Michael R. Klosner

**Passive Acoustic Localization of Sperm Whales
to Facilitate Ship Strike Avoidance**

UNIVERSIDADE DO ALGARVE

Faculdade de Ciências e Tecnologia

2022

Michael R. Klosner

Passive Acoustic Localization of Sperm Whales
to Facilitate Ship Strike Avoidance

Mestrado em Biologia Marinha

Supervisor:

Sérgio Manuel Machado Jesus[a]

[a]FCT, Universidade do Algarve, Campus de Gambelas 8005-139 Faro, Portugal

UNIVERSIDADE DO ALGARVE

Faculdade de Ciências e Tecnologia

2022

Declaração de autoria de trabalho

Statement of Authorship

Passive Acoustic Localization of Sperm Whales
to Facilitate Ship Strike Avoidance

_____

Michael R. Klosner

A Universidade do Algarve reserva para si o direito, em conformidade com o disposto no Código do Direito de Autor e dos Direitos Conexos, de arquivar, reproduzir e publicar a obra, independentemente do meio utilizado, bem como de a divulgar através de repositórios científicos e de admitir a sua cópia e distribuição para fins meramente educacionais ou de investigação e não comerciais, conquanto seja dado o devido crédito ao autor e editor respetivos.

The University of the Algarve reserves the right, in accordance with the terms of the Copyright and Related Rights Code, to file, reproduce and publish this work, regardless of the methods used, as well as to publish it through scientific repositories and to allow it to be copied and distributed for purely educational or research purposes and never for commercial purposes, provided that due credit is given to the respective author and publisher.

_____

Michael R. Klosner

Acknowledgements

I would like to thank the following individuals for their help, advice and support:

First of all, I would like to thank my advisor, Professor Sérgio Manuel Machado Jesus, for his invaluable guidance and advice, and for patiently putting up with my seemingly endless hurricane of questions, when clearly he had other important things to do! I always joke that he gave me a secondary degree (at no extra cost) in Signal Processing, something that I did not expect when I first chose this topic of research after taking his fascinating course in Bioacoustics at the University of the Algarve. Thank you Professor Jesus!

Secondly, I would like to thank my family, especially my parents Naomi and Jerome Klosner and my sister Lise Klosner Susi, as well as the rest of my family.

Thirdly, I would like to thank John W. Alves, who has been a surrogate son to me here in Portugal throughout these past two years.

Fourthly, I would like to thank my other "extended family" here in Portugal, the members of the Jewish Community of the Algarve (JCA) in Albufeira, especially Claudia da Rocha Valente Sil Monteiro for all her remarkably insightful advice and Ido Yitshaik for his endless work and dedication in bringing this wonderful community together.

And to all the friends who have given me tons of great guidance (and lots of laughs) over the past two years, including Richard Pasquinucci, Olivia Love Worthy, Eliezer Silverman, Shia Mandelbaum, Steven Brown and Corey Kotler, some of whom I've known since childhood, I truly thank you and love you all.

Finally, I would like to thank Yahweh, the God of Israel, for guiding my path from my youth, always showing me what I need to do and where I need to go, and giving me the means and wisdom to get there. To my father in heaven, I thank you for everything, including life itself.

Abstract

Ship strikes are one of the leading causes of premature mortality among whales, accounting for the deaths of approximately 20,000 each year, with untold more being injured. Given the exponential increase in shipping traffic, estimated at 2 - 3% year-over-year, the potential for collisions continues to grow. Due to their large size, preferred habitats and sea surface behavior, the sperm whale is one of the species most vulnerable to ship strikes. In some populations, collisions with maritime vessels are the leading cause of death, premature or otherwise. This is particularly concerning considering that the sperm whale is listed on the IUCN Red List of Threatened Species as "Vulnerable" globally and "Endangered" in the Mediterranean region.

Passive Acoustic Monitoring, or PAM, is an environmentally non-intrusive method by which naturally generated underwater sounds, such as the clicks made by sperm whales, are picked up by hydrophones (underwater recording devices) and analyzed to extract a variety of data, including the sound source's location. In the current research, we use a PAM methodology known as Time Difference of Arrival (TDOA) analysis, whereby different acoustic paths taken by sound waves from their source to a hydrophone are analyzed to extract the differences in time between their arrivals. Extracted TDOAs are compared to a theoretical model (in our case, the Bellhop ray tracing model) to extrapolate the source's localization, which can then be fed into a live marine traffic system such as MarineTraffic (marinetraffic.com) to alert ships in the area to the presence and locations of the whales, so that they may take preventative action. In this dissertation, I present, inter alia, a working prototype, developed on the Matlab platform, for the detection and localization of sperm whales based on their vocalizations (clicks).

Keywords

Sperm whales, Ship strikes, Passive Acoustic Monitoring, Acoustic localization, Ray Tracing, Bellhop model

Resumo

As colisões com navios são uma das principais causas de mortalidade prematura entre as baleias, sendo responsáveis pela morte de aproximadamente 20.000 baleias a cada ano, com um número incontável de feridos. Os números exatos são difíceis de determinar porque as baleias feridas frequentemente saem para o mar, onde morrem e depois afundam no fundo do mar, não sendo mais avistadas. Em casos raros, baleias feridas podem encalhar, como aconteceu na costa de Almada, Portugal, em abril de 2022, quando um cachalote com lacerações visíveis – acredita-se ter sido causado por emaranhamento nos rotores de um navio – deu à costa e posteriormente morreu. Se há algum valor redentor para esses encalhes, é que eles fornecem aos cientistas uma pletora de informações inestimáveis sobre as causas e efeitos das colisões com navios.

O cachalote é, sem dúvida, a espécie de cetáceo mais afetada por colisões com embarcações marítimas. Num estudo de 2018 de Díaz-Delgado et al., exames patológicos de 224 cetáceos encalhados, compreendendo 21 espécies diferentes, revelaram que o cachalote é, de longe, a espécie mais afetada por colisões de navios, representando quase metade (11 de 24) de todos os animais necropsiados mortos dessa maneira. Em algumas populações de cachalotes, as colisões com embarcações marítimas são tão comuns que são a principal causa de morte, prematura ou não. É o caso da região das Ilhas Canárias, onde se estima que cerca de 60% das mortes de cachalotes sejam atribuídas a golpes de navios.

Infelizmente, as colisões de navios com os cachalotes continuam a aumentar a uma taxa exponencial. Existem três razões identificáveis para isso:

A primeira é um aumento exponencial correspondente no tráfego marítimo. O número total de navios mercantes em todo o mundo mais que duplicou nos 8 anos entre 2004 e 2012 e mais que triplicou entre 1992 e 2012. Em 2018, mais de 92.000 navios mercantes navegaram pelos mares, transportando cerca de 12 mil milhões de toneladas de carga, um aumento de 35% em apenas uma década.

