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THESIS

**USING CASS TO ESTIMATE RECEIVED LEVELS
OF CONSPECIFIC BEAKED WHALES**

by

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**USING CASS TO ESTIMATE RECEIVED LEVELS OF CONSPECIFIC
BEAKED WHALES**

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ABSTRACT

Mesoplodon densirostris (*Md*) are deep-diving marine mammals that use echolocation to forage for prey. Recently, bottom-mounted hydrophones have been used to apply passive acoustic-tracking techniques, allowing a unique view of the group-foraging behaviors of *Md*. Preliminary analysis of tracks produced for individuals of multiple animal foraging groups revealed animals dive together, separate at depth, and reunite before ascending to the ocean surface. To better understand this observed behavior we utilize the Comprehensive Acoustic System Simulation with Gaussian Ray Bundle eigenray propagation model (CASS/GRAB) to model the known properties of *Md* echolocation clicks and estimate the received levels that individuals are exposed to from other group members (conspecifics). We hypothesize *Md* are separating to reduce acoustic masking of echoes. This is expected to be shown in two ways: (1) separation during the dive decreases received levels from conspecifics, and (2) echo levels (EL) from prey should be louder than the noise produced by conspecifics.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOA	angle of arrival
AUTEC	Atlantic Undersea Test and Evaluation Center
CASS/GRAB	Comprehensive Acoustic System Simulation with Gaussian Ray Bundle eigenray propagation model
dB re 1 μ Pa	decibel(s) reference pressure 1 micro Pascal
DBDB-V	Digital Bathymetric Database – Variable Resolution
DCLT	detection, classification, localization, and tracking
DTAG	Digital recording Tag
EL	echo level
ENR	echo to noise ratio
FM	frequency modulated
GROUPAM	group passive acoustic monitoring
HFBL	High-Frequency Bottom Loss
HYCOM	Hybrid Acoustic Coordinate Ocean Model
ICI	inter-click interval
kHz	kilohertz
<i>Md</i>	<i>Mesoplodon densirostris</i> (Blainville’s beaked whale)
MFAS	Mid-frequency active sonar
N_c	association history cache size
NL	noise level
OAML	Oceanographic and Atmospheric Master Library
RL	receive level
TDOA	time difference of arrival
TL	transmission loss
SL	source level
SLS	static localization solutions
SMC1	first-order smoothed click map
SMC2	second-order smoothed click map
SMGC	Surface Marine Gridded Climatology
μ s	microsecond

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EXECUTIVE SUMMARY

Blainville's beaked whales (*Mesoplodon densirostris* or *Md*) are one of 22 elusive cetacean species belonging to the beaked whale family Ziphiidae. Beaked whales became a focus of scientific research when mass strandings were linked to the presence of naval mid-frequency active sonar (MFAS) [1]. Historical data show a significant correlation between the presence of mass stranding events and navy sonar in the Bahamas [2]. Additionally, *Md* have been shown to be behaviorally sensitive to sonar [3], [4]. Since 2005, the Naval Undersea Warfare Center Division, Newport has been utilizing the existing bottom-mounted hydrophones at the Atlantic Undersea Testing and Evaluation Center (AUTEK) to identify and monitor *Md* [5]. The 1,500 km² range has been utilized to study group vocal behavior [6], behavioral response studies [4], and more recently passive acoustic tracking of individuals within a foraging group [7].

Passive acoustic tracking provides an opportunity to study the behavior of individuals within a foraging group. Initial findings show that group members dive together, separate at depth, and come back together before ascending to the surface [7]. One possible explanation of this behavior is *Md* separate to avoid acoustic masking from conspecifics, animals of the same species and in this case the same foraging group. To prevent masking of echoes, (1) Separation during the dive decreases received levels from conspecifics, and (2) Echo levels from prey should be louder than the noise produced by conspecifics. However, separation during foraging is limited by the need for individuals to track each other throughout the duration of the foraging dive, in order to reunite prior to surfacing. Specifically, foraging *Md* need to hear echoes from prey over the noise of conspecifics while maintaining the ability to passively track group members to facilitate the reunion at the end of the foraging dive. In this study, acoustic modeling is used to estimate the received levels of other foraging group members' vocalizations, and analyze the potential effects this has on their behavior.

A custom Detection, Classification, Localization and Tracking (DCLT) tool was utilized to track *Md* groups at AUTECH [7]. The DCLT tool uses a match filter to detect *Md* clicks from broadband recordings, and static localizations were estimated every two seconds. Localizations were calculated using a modified time difference of arrival method and a 12 second window [8]. The DCLT tool then used a multi-hypothesis tracker to link the static localizations together [9]. This resulted in tracks for individual animals for 19 multiple-animal foraging groups [7]. For this analysis, modeling pairs were selected when individual tracks contained localizations for both animals at the same point in time. Three pair types were defined, group of two, neighbor pair (in group of three), and outside pair (in group of three). The slant range between each modeled pair was calculated using the latitude, longitude, and depth. Time was normalized by dividing the time into the dive of each modeling point by the total duration of the group dive.

Separation in groups of two and neighboring whales in groups of three have a similar pattern of separation, while the outside pairs displayed a larger mean separation (Figure 1). Increased separation of outside pairs relative to neighbor and groups of two suggest individuals within a group are targeting a minimum separation. Prey in this study area are found to congregate in 100 m patches with 400–800 m separation between patches [10]. This corresponds to the separation seen in the passive acoustic tracks, suggesting separation in tracks could indicate that individual *Md* within a foraging group are foraging on separate prey patches, rather than pack hunting on a single prey patch.

Transmission loss (TL, dB re 1 μ Pa @ 1 m) was modeled using the Comprehensive Acoustic System Simulation with the Gaussian Ray Bundle (CASS/GRAB) eigenray propagation model [11], [12]. For each modeling pair, one whale was chosen as the source whale, while the other was designated as the receiver whale. Sources were modeled as omnidirectional, so acoustic reciprocity was assumed. Environmental data, such as wind speed, bathymetry, bottom type and sound speed profiles, were gathered from the Oceanographic and Atmospheric Master Library (OAML). These environmental properties extracted from the closest available data point to the source whale. FM and buzz clicks were simulated for each modeling pair by entering source properties, such as center frequency and pulse duration into CASS/GRAB.

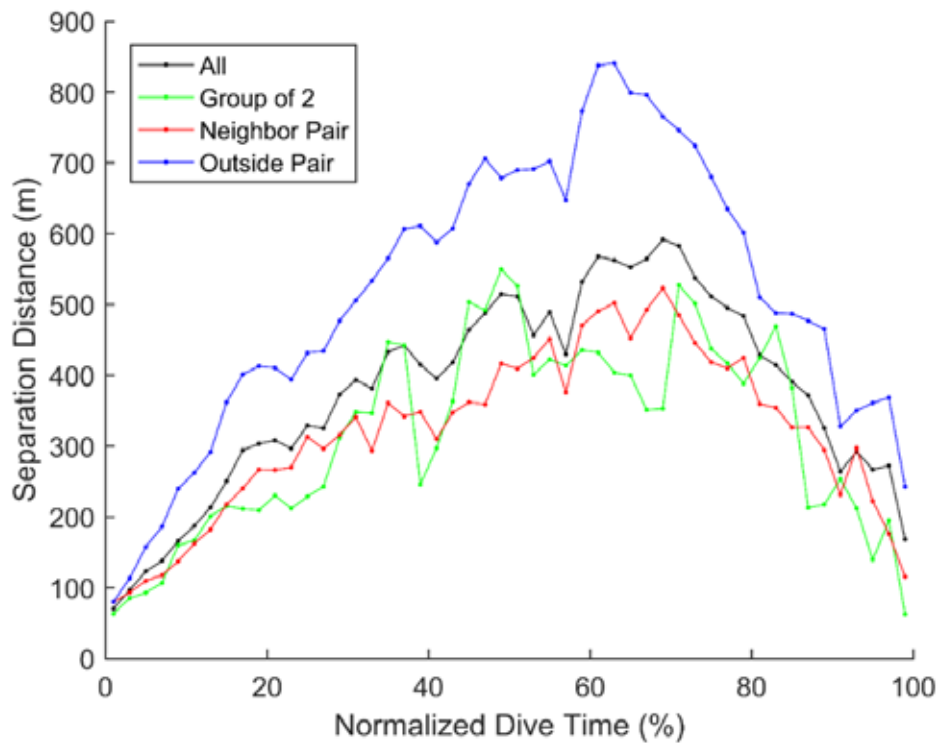


Figure 1. Mean separation of pair types

To account for the directionality, the beam pattern was used to adjust the source level (SL). The relative angle between head position of the whale pair was calculated in both directions, and was used to estimate the loss from peak SL associated with the beam pattern. The received level was then calculated using $RL = SL_{BP} + TL$, where SL_{BP} is the directional source level and TL is the transmission loss simulated by CASS/GRAB. The mean and standard deviation of FM and buzz clicks for all the modeled dives, and for each designated pair type can be seen in Table 1. The ambient noise in the bandwidth of FM clicks is around 50 dB [13]. The RL of both click types indicate foraging *Md* can clearly hear both click types from all members of their foraging group throughout the duration of the dive providing the opportunity to continuously track conspecifics.

