Project 9 Final Report

Modeling Right Whale Entanglement Events

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Executive Summary

This is the final report on developing an interactive virtual whale entanglement simulator (VWES). A draft manuscript has been completed and submitted for review to Marine Mammal Science based on this project. It is a methods paper describing the physics techniques and computational methods used in the simulator. Additional manuscripts are in preparation: (1) a detailed computational fluid dynamics study examining the hydrodynamic forces on a 10m North Atlantic right whale during steady gliding motion, and (2) an entanglement scenario paper examining the probability of entanglement and severity of the whale – rope interaction resulting from a whale's first encounter with fishing gear. Additional support for this project is from NOAA Grant #NA13NMF4720280.

Introduction

In the sections to follow, we provide an (1) outline the contents of our VWES methods manuscript including two entanglement case studies, and (2) briefly discuss the manuscript investigating whale drag forces from a detailed computational fluid dynamics study, and (3) outline the entanglement scenario manuscript.

VEWS Methods Manuscript

The majority of the computer science and physics simulation techniques used in the VWES have been discussed in our previous reports to NMFS, including especially the final report under NOAA Award # NA09NMF4520413, so they will not be repeated here. The focus of this report is on findings related to flipper and fluke entanglements. These findings will be included in the methods paper to demonstrate the utility of our VWES.

Figure 1 shows a typical fluke wrap (top image) and a typical body wrap involving the pectoral flippers (bottom image). Eg 3107 (NMFS E15-02) was a female born in 2001 that was entangled for between 57 and 266 days. The whale was disentangled on September 1, 2002 but was sighted dead on October 13, 2002. This whale had one prior entanglement interaction. Eg 3445 (NMFS E25-05) is a female born in 2004 and was entangled between nine and 297 days. She was partially disentangled on December 12, 2005 and last seen in 2006.

