

**MOVEMENTS OF THE FIRST SATELLITE-TAGGED CUVIER'S AND
BLAINVILLE'S BEAKED WHALES IN HAWAI'I**

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14. ABSTRACT Studies on the movement patterns and habitat use of cetaceans are often constrained by numerous factors including ship time, logistics, and the ability to track individuals over time. Obtaining information on beaked whales is especially difficult both due to their habits and their low population densities. To better understand movements of beaked whales in Hawai'i, Argoslinked satellite tags were remotely applied to the dorsal fins of three Blainville's beaked whales (<i>Mesoplodon densirostris</i>) and three Cuvier's beaked whales (<i>Ziphius cavirostris</i>) in 2006 and 2008, representing the first time that beaked whales have been tracked by satellite. Transmissions for Blainville's were received for 15, 16 and 23 days and for Cuvier's for 2, 13 and 24 days. All six individuals were tagged west of the island of Hawai'i. Five of the six individuals moved out of the study area but continued to remain associated with the island. All of the Blainville's and one of the Cuvier's moved into the Alenuihaha Channel, a site of naval antisubmarine warfare exercises that is difficult to survey due to unfavorable sea conditions. Movement patterns of tagged animals support the results of photo-identification studies which suggest the populations of both species are island-associated and that individuals exhibit strong site fidelity, both of which potentially increases the susceptibility of these small populations to anthropogenic impacts.					
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Abstract

Studies on the movement patterns and habitat use of cetaceans are often constrained by numerous factors including ship time, logistics, and the ability to track individuals over time.

Obtaining information on beaked whales is especially difficult both due to their habits and their low population densities. To better understand movements of beaked whales in Hawai‘i, Argos-linked satellite tags were remotely applied to the dorsal fins of three Blainville’s beaked whales (*Mesoplodon densirostris*) and three Cuvier’s beaked whales (*Ziphius cavirostris*) in 2006 and 2008, representing the first time that beaked whales have been tracked by satellite.

Transmissions for Blainville’s were received for 15, 16 and 23 days and for Cuvier’s for 2, 13 and 24 days. All six individuals were tagged west of the island of Hawai‘i. Five of the six individuals moved out of the study area but continued to remain associated with the island. All of the Blainville’s and one of the Cuvier’s moved into the Alenuihaha Channel, a site of naval anti-submarine warfare exercises that is difficult to survey due to unfavorable sea conditions.

Movement patterns of tagged animals support the results of photo-identification studies which suggest the populations of both species are island-associated and that individuals exhibit strong site fidelity, both of which potentially increases the susceptibility of these small populations to anthropogenic impacts.

Introduction

Information on movements of individuals is required to understand population structure and delineate stock boundaries. Unbiased information on where animals spend their time can also be used to identify important foraging habitats and assess the likelihood of repeated exposure to potential anthropogenic impacts, if human activities are spatially heterogeneous. In areas where conditions limit survey coverage, collecting unbiased information on movements is

problematic. If conditions allow for surveying all potential habitats, and sample sizes are large enough, photographic identification of individuals can be used to assess movements over all habitats. When survey conditions do not allow for broad coverage of all habitats, one method to examine movements is to instrument individuals with satellite tags, allowing for remote determination of locations.

Around the Hawaiian Islands the trade winds, predominantly coming from the east and northeast, interact with the land masses, creating areas where conditions are more conducive to cetacean sighting surveys. While areas to the west of the island of Hawai‘i can be calm, allowing for studies of deep-water species (e.g., McSweeney et al. 2007), trade winds effectively prohibit survey coverage off the eastern and northern shores of most of the islands, and in deeper waters west of the other main Hawaiian Islands.

Studies of beaked whales off the west coast of the island of Hawai‘i have allowed for assessment of diving patterns, habitat use, site fidelity, and aspects of social organization (Baird et al. 2006, 2008a; McSweeney et al. 2007). Mark-recapture analyses of photographically identified individuals of both Cuvier’s and Blainville’s beaked whales indicate very small population sizes in that area (Baird et al. unpublished). Individuals appear to show high levels of site fidelity over periods of up to 15 years (McSweeney et al. 2007). Given the overall low encounter rates with beaked whales and the difficulty studying them off other islands due to inclement sea conditions, assessing movements of beaked whales among the main Hawaiian Islands based on photographic re-identifications would require substantial investment of both resources and time. However, without information on movements it is difficult to assess what proportion of the population is effectively being sampled off the west coast of the island of

Hawai‘i.

In order to assess movements of individuals over a larger scale than the existing study area of McSweeney et al. (2007), we tagged beaked whales using a modified version of a tag used previously on killer whales (Andrews et al. 2008). In 2006 satellite tags were deployed on three Blainville’s beaked whales and one Cuvier’s beaked whale, and in 2008 we were able to deploy two additional satellite tags on Cuvier’s beaked whales off the island of Hawai‘i. Here we report information on movements of these individuals, the first beaked whales to have been satellite-tagged.

Methods

Tags and tag programming

Tags were constructed with a SPOT5 (Wildlife Computers, Redmond, Washington, USA), Argos-linked location-only Platform Transmitter Terminal (PTT). In 2006, the PTT’s were then modified for dorsal fin-attachment by adding an aluminum base plate with a threaded hole at each end of the plate for dart attachment. The entire tag and plate were then cast with an additional layer of epoxy to encapsulate the aluminum plate, providing a more hydrodynamic shape and additional thickness of material around the batteries to protect them from the high pressures anticipated during beaked whale dives. After modification, tag body dimensions were 65 x 30 x 22 mm. In 2008, tags were modified slightly, and the entire tag was cast as a one-step process. The aluminum plate was replaced by two fiberboard plates, and helicals were inserted to attach the darts. Dimensions of the new tags were 63 x 30 x 21 mm.

Each tag incorporated two 6.5 cm long medical-grade titanium darts that were screwed

into the holes in the bottom of the tag. The darts were designed to penetrate the connective tissue in the dorsal fin and remain embedded with a series of backwards facing 'barbs' which acted as anchors for the darts (see Andrews et al. 2008). Weight of the entire package was approximately 49 g. The transmitter itself was designed to remain external to the body to minimize the invasiveness of the technique (Fig. 1).