Table 1. Received levels (dB re 1 μ Pa) for designated pair types

Click Type	All Pairs		Group of 2		Neighbor Pair		Outside Pair	
	<i>Mean</i>	<i>Std</i>	<i>Mean</i>	<i>Std</i>	<i>Mean</i>	<i>Std</i>	<i>Mean</i>	<i>Std</i>
RL								
FM	141.1	12.71	142.2	17.74	141.85	17.45	136.2	17.3
Buzz	123.6	13.18	125.1	18.09	124.7	17.76	117.7	17.75

The RL for both click types are similar for the groups of two and nearest neighbor pair type, while the RL for outside pairs is lower by about five to six decibels. This corresponds with the greater separation distance. Mean RLs for each group type can be seen in Table 1. Assuming linear decreases in RL for each potential additional group member, the farthest separated pair in a group of five, the upper limit of groups observed in the area [14], would experience a mean RL of approximately 124 dB and 105 dB for FM clicks and buzz clicks, respectively. These estimated RLs are more than 70 dB above ambient suggesting *Md* can hear clicks of all group members. The ability to passively track other foraging group members may also be a contributing factor to the small group sizes seen in *Md*. The difficulty of passively tracking foraging group members will increase by the decreasing RL as separation increases, as well as the increased complexity of tracking a larger number of individuals.

To investigate the possibility of acoustic masking during group foraging maximum potential echo levels (EL) were calculated by assuming the prey was ensounded with an on-axis click at peak SL. ELs were calculated for FM click for prey distances ranging from 1 to 375 m. ELs were calculated for prey ranging from 0.1 to 10 meters from the whale. Echo levels were calculated using $EL = SL + 2 * TL + TS$, where SL is the source level of an on-axis echolocation click, TL is the one-way transmission loss based on the distance to prey, and TS is the target strength of squid (-39 dB [10]). The ELs of both click types were estimated to be well above ambient noise 50 dB for the entire range of prey distances calculated, leaving the RL of conspecific clicks as the largest source of noise while foraging.

The echo to noise ratio (ENR) is a metric used to compare the EL of buzz clicks produced by a single animal to the conspecific RLs received throughout the dive. . The ENR was calculated for both conspecific RL of FM and buzz clicks using $ENR = EL - NL$, where the noise level (NL) is considered to be the modeled conspecific RL. *Md* typically switch from FM clicks to buzz clicks when an individual is two to five meters from prey [15], [17]. Once the whale is 4 m from prey, echo levels from prey are estimated to be louder than 54% of the modeled FM click RL and 91% of the modeled Buzz click RL throughout the dive. By starting the buzz at such close proximity to the prey, the echoes are less likely to be masked by the vocalizations of other group members. The choice for *Md* to forage on separate prey patches may be driven by echoes from prey being masked by the echolocation clicks of other group members.

Passive tracking has revealed that *Md* dive together, separate at depth, and reunite before ascending to the surface. *Md* appear to be targeting a minimum separation, making it likely each individual is foraging on a separate prey patch. In order to reunite before ascending to the surface, *Md* would have to track each other throughout the dive. Modeling of FM and buzz clicks revealed conspecific RLs are above ambient noise throughout the foraging dive. This is also likely to be true for larger groups of four or five. When an individual begins buzzing during a capture attempt the EL received is louder than a majority of the conspecific RLs, thus reducing the likelihood of acoustic masking. We suggest whales separate to reduce acoustic masking while foraging, and small group sizes are beneficial to passive tracking of group members while foraging and still maintaining separation while foraging.

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I. INTRODUCTION

Blainville's beaked whales (*Mesoplodon densirostris* or *Md*) are one of 22 elusive cetacean species belonging to the beaked whale family Ziphiidae. These medium sized whales grow to a length of 14 to 16 feet, have a small dorsal fin, and can be found worldwide in tropical and warm temperate waters [1]. *Md* have been observed in small, tight groups ranging from 1–5 animals [2], which display a regular dive pattern starting with a deep foraging dive, often below 800 meters, followed by a series of shallow recovery dives [3], [4]. During the foraging dives, each individual *Md* produces between 4,000 and 5,000 frequency modulated echolocation clicks [5], while foraging for meso- and bathypelagic prey such as squid and fish [1]. After foraging *Md* ascend silently as to avoid detection by predators such as killer whales [6].

Beaked whales became a focus of scientific research when mass strandings were linked to the presence of naval mid-frequency active sonar (MFAS). One such event occurred in the Bahamas in March 2000. Over a 2-day period 18 marine mammals stranded, 15 of which were beaked whales [7]. Historical data show a significant correlation between the presence of mass stranding events and navy sonar in the Bahamas [8]. Additionally, *Md* have been shown to be behaviorally sensitive to sonar. The presence of nearby MFAS caused *Md* to stop echolocating and move away [9], [10].

This link between MFAS and beaked whale behavior led the U.S. Navy to institute a multi-faceted research program to study the effect of MFAS on cetaceans with a focus on beaked whales. A majority of the findings on foraging behavior and sound production of these elusive creatures comes from digital recording tags (DTAGs). The DTAG is a compact device that attaches to the dorsal surface of a marine mammal via suction cups. Each device contains a suite of sensors allowing researchers to study the movement and acoustic environment surrounding these mammals [11]–[13]. While DTAGs have been used to gain insight into individual behavior [4], [13], [14] and passive acoustic monitoring has been used to study large-scale population dynamics [15], [16], it is rare to successfully tag multiple animals in the same foraging group.

Click properties gathered from DTAG recordings have been used successfully in passive acoustic monitoring systems. Since 2005, the Naval Undersea Warfare Center Division, Newport has been utilizing the existing bottom-mounted hydrophones at the Atlantic Undersea Testing and Evaluation Center (AUTEK) to identify and monitor *Md* [17]. The 1,500 km² range has been utilized for estimating group vocal behavior [18], behavioral response studies [10], and more recently passive acoustic tracking of individuals within a foraging group [19].

Passive acoustic tracking provides an opportunity to study the behavior of individuals within a foraging group. Initial findings show that group members dive together, separate at depth, and come back together before ascending to the surface [19]. Groups of sperm whales have also been observed showing increased spatial distribution at depth when compared to separation at the surface [20]. One possible explanation of this behavior is that *Md* separate to avoid acoustic masking from conspecifics, animals of the same species and in this case the same foraging group. Prevention of masking effects can be measured in two ways; (1) separation during the dive decreases received levels from conspecifics, and (2) echo levels (EL) from prey should be louder than the noise produced by conspecifics. However, separation during foraging is limited by the need for individuals to track each other throughout the duration of the foraging dive, in order to reunite prior to surfacing. Specifically, *Md* foraging in groups need to hear echoes from prey over the noise of conspecifics while still maintaining the ability to passively track group members to facilitate the reunion at the end of the foraging dive. In this study, acoustic modeling is used to estimate the received levels of other foraging group members' vocalizations, and analyze the potential effects this has on their behavior.

II. METHODS

A. DATA SET AND TRACK ANALYSIS

The Atlantic Undersea Test and Evaluation Center (AUTECH) is located in a deep channel known as the Tongue of the Ocean off the coast of Andros Island, Bahamas. AUTECH is comprised of 82 bottom-mounted hydrophones covering an area of approximately 1,500 km² (Figure 1). The northwest corner of the range contains 14 hydrophones spaced approximately 1.8 km apart in two hexagonal arrays. These hydrophones have a bandwidth of 8–50 kHz. The remaining 68 hydrophones are spaced approximately 3.7 km apart in offset rows, and have a bandwidth from 50 Hz to 48 kHz. AUTECH is typically used to provide three dimensional tracking of navy assets, however it can also be used to passively detect the presence of *Md* [10].