O segundo fator é o comportamento específico de forrageamento do cachalote. Os cachalotes passam até 22 horas por dia caçando presas, incluindo cefalópodes e raias do fundo do mar, em profundidades de, em média, 600 a 1.000 metros, mas foram observados a mais de 2.000 metros. Nessas profundidades, eles devem enfrentar pressões extremas (superiores a 100 atmosferas) e escuridão total durante suas expedições de forrageamento, que podem durar até uma hora de cada vez. Como a visão é inútil nessas condições, acredita-se que os cachalotes usem a ecolocalização para localizar suas presas, produzindo uma série de cliques extremamente potentes que podem atingir níveis sonoros de 230 dB re 1 μPa a 1 m, tornando-os o

som de maior intensidade gerado por qualquer animal existente. Quando a baleia emerge (o que, como mamífero dotado de pulmões e não de guelras, eventualmente deve fazê-lo), está exausta de caçar, suster a respiração, suportar pressões extremas e gerar cliques intensos, e deve descansar na superfície do mar, geralmente por cerca de 10 minutos, antes de iniciar seu próximo mergulho. É durante esses períodos de descanso que os cachalotes ficam relativamente imóveis e, portanto, particularmente vulneráveis a colisões com navios. Por uma infeliz coincidência, em certas áreas do mundo, como as Ilhas Canárias e ao largo da costa sudoeste da península do Peloponeso e Creta, é diretamente nas rotas marítimas movimentadas que os cachalotes escolhem descansar, porque as características batimétricas que atraem cachalotes por suas excelentes oportunidades de forrageamento, como as beiras das plataformas continentais e desfiladeiros íngremes, se sobrepõem às principais rotas de navegação nessas regiões.

Um terceiro fator que causa um aumento no número de choques entre navios e cetáceos é o aumento do ruído submarino antropogénico que, como o volume de transporte, cresceu exponencialmente e que tem um efeito profundo não apenas nos cachalotes, mas na fauna marinha em geral. Estima-se que entre 1950 e 2007, os níveis de ruído ambiente de baixa frequência (25 - 50 Hz) nos oceanos, causados principalmente pelo constante ronco de fundo dos motores dos navios, aumentaram a uma taxa de 3,3 dB por década, chegando a 91 dB re 1 μPa^2/Hz em 2007, a mesma intensidade de um assobio de golfinho. Como os decibéis são calculados em escala logarítmica, isso equivale a duplicar a intensidade do ruído a cada 10 anos. Os efeitos do aumento da poluição sonora sobre cachalotes e outros cetáceos são múltiplos, incluindo permanente deficiência auditiva, dessensibilização comportamental aos perigos associados ao ruído do navio e interrupções na disponibilidade e distribuição de suas presas.

Embora a questão das colisões entre navios e baleias tenha recebido atenção crescente nos últimos anos, muito mais precisa de ser feito para mitigar esta forma completamente desnecessária e trágica de mortalidade de cetáceos. No caso dos cachalotes, há urgência, uma vez que muitos populações de cachalotes nunca se recuperaram tão rapidamente quanto o esperado após a promulgação da moratória internacional sobre a baleação comercial em 1986. Hoje em dia, a população mundial de cachalotes gira em torno de 200.000, pouco mais do que nos anos imediatamente anteriores à moratória, e muito menos do que os estimados 2 a 3 milhões de cachalotes que percorriam os mares em 1700, pouco antes de a espécie ser alvo de caça intensiva no século 19 por seu espermacete, uma mistura de ésteres de cera e triglicerídeos secretados nos órgãos produtores de som do crânio que era altamente valioso para uso em perfumes e velas. Como resultado, o cachalote permanece na Lista Vermelha de Espécies Ameaçadas da IUCN como "Vulnerável" globalmente e "Em Perigo, com Tendência Populacional: Diminuindo" na região do Mediterrâneo.

A Monitorização Acústica Passiva, ou PAM, é um método pelo qual sons subaquáticos gerados naturalmente, como cliques de cachalotes, são captados por hidrofones (dispositivos de gravação subaquática) e analisados para extrair uma variedade de dados. A PAM está a tornar-se cada vez mais popular na monitorização de cetáceos em geral, e cachalotes em particular, devido à combinação única de propriedades acústicas do clique "usual" do cachalote – volume, impulsividade e ampla faixa de frequência – o que o torna particularmente adequado para uso em técnicas de PAM. A vantagem da PAM em relação à monitorização da fauna marinha é que ele não é intrusivo: os sistemas PAM não geram som próprio e não envolvem contato direto com os animais. No entanto, a PAM pode ser usada efetivamente em uma variedade de aplicações, incluindo a determinação da presença e da localização de fontes de vocalização.

Na investigação atual, usamos um método conhecido como análise de diferença de tempo de chegada (TDOA), em que diferentes caminhos percorridos pelas ondas sonoras à medida que viajam entre a fonte e o hidrofone, como caminhos diretos e os refletidos na superfície, são analisados para extrair a diferença de tempo entre os tempos de chegada. Os TDOAs extraídos são então comparados a um modelo teórico (no nosso caso, o modelo de traçamento de raios Bellhop), para extrapolar informações de localização sobre a fonte, incluindo a sua profundidade, distância horizontal (alcance) do hidrofone e ângulo de azimute. O resultado final pretendido é a localização quase em tempo real de todos os cachalotes nas proximidades de uma série de hidrofones, que podem então ser incluídos num sistema de tráfego marítimo em tempo real, como o MarineTraffic (marinetraffic.com) para alertar os navios na área para a presença e a localização das baleias, para que possam tomar ações preventivas, como reencaminhamento, redução de velocidade e colocação de observadores humanos de mamíferos marinhos no convés. Nesta dissertação, apresento, entre outros, um protótipo de trabalho, desenvolvido na plataforma Matlab, para a deteção e localização de cachalotes com base nas suas vocalizações (cliques).

Palavras-chave

Cachalote, colisões com navios, monitorização acústica passiva, localização acústica, Ray Tracing, modelo Bellhop

Table of Contents

List of abbreviations, acronyms and symbols

ARGOS - Advanced Research & Global Observation Satellite
c - speed of sound
FFT - Fast Fourier transform
GPS - Global Positioning System
ICI - Interclick interval
IMO - International Maritime Organization
IPI - Interpulse interval
IUCN - International Union for Conservation of Nature
RD - Receiver depth
RR - Receiver range
SD - Source depth
SNR - Signal-to-noise ratio
SONAR - Sound navigation and ranging
TDOA - Time difference of arrival

Section 1: General Introduction

1.1. Overview

Dangerous interactions between sperm whales and seafaring vessels have been recorded for centuries, and have even entered into the common lore. Herman Melville's 1851 novel Moby Dick, which tells the story of the irascible Captain Ahab's obsession for revenge upon a sperm whale that had bitten off his leg, is based on a real incident – the 1820 ramming and subsequent sinking of the whaling ship Essex in the South Pacific by a sperm whale. While, in the novel, it is the sperm whale that ultimately kills Captain Ahab, dragging him down to the bottom of the sea where he meets his watery demise, in real life, the opposite is far more often true: many sperm whales are killed each year by ship strikes, after which they descend to the bottom of the sea, never to be heard from or seen again. (Ritter et al., 2019) This is one of the reasons that an exact assessment of sperm whale deaths by ship strikes is hard to come by. Still fewer strand[1] themselves and subsequently die after being heavily injured by ship strikes, often caused by being slashed by ships' rotors, as happened on the coast of Almada, Portugal in April, 2022. (See Figure 1.1.)

Sadly, ship strikes on sperm whales continue to rise, while many sperm whale populations continue to decline. (Notarbartolo di Sciara et al., 2012) These two factors are on a collision course (pun intended) to push an already vulnerable species to the brink of extinction. Hence the concept of the SAvE Whales (System for the Avoidance of Ship-Strikes with Endangered Whales) project, an interdisciplinary effort designed to "develop and test an automated system that listens out for sperm whales, locates them across busy routes of shipping traffic and provides captains with real-time information allowing them to avoid collisions." (OceanCare, 2020) While the project focuses on the waters of the Hellenic Trench off the Greek Peloponnese mainland and nearby island of Crete, if successful, it can serve as a pilot project to be replicated in other areas where ship-whale collisions are frequent.

---

[1] Please note that whenever the word "strand" in its various forms is used throughout this work, it is meant in the original sense of the word, "come aground on shore", and not in the more colloquial sense, "abandon".