Transmitters were duty-cycled to turn on during times of the day when satellite overpasses were most likely to occur. The likelihood of satellite overpasses were determined using the pass predictions generated from the Argos website. This predicts the overpass time for all satellites currently orbiting and capable of receiving uplinks from the PTT's in the general location of deployment. Tags can only be programmed to transmit in hourly blocks, and duty cycling was chosen to take advantage of hours where multiple satellites were passing overhead, with an emphasis placed on obtaining uplinks spread throughout the day. In 2006, tags were duty cycled to transmit daily for the first 30 days then every 3-5 days, with the first two tags transmitting six hours a day and the second two transmitting seven hours a day, during time blocks corresponding to the times with the highest frequency of satellite overpasses. The tags had a theoretical battery life of at least 22,000 transmissions and duty cycling was such that they could continue to transmit for up to 180 days if the tags remained attached. Several changes were made in 2008 in response to new information from the PTT manufacturer and information gained from deployment records of the 2006 tags. Estimates of theoretical battery life in 2008 were increased to 35,000 transmissions. Given the relatively short duration of signal contact in 2006, 2008 tags were set to transmit daily for the first 60 days and every other day thereafter. Repetition rate (minimum time between subsequent transmissions) was decreased from 45s in 2006 to 15s in 2008, based on surfacing information obtained from time-depth recorders

deployed on beaked whales in 2006 (Baird et al. 2008a) and from the average number of uplinks per overpass from the 2006 tags. This change was designed to allow more uplinks per overpass, and thus potentially better location qualities. In 2008, to increase the number of potential locations each day, tags transmitted for 12 hours per day during three four-hour time blocks corresponding to the times with the highest frequency of satellite overpasses. In 2008 tags were programmed to transmit from 0300-0700 HST, 0900-1300 HST, and 1400-1800 HST.

Field work

Field work was conducted off the west coast of the island of Hawai‘i during November and December 2006, August 2007, and April and May 2008. A 8.2 meter Boston Whaler with a custom-built bowsprit was used for tagging. Searches were conducted in a non-random, non-systematic manner, with effort concentrated primarily in areas where conditions were conducive to spotting odontocetes and which could be readily reached by small boat from Honokohau Harbor.

Tags were deployed from an estimated range of 2.5 - 10 m using a Dan-Inject JM Special 25 (Børkop, Denmark) pneumatic projector with a modified arrow to hold the tag in flight. Tags were attached to the dorsal fin or dorsal ridge area, to take advantage of the strong connective tissue in that region and provide the best location for a clear transmission of the signal when the animal surfaced. Both the target animal and other individuals within the groups were photographed before and during tagging, and the sex of tagged whales was determined using the presence/absence of erupted teeth and scarring patterns. Photographs of tagged whales and companion animals were compared to photo-identification catalogs (McSweeney *et al.* 2007) to determine sighting history.

Data acquisition and processing

PTT transmissions are received by a series of NOAA Polar Orbiting Environmental Satellites (POES) (Argos user manual¹). Each satellite has a visible circular ‘footprint’ of about a 5,000 km-diameter in which it can see transmitting tags. The polar orbiting path of the satellites means that there are fewer overpasses as you get closer to the equator. In Hawai‘i in 2008 for example, the total number of satellite passes over the region were between 15-18 times per day. The PTT’s signal can only be received by the satellite during its overpass (between 8 and 15 minutes, average of 10), but is dependent on the elevation of the overpass above the horizon. The path of each overpass is not the same elevation above the eastern or western horizon. As a result, some overpasses are of shorter duration and consequently are so low in the horizon that the calculation of accurate location, based on the Doppler-shift principle, is compromised. Within a single overpass, a satellite must receive at least two uplinks from the PTT in order to determine a location, and to improve the accuracy of the location these must be spread out across the duration of the overpass. The more messages received and the longer spread between first and last message during the overpass generally leads to a higher location class (see below).

Transmitter locations received from Argos include a location class (LC) indicating degree of accuracy in the reported position based both on the number of messages received in a single overpass, and the temporal spacing of those messages. LC 3, 2, and 1 each have a set estimate of accuracy; whereas LC 0, A, B, and Z are undefined. Therefore, all locations must be assessed for plausibility before being used to estimate an animal’s location (*e.g.* Argos User Manual, 2007,

¹ Available from <http://www.argos-system.org/manual>

Harris *et al.* 1990, Mate *et al.* 1997, Vincent *et al.* 2002). We used the Douglas Argos-Filter², version 7.06, to assess locations for plausibility, using two independent methods (distance between consecutive locations, and rate and bearings among consecutive movement vectors). The Douglas filter incorporates several user-defined variables in the filtering process, including maximum-redundant distance (Maxredun -- temporally near-consecutive points within a defined distance are kept by the filter), maximum sustainable rate of movement (Minrate – speed in km/hr based on a reasonable rate of movement sustainable for several hours or days), location classes to keep (the filter will automatically keep all LC's of this defined class and higher), and Ratecoef. The Ratecoef assesses locations by looking at the angle created by three subsequent points, and is based on the concept that the animal is unlikely to leave one location, travel towards a subsequent location, and then immediately move back to the same location again. The filter passes or fails a point depending on the distance between locations (Fig. 2). Larger angles become suspect (i.e. the filter becomes more conservative) as Ratecoef increases.

The maximum-redundant-distance was set at 3km (two or more near-consecutive points within 3 km of each other are kept by the filter). The maximum sustainable rate of movement was set at 15 km/h for 2006 data and 10 km/h for 2008 data, given the differences in transmission schedules between the two years leading to a larger number of locations, and a higher percentage of better LC's, in 2008. These rates of movement are much higher than that reported by McSweeney *et al.* (2007) while actively tracking tagged whales (minimum rate of horizontal movement for Blainville's beaked whales of 1.94 km/h, SD = 0.94), but faster rates of movement are likely attainable for at least short periods of time, and the higher rate helps retain

² Available from <http://alaska.usgs.gov/science/biology/spatial/douglas.html>

points which have spuriously large movement rates between them due to short amount of time between uplinks to the satellite. All Argos locations of class LC2 and better were automatically retained. Bearings between locations (Ratecoef) were assessed to further eliminate outlying points using a rate of coefficient of 15 in 2006 and 25 in 2008.

The cumulative distance covered, and the straight-line distance from deployment, were calculated using all filtered locations. Rates of horizontal movement were calculated among consecutive locations with time intervals from 4 to 24 hours; rates calculated from shorter and longer intervals were excluded. Due to sometimes low location quality and the steep near-shore bathymetry, some locations plot on land. These locations were retained for the purposes of calculating rates of movement, but were omitted for bathymetry calculations. Depth, slope, and distance to shore were extracted for all filtered locations by overlaying point location data on a bathymetric raster surface in ArcGIS Version 9.2 (ESRI, Redlands, California, USA). Depth (in meters) and slope values (in degrees) were transferred to point locations using the 'intersect point tool' in Hawth's analysis tools (Beyer 2004). A 50 m x 50 m multibeam synthesis bathymetry model from the Hawai'i Mapping Research Group³ was used. The model had areas of no data, so the grid was overlaid on a 3-arc second (90 m x 90 m) U.S. Coastal Relief Model bathymetry from the National Geophysical Data Center⁴ to provide 90 m resolution data where 50 m resolution data were absent. Due to the known error with satellite locations (true positions of the animal are likely within several kilometers of location depending on location class), we report the median values of our analysis to minimize the effect of outliers.