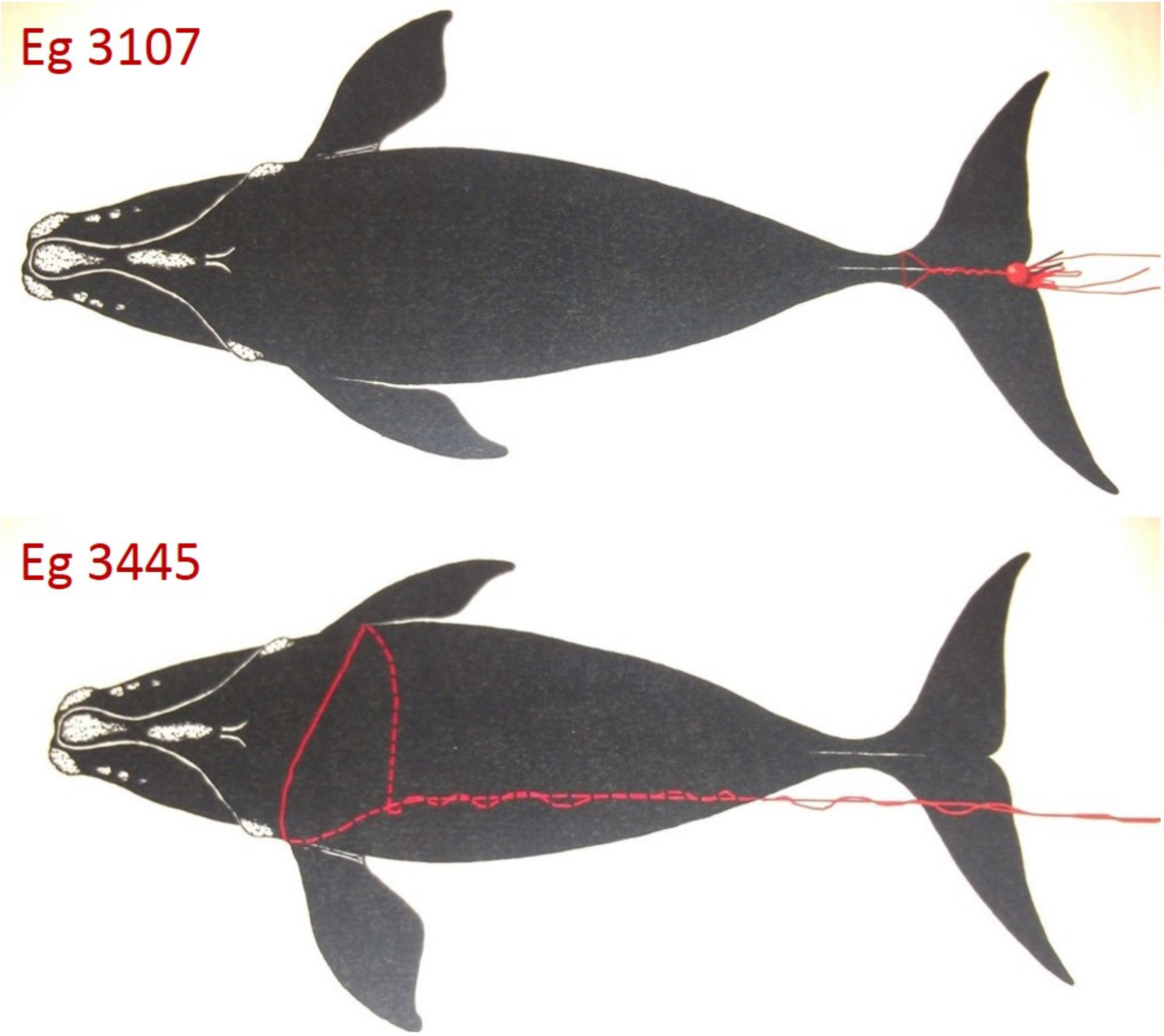


Figure 1. *Entanglement case studies. Top image Eg 3107 showing a typical caudal peduncle wrap. Bottom image Eg 3445 showing body wraps involving the pectoral flippers. (Drawings by S. Landry, Center for Coastal Studies).*

By using the VWES, it was found that the easiest way to generate a peduncle wrap is to execute a roll and turn before encountering the gear. As the whale passes by the gear the peduncle contacts the rope causing the rope to cross to the other side of the flukes. If the whale later executes a barrel roll while still trailing the gear, the rope wraps on itself and becomes difficult to shed afterward.

Body wraps involving the pectoral flipper, as in Eg 3445, are most easily generated if the whale executes a barrel roll when encountering the gear. In this scenario, the rope gets stuck at the anterior insertion of the pectoral flipper and wraps around the body as the whale executes the roll. We have further found that if the whale is lower in the water column, for example below 25% depth, the rope often wraps around the body in front of the pectoral flippers whereas the body wrap occurs posterior to the flippers if the role occurs higher in the water column. The effect of whale depth may have to do with the angle of ascent the whale attempts after encountering gear and/or the amount of line available (i.e., amount of 'slack') for interaction.

We have submitted a manuscript detailing the physics and computer science embedded in the VWES. This manuscript also investigates the two cited case studies. The manuscript was submitted in 2015 and we are currently revising it based in reviewers' comments. The co-authors for this manuscript are:

Laurens Howle – Duke University and BelleQuant Engineering, PLLC
Douglas Nowacek – Duke University
Tim Werner – New England Aquarium
Scott Kraus – New England Aquarium
Patrice McCarron – Maine Lobstermen's Association

The effort for the methods manuscript was supported under grants #NA09NMF4520413 and #NA13NMF4720280.

CFD Study Manuscript

While there are many estimates of hydrodynamic drag on whales in the literature, the drag estimates are wildly disparate and often derived from rather crude approximations; such as approximating the whale body as an ellipsoid, assuming laminar flow, and using classical solutions appropriate to laminar flow [1]. However, typical Reynolds numbers (the dimensionless speed) for swimming whales indicate that the flow is in the turbulent regime. Therefore, these classical solutions are inaccurate. In calculating the relative added energetic cost of towing gear, the baseline (not entangled) drag on the whale needs to be accurately known. In order to provide better estimates of drag on a representative 10m North Atlantic right whale, we conducted an extensive computational fluid dynamics study and collected drag and drag coefficient data over a large range of swimming speeds. The details of our comprehensive computational fluid dynamics study were presented in previous NOAA reports We presently have a manuscript in preparation with planned submission before the end of 2014. The co-authors on this manuscript are:

Laurens Howle – Duke University and BelleQuant Engineering, PLLC
Doug Nowacek – Duke University
Frank Fish – West Chester University

The effort for the CFD manuscript was supported under grant #NA09NMF4520413 and #NA13NMF4720280.

Entanglement Scenario Manuscript

North Atlantic right whales (*Eubalaena glacialis*) become entangled in non-mobile fishing gear at alarming and increasing rates [2], which can have serious consequences for the individual as well as the population. Individual whales can become seriously compromised and, in many cases, die from these entanglements. In addition to direct mortality, the serious injuries that often result can have long-term health consequences for the individual, and the rate at which these sub-lethal entanglements occur thus becomes a threat to the population.