Figure 1.1: [Left] A 14.8m-long sperm whale, apparently injured by collision with a ship, is stranded at the Fonte da Telha beach in Almada, Portugal on 15 April 2022. The whale subsequently died of its injuries. (From: Donn, 2022; "Injured Beached Sperm Whale Dies in Portugal," 2022) [Right] A deceased sperm whale beached in New South Wales, Australia, shows clear slash marks from a ship's propeller on its posterior region. (From: Lloyd & Ross, 2015)

1.2. Reasons for the steady increase in ship-whale collisions

Ship strikes upon sperm whales have been increasing exponentially over recent decades (Van Waerebeek & Leaper, 2008), threatening already vulnerable populations in the eastern Mediterranean and elsewhere. This increase is due to a number of factors, each of which we shall survey below.

1.2.1. Exponential increase in worldwide shipping

In recent decades, worldwide marine shipping traffic has consistently shown a year-to-year increase.[2] Figure 1.2 (top) shows estimates of yearly ship numbers, broken down by region, from 1992 through 2012. (Tournadre, 2014) The underlying data reveal that ship numbers more than doubled in the 8 years between 2004 and 2012, and more than tripled between 1992 and 2012. Furthermore, the data reveal an exponential – not linear – upward trend, which, if it continues, does not bode well for the manifold species threatened by the increased presence of these vessels, not only due to collisions, but also due to increases in pollution and ocean noise. As of 2018, over 92,000 merchant vessels sailed the seven seas, transporting close to 12 billion tons of cargo, an increase of 35% in just a decade. ("United Nations Conference on Trade and Development: Review of Maritime Transport 2019," 2020) (See Figure 1.2, bottom.) The obvious effect of this is that it elevates the probability of collisions between vessels and whales. In the Canary Islands region, it is estimated that nearly 60% of sperm whale deaths are attributed to blows from ships, making it the leading cause of sperm whale mortality, premature or otherwise. (Arregui et al., 2019) A study by Díaz-Delgado et

---

[2] With the exception of 2020, due to the depressive effects of the COVID-19 pandemic on the worldwide economy. (Millefiori et al. 2021)

al. (2018) paints an even more dire picture: of 16 stranded sperm whales examined pathologically between 2006 and 2012 in the Canary Islands, vessel collisions were deemed to be the most probable cause of death for 11 of them (68.8%). Furthermore, of the 224 animals, comprising 21 different cetacean species, on which necropsies were performed, sperm whales were found to be, by far, the species most affected by ship collisions, accounting for almost half (11 of 24) of all animals killed in this manner. (Díaz-Delgado et al., 2018)

Figure 1.2: **Increases in marine shipping**. [Top] Annual ship numbers from 1992 to 2012, globally and for each of four ocean basins. (From: Tournadre, 2014) [Bottom] Graph of international maritime trade broken down by cargo type for selected years, revealing a 35% increase between 2008 and 2018. The x-axis represents millions of tons loaded. (From: "United Nations Conference on Trade and Development: Review of Maritime Transport 2019," 2020)

1.2.2. Sperm whale foraging behavior

Sperm whales (*Physeter macrocephalus*) are large, elusive cetaceans that spend much of their time deep undersea hunting for prey. Sadly, it is this very predation behavior that makes them susceptible to ship

strikes, since they must eventually resurface to rest and refresh their air supply. During these resting periods, they are relatively immobile and hence particularly vulnerable to ship strikes. This is even more concerning considering that sperm whales are listed by the IUCN Red List of Threatened Species as "Vulnerable" globally (Taylor et al., 2019) and as "Endangered, with Population Trend: Decreasing" in the Mediterranean region (Notarbartolo di Sciara et al., 2012). Recently, it has been estimated that the Hellenic Trench, the locus of the SAvE Whales project, has a remaining sperm whale population of only 200 to 300 individuals. Furthermore, since the Hellenic Trench is a major foraging, calving and nursing hub for the eastern Mediterranean population of sperm whales, this number is believed to represent the totality of individuals in the entire eastern Mediterranean. (Frantzis et al., 2019; Frantzis et al., 2014) As a result of this, the area has been declared an IMMA (Important Marine Mammal Area) by the IUCN.[3]

Sperm whales spend up to 22 hours per day in deep dives below the sea's surface, usually at depths of 600 to 1000 meters, but they can reach depths beyond 2000 meters. There, they search for prey including cephalopods and deep-sea rays. A single dive by a sperm whale can last up to one hour, and during this time, the animal must contend with extreme pressures (greater than 100 atmospheres) and total darkness. (*About SAvE Whales*, 2019) In such conditions, prey cannot be identified by eyesight. Instead, sperm whales are believed to use echolocation by producing a series of loud clicks originating in their nasal cavities and emitted through an intracranial structure called "the junk", where it is focused and can reach sound levels of up to 230 dB re 1 μPa at 1 m. This makes the sperm whale the loudest animal in the world. A sperm whale click emitted at close range can kill a human.[4] The process of generating these clicks requires an enormous amount of energy. Thus, when the sperm whale surfaces (which, as a mammal equipped with lungs and not gills, it eventually must), it is exhausted from hunting, holding its breath, withstanding extreme pressures and generating loud clicks, and must rest at the sea surface, usually for around 10 minutes, before commencing its next dive.

By an unfortunate coincidence, in certain areas of the world it is directly in shipping lanes that these animals choose to rest because the bathymetric features that attract sperm whales for their excellent foraging opportunities, such as the edges of continental shelves and steep canyons, happen to overlap major shipping routes. (Frantzis et al., 2019)

---

[3] See https://www.marinemammalhabitat.org/hellenic-trench.
[4] See https://www.youtube.com/watch?v=zsDwFGz0Okg for an excellent explanation.
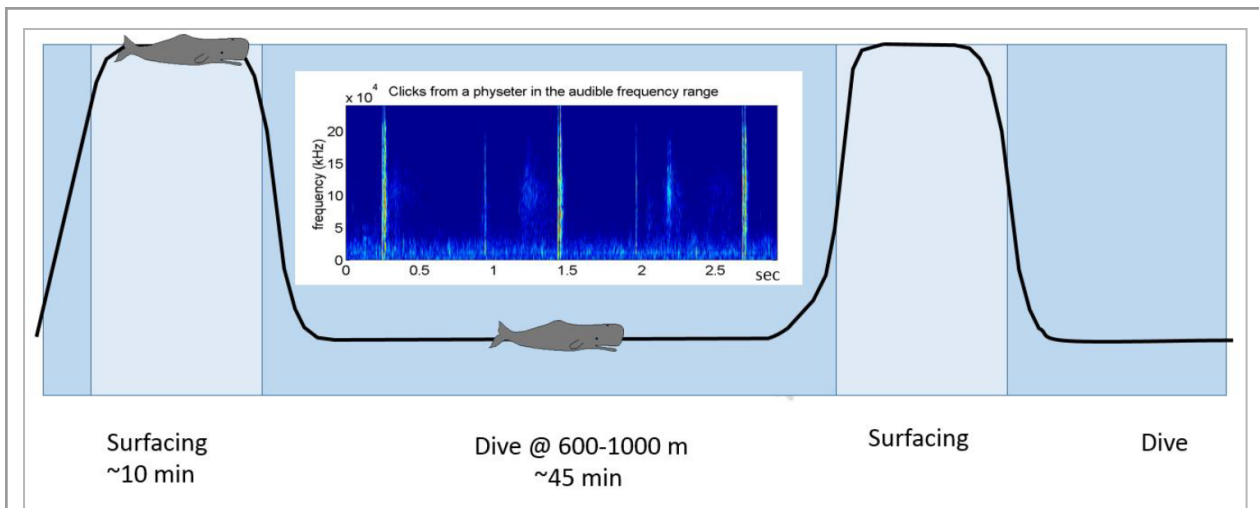
Figure 1.3: Graphic created by the SAvE Whales project to illustrate the dive cycle and click generation of a sperm whale. The predation behavior of sperm whales can place them in direct contact with vessels in high-traffic shipping lanes. (From: *About SAvE Whales*, 2019)