³Available from <http://www.soest.hawaii.edu/HMRG/Multibeam/index.php>

⁴Available from <http://www.ngdc.noaa.gov/mgg/coastal/coastal.htm>

Results

Three Blainville's beaked whales, two adult males and one adult female, were tagged in three different encounters during November and December 2006 with tags functioning from 15-23 days (Table 1). Three Cuvier's beaked whales were tagged, one (an adult female) in November 2006 and two (one adult female, one adult male) in the same group on May 5, 2008. Locations from the Cuvier's tagged in 2006 were only received for two days, while in 2008 locations were received for the adult female (HIZc027) over a 13 day period, and for the adult male (HIZc008) over a 24 day period (Table 1).

Blainville's beaked whales

Comparisons of photographs of the two tagged adult males (catalog numbers HIMd118 and HIMd120) and companion whales to our photo-identification catalog (McSweeney *et al.* 2007) indicated they had not been previously identified in the area, but both were associated with previously identified adult females. Comparison of photographs of the tagged adult female (HIMd001) indicated she was first identified in the study area in 1991, and had been previously documented 14 times (McSweeney *et al.* 2007). Both HIMd118 and HIMd120 were tagged in the northern portion of our study area and the tags transmitted over the course of 23 and 16 days respectively, though uplinks were not received on all days (Table 1). After remaining in the area of tag deployment for several days, both animals moved north out of our study area and into the Alenuihaha Channel, with HIMd120 spending 3 days on the northeast side of the island before moving back to the west (Fig. 3). Despite cumulative distances traveled of 410.4 km and 283.8 km, both animals remained close to the deployment location, with a median straight-line distance from tagging site of 32.0 km (range = 3.9 – 74.1) and 53.9 km (range = 20.0 – 85.3) for HIMd118 and HIMd120, respectively (Table 2). Excluding locations from the first three days,

there was no relationship between the number of days since tagging and the distance from tagging (regression, HIMd118, $r^2 = 0.002$, $p = 0.85$; HIMd120, $r^2 = 0.001$, $p = 0.90$).

HIMd001 was tagged at the very southern portion of our study area in a group with four other animals, three of which had been previously identified. Similar to the localized movements of HIMd118 and HIMd120, HIMd001 spent 11 days moving in a localized area off the southwest portion of the island, traveling no further than 37.0 km (median = 11.3, range = 2.7-37.0) from the deployment location. On day 12, HIMd001 traveled to the north out of the study area and into the Alenuihaha Channel, traveling a minimum cumulative distance of 102 km in 2 days. HIMd001 moved a maximum of 139.1 km away from deployment location by day 13 (Fig. 3). There was a strong positive relationship between the number of days since deployment and the distance from deployment taking into account movements after day three (regression, $r^2 = 0.726$, $p = 0.0004$). Minimum cumulative distance covered during the last five days of tracking represented 307 of the total 495.6 kilometers traveled (Table 2).

All three animals utilized similar depths and remained closely associated with the island of Hawai'i (Table 3). The degree of bathymetric slope over which the animals spent their time differed significantly among individuals (Kruskall-Wallis one-way ANOVA, $P < 0.001$). This difference was due to the degree of slope used by HIMd001 being significantly greater than that of both HIMd118 and HIMd120 (Mann-Whitney U test; $P < 0.001$, $P = 0.002$ respectively). Despite the differences in slope use among individuals, plots of the positions overlaid on bathymetric data indicated that all three animals remained associated with the slope of Hawai'i (Fig. 3).

Cuvier's beaked whales

Comparisons of identification photographs of the tagged Cuvier's beaked whales indicated that all three had been previously documented in the study area. HIZc012, the female tagged in 2006, had previously been seen in 2004 and twice before in 2006. HIZc027, the female tagged in 2008, had been documented in 2005, 2006, and 2007, while HIZc008, the male tagged in 2008, had been documented in 2004 and three times in 2006, although not previously associated with HIZc027. All three whales were tagged near the middle of our study area. Only three locations from the Cuvier's beaked whale tagged in 2006 were received and are not considered here further. The two individuals tagged in the same group in May 2008 spent the first four days within our study area before moving out of the study area to the south (Fig. 4). Based on proximity of locations that were closely spaced in time (0-168 min, median = 0 min, $n = 9$), the two whales likely remained together for the first eight days after the tags were attached. Distance among these nine pairs of locations over the eight day period ranged from 0.76 to 12.98 km (median = 3.4 km). Given the variable location qualities (and thus associated error with locations), and the fact that seven of the nine pairs of locations were obtained within two minutes of each other, it is likely the whales were much closer and surfacing in synchrony.

In general, the two Cuvier's beaked whales tagged in 2008 both remained associated with the island of Hawai'i, although both moved out of our study area during the period transmissions were received (Fig. 4). HIZc008 did leave the slope of the island during the tracking for a period of approximately 56 hours (out of ~537 hours of total tracking time) before returning to the slope of the island. Maximum distance to shore during this time was 54.8 km (median distance for entire tracking period = 25.8, Table 3). Although cumulative distance covered during the duration of tag transmissions were 316.4 km and 540.9 km, for HIZc027 and HIZc008,

respectively (Table 2), distances of locations from the original tagging locations ranged from 3.1 to 65 km (median = 50 km) and from 15 to 89 km (median = 54.5 km), for the two individuals. Excluding the first three days of locations after tag attachment, there was no significant relationship between the distance from deployment and the number of days since deployment (HIZc027, $r^2 = 0.106$, $p = 0.10$; HIZc008, $r^2 = 0.009$, $p = 0.58$).

Discussion

Although the durations of signal contact were relatively short, for Blainville's beaked whales 80 locations were obtained over 45 days from individuals in three different groups, providing more information on the movements of individuals of this species than has been obtained from any other method. By comparison, in 202 days of field effort over five years, McSweeney et al. (2007) documented just 19 sightings of Blainville's beaked whales in the same study area, with the disparity due both to the difficulty of detecting this species, even during good sea conditions, and their low density in the study area. Movements revealed by the satellite tag data support the supposition that both the Blainville's and Cuvier's beaked whale populations are island-associated, and helps extend our knowledge of habitat use and distribution of these species outside our study area. For both species, movement rates were low (Table 2), and despite cumulative distances covered over the duration of the tag transmissions of several hundreds of kilometers, the individuals remained relatively close to the original sites of tagging. For Blainville's beaked whales, HIMd120 moved furthest from shore of the three animals (Table 3), but still remained within a median distance of 27.7 km (range = 11.3 – 46.7). Throughout, the animals showed a distinct association with the slope of the island of Hawai'i (Fig. 3).

