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Analysis of the Spatial Distribution of Satellite-Tagged Sperm Whales (*Physeter macrocephalus*) in Close Proximity to Seismic Surveys in the Gulf of Mexico

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Abstract

Sperm whales (*Physeter macrocephalus*) in the northern Gulf of Mexico were tagged with Argos satellite-monitored radio tags during June to August of 2002 to 2005. Locations from 51 tagged whales were compared with locations of active airgun arrays from seismic surveys to determine if there was evidence of horizontal avoidance of the arrays. Only whale locations in close proximity (within 50 km) to an active survey were considered under the assumption that avoidance patterns would be more detectable closer to the sound source. A total of 122 locations from 26 whales occurred during or within 30 min of seismic survey lines with a calculated minimum distance of 5 km from an array. The distribution of the whale locations, relative to the airgun arrays, was analyzed to determine possible departures from complete spatial randomness. A test for bivariate uniformity ($p > 0.10$) and a modified quadrat count test ($p = 0.85$) produced no evidence of departures from complete spatial randomness. There was no evidence of directedness of orientation of the whale to the airgun array heading (Rayleigh test, $p > 0.70$). This analysis suggests that distances and orientations between whales and active seismic vessel airgun arrays at this scale appear to be randomly distributed with no evidence of horizontal avoidance. This is the first study to systematically examine the spatial distribution of sperm whales in relation to seismic survey activity from a satellite-tracking perspective. Additional studies using higher resolution data are needed to better understand how sperm whales may respond at finer scales.

Key Words: Argos satellite telemetry, Gulf of Mexico, airgun, seismic survey, anthropogenic noise, sperm whale, *Physeter macrocephalus*

Introduction

The sperm whale (*Physeter macrocephalus*) is classified as "Endangered" under the U.S. Endangered Species Act and is the most common species of large whale in the northern Gulf of Mexico (GOM) (National Marine Fisheries Service [NMFS], 2009). Sperm whales are found year-round on the northern GOM continental slope (Davis et al., 1998; Baumgartner et al., 2001) with an estimated abundance of about 1,300 (Waring et al., 2006) and include a resident breeding population within 100 km of the Mississippi River Delta (Davis et al., 2002). This area is also of interest to offshore oil industries and is extensively surveyed by seismic vessels using airgun arrays (Minerals Management Service [MMS], 2004). Seismic surveys produce sounds that can travel over several hundreds of kilometers (Gordon et al., 2004), raising concerns about the effects of airgun noise from seismic surveys on sperm whale behavior (NMFS, 2009).

Some behavioral responses of sperm whales to various anthropogenic noises have been documented. A decrease in sperm whale acoustic activity was correlated with an increase in total vessel activity in the GOM (Ioup et al., 2005). Controlled exposure experiments using naval sonar found horizontal avoidance and changes in diving and foraging behavior (Miller et al., 2012; Sivle et al., 2012). Results from studies examining behavioral responses specifically to seismic surveys, however, have been inconsistent. For example, a decrease in sperm whale presence around seismic vessels was reported in the GOM (Mate et al., 1994). A decrease in foraging behavior was also reported for sperm whales tagged with acoustic and movement recorders during an airgun exposure experiment in the GOM, though no horizontal avoidance was detected (Miller et al., 2009). Marine mammal observers aboard seismic vessels in the GOM reported that sperm whales were significantly further away from airgun arrays when arrays were at full power as compared to being silent (Barkaszi et al., 2012).

Conversely, a 10-mo study conducted off Angola during seismic explorations found that encounter rates (sightings/h, N = 124 sightings) of sperm whales were not significantly different between silent and active airgun status (Weir, 2008). However, the mean distance (2,594 m) of whales to seismic vessels during airgun operation was greater than when not firing, although the difference was not statistically significant (Weir, 2008). Stone & Tasker (2006) found no significant differences between sighting rates, distances to seismic vessels (median closest distance of approach to airgun array was < 2 km), and orientations of sperm whales to the arrays during active and inactive periods of seismic surveying in UK waters. Lastly, sperm whales in northern Norway that were exposed to airgun noise from a seismic survey vessel did not show any observable avoidance or change in acoustic behavior during feeding dives in response to the noise (Madsen et al., 2002). (For a more thorough review of studies involving sperm whales and airgun noise, see NMFS, 2009.)