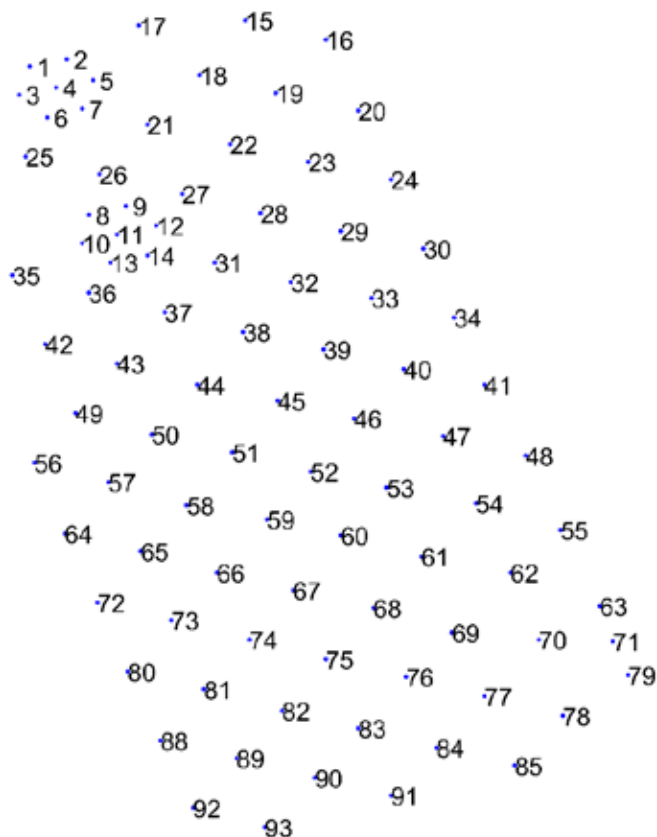


Figure 1. AUTECH hydrophone range

Two types of data are collected from the AUTEK range; broadband recordings, and archive files. Archive files are collected continuously and contain reports from several algorithms which process the acoustics in real time, including an *Md* classifier. Broadband recordings are only collected when observers are in the field and can be used for Detection, Classification, Localization and Tracking (DCLT) analysis. Archived data sets from 2005–2016 were searched for potential foraging groups by extracting *Md* reports from the archive files and forming vocal groups based on proximity of detections in space and time. Since *Md* clicks are highly directional [20], tracking efforts were focused on the northwest corner of the range to maximize the number of hydrophones picking up the same animals. Vocal groups identified for DCLT analysis had the following characteristics: (1) broadband recordings were available for the entire vocal period; (2) detections occurred on a minimum of 4 hydrophones located on one of the hexagonal arrays (Figure 1); (3) the hydrophone with the highest number of detections was both part of a hexagonal array and detected a minimum of 1000 clicks. Once a recording period was identified, audio files for each hydrophone were extracted from the start to the stop time of selected group foraging in WAV format for DCLT analysis [19].

A custom DCLT tool was utilized to track *Md* groups at AUTEK. This DCLT tool was designed in MATLAB and contains a graphical user interface, allowing the user to optimize parameter selection for each group. Audio wav files were uploaded into the DCLT tool which creates tracks in two steps; (1) detection and localization of *Md* clicks, and (2) association of localizations into track. The tracks produced by the DCLT tool were then post processed to finalize the multiple tracks in each group [19].

Step one of the DCLT tool detected *Md* clicks and produced static localization solutions (SLS) from the WAV files using a modified time difference of arrival method. First, *Md* clicks were identified using a replica correlator and an *Md* replica waveform created using hundreds of known *Md* clicks. Once identified, a first order smoothed click map (SMC1) was produced by forming a synthetic time series of impulses during a 12 second time window. To ensure only *Md* clicks were detected, the SMC1s were matched to a non-time windowed SMC1 of a different hydrophone, with a delay applied to the second hydrophone equal to the largest correlation peak. These SMC1s were then

multiplied creating the second order smoothed click map (SMC2). The SMC2 was validated if the inter-click interval (ICI), the time between clicks, is within the expected range of Md by using an autocorrelation function. These SMC2s were used to create TDOA measurements for a single hydrophone pair. TDOA associations between pairs of hydrophones were also determined; for example, if an SMC2 matches for pair AB and BC, a correlation is formed for pair AC. This increases the total amount of associations available. Once all hydrophone pairs are determined, hyperbolic positioning was used for a range of assumed depths. All pairs of TDOA measurements were looped through a weighting algorithm. For a SLS to gain appreciable weight there must be several TDOA measurements that have a low time delay error and a high level of association. Time windows were updated every 2 seconds creating a high overlap [21].

Step two of the DCLT tool used a multiple hypothesis tracker to create tracks for multiple animals. The tracking process begins by associating a SLS with a previous track or SLS data point. A SLS was considered to be associated with a track if the SLS error ellipse contains the current track position, or if the track position grows so that it intersects the SLS error ellipse, or both. The tracker created new hypotheses for each SLS associated with an existing track; no hypothesis averaging was used. This created a large number of possible tracks. Alternative hypotheses were maintained in the DCLT tool's memory until the track can "prove itself." This process was repeated for each set of SLS throughout the duration of the analysis. As each set of SLS were associated with track hypotheses the track score was calculated. Track score was based on "total confidence accumulation," where the amount of confidence in the track is proportional to the sum of the confidences of the SLS contained within the track. This confidence accumulation favored tracks with a long history. Once a track reached a designated history cache size (N_c), it was considered long enough for comparison. Tracks were eliminated if they were considered redundant. Tracks were considered redundant if they ended with the same N_c associations. When redundant tracks were found the tracker kept the hypothesis with the greatest track score. Once a track had greater than N_c associations it was pruned from the list of tracks. The tracks were sorted by the track score. The user defined the quota, or maximum number of tracks to store in memory. Once the number of tracks with greater than N_c associations reached the quota,

the tracker started eliminating the tracks with the lowest track scores. When analysis was complete, the tracker selected high-scoring, disconnected tracks to display to the user. The first track selected was the track with the highest track score. Any remaining tracks with a small number of overlapping SLS associations were then eliminated from the list. This process is then repeated with the remaining tracks [22].

The tracks produced by the DCLT tool were post processed and final tracks for the foraging group are chosen. In some instances, the DCLT tool could not track an animal for the entirety of the dive due to the geometry of the problem. In this case short tracks were connected manually based on proximity of the endpoints in time and space. Any points in the track indicating a higher swim speed than 4 m/s were removed. Overall 19 multiple-animal foraging groups were produced using the DCLT method as shown in Figure 2 [19].

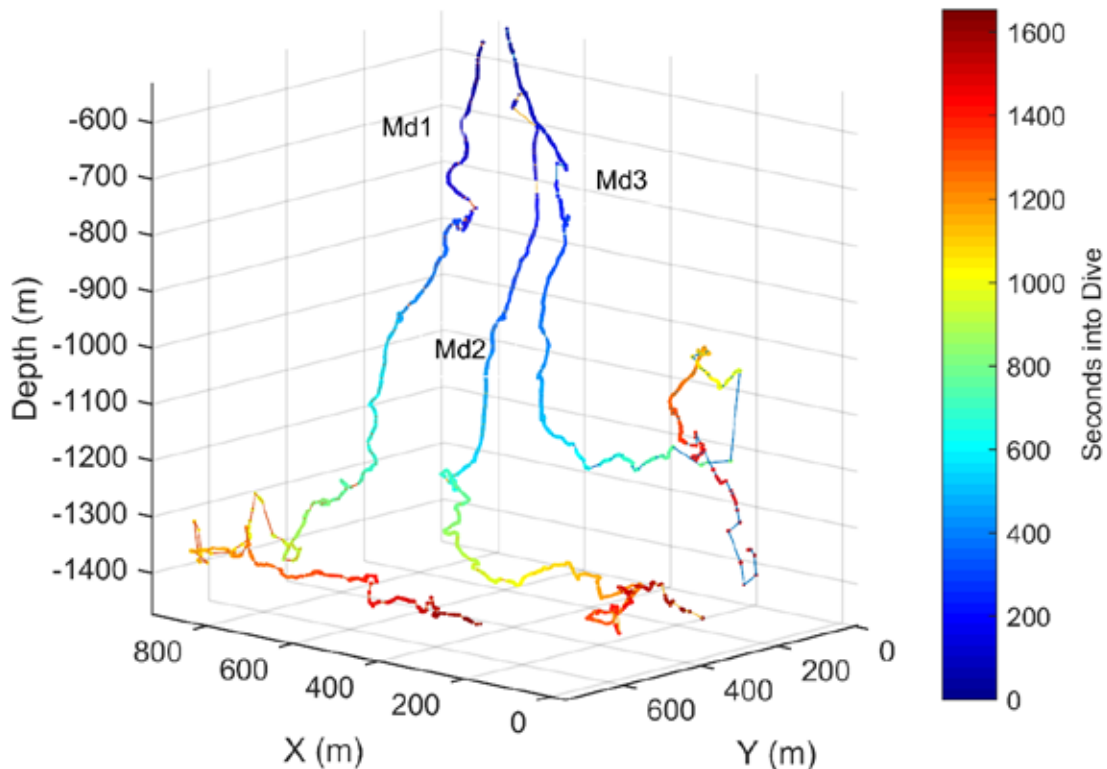


Figure 2. 3D tracks of three-member foraging group. Adapted from [19].