While some locations for Blainville's beaked whales were closer to the islands of

Kaho‘olawe or Maui, at no point during the tracking period did the whales move away from the slope of the island of Hawai‘i or towards other nearby bathymetric features. Even when HIMd001’s rate of movement more than doubled during the last 4 days of tracking, movements were confined to the slope of Hawai‘i (Fig. 3). These movements are consistent with those found by McSweeney *et al.* (2007) which show that Blainville’s beaked whales move throughout the study area and are not associated with a specific area or feature on the island of Hawai‘i. While the Cuvier’s beaked whale HIZc008 did move away from the slope of the island for two days (<10.5% of total tracking time), all other locations and those of HIZc027 remained associated with the island of Hawai‘i, also indicating a high level of site fidelity to the island of Hawai‘i (Fig. 4).

Habitat use revealed by the satellite data fits well with that found by visual surveys. The median calculated depth of satellite-derived locations for the tagged Blainville’s beaked whales (1,218 m, $n = 3$), and Cuvier’s beaked whales (2,561 m, $n = 2$) was similar to the mean sighting depths (922m, 2,029 m, respectively) of these species encountered during previous studies (Baird *et al.* 2006), and depth differences between the Blainville’s and Cuvier’s beaked whales (Fig. 5) were consistent with information from sighting surveys. The greater sighting depths documented from satellite tagged individuals (Fig. 5) likely reflects the bias from sighting surveys towards shallower waters of the study area. The significant difference in slope of locations among HIMd118, HIMd120 and HIMd001 indicated that slope angle does not likely influence prey availability or foraging strategies for this population. What little is known about diet indicates that Blainville’s beaked whales in other regions consume primarily squid and small fish (MacLeod *et al.* 2003). The significant difference in slope between HIMd001 and the two adult males may be attributed to a preference by HIMd001 for the southwestern side of the island

(which has a steeper slope) as suggested by the sighting history for that individual (McSweeney *et al.* 2007), and not necessarily a preference for a steeper slope.

The association with the island of Hawai‘i may be due to a local increase in productivity resulting from island-associated upwelling caused by strong local trade winds and island topography (Seki *et al.* 2001). Such associations with the main Hawaiian Islands have been documented for several species of cetaceans that feed in near-surface waters, presumably taking advantage of increased availability or predictability of prey (Baird *et al.* 2008b, 2008c; Benoit-Bird and Au 2003; McSweeney *et al.* in review). How such upwelling would increase the productivity or availability of the deep water prey of beaked whales is unknown however.

For Blainville’s beaked whales McSweeney *et al.* (2007) reported a higher re-sighting rate of adult females than adult males, despite almost equal numbers of each sex documented. The presence of two previously identified females associated with HIMd118 and HIMd120 at the times of tag deployments is consistent with the higher re-sighting rates and stronger site-fidelity of adult females to our study area.

The application of small dorsal-fin attached satellite tags allowed us to extend our knowledge of the study animals’ range and movement patterns. Previous boat-based studies of beaked whales have not been conducted in the Alenuihaha Channel due to consistently high sea states, and logistical challenges associated with small boat surveys. Prevailing weather conditions in the Alenuihaha Channel are generally very windy with large seas that increase in steepness as they are funneled between the islands of Maui and Hawai‘i. Aerial surveys conducted in the channel during the 2006 RIMPAC exercises reported the mean sea state as a

Beaufort 4-5 (Mobley 2006). Barlow et al. (2006) demonstrates a low encounter rate for *Mesoplodon* as sea states increase above a Beaufort 3, with more than a 10-fold reduction in encounter rates from a Beaufort 0-1 to a Beaufort 5. For these reasons, neither boat-based nor aerial-based visual observations (a key marine mammal mitigation measure used in conjunction with navy training exercises (Anonymous 2007)), would be likely to detect many of the beaked whales in this area.

Movements revealed by satellite tracking indicate that the range of at least some members of the population of Blainville's and Cuvier's beaked whales extends outside our study area and into the Alenuihaha Channel and the east side of the island, with HIMd118 and HIMd120 spending much of their time in or adjacent to the Channel (Fig. 3). As part of the Hawai'i Range Complex, all of the waters around the Hawaiian Islands may be used by naval forces for training exercises, and antisubmarine warfare exercises are known to occur in the Alenuihaha Channel (Anonymous 2007). These exercises include the use of mid-frequency active (MFA) sonar, and in the case of choke-point exercises, may include several simultaneous sources of MFA sonar. Several beaked whale strandings world wide have been linked to the use of naval sonar (*e.g.*, Simmonds and Lopez-Jurado 1991, Balcomb and Claridge 2001, Jepson et al. 2003, Cox et al. 2006).

Coupled with evidence of site-fidelity, association of individuals over time (McSweeney et al. 2007), and small population estimates (Baird et al. unpublished), these are likely small distinct groups of island-associated beaked whales. The re-sighting history of all three tagged Cuvier's beaked whales, and inclusion of at least one previously identified individual in each of the three Blainville's groups indicates the tagged animals are part of the island-associated

populations showing long-term site-fidelity. Small isolated populations are likely at greater risk from anthropogenic impacts (Weilgart 2007, Bräger et al. 2007). It follows that both Blainville's and Cuvier's beaked whales from these populations are likely to be subjected to a higher degree of population-level effects if exposed to anthropogenic impacts.

While these impacts may include fisheries interactions, environmental degradation (oil or chemical spill, depletion of primary food source), ship-strikes, and other anthropogenic noise sources, the potential impact of MFA sonar is likely high given the overlap in naval training areas and whale movement patterns. The Hawai'i-based longline fishery operates in waters greater than 45 km from shore, and a single mortality of Blainville's beaked whale has been reported associated with the fishery (Forney and Kobayashi 2007). Within the known range of these populations there are no longline fisheries, although there are a number of troll fisheries that may interact with cetacean populations (Nitta and Henderson 1992). No major shipping lanes are routed through this area, though large cruise ships do routinely visit the island and local tug and barge traffic transit the channel and may present a risk from ship strikes, petroleum spills or other waste.

Application of these types of satellite tags show promise for the study of small to medium-sized cetaceans where movement patterns and habitat use are difficult to assess through traditional means. Understanding these movements is critical for discerning stock structure and home ranges, particularly for species that may be at greater population-level risk from anthropogenic sources due to population size and ecology.