From 2002 to 2005, researchers from Oregon State University tagged sperm whales in the GOM with Argos satellite-monitored radio tags as part of the Sperm Whale Seismic Study (SWSS) supported by MMS, now the Bureau of Ocean Energy Management (BOEM), of the U.S. Department of the Interior. One objective of SWSS was to look for any changes in the behavior of sperm whales when subjected to man-made noise, specifically noise produced by airguns during seismic surveying (Jochens et al., 2008). Although the tagging study was designed to describe long-term (months to seasonal) movements of sperm whales, the opportunistic proximity of tagged whale locations to seismic vessel activity provided a means to explore possible behavioral responses to airgun noise.

The aim of this study is to investigate the spatial distribution of tagged sperm whales in close proximity (within 50 km) to active seismic arrays in the GOM for evidence of horizontal avoidance.

Methods

As part of SWSS, 51 sperm whales were tagged with satellite-monitored radio tags in the GOM during the summers of 2002 to 2005. The implantable tags, 49 Telonics ST-15 and 2 Telonics ST-21 UHF transmitters, were housed in stainless steel cylinders, 19 cm long by 1.9 cm diameter (Mate et al., 2007; Jochens et al., 2008), and were deployed with an air-powered applicator (Heide-Jørgensen et al., 2001). The locations of the tags were recovered using the Argos Data Collection and Location System. The tags transmitted only when above water and during specific hours of the day (duty cycles) that were chosen to maximize battery life and the probability that a satellite would be overhead. Telonics ST-15 tags deployed in 2002 transmitted during four 1-h periods each day for 90 d then switched to either four 1-h periods every third day or every fourth day. The ST-15 tags deployed in 2003 to 2005 only transmitted during four 1-h periods every fourth day. The two ST-21 tags transmitted during four 1-h periods every day.

The accuracy of an Argos location varies and is based on the number of transmissions from a tag received by the satellite while it is overhead. Each Argos location is assigned a quality index, termed *location class* (LC), with an estimated radius of error. LCs with the highest precision, LC 1, LC 2, and LC 3, have estimated errors such that 68% of calculated latitudes and longitudes are predicted to be within 500 to 1,500 m, 250 to 500 m, and < 250 m, respectively, of the true position (www.argos-system.org/manual/3-location/34_location_classes.htm); whereas lower-quality locations, LC 0, LC A, and LC B, have higher, or no, estimated errors. Though locations of lower quality were also recorded, only the highest-quality locations, LC 1, LC 2, and LC 3, were used in this study and were further filtered to remove those resulting in excessively high travel speeds. The 99th percentiles of sperm whale travel speeds between high-quality locations were calculated for locations < 12 h apart (6.0 km/h) and ≥ 12 h apart (3.5 km/h) and used as maximum speed thresholds. If the speed between sequential locations exceeded the threshold, the location that minimized total distance traveled from the previous location was retained, and the other was filtered out as contributing substantial error. Locations received during overlapping satellite orbits often result in very high speeds, so LC 1 locations within 20 min of higher-quality (LC 2 or LC 3) locations were also filtered out. If two LC 1 locations were within 20 min of each other, the location that minimized total distance traveled was retained, and the other was filtered out.

Data for 19,268 seismic survey lines, conducted in the northern GOM during the sperm whale tracking period (2002 to 2006), were provided by the International Association of Geophysical Contractors (IAGC). Data consisted of start-line and end-line times, and central shotpoint locations of the airgun array for those times. If a high-quality whale location occurred during a survey line, the location of the airgun array was estimated by interpolation for the time of the whale location, and the distance between the tagged whale and the array location was calculated. Whale locations within 30 min after the end of a survey line were also included, and distances were calculated using the end-line locations as these locations are temporally close enough to the survey to reflect any displacement that may have occurred.