Disentanglement efforts are often successful, but not always and they rely on detection of the entanglement, mobilization of resources and dangerous heroics on the part of humans. Preventing entanglements is the goal, and there has been significant effort in this area from a combination of equipment and management perspectives. Regulations requiring sinking or neutrally buoyant lines that run between traps on the bottom were a major regulation imposed on the fisheries, with the thought that right whales feeding at or near the bottom were becoming entangled in floating ground lines that looped up into the water column. Also, various types of breakaway or weak links have been incorporated into gear configurations in hopes that when whales become entangled they could break those links and minimize the amount of gear attached to them. Adaptive management schemes have also been developed to minimize entanglement risk, e.g., the ‘dynamic area management’ system, whereby gear had to be removed from the water when right whale concentrations were identified. Prevention is the goal, but many of the efforts pursued have little or no data describing their effectiveness; disentanglement efforts are still needed every year.

Understanding how whales become entangled is important to know if we are to prevent future entanglements. However, as extraordinarily few interactions with fishing gear have been observed, we have little knowledge of what happens when a whale actually encounters gear. We have become adept at diagramming the resulting entanglements from photographs, a skill initially developed and very effective for strategizing disentanglement efforts, e.g., where to cut lines. We had another idea for these entanglement ‘scenarios’, which is to use our ‘virtual whale entanglement simulator’ (VWES) to try to recreate them. The VWES is a collaborative tool built by biologists and engineers to create, in a gaming environment, a simulation where we can entangle whales and thus understand the accompanying problems (e.g., how the whales interacted with the gear to become entangled) as well as solutions (e.g., how we can design gear differently to reduce entanglement risk). This mechanically explicit model also allows us to calculate quantities such as drag and friction experienced by the whale from the gear attached to it, giving us information about the severity of entanglements.

In the VWES, we can recreate the observed entanglements in the hopes that a better understanding of them will inform and lead to methods of preventing them, i.e., we try to ‘reverse engineer’ the entanglements. Working with biologists, fishermen and engineers, we have created a series of entanglement scenarios that are representative of the gear types and observed entanglements. Here we simulate how they occurred and we then analyze the results of these scenario simulations to evaluate their severity and ultimately to plan for their prevention.

In Table 1 we show a number of the whale behavior scenarios we are simulating with the VWES. We have found that there is a probabilistic component to whether or not a whale remains entangled with the gear after first encounter. Therefore, for each of the scenarios, we run a number of simulations so that we may arrive at a probability that a certain behavior type will result in a lasting entanglement. The definition of a lasting entanglement that we adopt for this work is that if there is remaining contact between the whale and the gear after the whale has traveled 10 body lengths from the point at which it first encounters the gear then we score that as a lasting entanglement. On the other hand, if the whale contacts but sheds the fishing gear in the first 10 body lengths from first contact then we score that as a non-entanglement. For our present simulations, we run 128 realizations of each scenario.

Table 1. Matrix of possible whale behavior scenarios upon encountering fishing gear.

Hypothesis 1 to test: Does one type of whale behavior explain the different entanglement wraps observed?									
Distance from rope	**Behavior**	**Whale Speed and trajectory**	**Whale trajectory**	**Body orientation**	**Mouth**	**Contact Point**	**Current direction**	**Current speed**	**Rope collision point**
0m	One body roll per body length away from rope	Reduce velocity by 50%? Increase velocity by 50%	Maintain	Typical dorso-ventral axis perpendicular to plane of ocean surface	Mouth closed	Rostrum	Same as whale	.5 kn	Ocean surface - 5m below ocean surface
4m	Two rolls per body length away from rope							4 kn (but not in the up-current direction)	
	Downward dive with associated tail/pectoral /head movements	Continue apace (2kn)	Veer 20^0 away from rope	Dorso-ventral axis parallel to ocean surface (swimming on side)			Into right side of whale		Midway (25m) along length of rope
						Side of head			
		Increase velocity by 3X	Veer towards rope after head passes it	Upside-down (ventral side facing ocean surface)		Cinch in baleen	Into left side of whale		At depth, 5m above first trap
		Stop upon contact, then speed up to original velocity	When using "at depth," following contact whale should swim upward using ascent rate and angle from Doug			Flipper: mid-point of leading edge	Opposed to whale heading (but not for 4kn)		
						Flipper: Insertion point of leading edge on body			