1.2.3. Effects of increased noise pollution

One final factor causing the sharp increase in whale-boat collisions is the exponential rise in anthropogenic noise pollution in the seas, which has had a profound effect not just on sperm whales, but on marine life in general. It is estimated that between 1950 and 2007, low-frequency (25 - 50 Hz) ambient noise levels in the oceans increased at a rate of 3.3 dB per decade, reaching 91 dB re 1 μPa^2/Hz in 2007. (Frisk, 2012) Since decibels are calculated on a logarithmic scale, this amounts to a doubling of noise intensity every 10 years. This increase in noise level can be closely correlated to corresponding increases in shipping volume and world GDP; extrapolating forward, by 2030 an ambient sea noise level of 96 dB can be expected – the same loudness as a typical dolphin whistle, but on an uninterrupted basis. (See Figure 1.4.)
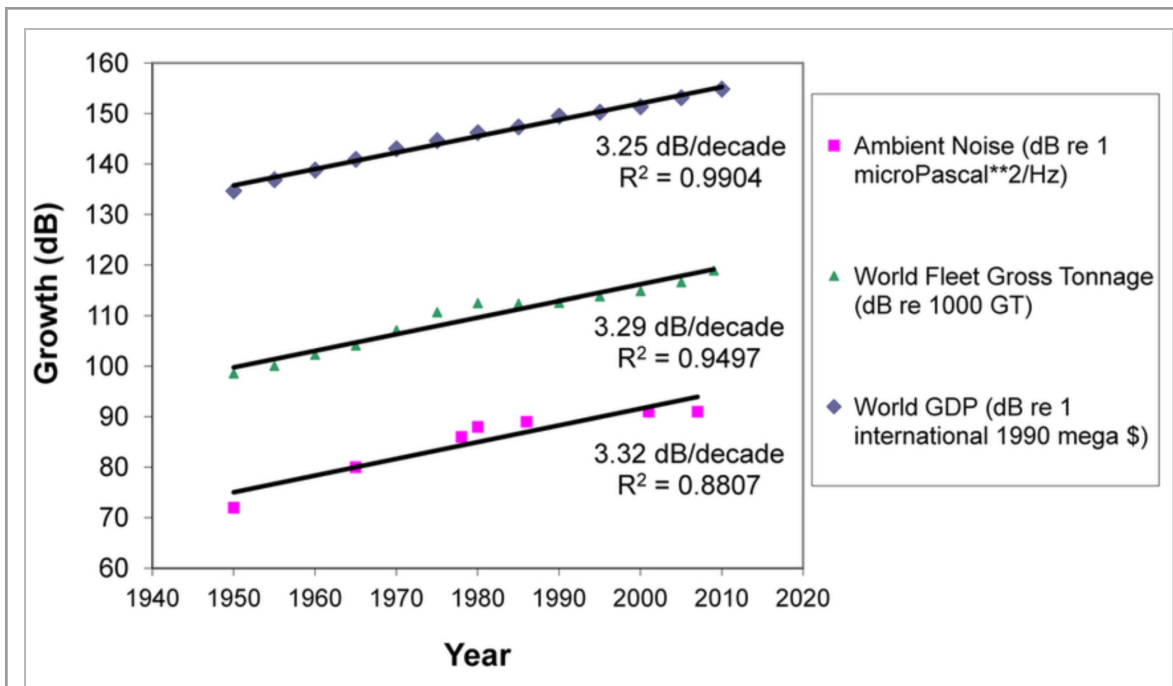
Figure 1.4: Between 1950 - 2007, ambient noise levels in the world's oceans rose by an estimated 3.3 dB per decade. This can be closely correlated to the rise in fleet gross tonnage and world GDP. Based on expected growths in GDP, an ambient noise level of 96 dB is predicted by 2030. (From: Frisk, 2012)

Human-generated underwater sounds come in a variety of forms, including continuous low-frequency sound generated by the engines of large ships, impulsive broadband sounds produced by air gun arrays used in undersea hydrocarbon exploration surveys, and high-intensity sonar waves linked to military activities. (Audoly et al., 2017; Hildebrand, 2005) (See Figure 1.5.) Some of these sounds can be heard hundreds or even thousands of kilometers away; and some, such as sonar, have been directly linked to mass cetacean stranding events of up to dozens of animals at a time. (Klinck et al., 2012; Hansen et al., 2022)
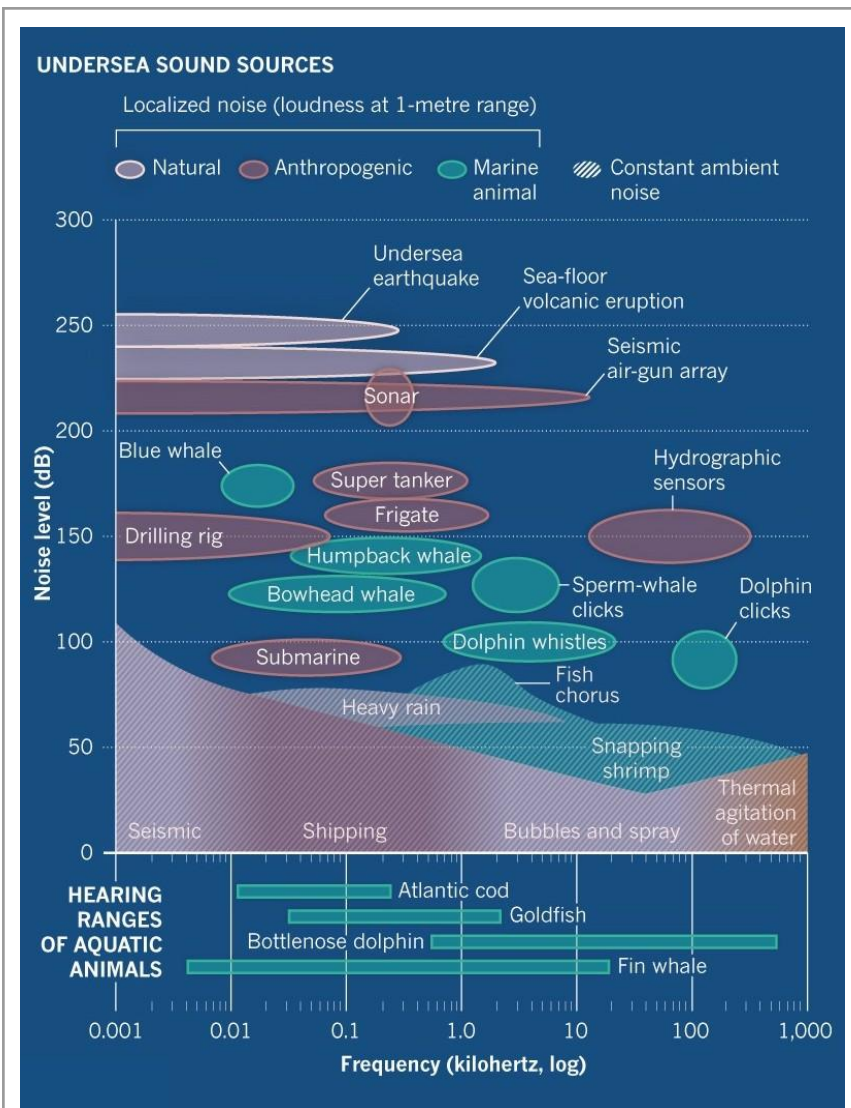
Figure 1.5: Examples of biogenic, geogenic and anthropogenic sounds common in the undersea soundscape, with their frequency ranges and sound levels. (From: Jones, 2019)

As may be expected, such a persistence and intensity of underwater noise has a profound effect on marine fauna, including both their physiology and behavior. In the case of sperm whales and other cetaceans, a number of specific phenomena have been identified which can lead to an increase in the probability of collisions with ships.