An optimal approach to measuring horizontal displacement would require frequent, accurate locations for an individual whale tracked during one seismic line. Unfortunately, multiple locations close in time from the same whale during the same seismic line are extremely rare in this study due to tag duty cycles, satellite orbit frequencies, and sperm whale diving behavior. Additionally, Argos location errors cause challenges for analyses at small spatial scales. Therefore, the spatial distribution of tagged whale locations relative to airgun arrays was analyzed to determine possible departures from complete spatial randomness (CSR) that might result from horizontal avoidance. Only whale locations within 50 km of an active array were considered in this analysis under the assumption that detectable patterns would be more apparent closer to the sound source.

Under conditions of CSR, whale locations (latitude and longitude pairs) would have a bivariate uniform distribution. A test for bivariate uniformity (Chen & Hu, 2014) was performed to check for deviations from CSR. Because this test could not be modified to account for multiple locations from the same whale (pseudoreplication; Machlis et al., 1985), only the location closest to the airgun array for each whale was included in this analysis under the same assumption that departures from CSR would be more apparent closer to the sound source. The locations were translated to a common central point and rescaled to values 0 to 1 with the airgun array position at the center (0.5, 0.5).

Additionally, a modified quadrat count test (Diggle, 1983), though less powerful than the test for bivariate uniformity, was also performed to test for deviations from CSR because it allowed inclusion of multiple locations from the same whale through weighting by individual whale sample sizes. This test was performed by mapping the full dataset of locations less than 50 km from arrays onto a 50-km radius circle with the airgun array at the center. The circle was partitioned into five concentric rings of equal areas (modified quadrats). The number of locations in each quadrat was tallied, and the contribution of a count from a whale with more than one location was weighted by the number of locations for that individual.

Though there is no direct measurement of acoustic exposure to the whale, the duration of exposure to airgun noise was estimated as the length of time between the start of the seismic line and the whale location. Linear regression was used to test if the duration of exposure was correlated with the distance from the airgun array. A positive correlation would suggest evidence of horizontal avoidance if whales exposed to airgun noise for longer periods of time were found further from the airgun arrays.

To determine if the bearings of tagged whales relative to seismic vessel headings were significantly different from random, a Rayleigh test was performed (Batschelet, 1981) after weighting the contribution of an individual by the number of locations for that individual. If the minimum distance value from all locations was significantly further from the airgun array than expected, it could suggest horizontal avoidance on a spatial scale much closer than 50 km. A Monte Carlo test was used to compare the sample minimum distance to the distribution of minima from 1,000 sets of randomly generated locations within 50 km of a central point (Manly, 1997).

Results

After matching high-quality whale locations (N = 1,597) with seismic lines (N = 19,268; Figure 1), a total of 122 locations from 26 whales were identified as having occurred during or within 30 min within 50 km of estimated array locations (Figure 2; Table 1). The 26 individual whales had from 1 to 15 matches, and the minimum distance calculated from all matched locations was 5 km from the airgun array (Table 1). No significant deviation ($G2 = 0.00054, N = 26, p > 0.10$; Chen & Hu, 2014) from bivariate uniformity was detected in the locations closest to the array for each whale. There was no evidence of deviations from CSR using a modified quadrat count test (Pearson's Chi-squared test ($df = 4, N = 6$), $\chi^2 = 1.38, p = 0.85$) as the weighted counts within quadrats were not significantly different from the expected number of counts assuming CSR. There was also no evidence for a preferred orientation of sperm whales to the seismic array based on the relative bearings of whale locations to the seismic vessel headings ($p > 0.70$; Rayleigh test; Figure 3).

When compared to the distribution of the randomly distributed simulated datasets, the minimum distance from an airgun array of all matched locations (5 km; Table 1) was not significantly further away than expected ($p = 0.73$). The reported p value is the cumulative relative frequency of the values from the randomly generated datasets where 73% of the simulated datasets had minima further away than 5 km. The durations of exposure (lengths of time elapsed between the start of the seismic lines and whale locations) ranged from 1.7 to 7.5 h with a grand mean of 3.4 h (SD = 1.80 h). Linear regression comparing distances with exposure duration did not show any significant linear correlation ($p = 0.54$).