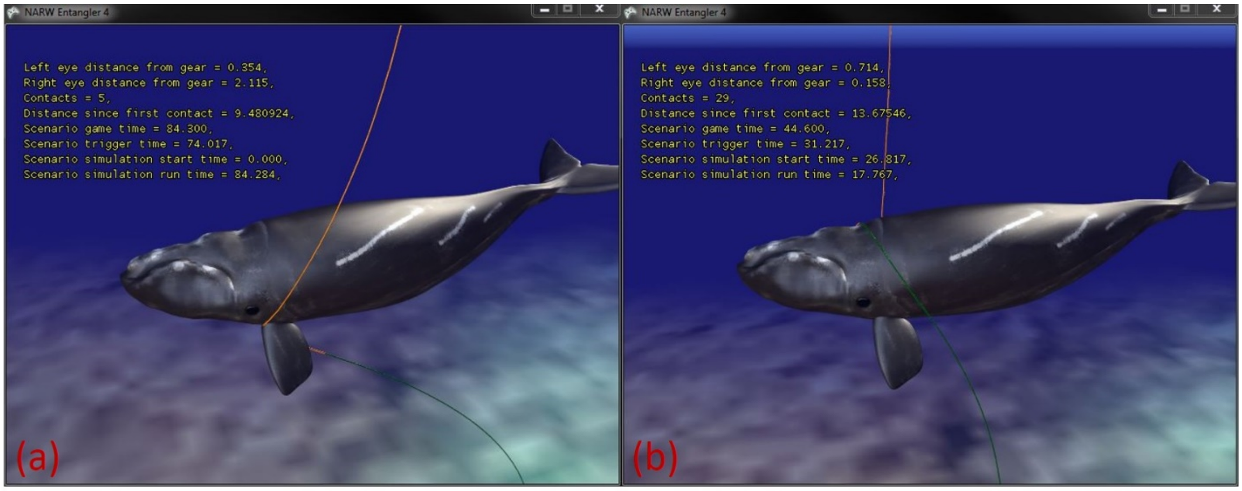
Gear configuration is also a likely contributor as to whether or not contact between the whale and the gear results in a lasting entanglement. This point is also being investigated with our VWES by considering the number of gear configurations using different line diameters, line breaking strengths, weak links, and number of traps among other variables. In Table 2, some of the gear configurations we are considering with the VWES scenario simulations are shown.

Table 2. Fishing gear configurations currently being tested with our VWES.

Hypothesis 2 to test: Varying rope breaking strength does not affect probability that whale will break free of rope							
Rope breaking strength (lbs)	**Rope diameter**	**Rope Cinch point**	**Whale body size (weight in kg)**	**Whale cinch point**	**No. traps (40-65lbs/ea)**	**Length of groundline between traps (fathoms)**	**Buoy flotation**
1000	3/8"	Upper	Yearling (5000)	Mid body	2	12	1 bullet buoy
1500	1/2"	Midway	8-year-old (17,000)	Base of tail	10		2 bullet buoys
2500		Lower	13-year-old (27,000)	Mouth?	40		40" poly ball
3500			Adult of 20+ years (53,000)				

For the purposes of this report, we will briefly discuss two of the entanglement scenarios and our preliminary findings. Specifically, two of the behavior scenarios that we will discuss here include the continue apace reaction and the roll away reaction. For the continue apace behavior, the whale continues to swim on its present heading upon encountering gear. The roll away behavior, on the other hand, causes the whale to execute one or more barrel rolls while maintaining the same heading.

Typical lasting entanglements resulting from these two behaviors are shown in Figure 2. The left image (a) shows the vertical rope getting stuck at the anterior insertion of the flipper and is a typical entanglement caused by the continue apace reaction. The right image (b) shows a body wrap resulting from a barrel roll. This type of wrap occurs as the rope gets stuck at the anterior insertion of the pectoral flipper then wraps the body as the whale executes the roll. A greater number of rolls generally results in greater entanglement complexities. The entanglement complexity is quantified by the number of contact pairs between rope segments and the whale.



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Left eye distance from gear = 0.354,
Right eye distance from gear = 2.115,
Contacts = 5,
Distance since first contact = 9.480924,
Scenario game time = 84.300,
Scenario trigger time = 74.017,
Scenario simulation start time = 0.000,
Scenario simulation run time = 84.284,
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Left eye distance from gear = 0.714,
Right eye distance from gear = 0.158,
Contacts = 29,
Distance since first contact = 13.67546,
Scenario game time = 44.600,
Scenario trigger time = 31.217,
Scenario simulation start time = 26.817,
Scenario simulation run time = 17.767,
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Figure 2. *Examples of entanglement complexity as quantified by the number of contacts between rope segments and whale collision bodies. Image (a) has a complxity of 5 and results from continue apace behaviour whereas (b) shows a complexity of 29 and results from roll away from rope behavior.*

In our preliminary investigation of the behavior scenarios, we have found that there can be a great deal of variance in lasting entanglement probability even within the same scenario type. For example, Table 3 shows the probability of lasting entanglements resulting from the continue apace behavior as a function of the whale's position in the water column. These results were generated using 128 Monte Carlo simulations with the whale located at 25%, 50%, and 75% of the water column height (0% indicates the seafloor whereas 100% indicates the sea surface). The probability of lasting entanglement is calculated as the number of interactions resulting in lasting entanglement divided by the total number of Monte Carlo simulations. As the table indicates, interactions with gear closer to the seafloor are less likely to result in lasting contact between the gear and the whale than interactions closer to the sea surface. Note that these results are specific only to the continue apace reaction and were generated with the whale flipper deployed into the maneuver configuration.