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Literature Cited

- ANDREWS, R.D., R.L. PITMAN, AND L.T. BALANCE. 2008. Satellite tracking reveals distinct movement patterns for Type B and Type C killer whales in the southern Ross Sea, Antarctica. *Polar Biology*.
- ANONYMOUS. 2007. Hawaii Range Complex Draft Environmental Impact Statement / Overseas Environmental Impact Statement (Revision 1, July 2007). Available from <http://www.govsupport.us/navynepahawaii/EIS.aspx> accessed January 2008.
- BAIRD, R.W., D.L. WEBSTER, D.J. MCSWEENEY, A.D. LIGON, G.S. SCHORR, AND J. BARLOW. 2006. Diving behaviour of Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales in Hawai'i. *Canadian Journal of Zoology* 84:1120-1128.
- BAIRD, R.W., D.L. WEBSTER, G.S. SCHORR, D.J. MCSWEENEY AND J. BARLOW. 2008. Diel variation in beaked whale diving behavior. *Marine Mammal Science* 24:630-642.
- BAIRD, R.W., D.L. WEBSTER, S.D. MAHAFFY, D.J. MCSWEENEY, G.S. SCHORR AND A.D. LIGON. 2008b. Site fidelity and association patterns in a deep-water dolphin: rough-toothed dolphins (*Steno bredanensis*) in the Hawaiian Archipelago. *Marine Mammal Science* 24:535-553.

- BAIRD, R.W., A.M. GORGONE, D.J. MCSWEENEY, D.L. WEBSTER, D.R. SALDEN, M.H. DEAKOS, A.D. LIGON, G.S. SCHORR, J. BARLOW, AND S.D. MAHAFFEY. 2008c. False killer whales (*Pseudorca crassidens*) around the main Hawaiian Islands: long-term site fidelity, inter-island movements, and association patterns. *Marine Mammal Science* 24:591-612.
- BALCOMB, K.C. AND D.E. CLARIDGE. 2001. A mass stranding of cetaceans caused by naval sonar in the Bahamas. *Bahamas Journal of Science* 5:1-12.
- BARLOW, J. M.C. FERGUSON, W.F. PERRIN, L. BALLANCE, T. GERRODETTE, G. JOYCE, C.D. MACLEOD, K. MULLIN, D.L. PALKA, AND G. WARING. 2006. Abundance and densities of beaked and bottlenose whales (family Ziphiidae). *Journal of Cetacean Research and Management* 7:263-270.
- BENOIT-BIRD, K.J., AND W.W.L. AU. 2003. Prey dynamics affect foraging by a pelagic predator (*Stenella longirostris*) over a range of spatial and temporal scales. *Behavioral Ecology and Sociobiology* 53:364-373.
- BEYER, H.L. 2004. Hawth's analysis tools for ArcGIS®. Version 3.21 [computer program]. Available from <http://www.spatial ecology.com/htools> [accessed 12 September 2005].
- BRÄGER, S., S.M. DAWSON, E. SLOOTEN, S. SMITH, G.S. STONE, AND A. YOSHINAGA. 2002. Site fidelity and along-shore range in Hector's dolphin, an endangered marine dolphin from New Zealand. *Biological Conservation* 108:281-287.
- COX, T.M., T.J. RAGEN, A.J. READ, E. VOS, R.W. BAIRD, K. BALCOMB, J. BARLOW, J. CALDWELL, T. CRANFORD, L. CRUM, A. D'AMICO, G. D'SPAIN, A. FERNÁNDEZ, J. FINNERAN, R. GENTRY, W. GERTH, F. GULLAND, J. HILDEBRAND, D. HOUSER, T. HULLAR, P.D. JEPSON, D. KETTEN, C.D. MACLEOD, P. MILLER, S. MOORE, D. MOUNTAIN, D. PALKA, P. PONGANIS, S. ROMMEL, T. ROWLES, B. TAYLOR, P. TYACK, D. WARTZOK, R. GISINER, J. MEAD, AND L. BENNER. 2006. Understanding the impacts of anthropogenic sound on beaked whales. *Journal of Cetacean Research and Management* 7:177-187.
- FORNEY, K.A., AND D.R. KOBAYASHI. 2007. Updated estimates of mortality and injury of cetaceans in the Hawaii-based longline fishery, 1994-2005. NOAA Technical Memorandum, NMFSC-SWFSC 412. 30pp.
- HARRIS, R.B., S.G. FANCY, D.C. DOUGLAS, G.W. GARNER, S.C. AMSTRUP, T.R. MCCABE, AND L.F. PANK. 1990. Tracking wildlife by satellite: current systems and performance. US Fish and Wildlife Technical Report 30, 60pp.
- JEPSON, P.D., M. ARBELO, R. DEAVILLE, I.A.P. PATTERSON, P. CASTRO, J.R. BAKER, E. DEGOLLADA, H.M. ROSS, P. HERRAEZ, A.M. POCKNELL, F. RODRIGUEZ, F.E. HOWIE, A. ESPINOSA, R.J. REID, J.R. JABER, V. MARTIN, A.A. CUNNINGHAM, AND A. FERNANDEZ. 2003. Gas-bubble lesions in stranded

- cetaceans: Was sonar responsible for a spate of whale deaths after an Atlantic military exercise? *Nature* (London) 425:575-576.
- MATE, B.R., S.L. NIEUKIRK, AND S.D. KRAUS. 1997. Satellite-monitored movements of the northern right whale (*Eubalaena glacialis*). *Journal of Wildlife Management* 61:1393-1405.
- MACLEOD, C.D., M.B. SANTOS, AND G.J. PIERCE. 2003. Review of data on diets of beaked whales: evidence of niche separation and geographic segregation. *Journal of the Marine Biological Association of the United Kingdom* 83:651-665.
- MCSWEENEY, D.J., R.W. BAIRD, AND S.D. MAHAFFY. 2007. Site fidelity, associations and movements of Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales off the island of Hawai'i. *Marine Mammal Science* 23:666-687.
- MCSWEENEY, D.J., R.W. BAIRD, S.D. MAHAFFY, D.L. WEBSTER, AND G.S. SCHORR. In review. Site fidelity and association patterns of a rare species: pygmy killer whales (*Feresa attenuata*) in the main Hawaiian Islands. *Marine Mammal Science*.
- MOBLEY, J.R. 2006. Results of 2006 RIMPAC surveys of marine mammals in Kaulakahi and Alenuihaha Channels. Pages F-53-F-64 in *Hawaii Range Complex Draft Environmental Impact Statement/Overseas Environmental Impact Statement (Draft EIS/OEIS) Volume 3 of 3*. Available at <http://www.govsupport.us/navynepahawaii/EIS.aspx> {accessed January 2008}.
- NITTA, E.T. AND J.R. HENDERSON. 1993. A review of interactions between Hawaii's fisheries and protected species. *Marine Fisheries Review* 55:83-92.
- SEKI, P.M., J.J. POLOVINA, R.E. BRAINARD, R.R. BIDIGARE, C.L. LEONARD, AND D.G. FOLEY. 2001. Biological enhancement at cyclonic eddies tracked with GEOS thermal imagery in Hawaiian waters. *Geophysical Research Letters* 28:1583-1586.
- SIMMONDS, M.P. AND L.F. LOPEZ-JURADO. 1991. Whales and the military. *Nature* (London) 351:448.
- VINCENT, C., B. J. MCCONNELL, V. RIDOUX, AND M. A. FEDAK. 2002. Assessment of Argos location accuracy from satellite tags deployed on captive gray seals. *Marine Mammal Science* 18:156-166.
- WEILGART, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. *Canadian Journal of Zoology* 85:1091-1116.