Three pair types were defined, the first is solely comprised of groups with only two members. Groups with three members were split into two categories. The outside pair was defined as the pair with the greatest separation; e.g. Md1 and Md3 (Figure 2), while a pair was designated as a neighbor pair when the central whale was paired with a member of the outside pair; e.g. Md2 paired with Md1 and Md2 paired with Md3 (Figure 2). In the rare case two animals crossed paths, the outside and neighbor pairs were redefined at the time of crossing. The slant range between each modeled pair was calculated using the latitude, longitude, and depth as defined in the passive acoustic tracks. Time was normalized by dividing the time into the dive of each modeling point by the total duration of the group dive, providing a measurement indicating the percentage of the dive complete. To determine if the separation in pair types are the same, a one-way analysis of variation (ANOVA) was conducted in MATLAB. In addition, a pairwise comparison of the ANOVA results using the Tukey Honest Significant Difference (Tukey HSD) criterion was conducted in MATLAB to show which, if any, pair types had a significant difference in mean separation.

B. MODELING

The Comprehensive Acoustic System Simulation with the Gaussian Ray Bundle (CASS/GRAB) eigenray propagation model was chosen for this study, as it is the standard U.S. Navy propagation model for frequencies between 10 kHz and 100 kHz. CASS/GRAB is a range dependent model, which groups rays into families based on surface interactions and turning points. The power average is then taken for each family of rays [23], [24]. For this analysis, modeling points were selected for a pair when each track contained localizations at the same point in time. The number of analysis points for each pair type can be seen in Table 1. Clicks were simulated by entering known source properties into CASS/GRAB, including pulse duration, pulse interval, and center frequency (Table 2). The output from CASS/GRAB is transmission loss (TL) in dB re 1 μ Pa @ 1 m.

Table 1. Analysis points by pair type

Group Size	2	3	
Number of Groups	10	9	
Pair Type	Group of 2	Neighbor Pair	Outside Pair
Total Analysis Points	2,021	5,763	3,350
Mean Analysis Points per Group	202	640	372

Table 2. Click properties of *Mesoplodon densirostris*

Click Type	FM Click	Buzz
Purpose	Localize/Classify	Capture
Peak Source Level (dB re 1 μPa @ 1 m)	220 ^[11]	205 ^{[11] [13]}
Center Frequency (kHz)	32.8 ^[20]	51.3 ^[13]
-10 dB Bandwidth (kHz)	26-51 ^[13]	25-80 ^[13]
Inter-Click Interval (ms)	200-500 ^[14]	3-20 ^[14]
97% Energy Duration (μs)	271 ^[13]	104 ^[13]

The acoustic reciprocity theorem states that for a point source located at position A and a point receiver located at position B the acoustic path is identical for a point source located at position B and a point receiver at position A. For each modeling pair, one whale was chosen as the source whale, while the other was designated as the receiver whale. Sources were modeled as omnidirectional, so acoustic reciprocity was assumed. Therefore, the selection of the source whale for the model was arbitrary, and the resulting TL was used for the reverse situation. Directivity was taken into account after the modeling process and is described in Section D of Methods.

Environmental data, such as wind speed, bathymetry, bottom type and sound speed profiles, were gathered from the Oceanographic and Atmospheric Master Library (OAML; Table 3). Wind speed data were extracted from the Surface Marine Gridded Climatology which provided monthly averages and had an available resolution of one degree. Seafloor composition and the associated geo-acoustic parameters had an available resolution of one degree. Bathymetry was obtained at the highest resolution available, ranging from 0.05-2.0 arc-minutes. The Navy Hybrid Acoustic Coordinate Ocean Model (HYCOM) data had an available resolution of 0.08 arc-degrees for the year 2014. Data were extracted for the 15th of the corresponding month of the dive and consisted of temperature, salinity, and depth. The sound speed was calculated using the Chen-Millero-Li sound speed equation [25]. These environmental properties were extracted from the closest available data point to the source whale and used in the CASS/GRAB model.

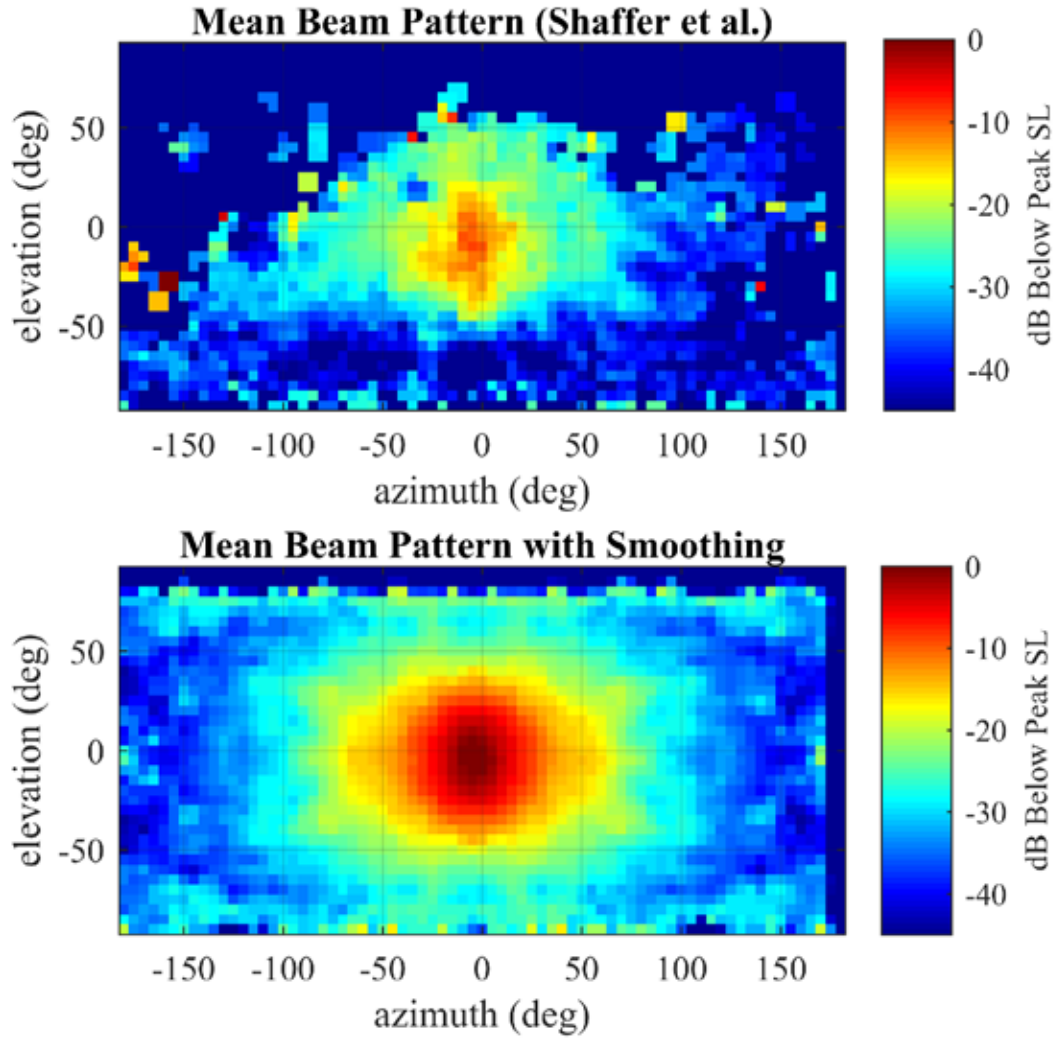
Table 3. Oceanographic and Atmospheric Master Library environmental databases used in CASS/GRAB

Parameter	Database
Bathymetry	Digital Bathymetric Database Variable Resolution (DBDB-V) Version 7.3
Seafloor Composition	High Frequency Environmental Acoustics (HFEVA) Version 2.0
Wind Speed	Surface Marine Gridded Climatology (SMGC) Version 2.0
Sound Speed	Navy Hybrid Acoustic Coordinate Ocean Model (HYCOM) Version 2.2

C. BEAMPATTERN

Md clicks are known to be highly directional. Shaffer et al. estimated the *Md* beam pattern using data from four tagged whales recorded on the AUTECH hydrophone range [20]. Echolocation clicks emitted by and recorded on the whale and received on the

surrounding hydrophones were detected and associated. The position of each animal's click was calculated using a multi-lateration tracking algorithm. The level of each click detected on the surrounding hydrophones was measured and the source level estimated along with the angle from the whale to the hydrophone. Data from multiple clicks and surrounding hydrophones were combined to estimate the horizontal and vertical beam-pattern (Figure 3, top). Since the data used to measure the beam pattern came from bottom-mounted hydrophones, it was assumed the measurements were biased toward the negative vertical axis and the actual beam pattern is more symmetrical around the peak as seen in beam patterns observed in the echolocation clicks of Risso's dolphins [26] and bottlenose dolphins [27]. For the purposes of this model, the beam pattern was assumed to be symmetrical across both axes through the peak. The new mean beam pattern was calculated and smoothed using the *smoothn* function in MATLAB (Figure 3, bottom) [28].