Table 3. Probability of entanglement vs. whale water column height resulting from continue apace whale behavior. Note that gear contact closer to the trap (lower in the water column) is less likely to result in entanglement.

Water Column Height	Probability of Entanglement	Number of Monte Carlo Runs
25%	0.023	128
50%	0.422	128
75%	0.984	128

An example of entanglement complexity versus time for the continue apace behavior scenario is plotted in Figure 3. In this figure we have shifted the origin of the time axis so that zero indicates the time of initial contact between the fishing gear in the whale. The individual points show the time series of the number of instantaneous contacts between gear and the whale skin. The apparent scatter in the data results from the method in which the no penetration constraint between a gear component in the whale skin is imposed. This constraint is imposed by adding a linear impulse during the next calculation step in order to keep the gear at the whale's skin surface. This linear impulse naturally results in a noisy signal. In the same figure we also show the smoothed number of contacts as the solid curve. In plotting the smoothed contacts, an inverse exponential filter is used on the instantaneous number of contacts. The figure shows that this particular interaction results in a lasting entanglement as defined earlier. For this simulation the whale is swimming at 1 m/s (approximately 2 kn) at 50% height of water column with the pectoral flippers in the deployed configuration.

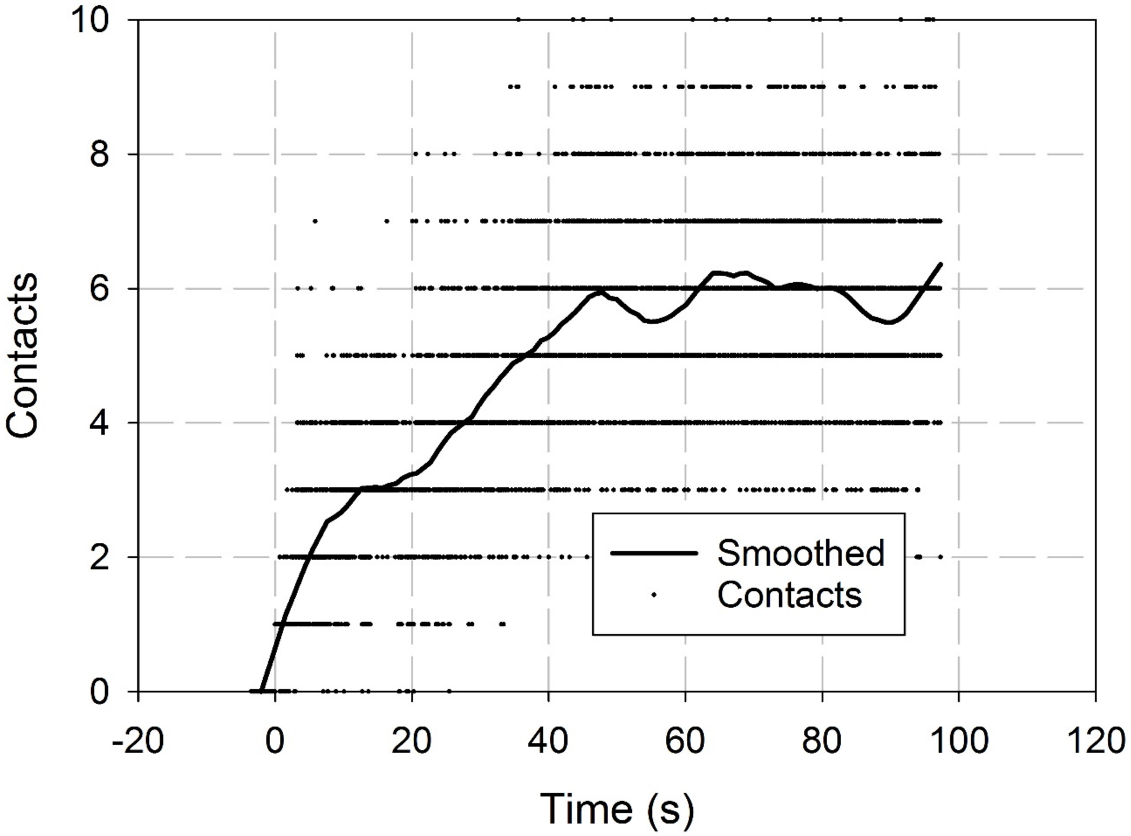


Figure 3. *Gear contact complexity for* <u>*continue apace*</u> *whale behavior. In this realization, the whale retains the gear and becomes entangled. The points show the instantaneous number of contacts. The solid line represents the contact data smoothed with an inverse exponential filter.*

