mammal Monitoring on Navy Ranges [M3R] program) during which satellite tags were deployed. During these eight efforts, 43 satellite tags were deployed on six different species of odontocete cetaceans (**Table 1**; Baird et al. 2011, 2012a, 2012b, 2013b, 2013c, 2014a, 2015). Results of field efforts through February 2014 have been previously summarized (Baird et al. 2015).

As part of the regulatory compliance process associated with the Marine Mammal Protection Act and the Endangered Species Act, the U.S. Navy is responsible for meeting specific monitoring and reporting requirements for military training and testing activities. In support of these monitoring requirements, this work was conducted in the Hawai'i Range Complex from 4 to 16 February 2015. This report presents findings from this monitoring effort, which was conducted in order to further our understanding of the following monitoring questions: what are the spatial-movement and habitat-use patterns (e.g., island-associated or open-ocean, restricted ranges vs. large ranges) of species that are exposed to mid-frequency active (MFA) sonar, and how do these patterns influence exposure and potential responses? The marine mammal monitoring reported here is part of a long-term monitoring effort under the U.S. Navy's Marine Species Monitoring Program. In addition to the results of work in February 2015, we incorporate previous efforts, including results from a vessel-based field effort off Kaua'i in October 2014, supported by the Navy's Living Marine Resources program.

As well as addressing the specific Navy monitoring questions and increasing our general understanding of the odontocete populations off Kaua'i and Ni'ihau, there are several secondary goals, including providing visual species verification for acoustic detections through the M3R program. M3R is a real-time PAM system implemented at three major Navy undersea test and training ranges: the Atlantic Undersea Test and Evaluation Center (2002–present, see

Morrissey et al. 2006), the Southern California Offshore Range (2006–present, see Falcone et al. 2009), and most recently at the PMRF (2011–present). An additional goal is to obtain cetacean movement and habitat use information on and around the PMRF before, during, and after a Submarine Commanders Course scheduled to be undertaken after the field efforts, using data obtained from satellite tags (see Baird et al. 2014b).

2. Passive Acoustic Monitoring Methods

2.1 PMRF Undersea Acoustic Range

The PMRF instrumented hydrophone range is configured with 219 bottom-mounted hydrophones, 199 which are available for PAM. They were installed in four phases, such that each system has different acoustic monitoring capabilities (**Table 2**). The four range systems are: the Shallow Water Training Range (SWTR), the Barking Sands Tactical Underwater Range (BARSTUR), the legacy Barking Sands Underwater Range Expansion (BSURE), and the refurbished BSURE. Each range consists of several offset bottom-mounted cables (strings), with multiple hydrophones spaced along each string to create hexagonal arrays.

2.2 M3R System

The M3R system consists of specialized signal-processing hardware and detection, classification, localization, and display software that provide a user-friendly interface for real-time PAM via 199 PMRF bottom-mounted hydrophones (Jarvis et al. 2014). Prior to 2015, the M3R system at the PMRF was used on seven occasions (**Table 1**) in collaboration with vessel-based field efforts. This combination approach provides visual species verifications for groups detected acoustically, as well as visual sightings of animals on the range that have not been acoustically detected. It also increases the encounter rate for vessel-based efforts. Increased encounter rates result in greater opportunities for deploying satellite tags (see below), as well as photo-identifying individuals and collecting biopsy samples for genetic studies.

Passive acoustic data pass through the range's operational signal-processing system and the M3R system in parallel. In this way, marine mammal monitoring does not interfere with range use. Signals from all of the hydrophones are processed in parallel, providing marine mammal detection, classification, and localization results for the entire range in real time. These real-time results allow a PAM analyst to isolate animal vocalizations on the range, confirm species classification, and choose optimal group localizations for attempting at-sea species verification. To date, classification is accomplished using software with manual review by an analyst. Classification may be to the species or guild level depending on the animal in question. Hydrophones are sampled at 96 kilohertz (kHz), providing an analysis bandwidth of 48 kHz. A Fast Fourier Transform (FFT)-based detector is implemented using an adaptive threshold (exponential average) in each bin of the FFT. If the bin energy is over the adaptive threshold, the bin(s) is(are) set to a "one" and a detection report is generated. All detections are archived, including the hard-limited (0/1) FFT output. Detections are classified first by type (whistle or click). Clicks are further categorized, based on the hard-limited FFT frequency content, into five descriptive categories: <1.5 kHz, 1.5–18 kHz (representative of sperm whales [*Physeter macrocephalus*]), 12–48 kHz (representative of delphinid species), 24–48 kHz (representative of beaked whales), and 45–48 kHz. Additional Support Vector Machine-based classifiers are also being tested with a focus on Blainville's (*Mesoplodon densirostris*) and Cuvier's beaked whales (*Ziphius cavirostris*). The basic FFT-based detector adjusted for low-frequency baleen whale calls runs in parallel. It provides an analysis bandwidth of 3 kHz and a frequency bin resolution of 1.46 Hertz (Hz).

These broad automatic classifications are further refined using MMAMMAL real-time display software. MMAMMAL displays a color-coded map of the hydrophones indicating the level of detection activity for each hydrophone. The hydrophone color code indicates the number of standard deviations each hydrophone is above the mean detection rate of all the hydrophones. The PAM user can select hydrophones from the map based on detection activity and display a real-time, hard-limited FFT-based spectrogram. These spectrograms are used by trained PAM personnel to classify the whistles and clicks to species level when possible. Prior to the February 2015 effort, detection archives from previous PMRF species verification efforts were reviewed to create a compilation of exemplar spectrograms for visually verified species including: rough-toothed dolphin, spinner dolphin (*Stenella longirostris*), bottlenose dolphin, false killer whale (*Pseudorca crassidens*), short-finned pilot whale, killer whale (*Orcinus orca*), and Blainville's beaked whale. This compilation provided a reference set for PAM personnel to identify vocalizing species during the test. Unique frequency characteristics based on the MMAMMAL spectrograms were visually identified and noted to aid in providing initial discrimination between species (**Table 3**). However, due to the small visual verification sample size for most species and high overlap in signal characteristics between many odontocete species, these characteristics are far from exhaustive for feature characterization. Additional factors such as typical travel speed, habitat depth range, and dispersion of groups based on field studies (e.g., Baird et al. 2013a), were used to help determine species priority for directing the small vessel to groups when multiple groups were present in the area.

Supplementary to MMAMMAL, Worldview software also displays the hydrophone layout, color-coded for detection rate, with the addition of satellite imagery and digital bathymetry as a background. The Worldview display includes the positions of vocalizing animals (each hereafter termed a posit) derived from automated localization software and frequency segmentation-based whale type similar to MMAMMAL. However, additional information is provided with each position to help the PAM user determine the accuracy of the automated localization, including the number of neighboring localizations and number of "same" localizations, where "same" is defined as the same position localized by multiple detections. Typically, a higher quantity of "near-neighbor" localizations indicates a more accurate localization. Due to the localization methodology, a single-click position is more likely to be a false positive than a cluster of click positions, each indicating several neighbors. The array, referenced by center hydrophone, is also indicated. Overlapping posits from multiple arrays also provides assurance that the posit is accurate. Automated click localizations provide the PAM user a real-time range-wide map for odontocete distribution of click classification type (e.g., beaked whale, sperm whale, small odontocete). In the absence of automatically generated positions, a MMAMMAL tool for semi-manual calculation of positions using hand-selected whistles or clicks is available. When the same click or whistle is visually observed on three or more hydrophones, the user can mark the time-of-arrival on each. These times are then used in a localization algorithm to determine the animal's position. This tool was most often used on bottlenose dolphin (indicated *Tt*) whistles to give the at-sea team a posit (within approximately 100 meters [m]) of a vocalizing individual. Typically, when a group of animals is present, a cluster of posits based on multiple vocalizing animals will be plotted around the position of the group. With time, the movement of the group is evident by the track of any one individual within the group. The Worldview display also includes several standard geographic tools such as the ability to measure distance, add points to the map, and include ship navigation data when available.

The Raven signal-analysis package (Cornell Laboratory of Ornithology) is also available for real-time analysis. An M3R interface module has been added to the program that allows selection of individual or small numbers of hydrophones for examination. The software is used to analyze selected hydrophone signals when questions arise as to signal type and origin. This is particularly useful for verifying the presence of beaked whale vocalizations. It has also proven useful for collecting time and frequency images and broadband cuts of selected signals.

Data post-processing is expedited by using the detection archives, which allow rapid evaluation of detections over long periods of time. Additionally, raw hydrophone data are recorded using the recently installed M3R disk recorder, allowing for detailed analysis of marine mammal and environmental signals. The disk recorder is capable of recording precisely time-aligned audio data from all 199 hydrophones.

Specific software tools have been developed for the automated isolation of Blainville's beaked whale click trains; then a second tool marks the position of individual foraging dives. These tools are being modified for the PMRF. As the mean group size and detection statistics for Blainville's beaked whales on the PMRF are determined, estimation of their density and distribution will be possible (Moretti et al. 2010).

2.3 Passive Acoustic Monitoring

PAM began at 0630 every morning and continued until the research vessel left the range, either to return directly to port or to survey in areas south of the range if weather conditions on the range were not suitable for small-boat operations or if the range was closed. At all times the PAM objective was to keep the scientists aboard the rigid-hulled inflatable boat (RHIB) informed of the species and distribution of vocalizing marine mammals that had been localized on the range, focusing in areas that were known to have suitable sea conditions for small-boat operations. A typical visual verification cycle initiates with a radio communication from the PAM operator to the vessel providing the species and locations (referenced by hydrophone for ease of communication) of all known groups vocalizing within a reasonable range of the RHIB. As an example, a communication would detail groups on the SWTR and BARSTUR ranges, but not the BSURE range if the RHIB was on the southern end of the SWTR area (see **Figure 1**). The decision of what group to pursue was left to the on-board scientists so that they could prioritize the combination of species preference, weather conditions, and time of day.

Once the group of interest was radioed back to the PAM team, this group was then followed closely using the M3R system by the PAM team, and an attempt was made to provide an updated position. Most often the posits were generated automatically by M3R. PAM operators assessed the posit and relayed the coordinates via radio. Sometimes localization involved manually waiting for and selecting whistles to localize. This process was termed a "manual posit." A best effort was made to also communicate the confidence level of the posit (i.e., the number of solutions at the same location or in the nearby area). Human error can occur when calculating manual whistle localizations, but this is typically minimal with trained PAM personnel. In addition, successive whistles were used to generate multiple solutions, which provide an increased level of confidence. As the vessel approached the group, additional position updates were communicated by the PAM team in real time until receiving confirmation that the on-the-water team had sighted the group. At that time, the PAM team remained on standby until they received additional communication to prevent disruption of tagging and photo-identification activities onboard the RHIB. While standing by, the PAM team continued to assess the entire range in the context of providing information for the next cycle.

Detection archives were collected from all hydrophones for the entire period, 24 hr per day. These archives capture all detection reports, and automated localizations generated during the test.

3. Field Methods

3.1 Tag Types and Programming

Nineteen satellite tags were available for deployment, including 14 location-dive tags (Wildlife Computers Mk10-A) and five location-only tags (Wildlife Computers SPOT5) in the LIMPET configuration. Each tag is attached with two titanium darts with backward facing petals, using either short (4.4-centimeter) or long (6.8-centimeter) darts (Andrews et al. 2008), depending on species (e.g., short darts for rough-toothed and bottlenose dolphins, long darts for short-finned pilot whales).