• Impulsive as well as chronic undersea noise has been shown to permanently impair hearing in cetaceans (Wang et al., 2021), including sperm whales. For instance, evidence of cellular damage to the Organ of Corti in the inner ears of long-finned pilot whales was detected by scanning electron microscopy in corpses recovered after mass stranding events in Scotland in 2012 and 2015. (Morell et al., 2017) Sperm whales have acute hearing – capable of finely discriminating frequencies in the range of 100 Hz to 30 kHz – upon which they heavily rely to track prey and avoid danger. (Schmidt et al., 2018) Any reduction in their hearing acuity renders them less able to aurally identify oncoming ships.

• The continuous low-frequency (30 - 200 Hz) roar of ship engines has been shown to behaviorally desensitize sperm whales to the danger associated with these sounds. As a result, sperm whales tend to remain in shipping lanes even as they hear ships encroaching. (Baraniuk, 2015)

• Sperm whales have been shown to reduce their predation activity in the presence of anthropogenic sounds such as sonar waves. When pre-recorded naval sonar was played back in the vicinity of sperm whales, they reduced their foraging activity by 50%, almost identical to the reduction that was registered in response to the playback of the calls of killer whales (orcas), the only significant predator of the sperm whale. The implication of these results is that sperm whales perceive a similar level of risk from the two sounds, and that in both cases they choose safety over feeding. (See Figure 1.6.) This raises questions about the long-term negative impacts of increased anthropogenic noise on the overall fitness level of sperm whales and, consequently, their ability to avoid dangers such as oncoming ships. (Miller et al., 2022)

Figure 1.6: Percent reduction in intense-foraging dive times in the presence of pre-recorded sonar sounds (y-axis) and killer whale sounds (x-axis), for 4 different species. Data reveal an almost identical response by the sperm whale to both sounds. Crosshairs represent 95% CI error bars. (From: Miller et al., 2022)
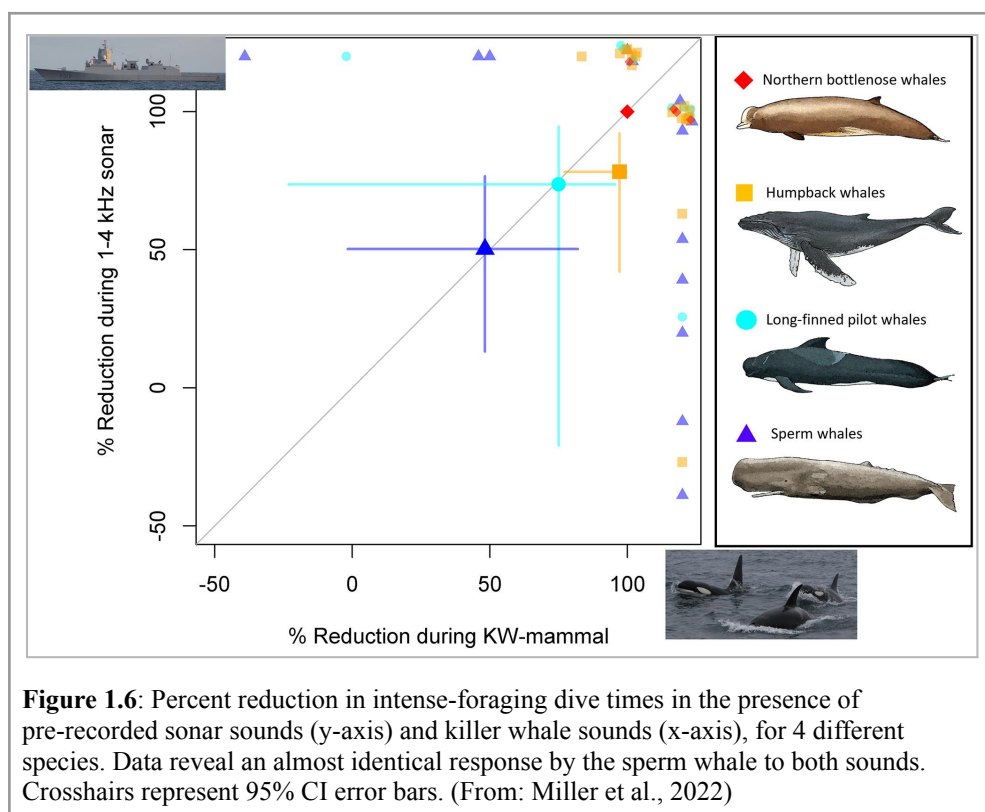
• Not only is predation behavior affected by anthropogenic noise, but so is the prey itself. Besides cetaceans, undersea noise negatively affects a wide variety of other marine vertebrates and invertebrates, including cephalopods (André et al., 2011), one of the mainstays of the sperm whale's diet. This can cause disturbances in the distribution and availability of prey, which can negatively affect the comprehensive health of the animals, as well as result in longer dive times that render the sperm whales more exhausted upon surfacing, and hence less able to avoid approaching ships.

1.2.4. Summary

Given the confluence of these three factors, namely: (1) the exponential increase in global marine traffic; (2) the precarious state of the worldwide and Mediterranean populations of sperm whales; and (3) the steady increase in anthropogenic undersea noise; it is incumbent upon all of us who have an affinity for these magnificent creatures to propose and implement appropriate plans and mechanisms in order to reduce the frequency of collisions between sperm whales and ships. The above reasoning provides not only a necessity, but a sense of urgency, in promoting any and all effective projects which would help alleviate one of the main causes of premature sperm whale mortality. The system that we plan to develop, test and deploy has the ability to do just that.

1.3. Sperm whale physiology, behavior and ecology

In order to build an effective system to detect the presence of sperm whales, it is essential to intimately understand their physiology, behavior and ecology. It goes without saying that this aim encompasses a huge scope of material. It is therefore my intention, in this section, to focus mainly on the elements of these topics that are directly related to the project at hand. Interspersed within this discussion will be some of the latest results in relevant research.

1.3.1. Overview

Sperm whales (*Physeter macrocephalus*) are large, majestic cetaceans of the order Artiodactyla [even-toed ungulates][5] (infraorder: Cetacea [cetaceans]; parvorder: Odontoceti [toothed whales]), and the only extant member of the family Physeteridae. Sperm whales, like all artiodactyls, exhibit a high degree of sexual dimorphism. In the sperm whale, the most obvious phenotypic expression of this is the great difference in sizes between the sexes. Adult male sperm whales are three times larger than their female counterparts (Panagiotopoulou et al., 2016), and are objectively huge for the animal kingdom: they reach an average length of 16 meters, and can grow as large as 21 meters, making them the largest toothed whales in the world and the largest animals on earth aside from the biggest of the baleen whales. (*Oceana: Sperm Whale*, 2021) In addition, sperm whales have the largest brain ever recorded of any species on earth, past or present. (Skarsoulis et al., 2022) One of the distinguishing visible features of the sperm whale is its enormous block-shaped head[6], which contains up to one-fourth of its body mass and spans up to one-third of its body

---

[5] This makes them distantly related to land mammals such as the hippopotamus, giraffe, camel and sheep, and this has been proven through fossil evidence, comparative genomics and comparative morphology. As a notable example of the latter, the sperm whale's stomach consists of four chambers, just as that of ruminants does. (Jiang et al., 2021)

[6] Hence its species epithet *macrocephalus*, meaning "large head" in Greek.

length. (Panagiotopoulou et al., 2016) Most of the head is occupied by the nasal complex, wherein the species' characteristic loud clicks are produced.