The lasting entanglement time series plotted in Figure 3 stands in contrast to the complexity time series shown in Figure 4. The series plotted in Figure 4 depicts another Monte Carlo simulation from the same set of runs used to generate Figure 3 (continue apace, 1 m/s, 50% water column height, deployed flippers). For the simulation depicted in Figure 4, the rope – whale interaction did not result in a lasting entanglement. Rather the initial interaction between the whale and gear starts out the same as the previous interaction but in this case the rope slides down the span of the flipper eventually shedding free from the flipper approximately 65 seconds (6.5 body lengths) after initial contact. Although it is difficult to depict from Figure 4, there is a slight peak in the number of contacts a few seconds after the rope is freed from the flipper. This occurs as the rope passes down the whale's body without contact but again briefly interacts with the whale at the tail fluke.

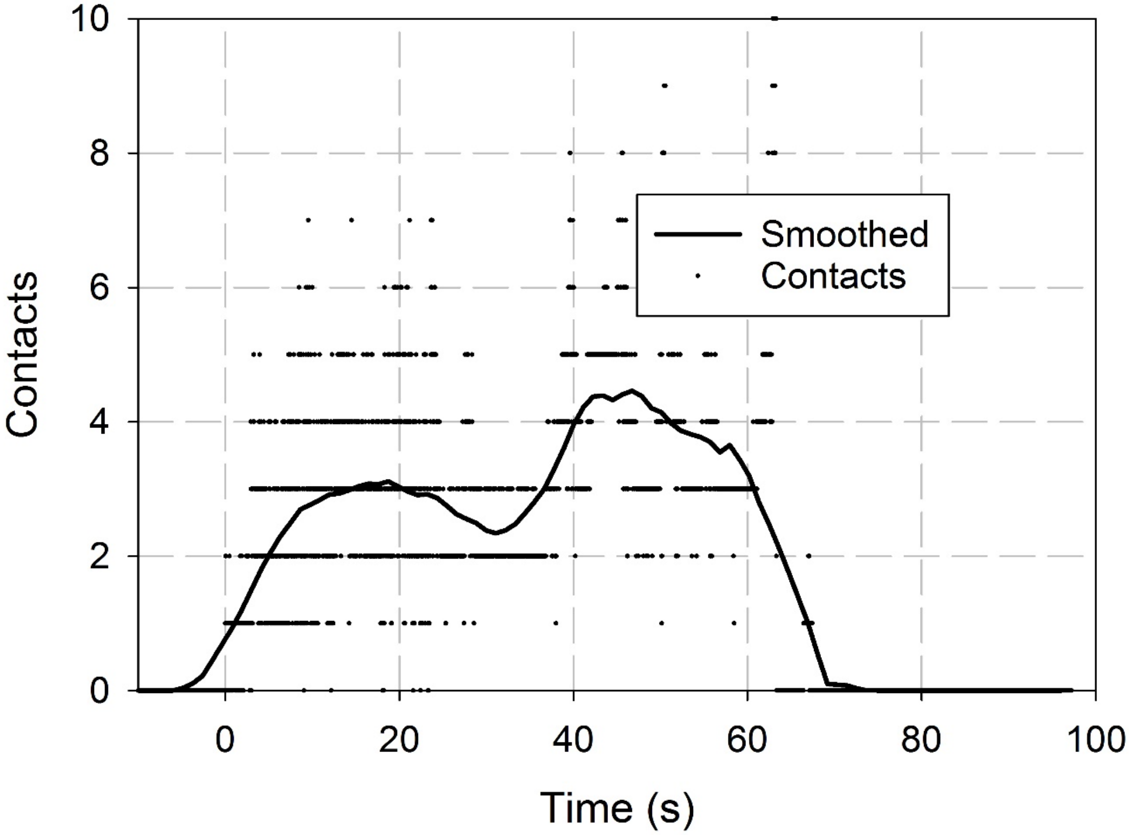


Figure 4. *Gear contact complexity for the* <u>*continue apace*</u> *whale behavior. In this realization the whale sheds the gear and does not become entangled. The points show the instantaneous number of contacts. The solid line represents the contact data smoothed with an inverse exponential filter.*

Unlike the water column height dependence on entanglement probability demonstrated by the <u>continue apace</u> behavior, the <u>roll away</u> behavior results in a 100% entanglement rate for 25%, 50%, and 75% water column heights. These results are shown in Table 4. For each of the three water column heights, we ran 128 Monte Carlo simulations and for each of these three sets of runs every simulation resulted in a lasting entanglement.