For each tag type (location-only or location-dive) there were different programming combinations depending on species. The combinations are based on the average number of respirations per hour from previous tagging studies, while taking into account the speed of surfacing and the likelihood of the tag remaining attached for longer than approximately 30 days, which varies by species. Location-dive tags programmed for short-finned pilot whales transmitted 17 hr/day with a maximum of 700 transmissions a day, giving an estimated battery life of approximately 25 days. Location-dive tags programmed for rough-toothed dolphins and bottlenose dolphins transmitted for 15 hr/day with a maximum of 700 transmissions per day, giving an estimated battery life of approximately 25 days. Location-dive tags were set to record a time series (recording depth once every 1.25 minutes for dolphins and once every 2.5 minutes for short-finned pilot whales), as well as dive statistics (start and end time, maximum depth, duration) for any dives greater than 30 m in depth, with depth readings of 3 m being used to determine the start and end of dives, thus dive durations are slightly negatively biased. Given typical odontocete descent and ascent rates of 1–2 m/second, dive durations recorded are likely only 3–6 seconds shorter than actual dive durations. Prior to the field effort, satellite pass predictions were carried out using the Argos web site to determine the best hours of the day for transmissions given satellite overpasses for the approximately 2-month period starting at the beginning of the deployment period.

A land-based Argos receiver station was set up on Mākaha Ridge, Kaua'i, to try to increase the amount of dive and surfacing data obtained from the location-dive tags. This is a similar system to that used in July 2013 and February 2014 (see Baird et al. 2014a, 2015); however, the system during this effort included three Telonics TGA-100 7-element antennas, each connected to a Telonics TSUR-400 uplink receiver, rather than a single antenna/receiver system. Each system was connected to a laptop with data recorded using Telonics Uplink Logger v. 1.00. The antennas were at a 456-m elevation, one oriented to the north, one oriented to the west, and one oriented to the southwest.

3.2 Vessel, Time and Area of Operations

The field project was timed to occur immediately prior to a Submarine Commanders Course scheduled for mid-February 2015. Ten days of effort was funded as part of the Navy's Marine Species Monitoring program, and an additional three days of effort was funded by the Living Marine Resources program, with funds left over from a field project in October 2014 that ended early due to a hurricane.

The vessel used was a 24-foot rigid-hulled Zodiac Hurricane, powered by twin Suzuki 140-horsepower outboard engines, and with a custom-built bow pulpit for tagging and biopsy operations. The vessel was launched each morning at sunrise, and operations continued in daylight hours as long as weather conditions were suitable. The primary launch site was the Kīkīaola small boat harbor, but alternative sites, including Port Allen and Nāwiliwili Harbor, were used when prevailing weather conditions warranted.

For calculating effort by depth and time within the PMRF instrumented hydrophone range boundaries, vessel locations were recorded on the global positioning system unit at 5-minute intervals. When weather conditions permitted and there were no range access constraints, the primary area of operations was the PMRF instrumented hydrophone range, with a focus on deep-water areas to increase the likelihood of encountering high-priority species. However, if there were no acoustic detections of high-priority species (e.g., species other than rough-toothed dolphins and bottlenose dolphins), survey effort was concentrated in deeper-water areas where working conditions were conducive to detecting and tagging high-priority species.

When positions from the M3R system were available, the RHIB would transit to specific locations in response to the positions and otherwise would survey areas for visual detection of groups. When conditions on PMRF were sub-optimal and there were better conditions elsewhere, or if the range was closed due to Navy activity, the RHIB team worked in areas off the range. The RHIB team communicated each morning with the PMRF Range Control prior to entering the range and remained in regular contact with Range Control throughout the day as needed to determine range access limitations.

3.3 During Encounters

Each group of odontocetes encountered was approached for positive species identification. Decisions on how long to stay with each group and what type of sampling (e.g., photographic, tagging, biopsy) were undertaken depended on a variety of factors, including current weather conditions and weather outlook, information on other potentially higher-priority species in the area (typically provided by M3R), and the relative encounter rates. Species encountered infrequently (short-finned pilot whales) were given higher priority than frequently encountered species (spinner, bottlenose, and rough-toothed dolphins). Extended work with frequently encountered species was typically only undertaken with groups that were suitable for tagging given behavior and sea conditions, and when no other higher-priority species were in areas suitable for working.

In general, species were photographed for species confirmation and individual identification. For each encounter we recorded information on start and end time and location of encounter, group size (minimum, best, and maximum estimates), sighting cue (e.g., acoustic detection from M3R, splash), start and end behavior and direction of travel, the group envelope (i.e., the spatial spread of the group in two dimensions), the estimated percentage of the group observed closely enough to determine the number of calves and neonates in the group, the number of individuals bowriding, and information necessary for permit requirements. For short-finned pilot whales, if individuals were clustered into subgroups with discrete gaps between subgroups of 400 m or more, the number of subgroups and the distance among subgroups was also noted, and, when possible, camera frames were noted to allow for sorting by subgroup.

If conditions were suitable for tagging, for all infrequently encountered species (e.g., short-finned pilot whales), we attempted to deploy at least one satellite tag per group. When more than one tag deployment was attempted within a single group, the second individual to be tagged was not closely associated with the first. For frequently encountered species (e.g., bottlenose dolphins, rough-toothed dolphins), we attempted to deploy one tag per group for the first cooperative group when no other high-priority species were known to be in the area. Decisions to deploy additional tags on frequently encountered species were based on the number of tags remaining to be deployed during the field effort, taking into account the number of remaining field days and the need to have tags available for high-priority species if encountered.

3.4 Data Analyses

Five-minute effort locations were processed with ArcGIS to determine depth and whether locations were inside or outside the PMRF instrumented range boundaries. Photographs of most species were sorted within encounters to identify individuals, and the best photos of each individual within an encounter were categorized as to photo quality and distinctiveness following methods outlined in Baird et al. (2008a, 2009). All individuals of most species were compared to individual identification catalogs (Baird et al. 2008a, 2009; Mahaffy et al. 2015) to determine sighting histories. For each species, associations among individuals and groups were assessed with SOCPROG 2.64 (Whitehead 2008), and associations were visualized using Netdraw 2.155 (Borgatti 2002). Pilot whales encountered were assigned a population (insular, pelagic, or unknown) based on associations, sighting histories, and movement patterns taken from tagging data. When tagging data were available, population identity of sub-groups recorded in the field was assessed independently and sub-groups with differing associations, sighting histories, and movement patterns were considered separate groups.

Locations of tagged individuals were estimated by the Argos System using the least-squares methods and were assessed for plausibility using the Douglas Argos-filter v. 8.5 to remove unrealistic locations, following protocols previously used (Schorr et al. 2009; Baird et al. 2010, 2011). Resulting filtered location data were processed with ArcGIS to determine depth, distance from shore, and location relative to PMRF boundaries. From this, the proportion of time spent within PMRF boundaries, as well as the number of times an individual was found inside the range boundaries, was estimated for each individual. For estimating the proportion of time within the range boundaries, when consecutive locations spanned the boundary, the time spent inside the boundary was considered to start at the last location outside the boundary and end at the time of the last location inside the boundary. The number of times an individual was found inside the range boundaries was determined by examining whether consecutive locations were inside or outside of the range boundary.

Probability density maps were generated using all filtered satellite-tag data for all individuals of each of three species satellite tagged off Kauaʻi. Location data from the first 24 hours post-tagging were removed to address potential bias associated with the location where individuals were tagged. Kernel density polygons were generated using the R package adehabitatHR v.

0.4.11[1] and corresponded to the 50, 95 and 99 percent densities. Polygons were plotted in Google Earth Pro v. 7.1.2.2041.

When more than one tag was deployed on the same species, we assessed whether individuals were acting in concert during the period of overlap by measuring the straight-line distance (i.e., not taking into account potentially intervening land masses) between pairs of individuals when locations were obtained during a single satellite overpass (approximately 10 minutes). We used both the average distances between pairs of individuals and the maximum distance between pairs to assess whether individuals were acting independently, following protocols described by Schorr et al. (2009) and Baird et al. (2010).

Data obtained from the shore-based Argos uplink receivers and from the Argos System were processed through the Wildlife Computers DAP Processor v. 3.0 to obtain diving and surfacing data from the location-dive tags.

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[1] https://www.movebank.org/node/14620

4. Results

From February 4 to 16, 2015, there were 1,132 km (63.4 hr) of small-vessel field effort, with the boat on the water 9 of the 13 days (**Table 4**). There was no survey effort on 4 days due to high winds, with winds forecasted from 20 to 25 knots from the west, northwest, or southwest. Westerly, southwesterly, or northwesterly winds were forecasted/present on 6 of the remaining 9 days, ranging from 15 to 20 knots, further limiting survey effort on the PMRF. On three of these days the research vessel was launched from Nāwiliwili Harbor and efforts were restricted to off the east side of Kaua'i, and on 1 day the vessel was launched from Port Allen and efforts were primarily to the east of Kaua'i due to unworkable conditions off the south shore. The research vessel was launched from Kīkīaola small boat harbor on 5 days, but the range was either unworkable due to winds (1 day) or range restrictions (2 days) for 3 of the 5 days. Acoustic monitoring with the M3R system was thus only undertaken on 2 days. On those days, acoustic monitoring was undertaken prior to the RHIB entering PMRF each day and concluded after the RHIB left the range, for a total of 21.5 hr of acoustic monitoring (**Table 5**).

Overall, there were 35 sightings of at least five species of odontocetes and one species of mysticete other than humpback whales (which were not approached), five of which were on PMRF (**Figure 1**, **Table 6**). Bottlenose dolphins were encountered on seven occasions, spinner dolphins on two, rough-toothed dolphins on 20, short-finned pilot whales on three, unidentified odontocetes once, dwarf sperm whales once, and fin whales once. Three of the five encounters on PMRF (two groups of pilot whales and one group of bottlenose dolphins) were directed by acoustic detections from the M3R system. The remaining two encounters (bottlenose dolphins) were visually sighted on the edge of the range on our last day of field effort, when the range had been closed until mid-afternoon and no M3R monitoring was being undertaken. Two dead whales were found floating offshore north of Kaua'i in advanced states of decay, one humpback whale and one sperm whale (**Figure 1**). These are the first dead cetaceans documented during CRC's research efforts in Hawaiian waters.

During the encounters 17,740 photos were taken for individual identification and nine satellite tags were deployed on three species (**Table 7**). Identification photos were obtained from two encounters with spinner dolphins for contribution to a photo-identification catalog held at the Pacific Islands Fisheries Science Center, but no attempts were made to tag this species due to the small size of their dorsal fins.

4.1 Short-finned pilot whales

Short-finned pilot whales were encountered on three occasions, with two of the three sightings on the PMRF (**Figure 1**). During the three encounters 58 identifications were obtained, and of those 35 were of distinctive individuals with good- or excellent-quality photos. From 6 to 21 identifications were obtained from each of the three encounters. The 35 individuals represented three different social groups, each seen just once during the field effort. All individuals were compared to our photo-identification catalog (Mahaffy et al. 2015). Seven of the 35 distinctive individuals had been photo-identified in previous years, one of eight distinctive individuals from one encounter and all six distinctive individuals from another encounter. The previously re-sighted individuals were all linked by association with the main component of the social network of short-finned pilot whales photo-identified off Kauaʻi and Niʻihau (**Figure 3**), indicating they are part of the resident island-associated community. Satellite tags were deployed on two individuals in one of these resident groups (**Table 6**); weather conditions and behavior of the whales prevented deployment of tags on the second resident group. Locations were obtained from the tags on the two individuals for 7.5 days (GmTag114, catalog ID HIGm1174) and 10 days (GmTag115, catalog ID HIGm2483). HIGm1174 was first documented off Oʻahu in 2008, while HIGm2483 had not been previously documented (**Table 8**). An analysis of the distances between satellite-derived locations for HIGm1174 and HIGm2483 during the period of overlap (not shown) indicates that they remained generally associated during this period, with a median distance between the two individuals of 1.7 km (maximum = 10.4 km). When location classes are restricted to LC1 and greater (n=4 pairs of locations), the median distance between the two individuals was only 0.7 km (maximum = 1.3 km), suggesting they were closely associated during the period of overlap. The two individuals spent between 25 and 29.7 percent of their time on PMRF (**Table 9**), with movements offshore to the east of Kauaʻi and Niʻihau (**Figure 4**).