Table 1. Details of beaked whale satellite tag deployments. Species: Md = *Mesoplodon densirostris*; Zc = *Ziphius cavirostris*. Photographs of tagged whales were compared to existing individual photo-identification catalogs to determine individual identification number. Sex (M = male; F = female) of tagged whales determined based on presence of erupted teeth and scarring patterns (see McSweeney et al. 2007). Total number of locations determined after processing data through the Douglas Argos-Filter, taking into account distance between consecutive locations and rate and bearings among consecutive movement vectors (see text for details).

Species	Individual identification number	Sex	Deployment date	Date of last location obtained	Duration of signal contact (days)	# of days locations were obtained	Total # of locations after filtering
Md	HIMd118	M	22 Nov 06	15 Dec 06	23	16	25
Md	HIMd120	M	22 Nov 06	08 Dec 06	16	14	20
Md	HIMd001	F	04 Dec 06	19 Dec 06	15	15	36
Zc	HIZc012	F	30 Nov 06	02 Dec 06	2	2	3
Zc	HIZc027	F	05 May 08	18 May 08	13	12	33
Zc	HIZc008	M	05 May 08	28 May 08	24	19	41

Table 2. Information on movements of individual beaked whales (see Table 1) determined using locations from satellite tags after processing through the Douglas Argos-Filter. Individual HIZc012 was omitted due to the small sample size. Cumulative horizontal distance moved was calculated using straight-line distances between all filtered locations. Rates of horizontal movement were calculated among consecutive pairs of locations with time intervals from 4 to 23 hours, thus sample sizes differ from Table 1. These represent minimum rates, as movements between locations were likely not always in a straight-line, and do not take into account vertical movements (diving).

Individual identification number	Cumulative distance moved (km)	Distance from tagging location (km) Median (max)	Rate of horizontal movement (km/h) Median (range) n
HIMd118	410.4	32.0 (74.1)	1.31 (0.5 – 3.25) 15
HIMd120	284.8	53.9 (85.3)	0.84 (0.2 – 2.83) 14
HIMd001	495.6	19.9 (139.1)	1.22 (0.33 – 8.06) 28
HIZc027	316.4	50.3 (65.1)	1.07 (0.11 – 3.97) 13
HIZc008	540.9	54.5 (88.9)	1.46 (0.16 – 4.17) 28

Table 3. Details of habitat use by individual beaked whales (see Table 1) based on a bathymetry analysis of filtered satellite location data using ArcGIS. The number of locations may be lower than in Table 1 due to a small number of locations plotting on land. See text for details of analysis.

Individual identification number	Number of locations	Depth (m) Median (Range)	Distance to Shore (km) Median (Range)	Slope (degrees) Median (Range)
HIMd118	25	1,108 (777 - 2,635)	21.2 (13.5 - 43.9)	2 (0 - 18)
HIMd120	20	1,218 (802 - 2,721)	27.7 (11.3 - 46.7)	4 (1 - 20)
HIMd001	36	1,455 (49 - 3,430)	7.1 (0.4 - 46.0)	11 (1 - 29)
HIZc027	30	2,253 (1,098 - 3,925)	11.4 (2.1 - 26.1)	11 (1 - 23)
HIZc008	40	2,870 (1,307 - 4,822)	25.8 (5.1 - 54.8)	8 (1 - 25)



Figure 1. Top. Photo of adult male Blainville's beaked whale (HIMd118) with satellite tag attached to the dorsal fin. Bottom. Photo of adult female Cuvier's beaked whale (HIZc027) with satellite tag on dorsal ridge immediately behind and below dorsal fin. Photos by R.W. Baird.