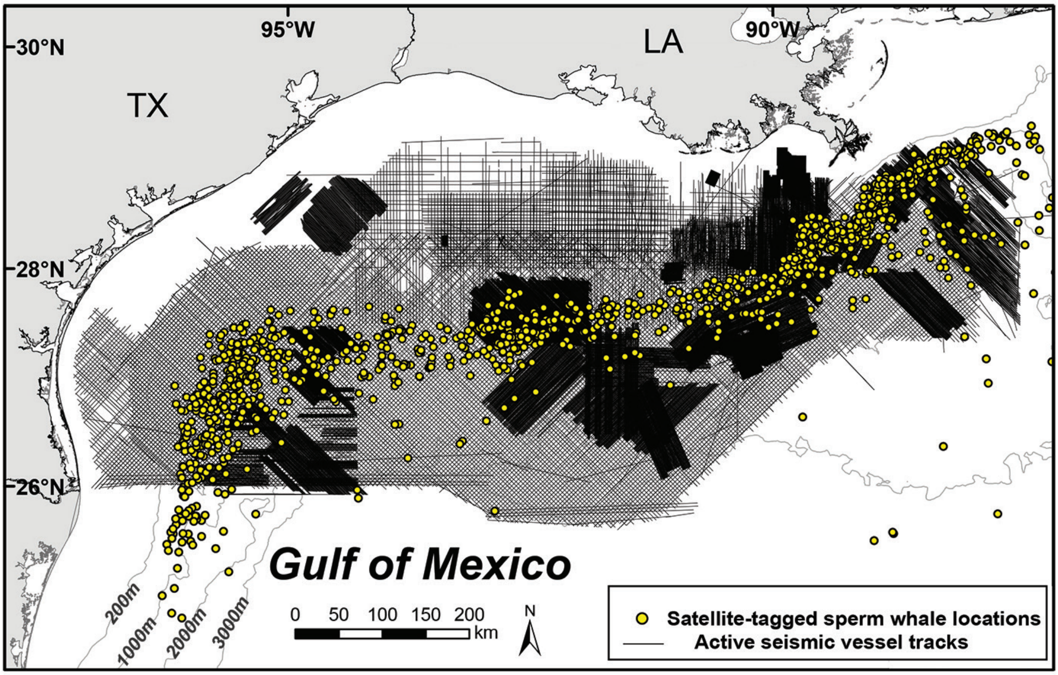

Figure 1. Satellite-tagged sperm whale (*Physeter macrocephalus*) locations and seismic survey lines in the northern Gulf of Mexico (GOM) from 2002 to 2006