One of the three groups of pilot whales had good-quality photos of 21 distinctive individuals, none of which had previously been photo-identified. Satellite tags were deployed on two individuals, although one tag only transmitted for approximately 1 hr. Location data for the second individual (GmTag117, catalog ID HIGm2523) were obtained over a 45-day period. During this time the whale was only briefly inside the PMRF boundaries, spending less than 1 percent of its time there (**Table 9**). Over the 45-day period the whale ranged broadly offshore around the main Hawaiian Islands, moving to the west, then back to the east south of Kauaʻi, to the north between Kauaʻi and Oʻahu, and offshore to the north of the islands as far east as Hawaiʻi Island (**Figure 4**). Based on the lack of re-sightings of the group and the wide-ranging movements, this group is likely from the pelagic/open-ocean population.

Very few individuals from the open-ocean population have been previously satellite tagged. These include three individuals tagged off Oʻahu in 2010 (Baird et al. 2013b) and one individual tagged off Kauaʻi in October 2014, both through field efforts funded by the Living Marine Resources program. Movements of the individuals tagged in 2010 were broadly ranging north and south of the main Hawaiian Islands (Figure 13 in Baird et al. 2013b), and the individual tagged in October 2014 (GmTag104, catalog ID HIGm0263, see **Table 7, Figure 4**) moved to the north of Oʻahu and then far to the west of the main Hawaiian Islands, near French Frigate Shoals within the Papahānaumokuākea Marine National Monument.

Given evidence suggesting that satellite tag deployments on pilot whales off Kauaʻi represent individuals both from the insular population and an open-ocean or pelagic population, probability density maps were plotted separately for individuals known or suspected to be from the open-ocean population (i.e., the three individuals tagged off Oʻahu in 2010, as well as GmTag104 and GmTag117) and the 13 individuals known to be from the island-associated population (**Figure 5**). The calculated area of the core range (inside the 50 percent isopleth) is more than 20 times larger for the individuals from the pelagic population (122,119 km^2) than for the island-associated population (6,157 km^2; **Table 11**), despite the much smaller sample size for pelagic individuals.

4.2 Rough-toothed dolphins

Rough-toothed dolphins were encountered on 20 occasions, with all of sightings outside of PMRF boundaries and 18 of the 20 off the east side of Kauaʻi (**Figure 1**). Although three individuals were satellite tagged, data were only obtained from two of the three tags, one a location-dive tag and one a location-only tag (**Table 7**). Both individuals were tagged off the east side of Kauaʻi, whereas all previously tagged rough-toothed dolphins have been tagged off the west side of Kauaʻi.

Identification photos were obtained from 16 of the 20 encounters, representing 118 identifications. Restricting these to good- and excellent-quality photos of distinctive and very distinctive individuals, 89 identifications were obtained, representing 81 individuals, with eight individuals seen twice during the field effort. A comparison of the 81 individuals to our photo-identification catalog of this species (Baird et al. 2008b) revealed that 33 of the individuals had been previously photo-identified off Kauaʻi (including two of the tagged individuals, although tag data were only obtained from one), and one individual had been previously photo-identified off Oʻahu (**Table 8**). A social network analysis indicates that both of the tagged individuals for which data were obtained are linked by association with the main social cluster of rough-toothed dolphins off Kauaʻi and Niʻihau (**Figure 6**).

Location data were obtained for 21.8 (SbTag014, catalog ID HISb1668) and 14.3 days (SbTag015, catalog ID HISb2045), and dive data were obtained for 104.1 hours from HISb2045.

An analysis of distances between locations of the two individuals obtained during the same satellite overpasses (not shown) revealed that those distances varied widely, with a mean distance between them of 16.5 km (maximum of 65.9 km). While there were five occasions when the two individuals were within 1 km of each other, overall the movement data from the two individuals suggested they were acting independently. During the period of tag attachment both individuals circumnavigated Kauaʻi (**Figure 8**) and spent time in the channel between Kauaʻi and Niʻihau. There were four different periods for HISb1668 and eight periods for HISb2045 where the individuals were inside the PMRF boundary, respectively, with 17.5 percent and 26.7 percent of their time spent inside the range boundary (**Table 9**).

A probability density map using tag data from all 14 rough-toothed dolphins satellite tagged off Kauaʻi, excluding data from one of each pair of individuals acting in concert, and with the first 24 hours of data from each individual omitted, indicated that the channel between Kauaʻi and Niʻihau represents the core area for these individuals (**Figure 8**), with a large proportion of the core area overlapping with the PMRF.

Dive data indicated that HISb2045 exhibited relatively shallow dives (median and maximum depths of 57.5 and 351.5 m, respectively; **Table 10**). Given that the median depths of locations for HISb2045 was 1,680 m (**Table 9**), all dives were likely to mid-water.

4.3 Bottlenose dolphins

Bottlenose dolphins were sighted on seven occasions (**Figure 1**) and photos were obtained from six of the seven encounters, representing 80 identifications. Restricting analyses to good-quality photographs of distinctive individuals, there were 46 identifications representing 39 individuals. A comparison to the long-term photo-identification catalog (Baird et al. 2009) indicated that 33 of the 39 individuals were previously documented, all off Kaua'i and/or Ni'ihau. Of those 33 that were previously documented, 10 had been seen in one previous year, 17 had been seen in 2 previous years, 10 had been seen in 3 previous years, eight had been seen in 5 previous years, and one had been seen in 6 previous years. Eight of the individuals were first documented off Kaua'i and Ni'ihau over 11 years earlier (maximum span of years = 11.7), during CRC's first field project off Kaua'i in 2003 (Baird et al. 2003). Individuals from all encounters where more than a single individual were photo-identified (n=5, see **Table 5**) were linked by association in a single social network (**Figure 9**), indicating they were all from the island-associated population. Excluding 15 individuals photographed off Ka'ula Island, 95.4 percent of the individuals photo-identified off Kaua'i and Ni'ihau since 2003 have been linked by association within this social network, suggesting that non-resident bottlenose dolphins rarely visit the area.

Two individuals were satellite tagged, both with location-dive tags, on two different days (**Table 7**), although dive data were only obtained from one of the two tags (**Table 10**). An assessment of distances between locations of the two individuals during the same satellite overpasses (not shown) indicated that those distances varied widely, with a median distance between them of 43.2 km (maximum of 60.5 km). There was no occasions when the two individuals were within 2 km of each other, thus they appeared to be travelling independently. One individual (TtTag022, catalog ID HITt0904) was tagged off the east side of Kaua'i, the first bottlenose dolphin satellite tagged off the east side of the island. HITt0904 remained associated with the east and southeast side of the island over the 7.2 days of signal contact (**Table 7; Figure 10**). HITt0904 had not previously been documented (**Table 8**), and was the only distinctive individual in a group of three, thus did not link by association to the resident social network (**Figure 9**). The other individual (TtTag023, catalog ID HITt0911) was tagged off the west side of the island and used the north, south, and west sides of the island (**Figure 10**). Median depths at tag locations were 80 m for HITt0904 and 275 m for HITt0911 (**Table 9**). Sixty-four hours of dive data were obtained from HITt0904, and median depth of dives was 79.5 m (maximum = 423.5), suggesting that most dives were to, or close to, the bottom (**Table 10**).

Tracks of two individual bottlenose dolphins satellite tagged in October 2014 are also shown in **Figure 10**. One of the two individuals (TtTag019, catalog ID HITt0898) spent nine days around Kaua'i before moving to an area south of O'ahu, remaining there for a further 6 days before the tag stopped transmitting (**Figure 10**). A probability density map of tag data from all 12 bottlenose dolphins tagged off Kaua'i indicates that much of the 50 percent core area overlaps with the PMRF (**Figure 11**). Assessment of the area within the 50 percent, 95 percent and 99 percent isopleths from the kernel density analysis indicates that bottlenose dolphins off Kaua'i have the smallest ranges of any of the three species examined (**Table 11**).

4.4 Fin whales

Two adult fin whales were encountered in deep water (2,800 m) to the southwest of Kaua'i on February 12, 2015. These were the first fin whales documented in CRC's research off Kaua'i or Ni'ihau. Although we were unable to get close enough to attempt to tag, both individuals were distinctive and good-quality photographs were obtained for individual identification. Prior to this field effort no photo-identification catalog existed for fin whales in Hawaiian waters, so a catalog was established with all known identifications available, including six fin whales photographed during a National Marine Fisheries Service 2010 survey, one fin whale documented off Kaua'i in 2010, one fin whale documented during CRC research off Lāna'i in December 2012, and three fin whales photographed off Hawai'i Island in January 2015. No matches were found among the 13 identifications in the catalog.

5. Discussion and Conclusion

Over the 13-day field effort it was only possible to work on the PMRF on 2 days, primarily due to strong prevailing winds coming from the west (**Table 5**). Given the low densities of most species of odontocetes around the main Hawaiian Islands (Baird et al. 2013a), the amount of field effort, particularly in deep waters (**Figures 1 and 2**), was not enough to have a high likelihood of encountering many of the high-priority deep-water species, such as Cuvier's beaked whales, sperm whales, or melon-headed whales. There was one sighting of dwarf sperm whales off the south shore of Kaua‘i (**Figure 1**), CRC's first sighting of this species off Kaua‘i since a field project in 2003 (Baird et al. 2003).

While strong prevailing winds precluded extending much effort into the PMRF, it did provide an opportunity to survey off the east side of Kaua‘i, an area not surveyed in our small-boat work since 2003 (see Baird et al. 2003). The large number of sightings of rough-toothed dolphins off the east side of Kaua‘i (18 of 20; **Figure 1**) was particularly notable, with an overall sighting rate of rough-toothed dolphins approximately an order of magnitude higher than has been typical for projects off the west side of Kaua‘i during this time of year (see Baird et al. 2012b, 2013c, 2015). Based on the high proportion of photo-identified individuals that had been previously documented off the island (33 of 81; 40.7 percent), these individuals appear to be part of the resident island-associated population.

Satellite-tag data obtained from short-finned pilot whales, bottlenose dolphins, and rough-toothed dolphins all increased our understanding of how these three species use the area, and the addition of tags deployed on two rough-toothed dolphins and a bottlenose dolphin off the east side of the island help reduce potential spatial biases resulting from tag deployment locations. Although data are available from these three species, they represent four different populations. Satellite-tag data are available from both the insular and pelagic short-finned pilot whale populations, and the tag data illustrate vastly different ranges (see **Figure 8** and **Table 11**). In all three species, the core areas (represented by the 50 percent kernel polygons) overlap with the PMRF to varying degrees (**Figures 5, 8,** and **11**), reflecting the importance of the channel between Kaua‘i and Ni‘ihau to these species, and also having implications for exposure to MFA sonar. Preliminary acoustic propagation analyses of sonar use on the PMRF during Submarine Commanders Courses suggest that MFA sonar on the PMRF is generally audible to cetaceans throughout the PMRF (S.W. Martin, National Marine Mammal Foundation, personal communication). These high-density areas overlapping with the PMRF indicate that individuals from all three insular populations likely have repeated exposures to audible levels of MFA sonar at the PMRF.

In order to understand the potential impacts of MFA sonar exposure to species encountered, it is necessary to evaluate exposure at the social group level. The tag deployments to date on bottlenose and rough-toothed dolphins appear to be from the known resident populations (see also Baird et al. 2008b, 2009, and Martien et al. 2011). Given the overlap in core areas with the PMRF (**Figures 8 and 11**), it is likely that individuals within these resident populations are repeatedly exposed to MFA sonar. However, the deployments of satellite tags on pilot whales occurred from three social groups with varying re-sighting histories among the islands (**Table 8**). Two of the groups from the resident population may receive more frequent exposure to MFA sonar when compared to the one group from the pelagic population (**Figure 5**), illustrating that the amount of exposure to MFA sonar will likely vary by social cluster. Reactions to MFA sonar are likely to be influenced by prior exposure history, thus understanding potential consequences of exposure, both to the social group and to the population, will benefit from an increased understanding of the social organization of the population. For example, repeated exposure might lead to permanent threshold shifts in individuals in the resident population, but they might also have become more habituated to the noise, and developed behavioral adaptations to reduce their exposure. Individuals in the pelagic population will be exposed less often, but they will also be less likely to have developed behavioral responses that allow them to deal with high levels of exposure.