Top: Mean source level (dB re 1 μ Pa) of four tagged whales detected by bottom mounted hydrophones in AUTECH. Source [20]. Bottom: Beam pattern used for modeling applied symmetry about the max and smoothing.

Figure 3. Average transmitted beam pattern

D. CONSPECIFIC RECEIVED LEVEL

To account for the directionality, the beam pattern was used to adjust the SL. The track angle was used as a proxy to head position for each animal in the pair. The relative angle between head position of the source whale and the receiver whale was calculated for each whale pair. This calculation was performed twice, using each animal in the pair as a source and receiver. This relative angle was used to estimate the loss from peak source

level associated with the beam pattern (Figure 3). This loss was subtracted from the peak SL. The received level was then calculated using Eq. (1), where SL_{BP} is the directional source level and TL is the transmission loss simulated by the CASS/GRAB model. Each modeling pair resulted in two directional dependent conspecific RLs. Directionality of hearing was not taken into account for this study.

$$RL=SL_{BP}+TL \quad (1)$$

E. ECHO LEVELS

Md use echolocation to locate and forage for prey. Squid is a preferred prey of *Md* [1]. To investigate the possibility of acoustic masking during group foraging maximum potential echoes were calculated by assuming the prey was ensonified with an on-axis click at peak SL. FM clicks are utilized in the majority of the foraging dive for identification and localization [12]. To determine maximum range to prey, we assume the echoes are received and processed before the next click is produced. The maximum prey range (R_{max}) was determined to be 375 m using Eq. (2), where ICI_{max} is the upper limit of the inter-click interval (Table 2), and c is the sound speed, in this case assumed to be 1500 m/s. ELs were calculated for FM clicks for prey distances range from 1 to 375 m. Buzz clicks are utilized during the capture phase [12], ELs were calculated for prey ranging from 0.1 to 10 meters from the whale.

$$R_{max}=ICI_{max} * c/2 \quad (2)$$

ELs were calculated using Eq. (3), where SL is the source level of an on-axis echolocation click, TL is the one-way transmission loss based on the distance to prey, and TS is the target strength of squid. Prey mapping studies indicate squid have a target strength of -39 dB on the west side of the AUTEK range [29]. SL was assumed to be peak on-axis click regardless of the distance to prey. The echo to noise ratio (ENR) is a metric used to compare the EL of buzz clicks produced by a single animal to the conspecific RLs received throughout the dive. The ENR was calculated for both conspecific RL of FM and buzz clicks using Eq. (4), where the noise level (NL) is the modeled conspecific RL.

$$EL = SL + 2 * TL + TS \quad (3)$$

$$ENR = EL - NL = SL - 2TL + TS - NL \quad (4)$$

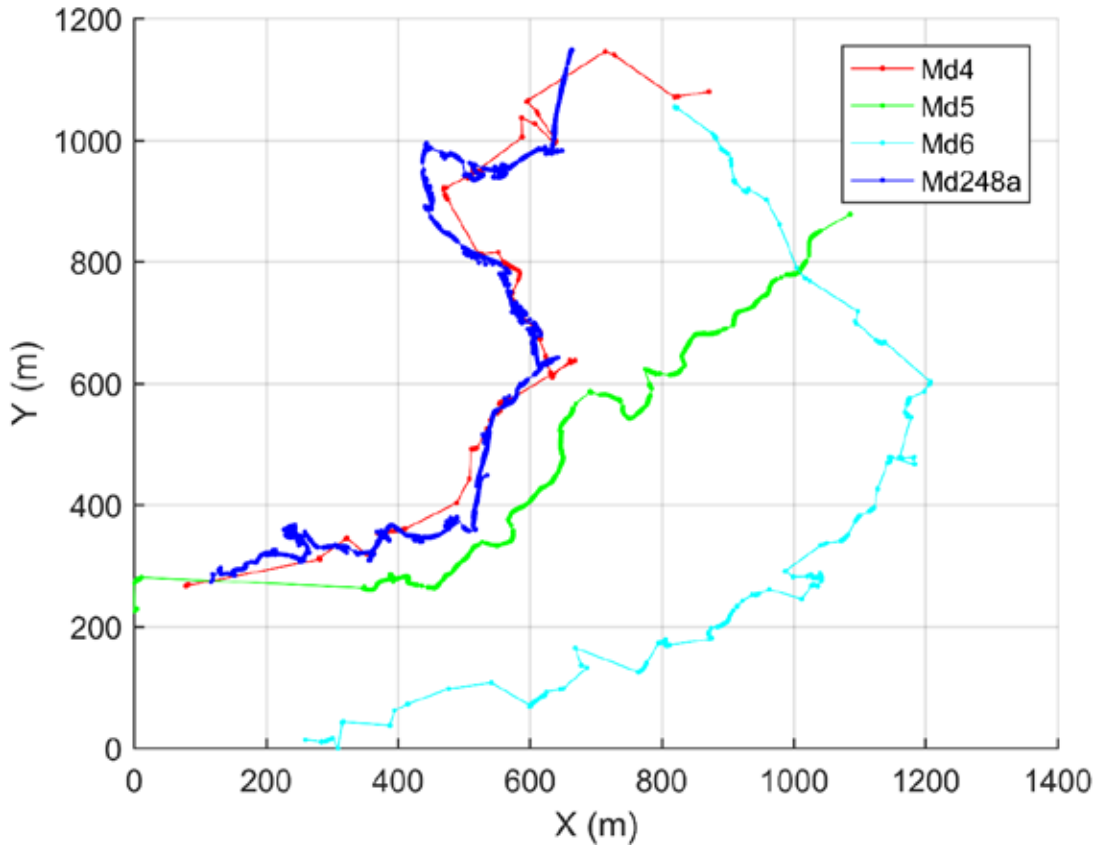
F. MODEL VALIDATION

To validate the model, we looked at a single foraging group that is unique in the fact that tracks are available from passive acoustic tracking and a DTAG was deployed on one of the group members. In September 2007, a DTAG was attached to a whale and used to track motion with sensors including a 3-axis accelerometer, a 3-axis magnetometer, and pressure sensor. A dead reckoning track for the tagged animal was produced (Md248a, Figure 4) using methods described by [11]. The received level of clicks detected on the DTAG, and identified as *Md*, were separated into two categories, tagged whale and non-tagged whale. Clicks were considered from the tagged animal if there was energy present below 15 kHz and the angle of arrival (AOA, Eq. (5)) was close to zero, where t is the time delay between the two hydrophones on the DTAG, c is the sound speed in seawater, and d is the distance between hydrophones [13]. Clicks from the tagged animal were excluded from the analysis and the remaining were assumed to be from the other two animals within the foraging group. The RLs of the non-tagged whales' echolocation clicks were calculated using the methods described in the 2007 Behavioral Response Study Cruise Report [30].

$$AOA = \sin^{-1}(tc/d) \quad (5)$$

Passive acoustic tracking was used to generate tracks for the three foraging whales as described in Section A of the Methods (Md4-Md6, Figure 4). The highest resolution track was produced for Md5, the closest vocalizing whale to the tagged whale. It was assumed the greatest received levels would come from Md5 since it was the neighboring whale for the majority of the dive. Md6 was excluded from this analysis due to the quality of the passive acoustic track. To determine if the model was representative of real life, the modeling process described in Sections B through D of the methods were conducted. In this modeling scenario, the tagged whale (Md248a) was considered the receiver and Md5 was considered the source. Track Md248a was chosen over track Md4 to represent the tagged whale because it had a higher resolution. These levels were then compared to those

measured using data recorded directly on the DTAG. The resolution of the passive acoustic tracks reduced the sample size of available FM clicks to model, and did not allow us to account for the fine tune head and body movements that occur during foraging. This therefore limited analysis of RL to the dive as a whole, rather than analyzing RL at specific times during the dive.



Md4, Md5, and Md6 (red, green, and cyan respectively) were tracked using passive acoustics. Md248a (blue) is the same individual as Md4 tracked using DTAG. Tracks Md5 and Md248a were used for the modeling process.

Figure 4. Passive acoustic tracks and DTAG track of three member foraging group at AUTECH used for validation of model

III. RESULTS

A. MODEL VS. DTAG

To determine if the model is producing results similar to the real world, a single group with a DTAG deployed was analyzed using the model and the DTAG data. A histogram of the conspecific RLs detected on the DTAG can be seen in Figure 5 (top). The mean of the conspecific RLs of FM clicks detected on the DTAG is 140 ± 6 dB re 1 μ Pa. A histogram of the modeled RL of conspecific FM clicks produced by Md5 received by Md248a can be seen in Figure 5 (bottom). The modeled scenario of this dive determined the mean FM click RL to be 143 ± 11 . The modeled results had a larger range of RLs (120-170 dB) compared to the DTAG (125-160 dB). The DTAG captures a larger amount ($>3x$) of clicks than we were able to model.