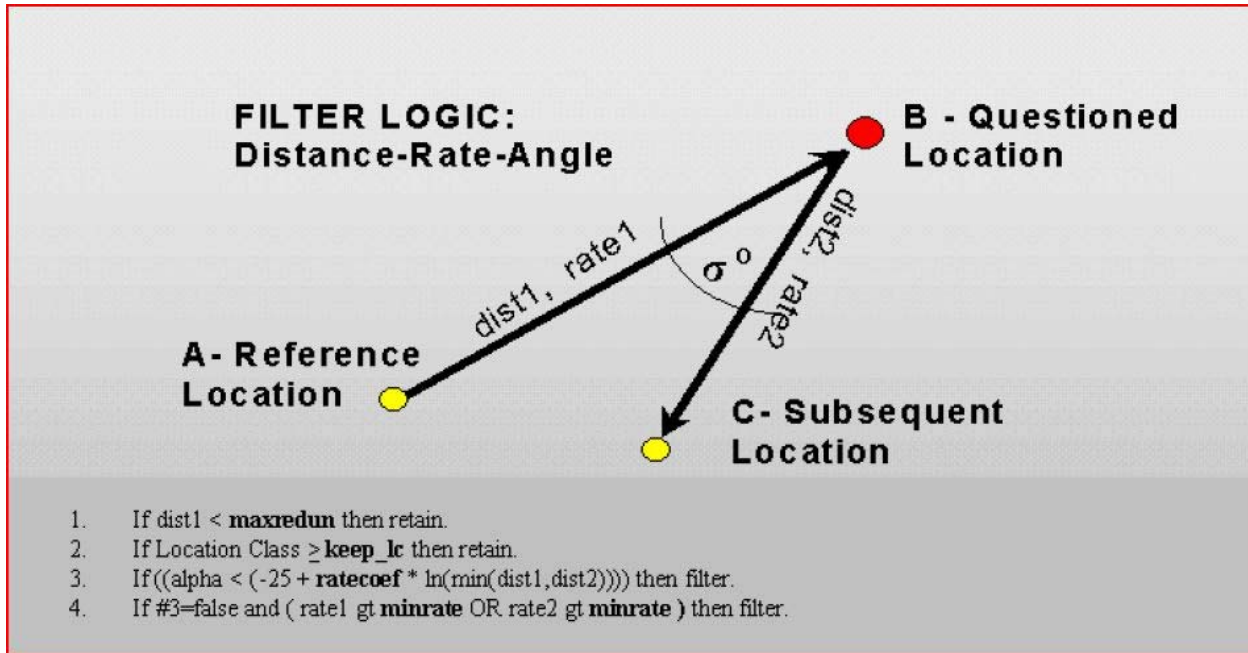


Figure 2. Illustration of the logic steps followed by the Douglas filter in relation to the Ratecoef portion of the filter (figure from the Douglas Argos-Filter, Version 7.03 manual, 2006). Maxredun is the maximum-redundant distance (temporally near-consecutive points within a defined distance that are kept by the filter). Keep_lc indicates the location classes to keep (the filter will automatically keep all LC's of this defined class and higher). Ratecoef is the rate of coefficient used in assessing locations, considering the angle created by three subsequent points, and is based on the idea that an animal is unlikely to leave one location, travel towards a subsequent location, and then immediately move back to the same location again. Minrate is the maximum sustainable rate of movement between consecutive points (based on a reasonable rate of movement sustainable for several hours or days).

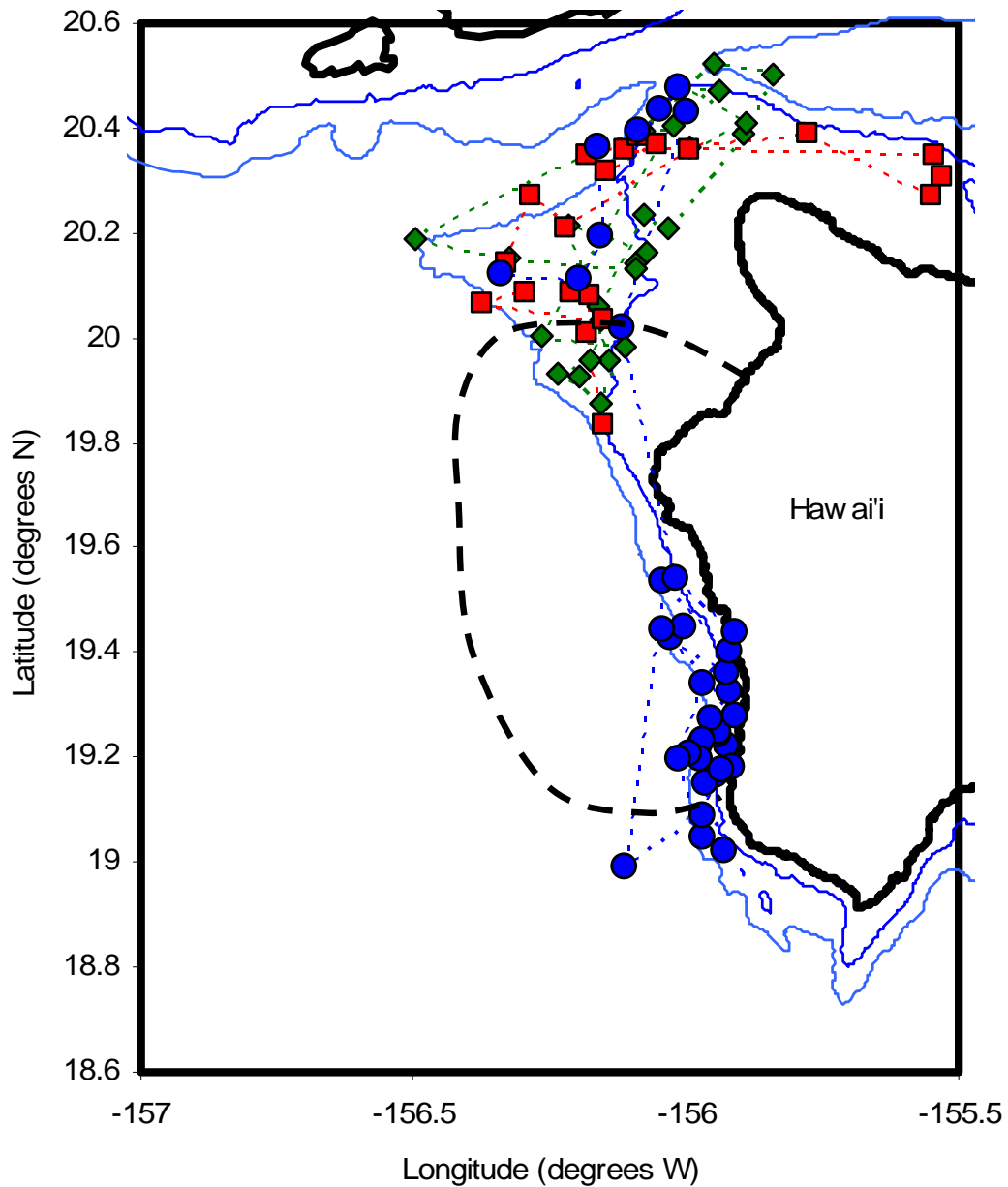


Figure 3. Satellite derived locations of Blainville's beaked whales after processing through the Douglas Argos-Filter, with dashed lines connecting consecutive locations. HIMd118 is indicated by green triangles, HIMd120 is indicated by red squares, and HIMd001 is indicated by blue circles. The approximate boundary of the study area is shown with a heavy black dashed line. The 1,000 m and 2,000 m depth contours are shown.