As photo-identification sample sizes increase, the ability to estimate abundance of the respective populations with higher levels of precision improves, as does the potential for using these datasets to examine age and sex structure as well as trends in abundance for these populations. The presence of island-associated resident populations of these species off the island of Hawai‘i, an area with less frequent exposure to MFA sonar, will also provide a useful comparison of age and sex structure of populations with varying levels of exposure of MFA sonar.

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8. Figures

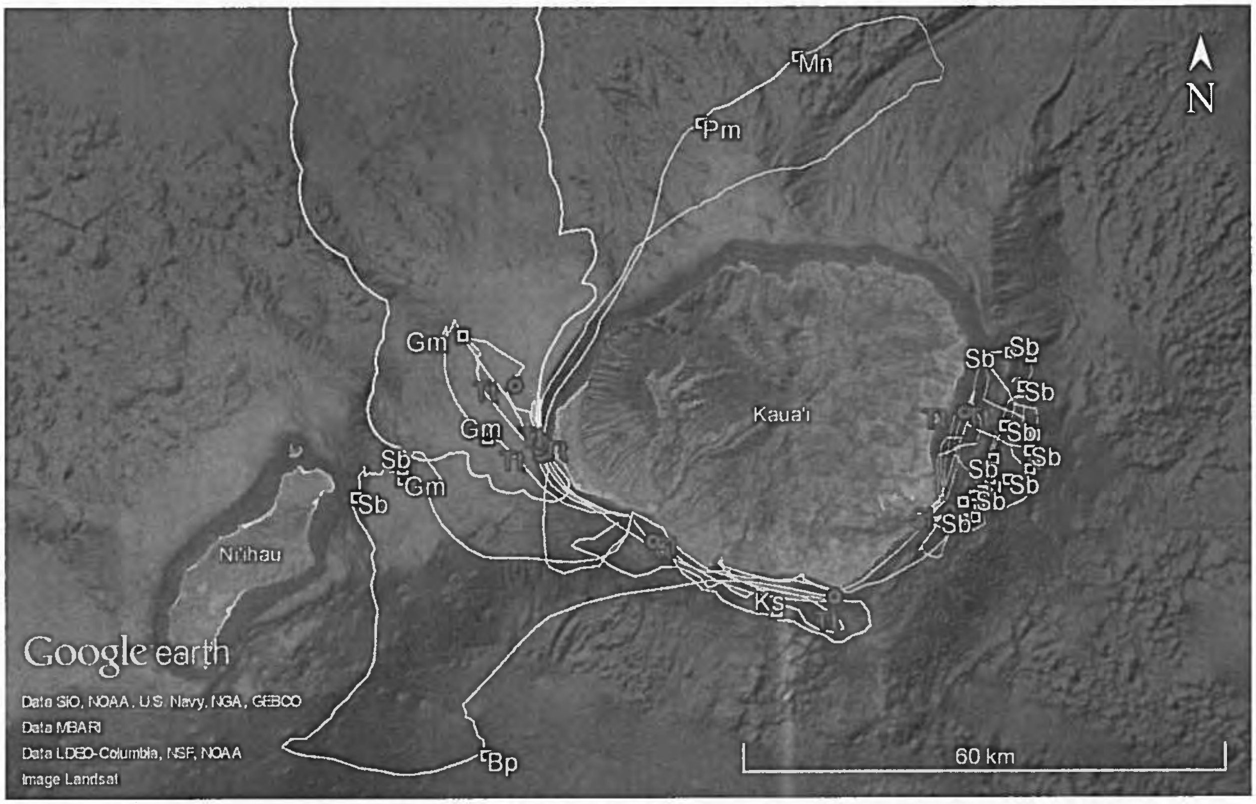


Figure 1. February 2015 tracklines of small-vessel field effort (yellow) and sighting locations (symbols with species abbreviations as labels). The single sperm whale (Pm) and humpback whale (Mn) shown were dead animals. Sightings of live humpback whales are not shown as most groups were not approached. Symbols and labels for bottlenose dolphins (Tt) and spinner dolphins (Sl) are shown in red for clarity. The overall PMRF boundary is indicated with a solid white line. Bp = ***Balaenoptera physalus*****; Gm =** ***Globicephala macrorhynchus*****; Ks =** ***Kogia sima*****; Mn =** ***Megaptera novaeangliae*****; Pm =** ***Physeter macrocephalus*****; Sb=** ***Steno bredanensis*****; Sl =** ***Stenella longirostris*****; Tt =** ***Tursiops truncatus*****.**

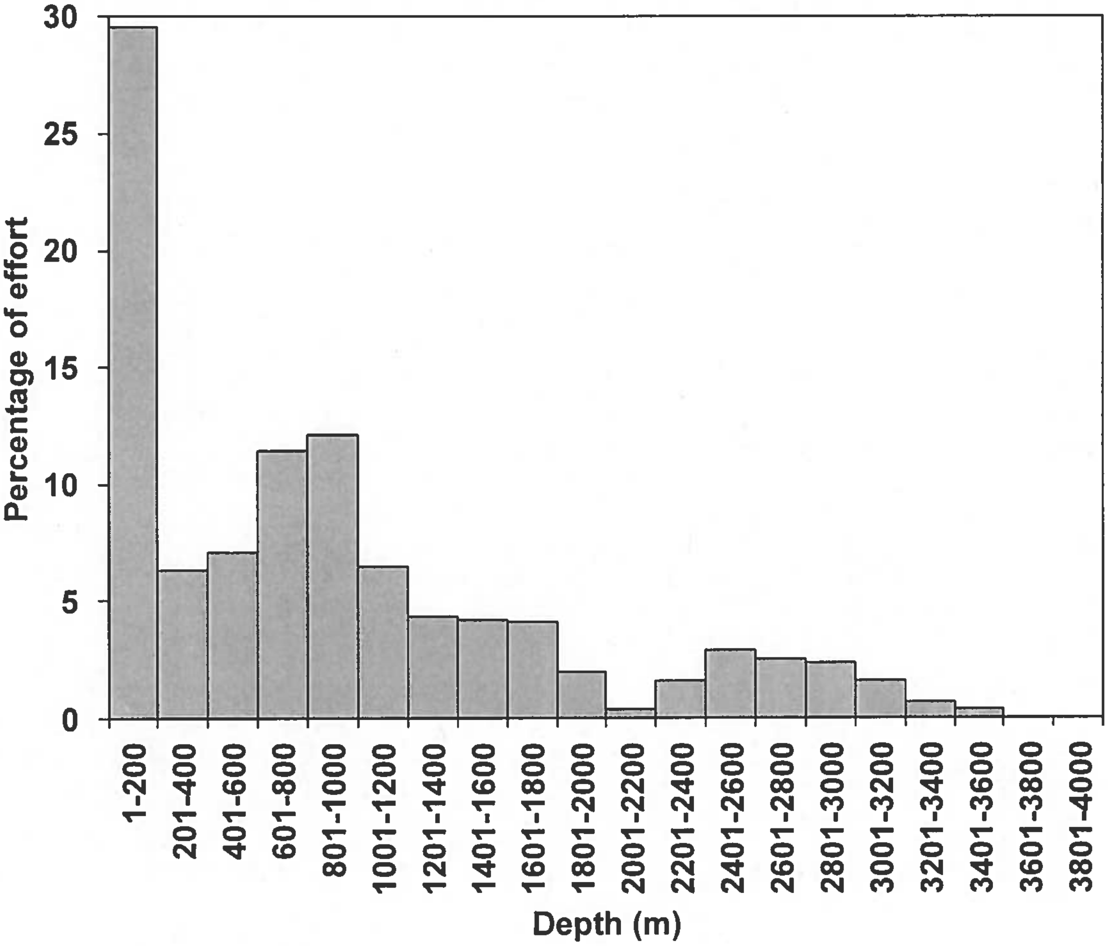


Figure 2. Depth distribution of small-vessel effort during February 2015 field effort.

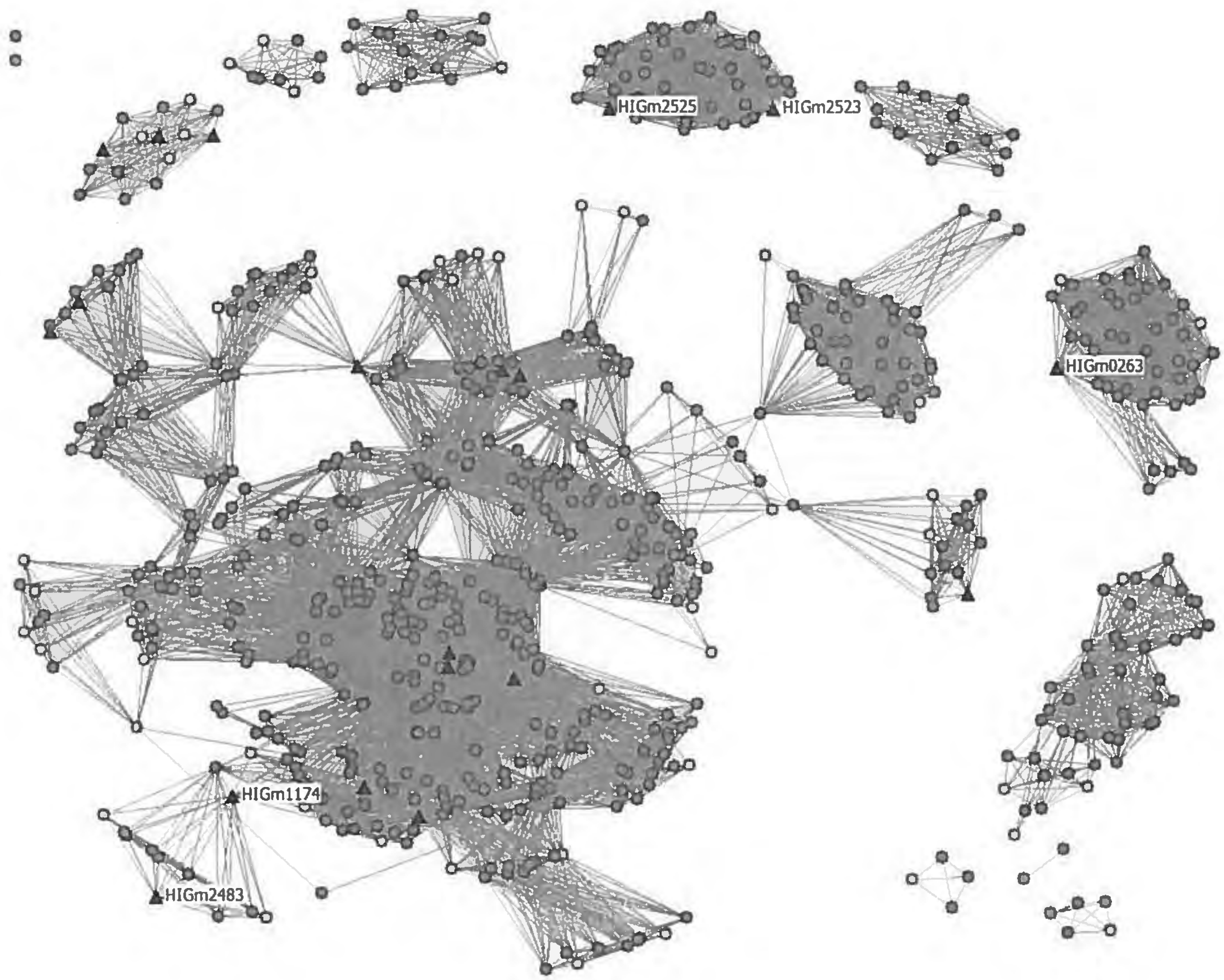
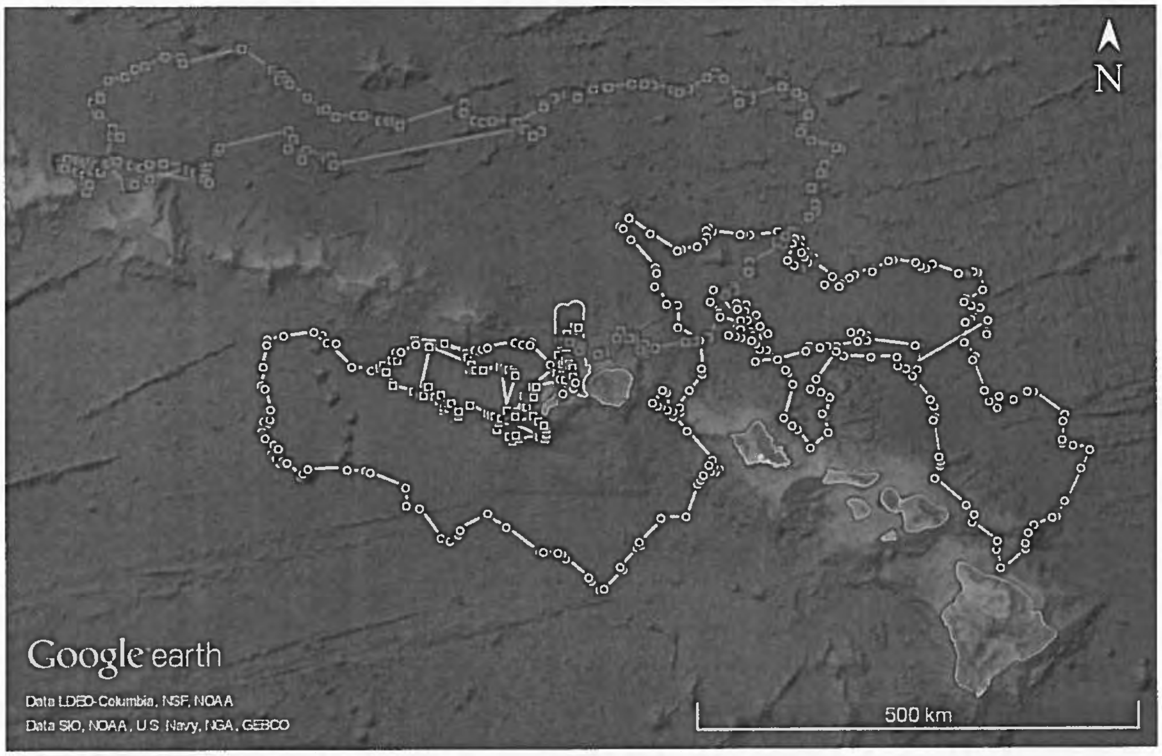