Table 4. Mean, standard deviation, and sample size of data for model validation

Data Set	Mean RL (dB re 1 μPa)	Standard Deviation (dB re 1 μPa)	Sample Size
DTAG	140	6	1599
Model	143	11	494

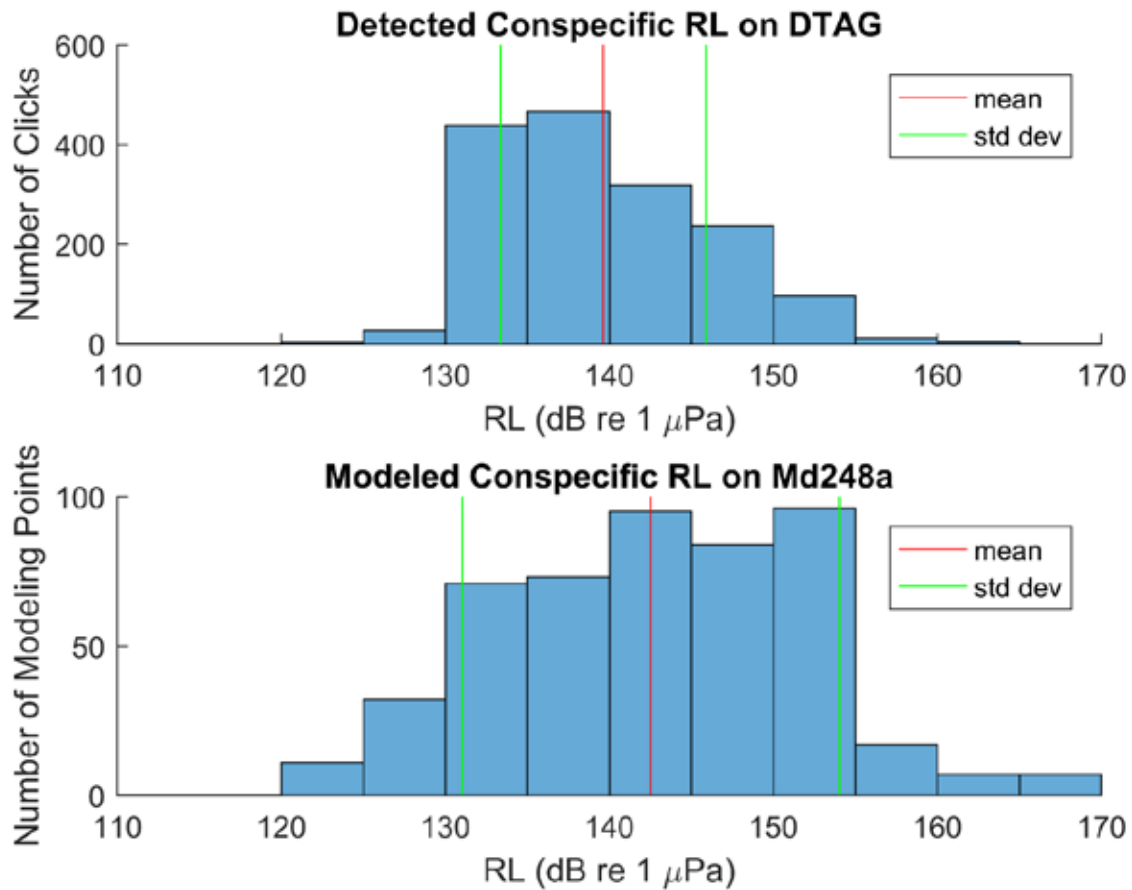


Figure 5. Modeled and DTAG detected received levels of foraging group member

B. SEPARATION AT DEPTH

Passive acoustic tracking conducted at AUTECH indicates whales dive together, separate at depth, and reunite before surfacing [19]. The mean separation of all pair types can be seen in Figure 6. Pair types were divided into three groups (groups of 2, neighbors, and outside pairs). The mean separation of each pair type (Figure 7) reveals the separation in groups of two and neighbor pairs are similar while outside pairs display a larger separation.

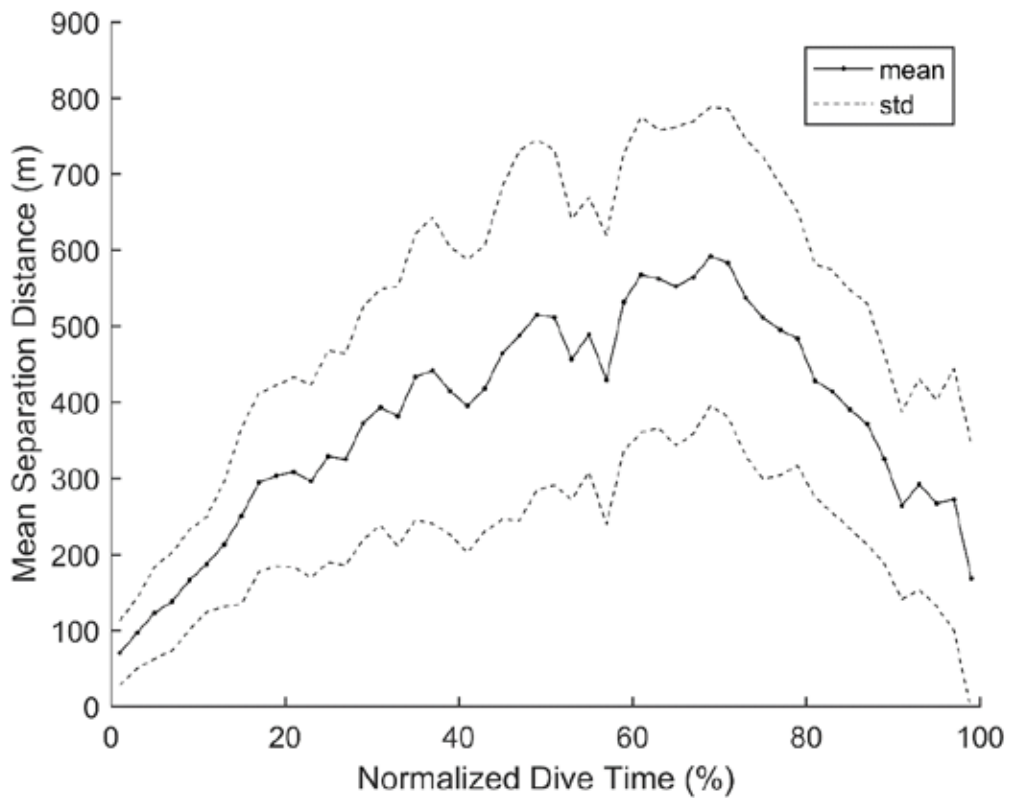


Figure 6. Mean separation of all pair types

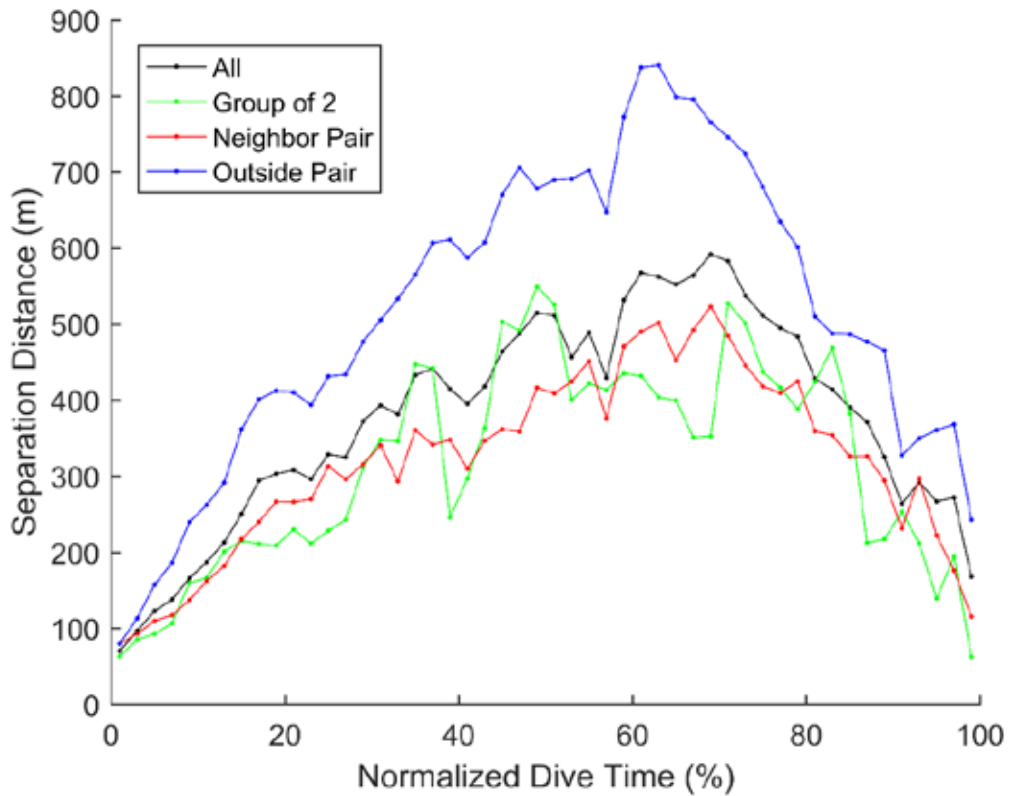


Figure 7. Mean separation of each pair type

To analyze the difference in separation of each pair type a one-way analysis of variance (ANOVA) was conducted using MATLAB. The purpose of the ANOVA is to determine whether different groups of an independent variable (i.e., pair type) have different effects on the same response variable (i.e., separation). The p -value of this ANOVA was equal to zero indicating the pair types do not have equivalent mean separations. The boxplots of this analysis can be seen in Figure 8.