Table 4. Probability of entanglement vs. whale water column height resulting from roll away from rope behavior. For these simulations, the whale behavior was triggered at a distance of 2m from the gear and the whale completed one roll.

Water Column Height	**Probability of Entanglement**	**Number of Monte Carlo Runs**
25%	1.00	128
50%	1.00	128
75%	1.00	128

An exemplar complexity time series for the roll away behavior is plotted in Figure 5. Like the previous complexity time series plots, the time origin is shifted to the point of initial contact. The points indicate the instantaneous number of contacts and the solid curve shows the number of contacts smoothed with an inverse exponential filter. For this Monte Carlo simulation, the whale behavior is triggered when the gear is 2m away from the closest eye. Upon behavior trigger, the whale executes a single barrel roll while maintaining its previous course. The roll is completed in one body length or 10 seconds at the swimming speed of 1 m/s (for this 10m whale). The figure shows the number of contacts starting at zero and increases through the 10-second barrel roll maneuver. The number of contacts continues to increase until approximately 20 seconds as the whale takes up additional slack in the trap rope and the rope tightens its wrap around the whale body. For all of the simulations we observed the rope passing over the top of the flipper that makes first contact with the rope and then passes twice around the body, once from the anterior insertion of the flipper and again from the posterior insertion of the flipper. In other words, a single barrel roll results in two line wraps around the body; one under the whale leading to the surface marker and another under the body then over the dorsal ridge posterior to the nares and then down to the trap.

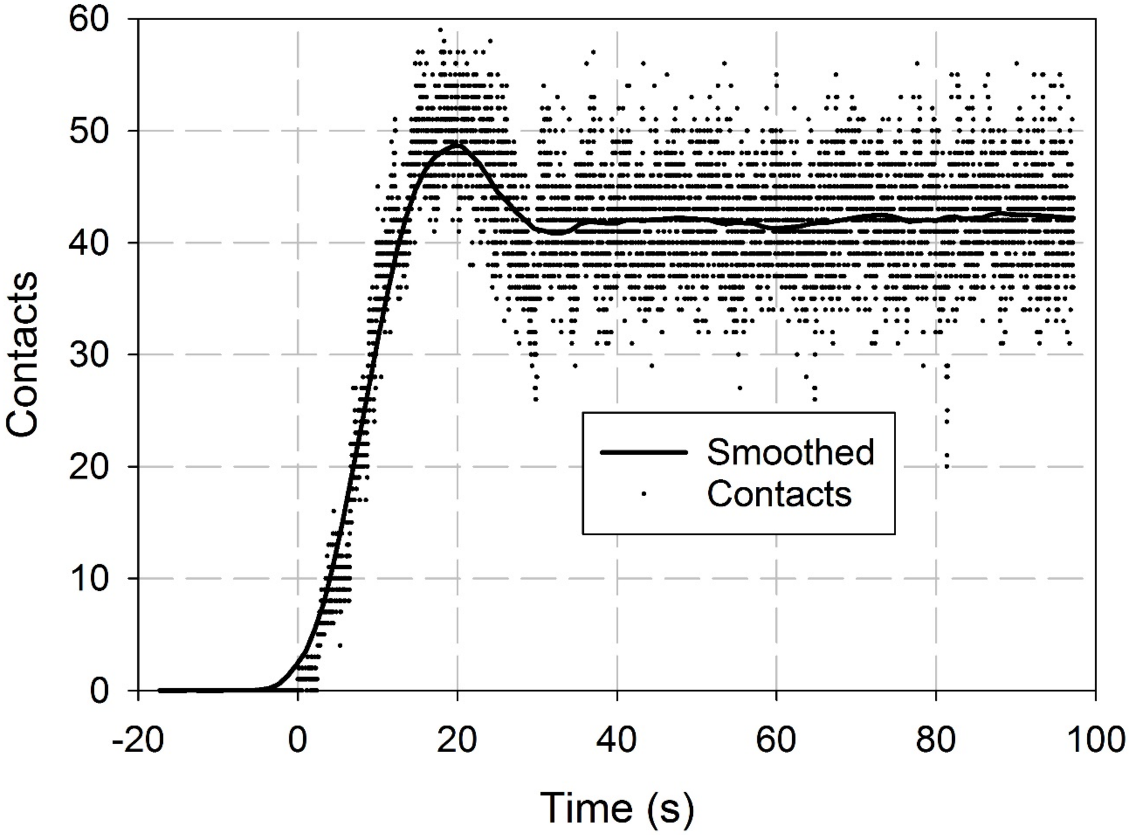
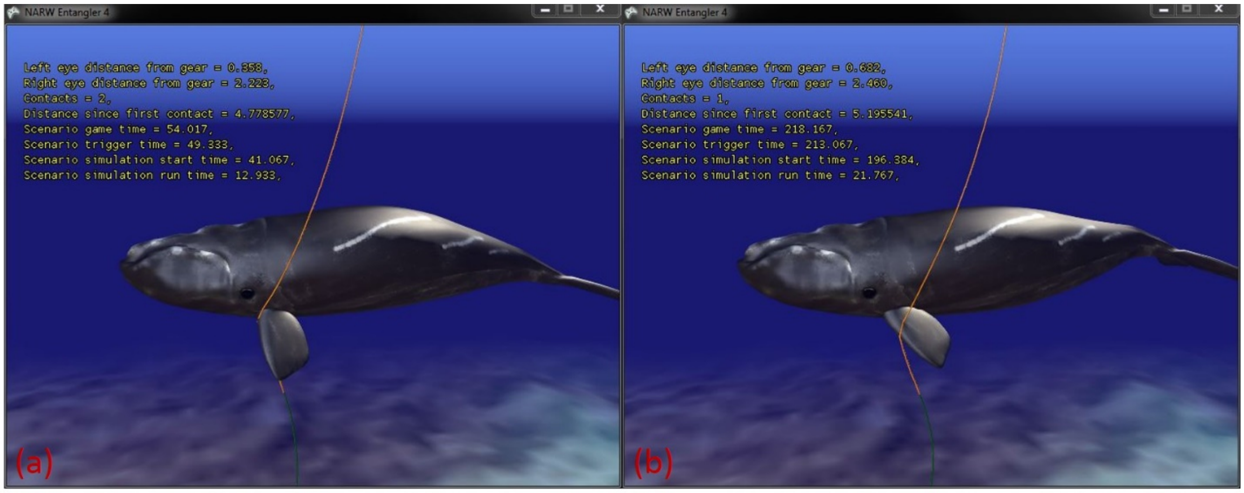