Figure 1.7: **Anatomy of the sperm whale**. The above photograph is of a reassembled sperm whale originally beached off of the city of Nantong, southeast China in 2016, and subsequently preserved using plastination, a recently-developed technique whereby bodily fluids and fats are replaced by a hardening polymer, rendering the sample durable and devoid of foul odors. This is the largest animal ever to be preserved by this method. The left side of the sperm whale [top] exposes its internal organs, while the right side [bottom] shows its muscle structure. (From: Jiang et al., 2021)

1.3.2. Social structure

Except for occasional socialization, adult males (bulls) live solitary lives outside of mating season, while females live with juveniles and suckling calves in transgenerationally-stable matriarchal groups called pods or social units, which consist of on average 12 individuals. This difference between the social structure of adult males and adult females is another conspicuous example of the sperm whale's sexual dimorphism, this time behavioral. (Sarano et al., 2021) A recent study assessing associations between whales and genetic data has shown that pods consist mostly, though not exclusively, of first-degree (mother / offspring) and second degree (half-sibling or grandparent / grand-offspring) kin. Long-term kinship-based relationships, and not just the utilitarian need for communal cooperation, seem to be important factors in determining the complex social structure of the sperm whale. (Konrad et al., 2018)

A related genomic study which took place off the coast of Mauritius in the Indian Ocean bolstered this conclusion by constructing a "family tree" for individuals in a stable social unit of sperm whales, dubbed "Irène's group" (based on the name of the female that was shown to have the most first-degree connections

with other members.) Sloughed skin fragments (dead cells exuded from the skin's surface) were gathered from 24 of the 28 group members and their mitochondrial DNA (mtDNA) and nuclear microsatellites were sequenced at known polymorphic loci. All but one presented an identical mtDNA haplotype (SW_M1) at the examined 638 bp fragment, a haplotype that is rare in the western Indian Ocean, confirming their close matrilineal heritage. Analysis of microsatellite polymorphisms allowed for further deconstruction of the group by identifying first- and second-degree relationships among 22 of the 24 sequenced individuals. (See Figure 1.8.) Only "Vanessa" and "Claire" were found to have no such relationships. Furthermore, "Claire", the one specimen that did not express the group's common mtDNA haplotype, was found to have a haplotype more common to the Seychelle islands, located 1,750 km north of Mauritius. Therefore, it is believed that she was adopted by the group – a phenomenon which has been previously observed but never confirmed genetically – buttressing the premise that matrilineal kinship primarily, but not exclusively, determines the makeup of sperm whale social groups. (Sarano et al., 2021)
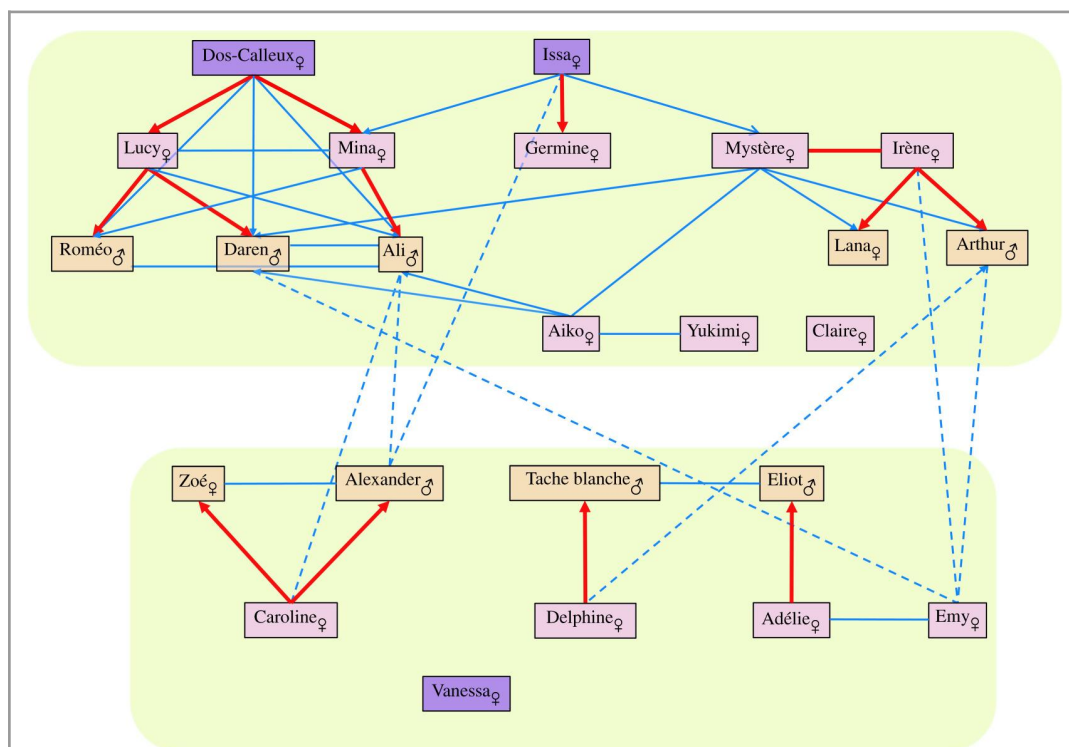
Figure 1.8: **Kinship relationships in sperm whale social units**. The above schematic diagram shows the kinship relationships among 24 members of "Irène's group", a stable social unit of sperm whales near Mauritius in the Indian Ocean. Red lines represent first-degree kin relationships; blue lines represent second-degree kin relationships. The researchers noted that the group appears to be in the process of fissioning into two subgroups, so dotted blue lines denote second-degree relationships across the subgroups, while solid blue lines denote second-degree relationships within a subgroup. (No inter-subgroup first-degree relationships were found.) Nodes, too, are color-coded: orange denotes (young) males, light purple denotes young females and dark purple denotes older females. Results of the study showed that all but two members of the group have first- or second-degree matrilineal relationships to at least one other member of the group, supporting previous studies which showed that sperm whale social groups are primarily, but not exclusively, organized matrilineally. (From: Sarano et al., 2021)

Within pods, females give birth every 4 - 20 years, almost always to a single offspring. Sucklings nurse on lactating mothers until between 19 and 42 months of age, but are not always nursed by their own biological mothers: alloparental nursing is common within sperm whale pods, as is alloparental care, or "babysitting" (Sarano et al., 2021), a phenomenon frequently noted in K-selected species (Riedman, 1982). Females reach sexual maturity at the age of 9 years, while males do so at 18 years old. Thus, the sperm whale epitomizes the K-selected species (Whitehead, 2002, p. 1167), characterized by few offspring, a high level of parental care and slow maturation. Clearly, each sperm whale lost to a ship strike or other premature form of mortality is not easily replaced.