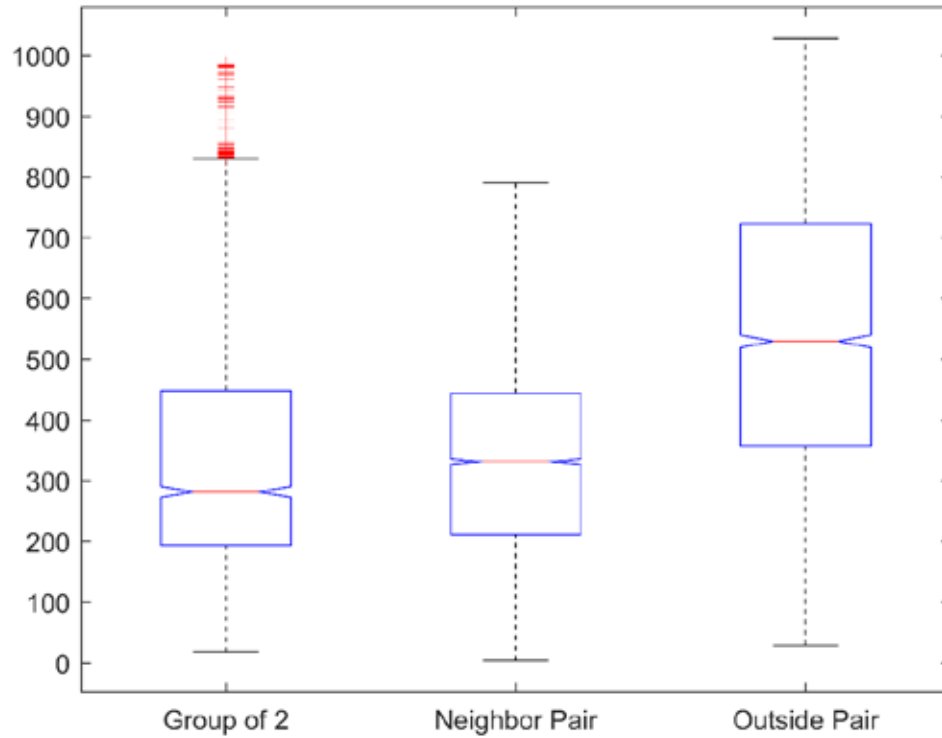


Figure 8. ANOVA analysis of separation by group type pairing

A pairwise comparison of the ANOVA results was conducted using the Tukey's honest significant difference (HSD) criterion (Figure 9). The Tukey comparison revealed the separation of the outside pair was significantly different than the separation observed in both of the other pair types, while the group of 2 and neighbor pair types were not significantly different from each other (Figure 9).

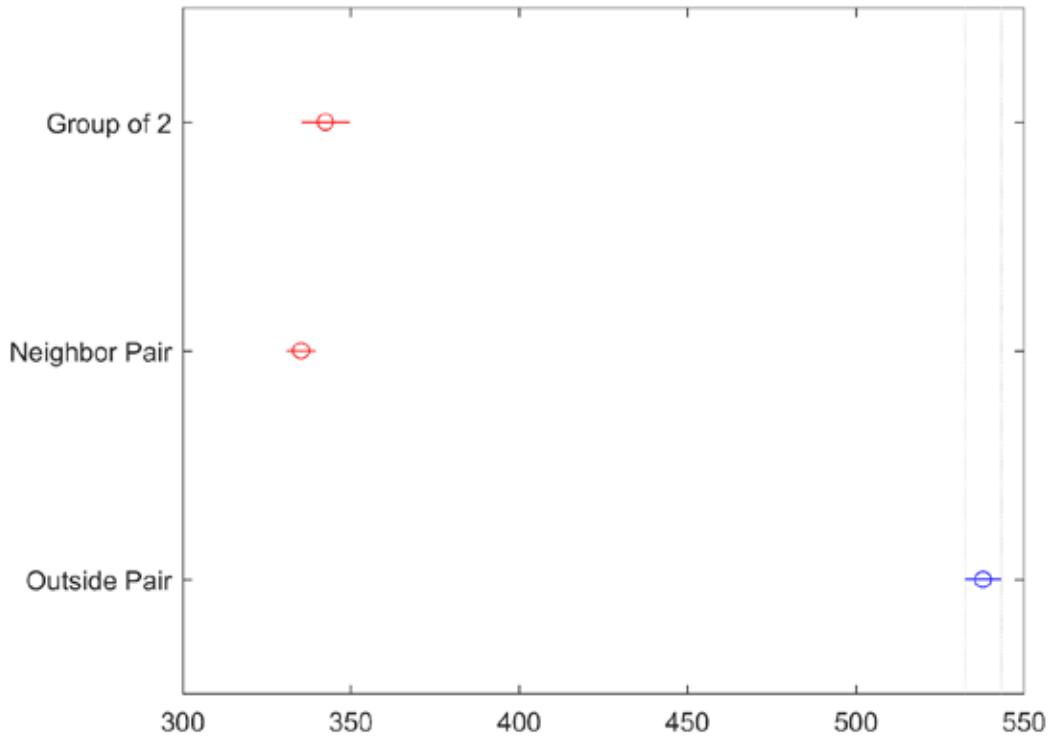


Figure 9. Tukey HSD comparison of group type pairings

C. RECEIVED LEVELS

The mean and standard deviation of FM and buzz clicks for all the modeled dives, and for each designated pair type can be seen in Table 5.

Table 5. Received levels (dB re 1 μ Pa) for designated pair types

Click Type	All Pairs		Group of 2		Neighbor Pair		Outside Pair	
	<i>Mean</i>	<i>Std</i>	<i>Mean</i>	<i>Std</i>	<i>Mean</i>	<i>Std</i>	<i>Mean</i>	<i>Std</i>
RL								
FM	141.1	12.71	142.2	17.74	141.85	17.45	136.2	17.3
Buzz	123.6	13.18	125.1	18.09	124.7	17.76	117.7	17.75

D. ECHO LEVELS

Estimated echo levels for FM clicks can be seen in Figure 10 for prey distances up to 375 m. Echo levels remain above 100 dB re 1 μ Pa until the prey is about 100 m away. The ambient noise in the bandwidth of FM clicks is around 50 dB [31]. The EL of FM clicks are above this ambient noise level for the entire range of prey distances.