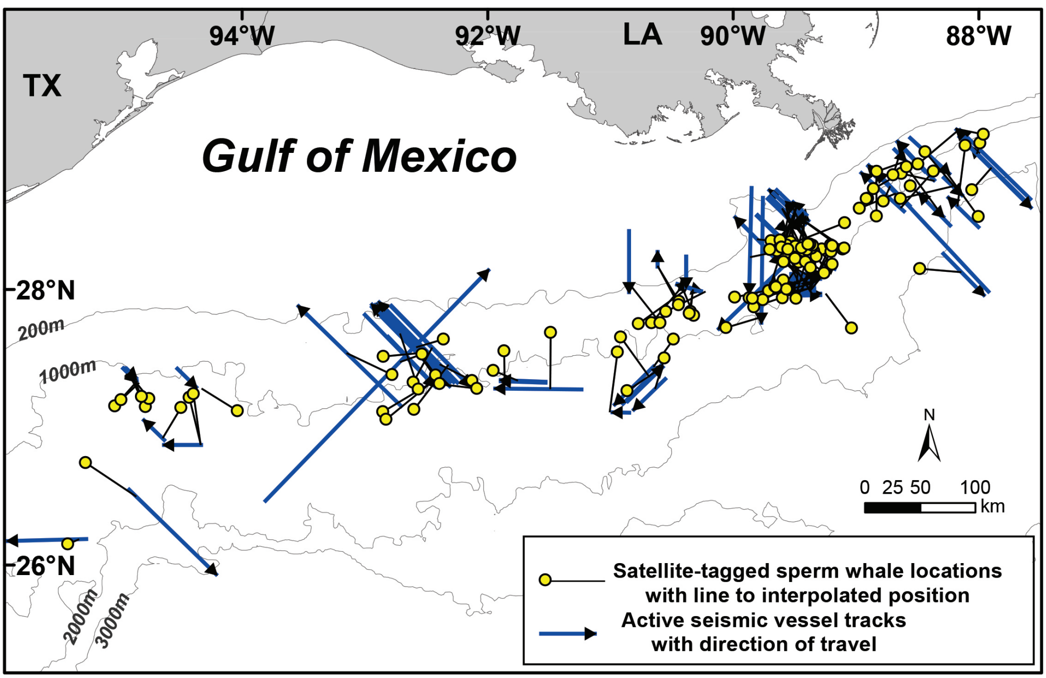

Figure 2. Satellite-tagged sperm whale locations recorded during or within 30 min after an active seismic survey and within 50 km of the airgun array. Locations of the arrays at the time of the whale location are interpolated from the survey start-line and end-line times. The distance from the whale location to the interpolated array position is shown in black, the seismic survey line is blue, and the arrow indicates the direction of travel.

Table 1. Number of locations per whale and descriptive statistics for distances between whale locations and interpolated seismic vessel airgun array locations for 26 satellite-tagged whales. Whale locations were during active seismic surveying or within 30 min of the end of the survey line and were less than 50 km from the airgun array.

Tag ID	Number of locations per whale	Mean distance (km)	Median distance (km)	Standard deviation (km)	Minimum distance (km)	Maximum distance (km)
2505647	3	35.2	34.7	11.97	23.5	47.4
2505649	8	25.2	26.4	13.15	5.0	43.2
2505650	5	24.7	18.3	16.51	10.0	49.2
2505654	3	31.5	33.0	3.73	27.2	34.2
2505655	9	34.3	33.4	9.14	22.5	47.6
2505660	3	39.4	45.2	10.14	27.7	45.4
2505669	10	36.3	36.8	10.29	13.5	49.2
2505670	2	29.4	29.4	6.79	24.6	34.2
2505678	2	45.2	45.2	3.60	42.6	47.7
2505685	2	31.8	31.8	19.26	18.2	45.5
2505701	15	29.8	26.3	12.33	9.7	49.7
2505709	9	29.8	25.0	13.50	7.1	48.3
2505710	10	30.5	31.2	7.16	20.7	43.7
2505719	2	38.4	38.4	12.46	29.6	47.2
2505720	1	34.4	34.4	NA	34.4	34.4
2505726	6	18.8	19.2	9.04	9.0	33.1
2800827	1	42.4	42.4	NA	42.4	42.4
2800828	8	29.5	29.3	8.67	17.8	39.7
2801385	6	33.0	35.2	14.06	8.5	48.8
2805654	2	30.4	30.4	15.74	19.3	41.6
2805710	4	33.4	32.5	12.34	21.5	47.0
2805719	1	40.2	40.2	NA	40.2	40.2
2805720	2	45.7	45.7	4.29	42.6	48.7
3202083	1	9.4	9.4	NA	9.4	9.4
3205670	4	23.4	24.8	8.99	13.0	31.0
3705726	2	29.2	29.2	0.38	29.0	29.5

NA = Not applicable

Discussion

The study results showed that locations obtained from tagged sperm whales within 50 km of active seismic survey airgun arrays appeared to be randomly distributed. There were no apparent patterns in the distances and bearings from whale locations to the airguns nor a correlation between duration of exposure and distance, thereby suggesting no horizontal movement response to the presence of an active airgun array at the scale of this study (5 to 50 km).

Sperm whales have been recorded closer than 5 km to airgun arrays in observational studies using onshore or onboard observers. Stone & Tasker (2006), for example, reported the median distance of sperm whale groups as being less than 2 km from active airgun arrays in UK waters.