A study by Konrad et al. (2019) analyzed in detail the phenomena of alloparental nursing and alloparental care within social units of sperm whales near the island of Dominica in the eastern Caribbean. While for at least 87.5% of the calves the primary nurse (the female most often observed feeding the calf) was its biological mother, around 50% of the calves were also observed suckling on one or two other adult females. Similar results were obtained regarding parental care: while a calf's genetically-determined mother was most likely to be its caretaker (71% of the time), for the remaining 29% of the time, the calf was cared for by other members of the group. This implies that close to one-third of a calf's time is spent with alloparents. Furthermore, these babysitters were most likely to be females, either adults (14.1% of total time) or juveniles (10.2% of total time), and the more closely related the female was to the calf's biological mother, the more likely it was to be both the calf's nurse and the calf's babysitter. (See Figure 1.9.) Thus, even in the case of alloparental care, maternal kinship plays an important role. (Konrad et al., 2019)
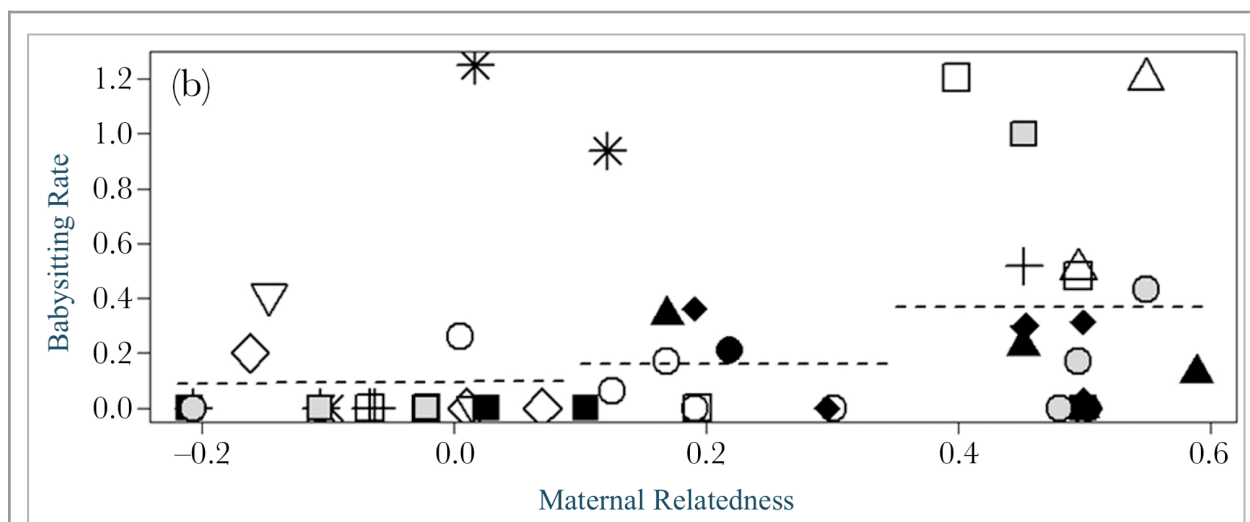
Figure 1.9: **Alloparental care in sperm whale pods**. Konrad et al. (2019) found a positive correlation between maternal relatedness of babysitters to their charges and babysitting rate. Each data point represents an calf / alloparent pair and each unique shape / shading combination represents an individual calf. Dashed lines represent, from *right* to *left*, the mean babysitting rate of first-degree maternal relatives (grandmothers or half-siblings), more distant relatives, and non-relatives. (From: Konrad et al., 2019)

A fascinating side note: How exactly do sperm whales nurse?

Nursing is an essential activity which takes place near the water's surface while the whales are particularly disabled and defenseless against ship strikes. The behavior of sperm whale suckling has always been somewhat of a mystery. This is complicated by the fact that suckling takes place below the water's surface and therefore its exact nature is difficult to observe. Although short dives by calves to the underbelly of their female escorts ("peduncle dives") have generally been assumed to be for the purpose of nursing, this common assumption has been questioned over the years due to the peculiar shape of the sperm whale's mouth, which features a suspended, reduced lower jaw (in comparison to its engorged nasal cavity) that does not seem to be conveniently shaped for a calf to hold the mother's nipple directly in its mouth and draw milk. Furthermore, no direct evidence of milk transfer has ever been documented.

Shane Gero and Hal Whitehead, two of the world's foremost sperm whale behaviorists, published a 2007 study which attempted to clarify the issue of sperm whale nursing behavior. They followed a group of sperm whales in the Caribbean and Sargasso seas and collected data on their peduncle dives, including the duration of each dive (mean = 14.2 sec) as well as each set ("bout") of dives (mean = 5.7 min, comprising 24.4 individual dives), the surface interval between dives (mean = 5.8 sec.) and the side of the adult female escort on which the calf dived (a clear preference for the left side was observed). In addition, snorkelers made direct underwater observations of the dives. The observations revealed an unexpected behavior: in not a single one of the peduncle dives was the calf ever observed placing its mouth adjacent to the underbelly of its mother; instead, the calf would press its blowhole (located in the upper left region of the head) against the underbelly and remain in this position for a few seconds before detaching and resurfacing. Gero and Whitehead proposed the novel idea of nasal suckling, whereby the mother actively ejects milk through the calf's blowhole directly into its left nasal passage, after which the calf surfaces and drinks the milk by releasing it from the nasal passage into its oral cavity. While seemingly far-fetched (no other mammal is known to ingest milk in this fashion), the researchers emphasized that this hypothesis explains other calf behaviors as well, such the frequent resurfacing between peduncle dives (not typical of other odontocetes), and is in line with other known aspects of sperm whale physiology, such as their ability to use their left and right nasal passages independently, breathing through their left nasal passage while producing clicks through their right one. If correct, this nursing behavior represents a unique evolutionary adaptation of the sperm whale to circumvent its physical inability to engage in oral sucking. (Gero & Whitehead, 2007)

A recent underwater photography expedition by Russian photographer Mike Korostelev (Bunyan, 2020) raised another possibility: a mother sperm whale was seen releasing her milk directly into the surrounding