Figure 3. Social network of photo-identified short-finned pilot whales off Kaua'i and Ni'ihau, with all tagged individuals (including those tagged in previous efforts) noted by blue triangles. Those individuals tagged in February 2015 and October 2014 are indicated with ID labels. This includes all individuals categorized as slightly distinctive, distinctive, or very distinctive, with fair-, good-, or excellent-quality photographs (see Mahaffy et al. 2015), with a total of 685 individuals shown (the main cluster contains 487 individuals). The lone points in the upper left corner of the figure are of individuals that have not been sighted with any others that meet the photo quality and distinctiveness criteria.



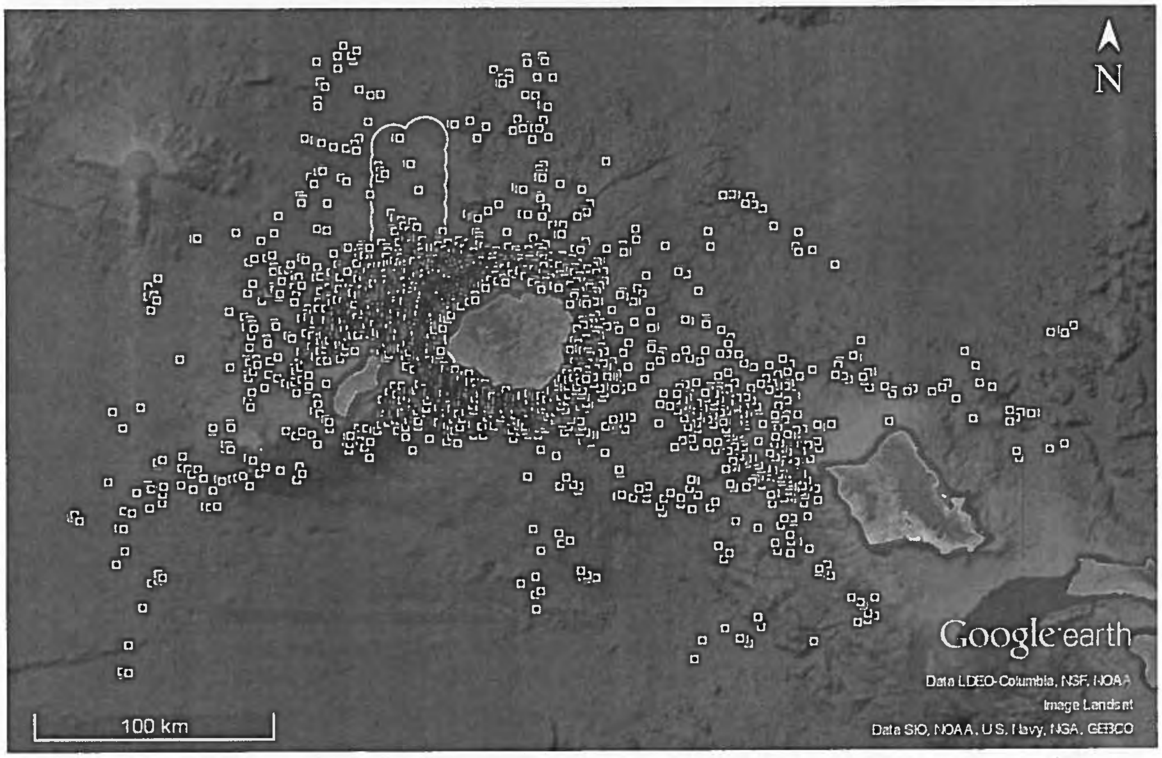


Figure 4. Top. Locations from short-finned pilot whales tagged off Kaua'i and Ni'ihau in October 2014 and February 2015. Lines connect consecutive locations. GmTag104 (red) was tagged in October 2014 and tracked over 28 days. GmTag114 and GmTag115 (yellow) were tagged in the same group in February 2015 and tracked over a total of 10 days. GmTag117 (white) was tagged in February 2015 and tracked over 45 days. Bottom. Locations from all 13 previous short-finned pilot whale tag deployments off Kaua'i. The PMRF boundary is shown in white.

Figure 5. Probability density representation of short-finned pilot whale location data from satellite tag deployments off Kaua'i. Location data from the first 24 hours of each deployment were omitted to reduce tagging area bias, and only one of each pair of individuals with overlapping tag data that were acting in concert were used. Top. Individuals known to be part of the open-ocean population (n=5), including three individuals tagged off O'ahu in 2010. Bottom. Individuals known to be part of the resident island-associated population (n=13). The red area indicates the 50% density polygon (the "core range"), the light blue represents the 95% polygon, and the green represents the 99% polygon. The PMRF boundary is shown as a solid white line.

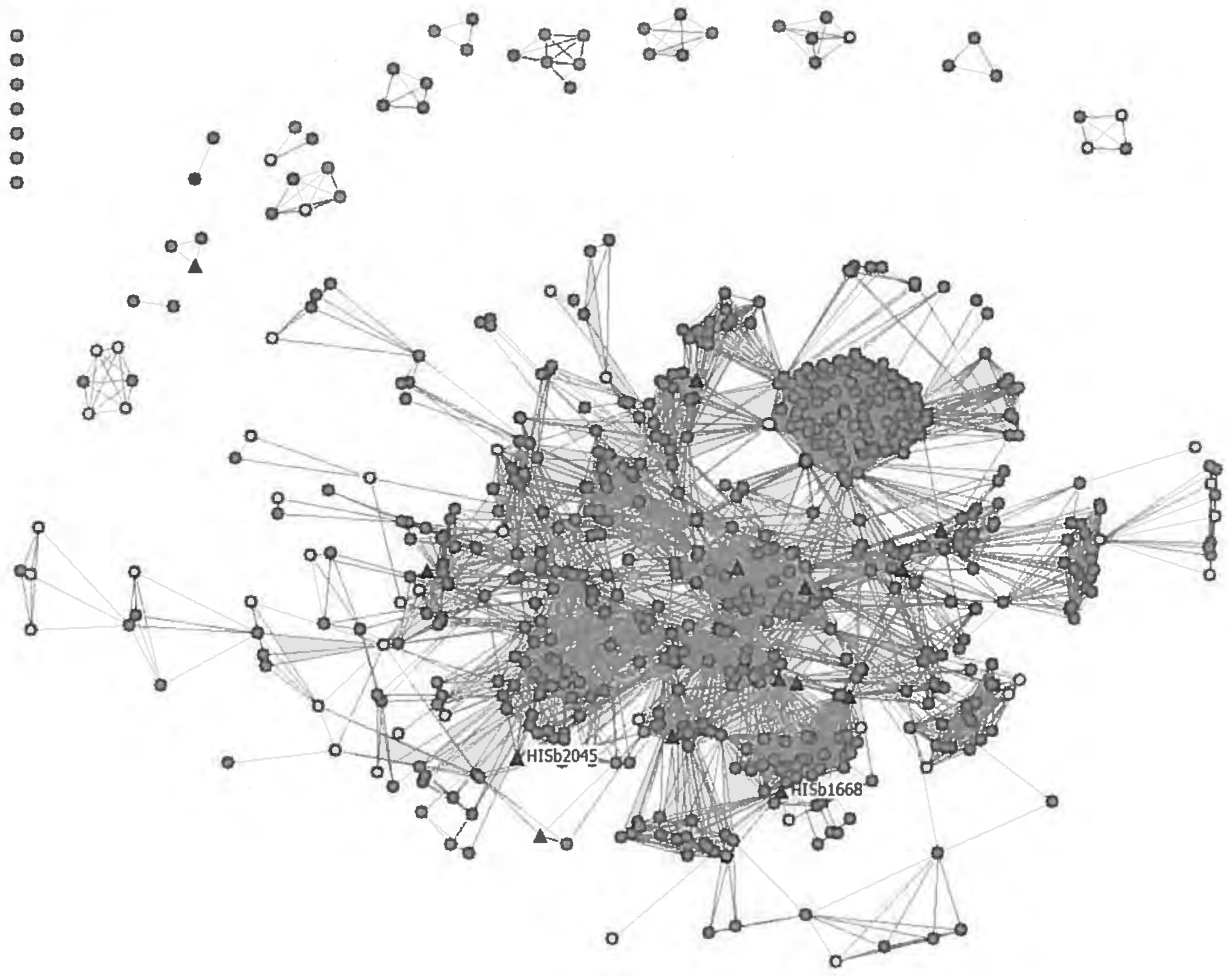
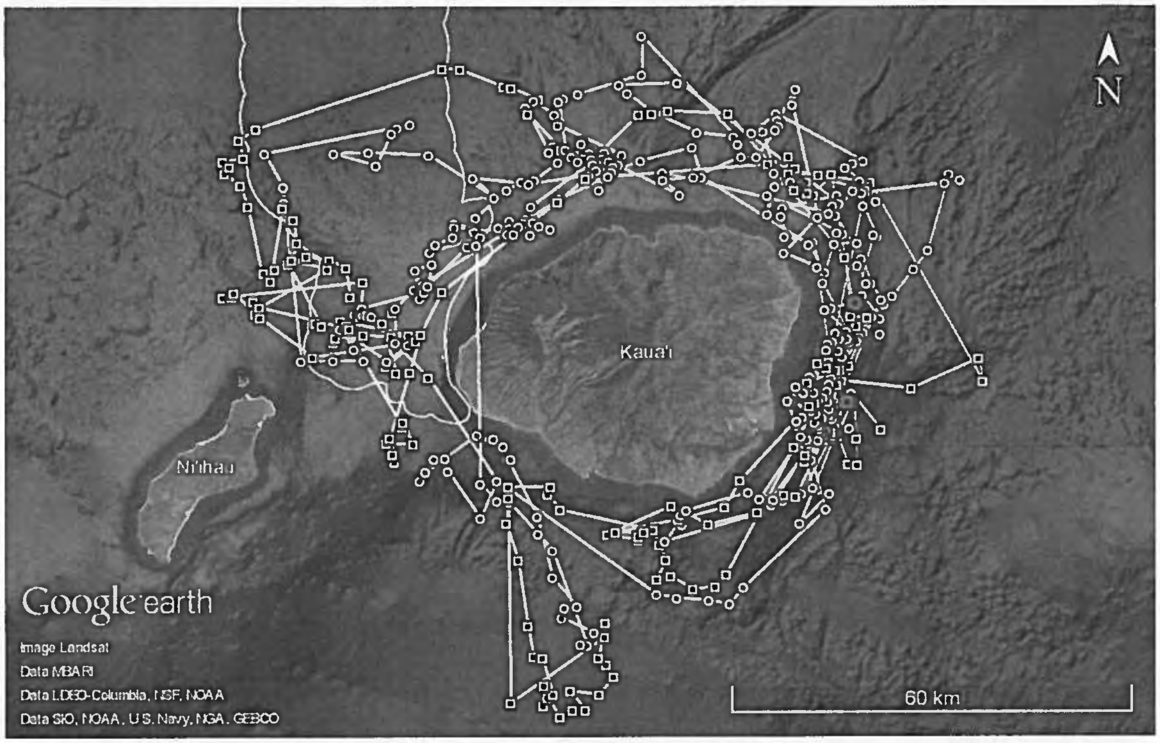