Figure 5. *Gear contact complexity for roll away whale behavior. The points show the instantaneous number of contacts. The solid line represents the contact data smoothed with an inverse exponential filter.*

The final whale behavior scenario we discuss here is a second set of continue apace simulations, but this time the pectoral flipper is maintained in the cruising configuration (swept aftward). The flipper configurations are shown in Figure 6. The left-hand image (a) shows the deployed or maneuvering configuration and the right hand image (b) shows the swept or cruising configuration. We conducted 128 Monte Carlo simulations with the aftward swept configuration for each of the water column heights of 25%, 50%, and 75%. For all of these Monte Carlo simulations, the results of which are shown in Table 5, the trap rope was shed from the pectoral flipper, interacted briefly again with the tail fluke, and was then shed free from the whale. Based on these results, and given the number of sightings of North Atlantic right whales with flipper wraps, we feel that it is unlikely that whales interact with fishing gear while maintaining aftward sweep of their pectoral flippers.



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Left eye distance from gear = 0.358,
Right eye distance from gear = 2.223,
Contacts = 2,
Distance since first contact = 4.778577,
Scenario game time = 54.017,
Scenario trigger time = 49.333,
Scenario simulation start time = 41.067,
Scenario simulation run time = 12.933,
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```
Left eye distance from gear = 0.682,
Right eye distance from gear = 2.460,
Contacts = 1,
Distance since first contact = 5.195541,
Scenario game time = 218.167,
Scenario trigger time = 213.067,
Scenario simulation start time = 196.384,
Scenario simulation run time = 21.767,
```

Figure 6. *Flipper sweep configurations (a) deployed configuration, (b) swept configuration. The deployed configuration is more likely to result in entanglements involving the flipper.*

Table 5. Influence of the flipper sweep angle on entanglement probability for continue apace whale behavior. These simulations show that the swept flipper configuration results in the rope being shed from the flipper but the deployed flipper configuration results in a finite probability of entanglement.

Water Column Height	**Deployed Flipper Probability**	**Swept Flipper Probability**	**Number of Runs**
25%	0.023	0.00	128
50%	0.422	0.00	128
75%	0.984	0.00	128

Our next step is to prepare a manuscript for submission before the end of 2016. The co-authors on this manuscript are:

Laurens Howle – Duke University and BelleQuant engineering, PLLC
Doug Nowacek – Duke University
Tim Werner – New England Aquarium
Scott Kraus - New England Aquarium

The effort for the behavior scenario manuscript was also supported under grant #NA13NMF4720280.

Bibliography

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