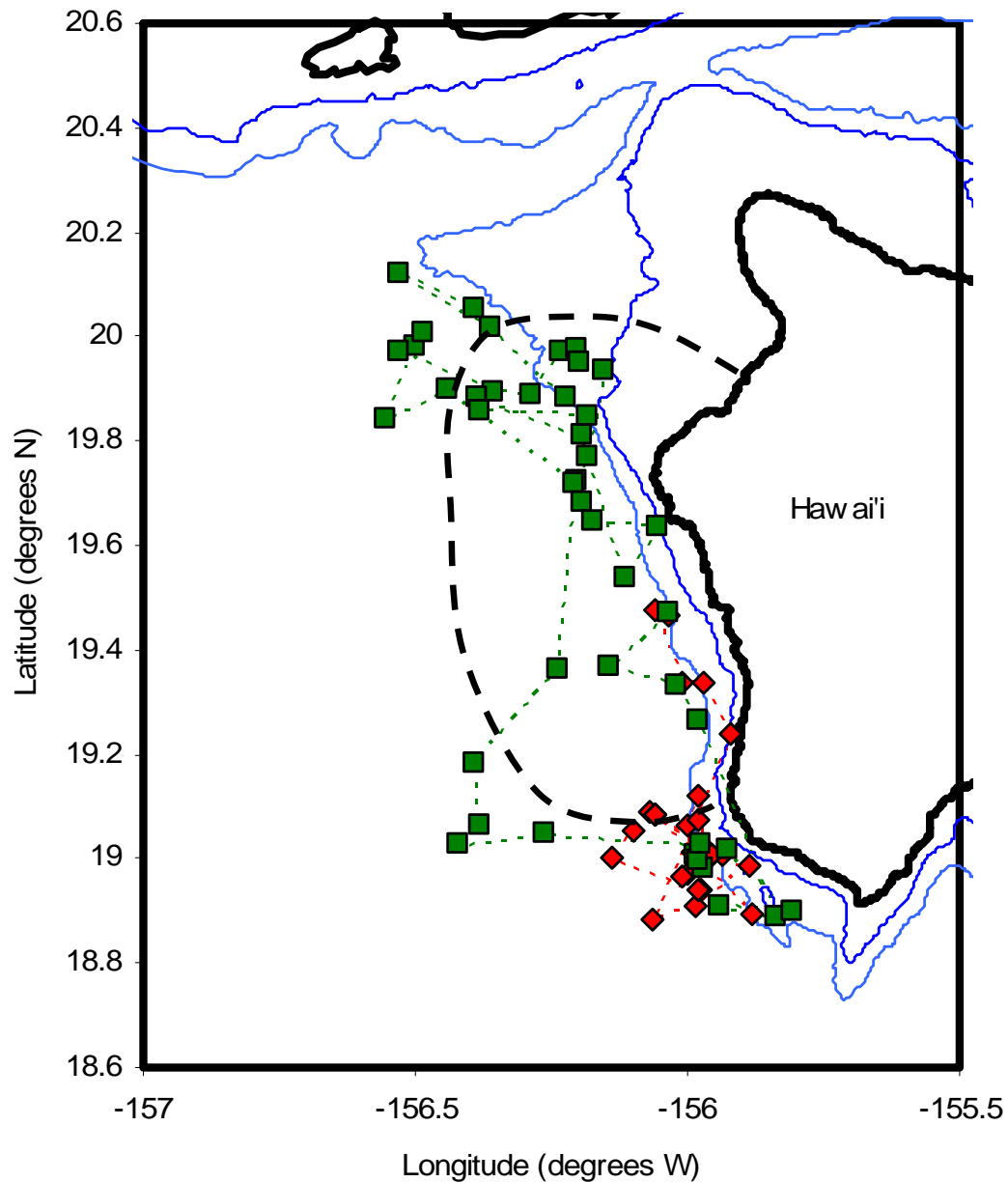


Figure 4. Satellite derived locations of Cuvier's beaked whales, May 2008, after processing through the Douglas Argos-Filter, with dashed lines connecting consecutive locations. Locations of the adult male (HIZc008) are represented with green squares while the adult female (HIZc027) are red diamonds. The approximate boundary of the study area is shown with a heavy black dashed line. The 1,000 m and 2,000 m depth contours are shown.

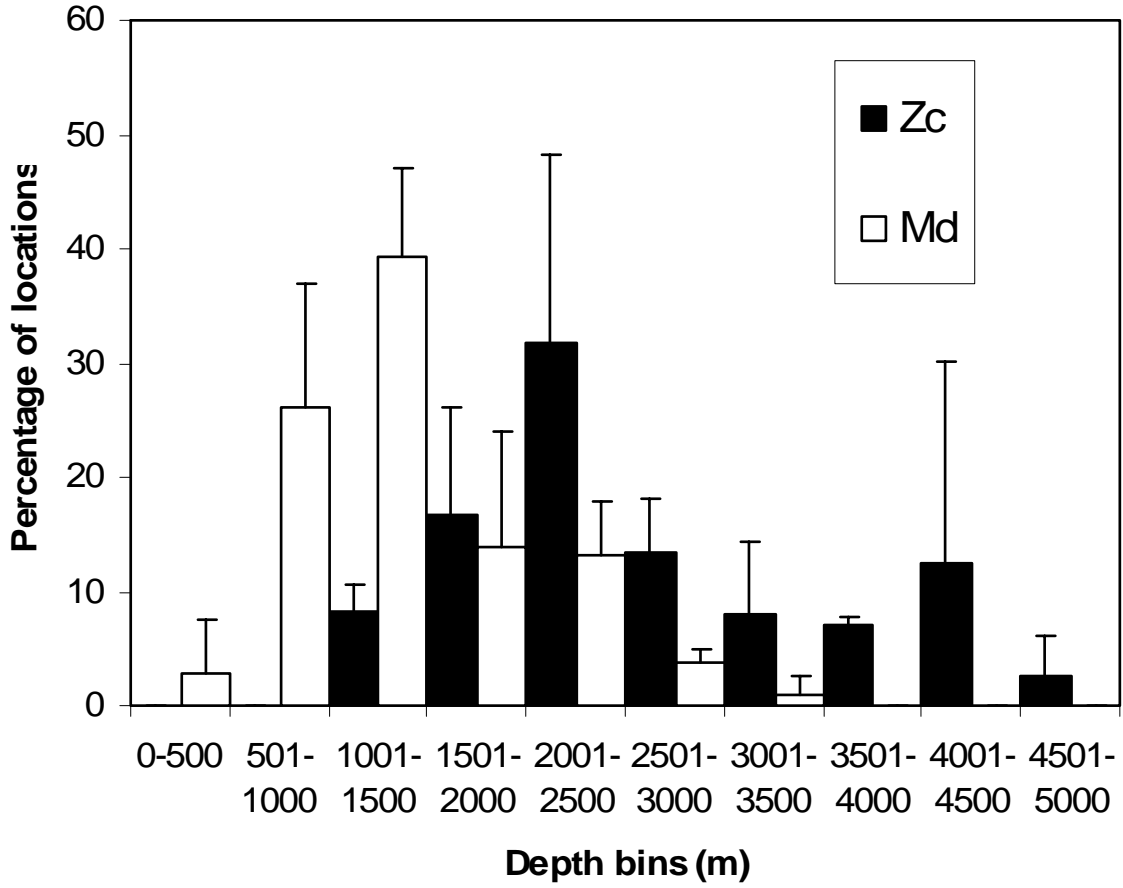


Figure 5. Depths of locations by species. For each species the average percentage of locations in each depth category is shown plus one standard deviation (Blainville's $n = 3$, Cuvier's $n = 2$).