Figure 6. Social network of rough-toothed dolphins photo-identified off Kaua'i and Ni'ihau from 2003 through February 2015, with tagged individuals noted by blue triangles. Those individuals tagged in February 2015 for which data were obtained are indicated with ID labels. This includes all individuals categorized as slightly distinctive, distinctive, or very distinctive, with fair-, good-, or excellent-quality photographs (see Baird et al. 2008b), with a total of 654 individuals shown (the main cluster contains 596 individuals). The lone points in the upper left corner of the figure are of individuals that have not been sighted with any others that meet the photo quality and distinctiveness criteria.



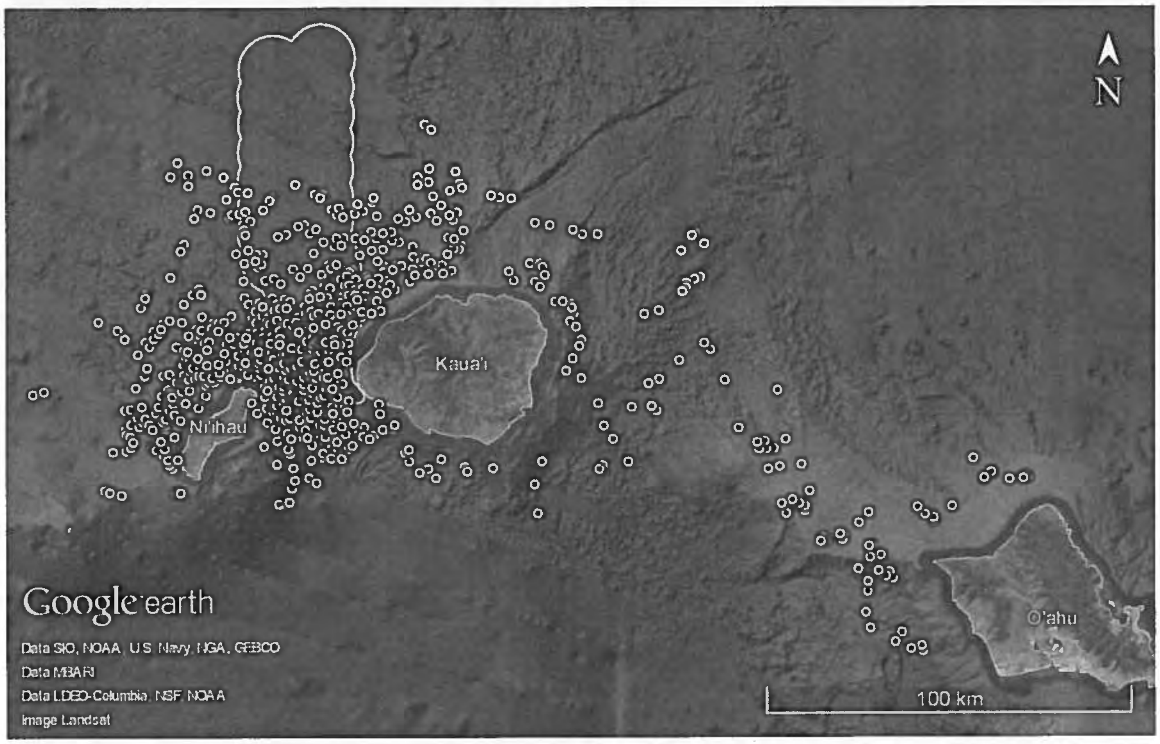


Figure 7. Top. Locations of rough-toothed dolphins satellite tagged in February 2015 (yellow circles SbTag014; white circles SbTag015), with lines connecting consecutive locations. Tagging locations are shown in red. Bottom. Locations of 12 previous satellite-tagged rough-toothed dolphins, including individuals tagged in July/August 2011 (three individuals), January 2012 (one individual), June/July 2012 (three individuals), February 2013 (one individual), July 2013 (two individuals) and February 2014 (two individuals). The PMRF boundary is shown as a solid white line.

Figure 8. A probability density representation of rough-toothed dolphin location data from all 14 satellite tag deployments off Kaua'i. Location data from the first 24 hours of each deployment were omitted to reduce tagging area bias, and only one of each pair of individuals with overlapping tag data that were acting in concert were used. The red area indicates the 50% density polygon (the "core range"), the light blue represents the 95% polygon, and the green represents the 99% polygon. The PMRF boundary is shown as a solid white line.

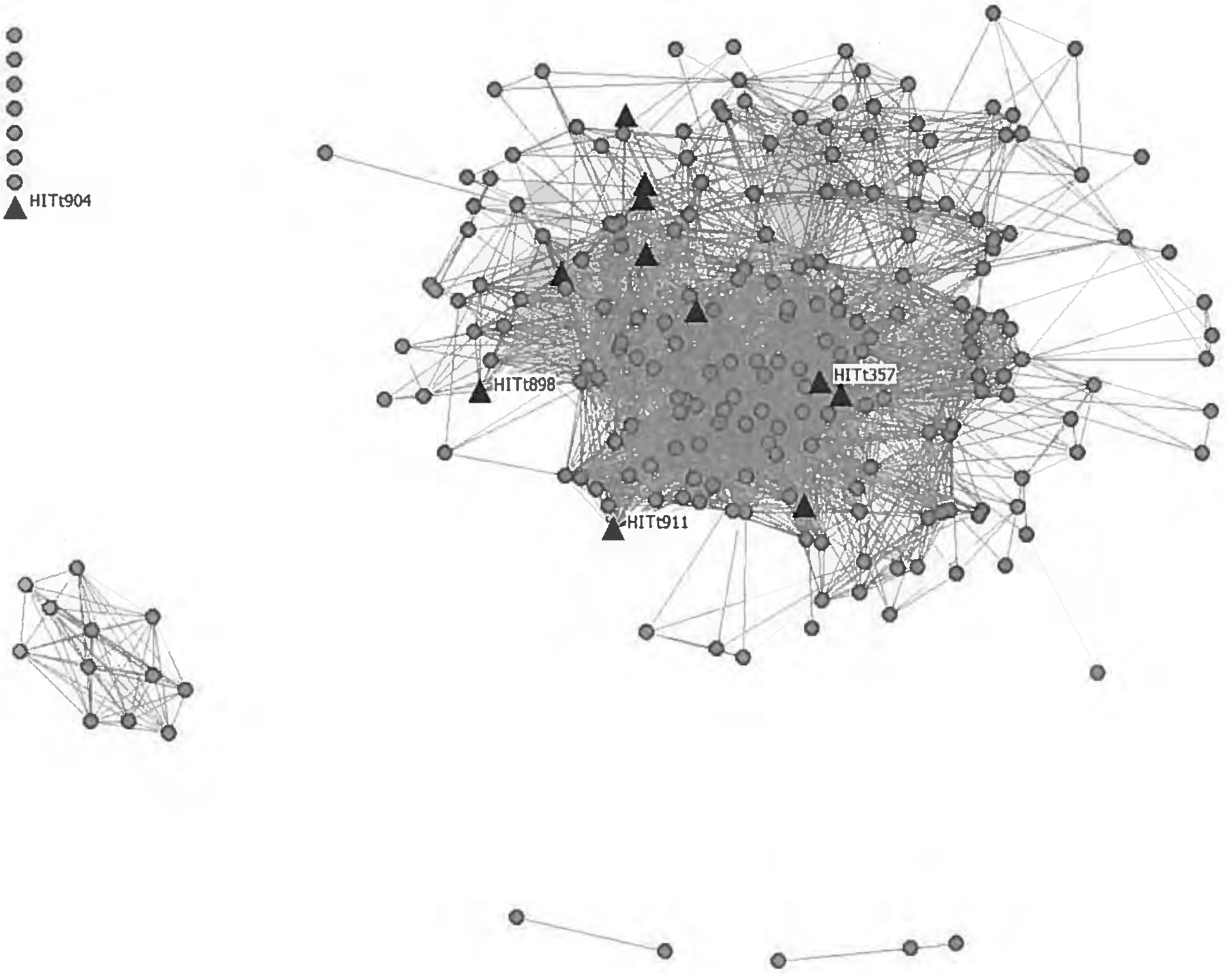


Figure 9. Social network of bottlenose dolphins photo-identified off Kaua'i and Ni'ihau from 2003 to February 2015, with tagged individuals noted by black triangles, with individuals tagged in October 2014 and February 2015 identified with ID labels. This includes all individuals categorized as slightly distinctive, distinctive, or very distinctive, with fair-, good-, or excellent-quality photographs (see Baird et al. 2009), with a total of 236 individuals shown (the main cluster contains 211 individuals). The cluster of 12 individuals in the lower left and three of the singletons in the upper left were photographed off Ka'ula Island to the southwest of Ni'ihau. The lone points in the upper left corner of the figure are of individuals that have not been sighted with any others that meet the photo quality and distinctiveness criteria.