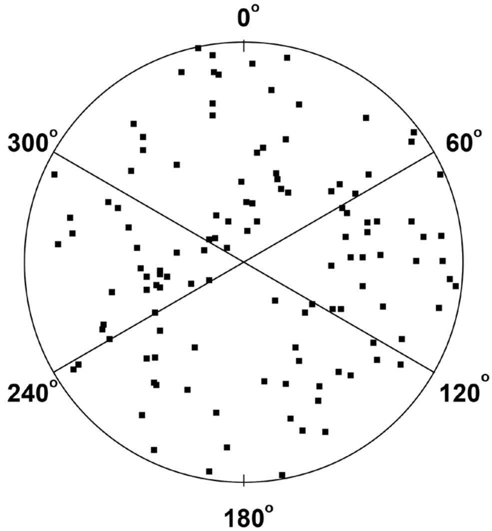

Figure 3. Distances and bearings of satellite-tagged sperm whale locations relative to active seismic vessel headings; *N* = 122 whale locations from 26 satellite-tagged whales. The center of the figure represents the central shotpoint location of the airgun array at the time of the whale location. The radius of the circle is 50 km.

Marine mammal observers on seismic vessels in the GOM between 2002 and 2008 (Barkaszi et al., 2012) documented 139 occasions when sperm whales were detected inside the exclusion zone (defined as within 500 m of the center of the airgun array and/or within the immediate vicinity of the vessel) of which at least 74% were during full-power operations. In that study, the median closest approach to the array recorded for each sperm whale group was 1.8 km during full power and 1 km when silent. In addition to the distribution characteristics of minimum distances from randomly generated data, this literature suggests that the lack of tagged sperm whale locations closer than 5 km of an active array in this study is likely due to a small sample size of locations and not to horizontal avoidance.

Sperm whale responses to airgun sound are not limited to horizontal displacement. Barkaszi et al. (2012) suggested that behaviors such as an increase in surface activity and a reduction in blow rate may be responses to the presence of an active seismic array. In a controlled exposure experiment, the whale closest to the seismic array (1.4 to 5.7 km) rested at the surface for 4 h during the exposure and dove soon after the airgun noise stopped (Miller et al., 2009).

Sperm whales have also been shown to respond to other, non-airgun-related anthropogenic sounds. A sperm whale made an unusually shallow deep dive during a silent exposure to a sonar vessel (Sivle et al., 2012). Sperm whales were shown to decrease acoustic activity with increasing general ship traffic (Ioup et al., 2005), and solitary sperm whales increased the number of near-surface events while in the presence of whale-watching vessels (Cosentino, 2016). These examples exemplify the need to differentiate a response to the presence of a vessel from a response to the noise created by airgun arrays and may serve as a confounding factor to the results presented herein as the extent of other vessel activity in the study area is unknown.

Detection of changes in diving and foraging behavior and horizontal displacements at small scales would require different tag technology than that used in this study. There are high-resolution data loggers (e.g., D-Tag; Johnson & Tyack, 2003) capable of recording the whales' diving behavior and approximate received sound levels. However, these tags are typically attached for periods < 12 h, which limits the possibilities of interacting with sources of anthropogenic sound. A high-resolution data logger with a longer attachment duration would allow collection of baseline sperm whale behavioral data prior to the presence of seismic or other vessels and during varying exposures to airgun noise. Including GPS capability in the tag would provide more accurate and frequent locations than those derived through the Argos system, permitting detection of responses, such as horizontal avoidance, at a finer scale.

This is the first study to examine the distribution of sperm whales in relation to seismic survey activity using Argos satellite-tracking technology. It provided a large-scale opportunity to study the potential for sperm whale horizontal avoidance of airgun arrays. It also exposed the limitations of this technology to address such questions. The results highlight the need for future experiments to investigate if and what responses occur at specific scales. To that end, controlled exposure experiments using tags that provide high-resolution location, dive, and acoustic data (both received by the sperm whales as well as produced by them), preferably over a period of weeks, appear to be the logical next step. Until better information becomes available, agencies tasked with the management of protected and endangered species should apply the precautionary principle. Given the considerable growth and expansion of activities associated with the offshore oil industry in the GOM in recent years, an improved program for sperm whale monitoring should be implemented.

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