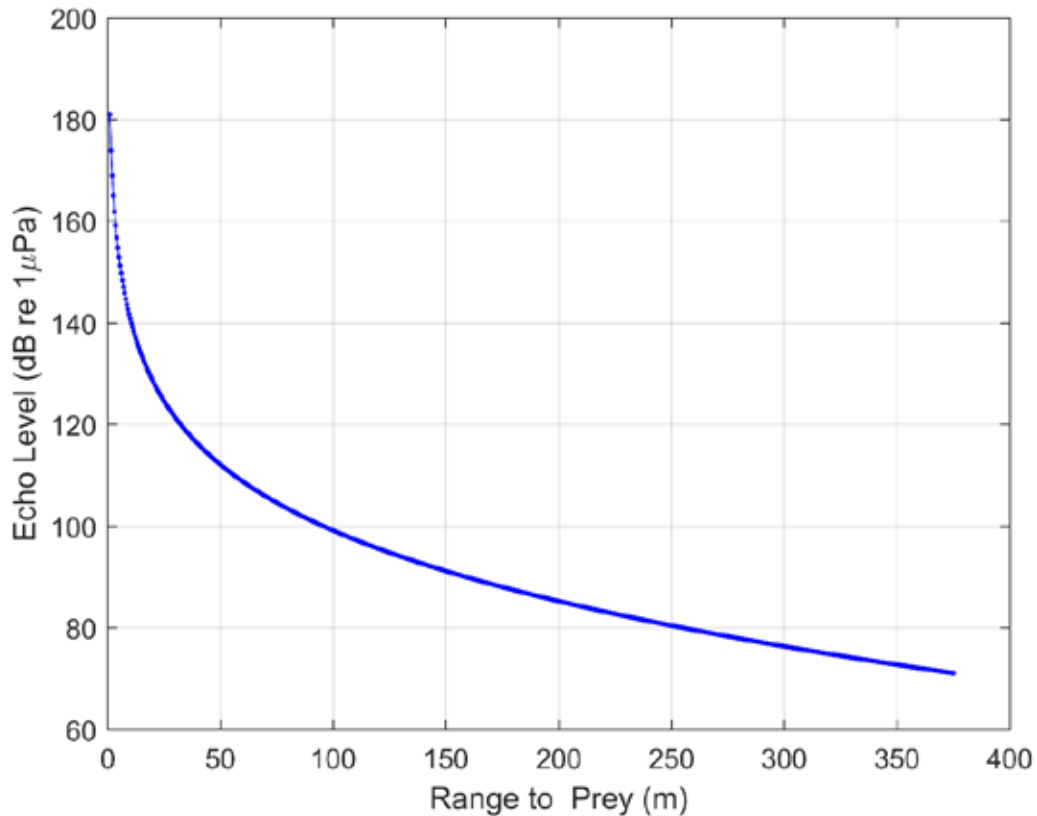


Figure 10. Estimated echo level of squid from FM clicks

ELs of Buzz clicks were estimated for prey ranging from 0.1 to 10 m from the echolocating animal as seen in Figure 11. The primary factor in the difference in the EL in buzz and FM clicks is the source level at which each click type is produced. Buzz clicks have a slightly higher TL due to the higher frequency, however, this effect of absorption is very low given the relatively short distance to prey. The ELs of buzz clicks were estimated to be well above ambient noise 50 dB for the entire range of prey distances calculated.

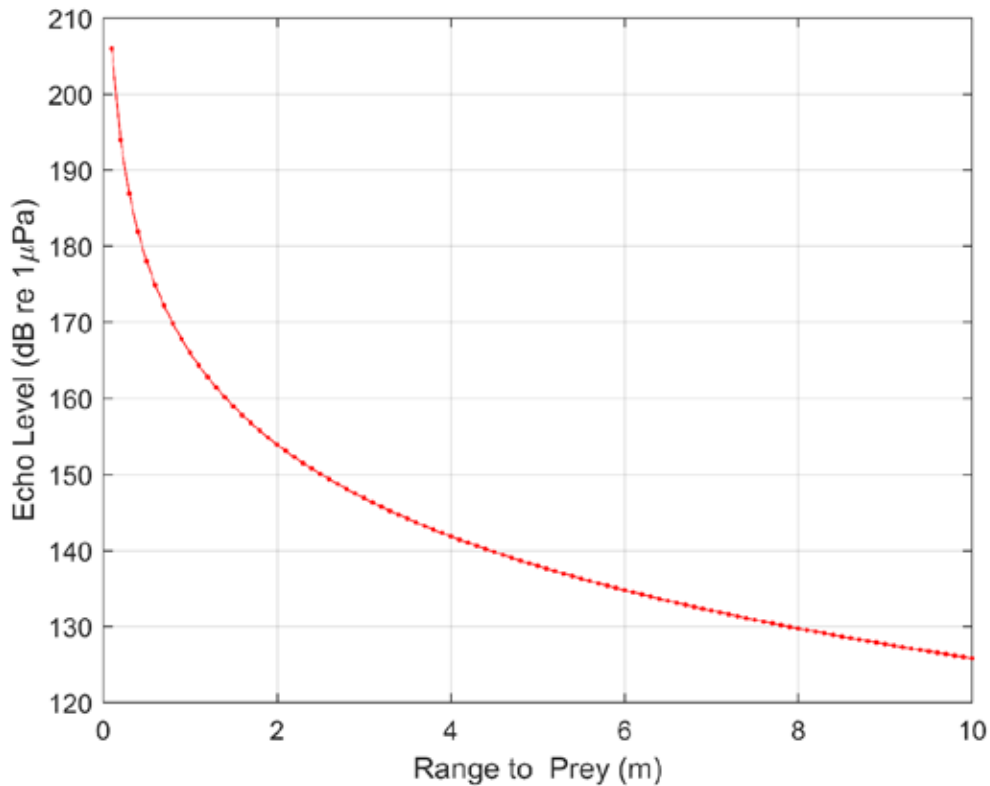


Figure 11. Estimated echo level of squid from buzz clicks

Md typically switch from FM clicks to buzz clicks when an individual is two to five meters from prey [11], [14]. For this reason the ENR was calculated for 1–7 meters from prey (Table 6). Once the foraging whale is four meters from prey, echo levels from prey are estimated to be louder than 54% of the modeled FM click RL and 91% of the modeled Buzz click RL throughout the dive.

Table 6. Percentage of modeling pairs with positive ENR at various prey distances

Distance from Prey (m)	1	2	3	4	5	6	7
+ENR FM	98%	83%	68%	54%	43%	33%	25%
+ENR Buzz	100%	99%	96%	91%	86%	80%	74%

IV. DISCUSSION

A. MODEL FIT

Overall, the model is considered a realistic approximation of the measured data. The model used positions from tracks with a sampling period of 2 seconds, while every click from foraging group members is accounted for on the DTAG. The model also used track heading as a proxy for head position; the resolution of the tracks and this approximation does not account for the fine tune movements of the head and body observed during foraging. The reduced sample size and accuracy of head position are the most likely causes for the increased standard deviation in the modeled RLs. The model also used the peak SL for calculation of RL. All clicks will not be produced at the same SL, so a slightly higher mean RL was expected.

B. SEPARATION, FORAGING STRATEGY, AND ACOUSTIC MASKING

Md have displayed extreme synchrony in foraging dives. This behavior is thought to be a form of predator avoidance, specifically avoidance of killer whales [6]. In order for individuals to ascend silently from a foraging dive and maintain their group, group members must be in close proximity at the end of the foraging dive. This leaves two potential foraging strategies, (1) pack hunting on a selected prey patch or (2) foraging individually on separate prey patches and reuniting before the ascent.

Passive acoustic tracking revealed individuals dive together, separate at depth, and reunite before ascending. Increased separation of outside pairs relative to neighbor pairs and groups of two suggest individuals within a group are targeting a minimum separation; rather than maximum separation, where we would expect the outside pair to resemble groups of two and the neighboring pairs would be closer together. Prey in this study area are found to congregate in 100 m patches with 400–800 m separation between patches [29]. This corresponds to the mean separation seen in the passive acoustic tracks (Figure 7), suggesting separation in tracks could indicate that individual *Md* within a foraging group are foraging on separate prey patches, rather than pack hunting on a single prey patch.

In order for individuals to come together before the ascent, individuals need a method for keeping track of other group members. Individuals produce FM clicks almost constantly, throughout the duration of the foraging dive. The ambient noise in the bandwidth of FM clicks is around 50 dB [31]. The RL of both click types indicate foraging *Md* can clearly hear both click types from all members of their foraging group throughout the duration of the dive. The RL for both click types are similar for the groups of two and nearest neighbor pair type, while the RL for outside pairs is lower by about five to six decibels. This corresponds with the greater separation distance.

The upper limit of groups observed in the area is 5 individuals [2]. Assuming linear decreases in RL for each potential additional group member, the farthest separated pair in a group of five would experience a mean RL of approximately 124 dB and 105 dB for FM clicks and buzz clicks, respectively. These estimated RLs are more than 70 dB above ambient suggesting *Md* can hear clicks of all group members. The ability to passively track other foraging group members may be a contributing factor to the small group sizes seen in *Md*. The difficulty of passively tracking foraging group members will be increased by the decreasing RL as separation increases, as well as the increased complexity of tracking a larger number of individuals.

DTAG studies have shown *Md* switch from the FM click to the buzz click when the individual is 2–5 meters from the prey target [13]. As seen in Table 6, an echo of a buzz click will be received at a higher RL than 54% of FM clicks and 91% of buzz clicks produced by other foraging members throughout the entire dive. By starting the buzz at such close proximity to the prey, the echoes are less likely to be masked by the vocalizations of other group members. Buzz clicks are produced at a significantly faster inter-click interval, ensuring echoes will be received in between received FM clicks from other foraging group members. Centroid frequency differences in FM and buzz clicks increases ability to decipher these signals even during temporal overlap.

Acoustic masking is an obstacle many signaling species face. When multiple signaling species occupy the same space, adaptations or behavioral changes can increase the fitness. For example, singing nightingales are observed to time song onset to occur in pauses in other species song, therefore, avoiding temporal overlap [32], Katydidids show diel

shift of signaling when species with a similar spectral signals were present [33]. Mammal and bird species have been shown to increase vocal amplitude in response to increased background noise, known as the Lombard effect [34]–[36]. The choice for *Md* to forage on separate prey patches may be driven by echoes from prey being masked by the echolocation clicks of other group members.

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