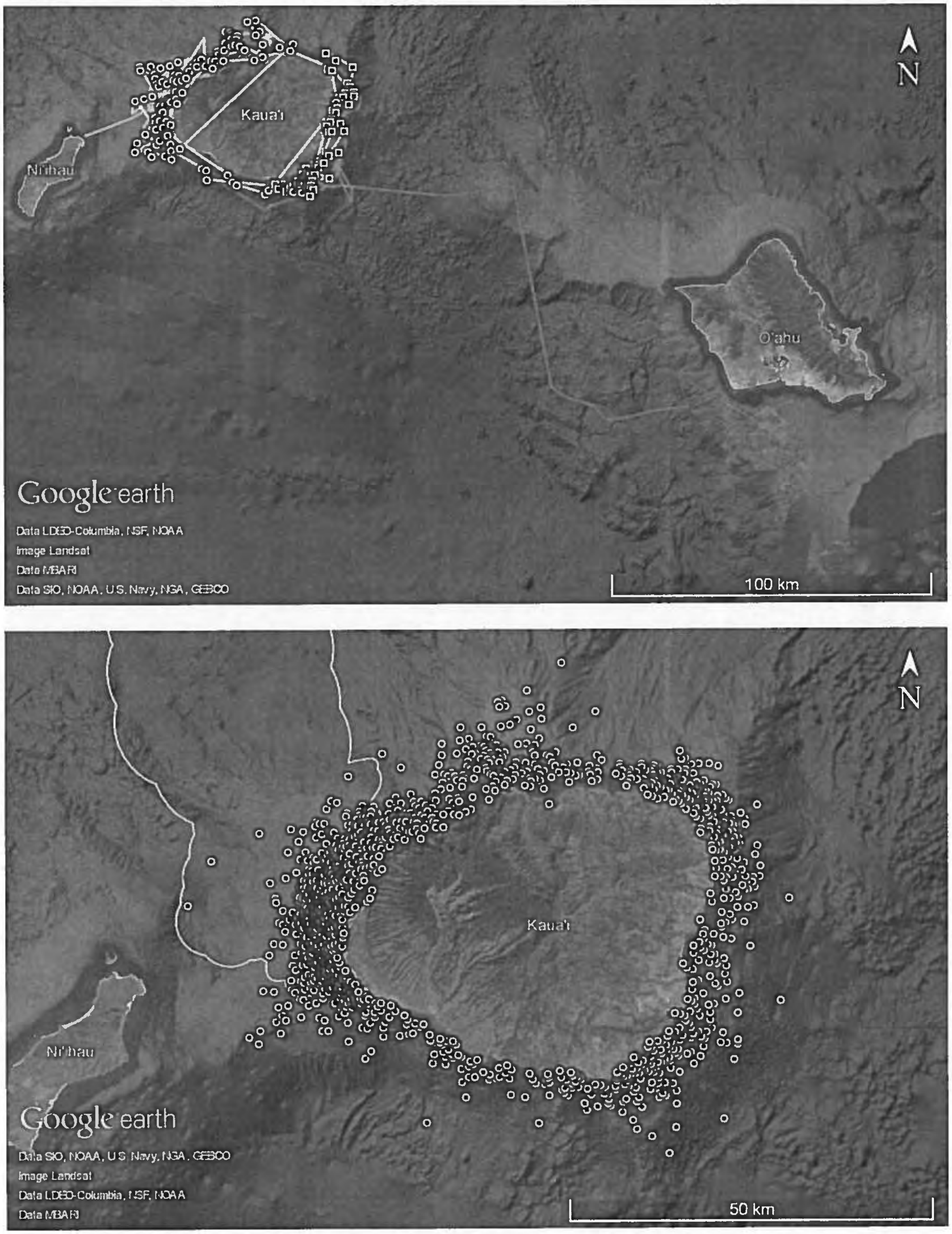


Figure 10. Top. Bottlenose dolphins satellite tagged in October 2014 and February 2015. Tracks only are shown for TtTag019 (red) and TtTag020 (green), while tracks and locations are shown for TtTag022 (yellow squares) and TtTag023 (white circles). Bottom. Locations of eight previous satellite-tagged bottlenose dolphins, including individuals tagged in August 2011 (one individual), June 2012 (two individuals), February 2013 (three individuals), February 2014 (two individuals). The boundary of PMRF is shown as a solid white line.

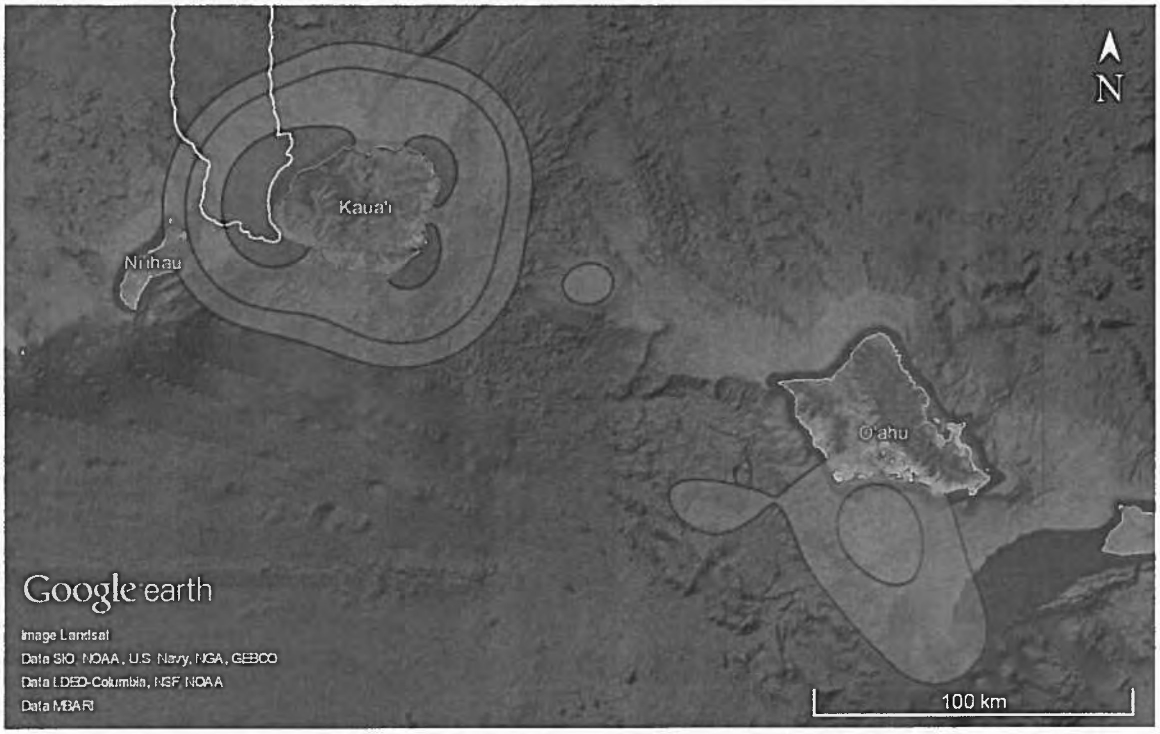


Figure 11. Kernel-density representation of bottlenose dolphin location data from all 12 satellite tag deployments off Kaua'i. Location data from the first 24 hours of each deployment were omitted to reduce tagging area bias and only one of each pair of individuals with overlapping tag data that were acting in concert were used. The red area indicates the 50% density polygon (the "core range"), the light blue represents the 95% polygon, and the green represents the 99% polygon. The PMRF boundary is indicated by a solid white line.

9. Tables

Table 1. Details of previous field efforts off Kaua'i involving small-vessel surveys, satellite tagging, or M3R passive acoustic monitoring.

Dates	Hours Effort	Odontocete Species Seen[1]	Species Tagged (number tagged)	Odontocete Species Detected on M3R
25-30 Jun 2008	53.8	*Pe, Sb, Gm, Sl*	*Gm* (1), *Pe* (3)	N/A
16-20 Feb 2011	33.9	*Tt, Sb, Gm, Sl*	*Gm* (3)	N/A
20 Jul-8 Aug 2011	118.8	*Tt, Sb, Sl, Sa, Oo*	*Tt* (1), *Sb* (3)	*Tt, Sb, Sl*
10-19 Jan 2012	42.2	*Tt, Sb, Gm, Sl, Md*	*Sb* (1), *Gm* (2)	*Tt, Sb, Gm, Sl, Md*
12 Jun-2 Jul 2012	115.7	*Tt, Sb, Gm, Sl, Sa, Pc*	*Tt* (2), *Sb* (3), *Pc* (3)	*Tt, Sb, Gm, Pc*
2-9 Feb 2013	55.9	*Tt, Sb, Sl, Gm*	*Tt* (3), *Sb* (1), *Gm* (2)[2]	*Tt, Sb, Sl, Md, Pm*
26 Jul-2 Aug 2013	36.6	*Tt, Sb, Sl, Pc*	*Sb* (2), *Pc* (1)	*Tt, Sb, Pc, Md, Zc, Pm*
1-10 Feb 2014	66.3	*Tt, Sb, Sl, Md, Gm*	*Md* (2)[2], *Tt* (2), *Sb* (2), *Gm* (6)	*Tt, Sb, Md, Gm*
7-17 Oct 2014	77.7	*Tt, Sb, Sl, Gm, Fa, Pc, Pm*	*Tt (2),Gm (1), Pc (2), Pm (1)*	*Tt, Pc, Md*
Total	**600.9**		*Gm* (15)[2], *Pe* (3), *Tt* (10), *Sb* (12), *Pc* (6), *Md (2)*[2], *Pm (1)*	

[1] Species codes: *Tt* = *Tursiops truncatus*, *Sb* = *Steno bredanensis*, *Gm* = *Globicephala macrorhynchus*, *Pe* = *Peponocephala electra*, *Sl* = *Stenella longirostris*, *Sa* = *Stenella attenuata*, *Oo* = *Orcinus orca*, *Pc* = *Pseudorca crassidens*, *Pm* = *Physeter macrocephalus*, *Md* = *Mesoplodon densirostris*, *Zc* = *Ziphius cavirostris*.

[2] One tag did not transmit for each species.

M3R = Marine Mammal Monitoring on Navy Ranges

Table 2. **PMRF undersea range characteristics.**

Range Area Name	Depth Range (m)	Hydrophone Numbers (string names)	Hydrophone Bandwidth
BARSTUR	~1,000-2,000m	2-42 (1-5) 1,10,21,24,37,41	8-40 kHz 50 Hz-40 kHz
BSURE Legacy	~2,000-4,000m	43-60 (A,B)	50 Hz-18 kHz
SWTR	~100-1,000m	61-158 (C-H)	5-40 kHz
BSURE Refurbish	~2,000-4,000m	179-219 (I-L)	50 Hz-45 kHz

Hz = Hertz; kHz = kilohertz; m = meters; ~ = approximately

Table 3. **Observations of acoustic features used for species identification and differentiation from passive acoustic monitoring during previous M3R field efforts.**

Species[1]	# Visual Verifications	Whistle Features	Click Features	Distinctive Spectrogram Features	Acoustically Similar Species
Sb	30	8-12 kHz, short sweeps centered at ~10 kHz	12-44 kHz with most energy 16-44 kHz	Short narrowband whistles centered at 10 kHz, lots of 12-44 kHz clicks	*Pc* (whistles)
Sl	5	8-16 kHz, highly variable	8-48 kHz, distinct presence of 40-48 kHz click energy, single animal similar to *Zc*	HF click energy from 40-48 kHz. Loses LF click energy first. Long ICI for single species.	*Md, Zc* (clicks) *Tt* (whistles)
Tt	25	primarily 8-24 kHz, highly variable, lots of loopy curves	16-48 kHz, short ICI	Density of clicks and whistles. Very wideband, long duration loopy whistles.	
Gm	10	Combination of short 6-10 kHz upsweeps with long 10-24 kHz upsweeps	12-44 kHz, repetitive, slowly changing ICI	Very wide band but short duration whistles. Often single up or down sweeps.	*Tt*
Pc	4	5-8 kHz upsweeps, loopy whistles 8-12 kHz	8-48 kHz, most energy 8-32 kHz, continual presence of energy to 8 kHz	Click energy at 8 kHz, extending upwards to 32-40 kHz.	*Sb* (whistles), need to pay close attention to clicks to differentiate
Md	4	n/a	24-48 kHz, 0.33 s ICI	Consistent ICI and click frequency content.	

[1] See footnote to **Table 1**.

ICI = inter-click interval; kHz = kilohertz; n/a = not applicable; ~ = approximately

Table 4. February 2015 small-boat effort summary.

Date	Total km	Total Hours on Effort	Number of Odontocete Sightings Total	Depart Time HST	Return Time HST	Total km Beaufort 0	Total km Beaufort 1	Total km Beaufort 2	Total km Beaufort 3	Total km Beaufort 4-5
04 Feb 2015	131.2	7.7	4	7:03	12:40	0	2.8	18.1	8.3	102.0
05 Feb 2015	63.4	4.1	8	7:05	15:44	0	2.5	51.4	9.5	0
06 Feb 2015	90.8	5.2	1	7:21	14:26	0	3.1	65.0	14.4	8.3
07 Feb 2015	85.6	4.6	1	7:32	8:17	0	8.3	35.4	30.2	11.7
08 Feb 2015	81.5	4.2	1	7:19	16:08	0	0	11.6	10.2	59.7
11 Feb 2015	81.1	5.7	8	7:24	10:45	0	0	25.8	38.9	16.4
12 Feb 2015	223.4	11.4	4	7:14	15:40	10.0	38.1	175.3	0	0
15 Feb 2015	153.2	9.2	3	7:16	15:32	0	8.4	48.5	72.2	24.1
16 Feb 2015	222.3	11.3	4	7:59	14:47	8.0	62.6	79.5	53.2	19.0
Total	1,132.5	63.4	34							

HST = Hawai'i Standard Time; km = kilometers

Table 5. February 2015 M3R effort summary.

Date	Range Availability for Small Boat Operations		PAM Effort (HST)	
	Area	Time	Start	Stop
08 Feb 2015	BARSTUR	0630-1700	0630	1700
15 Feb 2015	BARSTUR	0630-1700	0630	1630

HST = *Hawai'i* Standard Time

Table 6. Odontocete and fin whale sightings from small-boat effort during February 2015. Details on two dead whales found during the survey are also included.

Date	Time (HST) of Visual Sighting	Species[1]	Group Size	# Satellite Tags Deployed	On PMRF (yes/no)	# distinctive individuals photo-identified with good/excellent photos	# distinctive individuals previously photo-identified (excluding within-day)	Visual ID Position	
								Latitude °N	Longitude °W
04-Feb-15	9:24	Sb	9	0	no	7	2	22.04867	159.24547
04-Feb-15	10:17	Sb	12	1[2]	no	6	3	22.09218	159.22363
04-Feb-15	11:07	Sb	18	1	no	14	3	22.12519	159.21374
04-Feb-15	11:39	Sb	5	0	no	0	0	22.13003	159.23868
05-Feb-15	7:44	Sl	60	0	no	N/A	N/A	21.95495	159.31132
05-Feb-15	7:52	Sb	18	0	no	7	5	21.96433	159.29576
05-Feb-15	8:14	Sb	1	0	no	0	0	21.97136	159.28236
05-Feb-15	8:23	Sb	1	0	no	0	0	21.97631	159.27218
05-Feb-15	8:33	Sb	11	0	no	7	5	21.98098	159.25753
05-Feb-15	8:57	Sb	3	0	no	3	0	21.95883	159.27662
05-Feb-15	9:06	Sb	4	0	no	2	1	21.94753	159.28171
05-Feb-15	9:19	Sb	4	0	no	1	0	21.94543	159.29637
06-Feb-15	10:54	Tt	3	0	no	3	3	22.06484	159.29273
07-Feb-15	10:01	Ks	2	0	no	1	0	21.84373	159.51952
08-Feb-15	8:34	Gm	13	1	yes*	8	1	22.03670	159.86461
11-Feb-15	8:01	Sb	8	0	no	4	0	22.01210	159.25912
11-Feb-15	9:09	Sb	2	0	no	1	1	22.03831	159.20996
11-Feb-15	9:26	Sb	1	0	no	1	0	22.02102	159.21606
11-Feb-15	9:28	Sb	6	0	no	0	0	22.00590	159.21007

Date	Time (HST) of Visual Sighting	Species[1]	Group Size	# Satellite Tags Deployed	On PMRF (yes/no)	# distinctive individuals photo-identified with good/excellent photos	# distinctive individuals previously photo-identified (excluding within-day)	Visual ID Position	
								Latitude °N	Longitude °W
11-Feb-15	9:59	Sb	13	1	no	13	7	22.00040	159.21552
11-Feb-15	10:49	Sb	8	0	no	6	4	21.98922	159.24223
11-Feb-15	11:06	Sb	19	0	no	14	4	21.98962	159.26344
11-Feb-15	11:46	Tt	3	1	no	1	0	22.06389	159.29317
12-Feb-15	9:02	Sb	2	0	no	1	0	22.00245	159.96610
12-Feb-15	9:06	Gm	40	2	no	21	0	21.99080	159.96573
12-Feb-15	11:35	Sb	4	0	no	2	1	21.97093	160.02147
12-Feb-15	14:48	Bp	2	0	no	2	0	21.68461	159.86689
12-Feb-15	17:48	Tt	45	0	no	0	0	21.86014	159.44959
15-Feb-15	8:21	Sl	130	0	no	N/A	N/A	21.92255	159.66659
15-Feb-15	13:43	Tt	20	0	yes*	13	13	22.09544	159.83162
15-Feb-15	14:55	Gm	17	0	yes*	6	6	22.15049	159.89429
16-Feb-15	13:12	UnID	2	0	no	0	0	22.48921	159.43122
16-Feb-15	16:49	Tt	26	1	no	22	19	22.03217	159.79973
16-Feb-15	18:03	Tt	4	0	yes	3	2	22.02668	159.80234
16-Feb-15	18:07	Tt	9	0	yes	4	3	22.01903	159.80018
16-Feb-15	13:57	Mn[3]	1	N/A	no	N/A	N/A	22.45936	159.49262
16-Feb-15	14:50	Pm[3]	1	N/A	no	N/A	N/A	22.38578	159.60754

[1] See footnote to **Table 1**, [2] No data obtained from tag. [3] Dead whale found floating in advance state of decay. Ks = *Kogia sima*, UnID = unidentified odontocete; HST = Hawai'i Standard Time; ID = identification; km = kilometer; N/A = not applicable; PAM = passive acoustic monitoring; °N = degrees North; °W = degrees West; *Sighting a result of being directed to the location of PAM detections but files of acoustic detection locations corrupted.

Table 7. **Details on satellite tags deployed during February 2015 field effort and October 2014 effort for species included in mapping (bottlenose dolphins and short-finned pilot whales, no rough-toothed dolphins were tagged in October 2014).**

Species[1]	Tag ID	Individual ID	Date Tagged	Sighting #	Duration of Signal Contact (days)	Lat (°N)	Long (°W)	Tag Type	Sex
Tt	TtTag019	HITt0898	14-Oct-14	2	14.78	22.06	159.80	Mk10A	Unknown
Tt	TtTag020	HITt0357	15-Oct-14	1	12.32	22.10	159.85	Mk10A	Male
Tt	TtTag022	HITt0904	11-Feb-15	10	7.20	22.07	159.29	Mk10A	Unknown
Tt	TtTag023	HITt0911	16-Feb-15	3	15.65	22.07	159.81	Mk10A	Unknown
Sb	SbTag013	HISb1480	4-Feb-15	3	0	22.10	159.23	Mk10A	Unknown
Sb	SbTag014	HISb1668	4-Feb-15	5	21.82	22.13	159.22	SPOT5	Unknown
Sb	SbTag015	HISb2045	11-Feb-15	7	14.34	21.99	159.22	Mk10A	Unknown
Gm	GmTag104	HIGm0263	8-Oct-14	3	27.99	22.50	159.89	Mk10A	Male
Gm	GmTag114	HIGm1174	8-Feb-15	1	7.55	22.16	159.91	Mk10A	Male
Gm	GmTag115	HIGm2483	8-Feb-15	1	10.07	22.16	159.91	SPOT5	Male
Gm	GmTag116	HIGm2525	12-Feb-15	2	0.10	22.00	160.00	Mk10A	Unknown
Gm	GmTag117	HIGm2523	12-Feb-15	2	45.00	22.00	160.01	SPOT5	Male

[1] See footnote to **Table 1**. °N = degrees North; °W = degrees West; # = number

Table 8. Details on previous sighting histories of individuals satellite tagged in February 2015 and those tagged in October 2014 included in mapping.

Individual ID	Date First Seen	# Times Seen Previously	# Years Seen Previously	Islands Seen Previously	Social cluster
HITt0898	14-Oct-14	0	0	N/A	N/A
HITt0357	16-Oct-05	7	3	Kaua'i	N/A
HITt0904	11-Feb-15	0	0	N/A	N/A
HITt0911	16-Feb-15	0	0	N/A	N/A
HISb1480	21-Jul-11	4	2	Kaua'i	N/A
HISb1668	30-Jun-12	2	1	Kaua'i	N/A
HISb2045	11-Feb-15	0	0	N/A	N/A
HIGm0263	11-Nov-05	1	1	Kaua'i	-
HIGm1174	24-Aug-08	1	1	O'ahu	W11
HIGm2483	08-Feb-15	0	0	N/A	-
HIGm2525	12-Feb-15	0	0	N/A	-
HIGm2523	12-Feb-15	0	0	N/A	-

ID = identification; # = number; N/A = not applicable

Table 9. Information from GIS analysis of satellite-tag location data from February 2015 field effort.

Individual ID[1]	Social Cluster	# Locations	# Periods Inside PMRF Boundaries	% Time Inside PMRF Boundaries	Total Minimum Distance Moved (km)	Median / Maximum Distance from Deployment Location (km)	Median / Maximum Depth (m)	Median / Maximum Distance from Shore (km)
HITt0904	N/A	92	0	0	433.3	22.0/29.1	80/1,372	2.1/7.4
HITt0911	N/A	123	9	23.3	731.4	15.2/54.0	275/1,321	4.5/16.8
HISb1668	N/A	286	4	17.5	1,482.2	33.1/90.4	1,450/4,099	10.0/33.2
HISb2045	N/A	179	8	26.7	1,044.4	52.6/99.5	1,680/4,276	12.2/36.8
HIGm1174	W11	92	2	29.7	783.0	74.1/209.09	4,294/4,603	45.4/114.2
HIGm2483	-	42	1	25.0	609.8	76.6/167.8	3,246/4,570	23.2/107.7
HIGm2523	-	346	1	0.7	4,251.9	285.0/585.4	4,549/5,704	132.1/246.8

ID = identification; km = kilometers; m = meters; # = number; % = percent; N/A = not applicable. [1] Only three locations obtained from HIGm2525 so information not included here.

Table 10. Dive information from satellite tags deployed during February 2015 field effort.

Individual ID	# Hours Data	# Dives ≥ 30 m	Median Dive Depth (m) for Dives ≥ 30 m	Maximum Dive Depth (m)	Median Dive Duration[1] (min)	Maximum Dive Duration[1] (min)
HITt0904	64.1	230	79.5	423.5	2.93	7.43
HISb2045	104.1	228	57.5	351.5	4.30	9.53
HIGm1174	99.6	344	83	1,184	8.23	23.13

[1] Duration of dives underestimated as time spent in top 3 m not included. Typical rates of ascent/descent are in the 1-2 m/second range, so durations likely only underestimated by 3-6 seconds.

m = meters; min = minutes; # = number; ≥ = greater than or equal to

Table 11. Areas within 50% ("core range"), 95% and 99% isopleths based on kernel density analyses of satellite tag data.

	Area (km^2) within selected isopleths based on kernel density		
Species/population	50%	95%	99%
Bottlenose dolphin	1,210	7,239	12,281
Rough-toothed dolphin	1,656	14,318	21,691
Short-finned pilot whale – insular population	6,157	47,849	75,653
Short-finned pilot whales – pelagic population	122,119	577,058	755,166

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