water, after which her calf was photographed ingesting the cloud of milky water. (See Figure 1.10.) The enigmatic story of sperm whale suckling behavior still remains ongoing to this day.
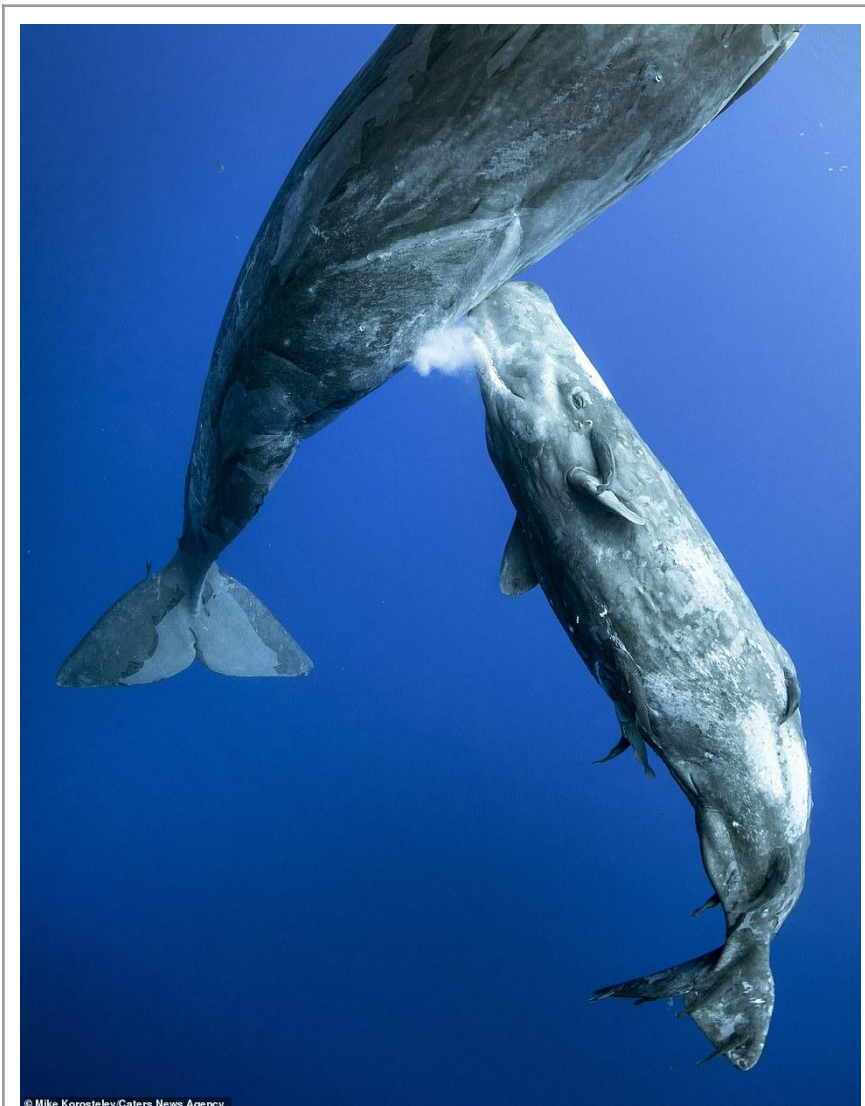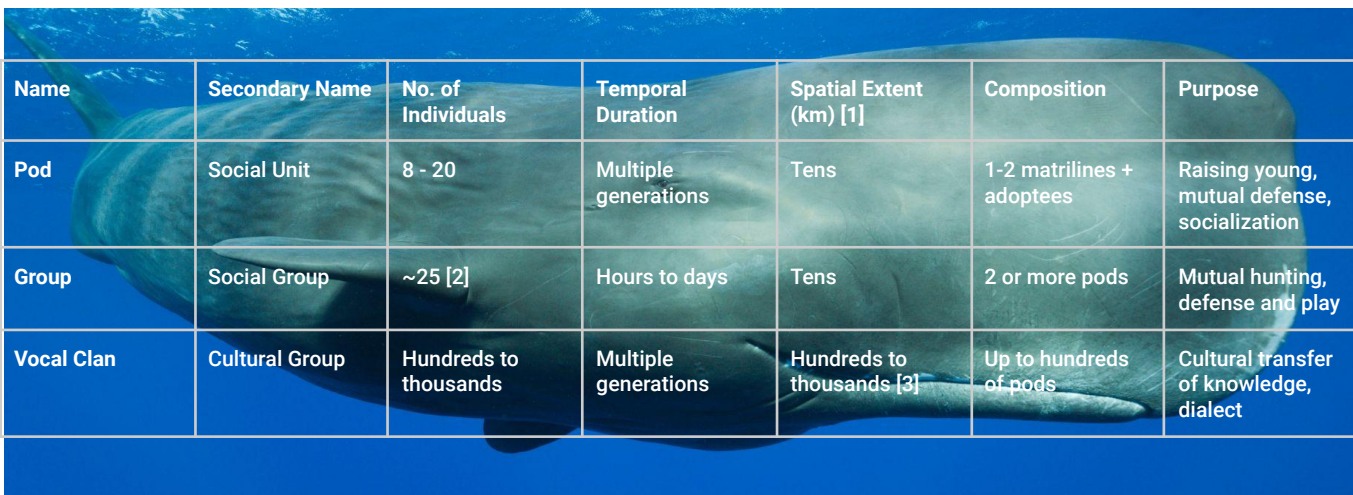
Figure 1.10: **Photograph of sperm whale nursing**. A mother sperm whale is photographed in the Indian Ocean injecting its milk directly into the surrounding water for its calf to imbibe. Though both oral and nasal suckling have been suggested as the means by which calves ingest mother's milk, the exact nature of sperm whale nursing is still a mystery to this day. The photograph was taken in 2020 by Russian underwater photographer Mike Korostelev. (From: Bunyan, 2020)

While intergenerationally stable social units ("pods") are the nuclear social structure for sperm whale females and young, they are not the only social structure in which sperm whales organize themselves. As is typical of K-selected species, the social structure of the sperm whale is multi-layered and hierarchical. Superimposed upon the pod is the social group ("group"), a temporary agglomeration of pods that can last anywhere from a few hours to a few days (Gero et al., 2015). While the exact purpose of the group is

unknown, it has been suggested that groups assemble for reasons of joint foraging, mutual defense and play. Groups, however, are not merely random collections of pods: all pods in a group are drawn exclusively from a single "vocal clan", the highest-order superstructure of the sperm whale's social organization; even sympatric pods will rarely associate with each other if they are from different vocal clans. (Vachon et al., 2022). A vocal clan (also called a "cultural group") can consist of hundreds of pods comprising thousands of sperm whales, all of which share a unique, clearly identifiable click dialect, a repertoire of coda clicks[7] distinct from that of other vocal clans. (Gero et al., 2015) (See Table 1.1.)

Name	Secondary Name	No. of Individuals	Temporal Duration	Spatial Extent (km) [1]	Composition	Purpose
Pod	Social Unit	8 - 20	Multiple generations	Tens	1-2 matrilines + adoptees	Raising young, mutual defense, socialization
Group	Social Group	~25 [2]	Hours to days	Tens	2 or more pods	Mutual hunting, defense and play
Vocal Clan	Cultural Group	Hundreds to thousands	Multiple generations	Hundreds to thousands [3]	Up to hundreds of pods	Cultural transfer of knowledge, dialect

Table 1.1: **Sperm whale social structures**. Table of sperm whale social structures from the smallest to the largest. As is typical of K-selected species, sperm whales organize themselves into complex, multi-layered societies.

[1] The maximum distance between any two elements of the structure at a given time; as opposed to spatial distribution, the total area covered by the structure through migrations.
[2] Whitehead et al., 1991
[3] Vachon et al., 2022

A 2022 study led by Felicia Vachon of the Whitehead Lab at Dalhousie University in Halifax, Nova Scotia identified three distinct vocal clans of sperm whales around the Lesser Antilles archipelago in the Eastern Caribbean, and found strong evidence of fine-scale habitat partitioning between them. Groups of sperm whales were followed acoustically and by eye, and affiliations of individuals to pods and groups were documented based on visually observed associations. Close to 800 hours of audio recordings were made and over 5,500 coda clicks were extracted from these recordings and scrutinized to establish the various repertoires of vocal clans in the area. Two distinct (and previously documented) vocal clans (EC1 and EC2) were recovered, as well as evidence of a potential third clan (EC3). The acoustic data were cross-referenced with GPS fixes to create a heat map of the spatial distribution of the three clades. (See Figure 1.11.) The map reveals that while all three clans cohabit the same general area, there is a clear granular spatial separation between vocal clans EC1 and EC2, and only minor overlap between EC2 and EC3. Furthermore, the

---

[7] Coda clicks are one of the four basic types of sperm whale clicks, and are produced almost exclusively by females and young in social settings.

boundaries of the clans' distributions, on the order of hundreds of kilometers, seem to be much smaller than those recorded in other regions such as the Eastern Tropical Pacific. (Vachon et al., 2022)

Since vocal clans generally consist of such a large number of whales that they contain many individuals which are not close kin, one of the main inferences to be gleaned from this and related studies is that dialect is not transferred genetically between generations of sperm whales. Rather, there seems to be a cultural facet to the development of a vocal clan's dialect. (Konrad et al., 2018). What is innovative about the Vachon study is the hypothesis that other behaviors, such as habitat selection, may also be socially-mediated forms of knowledge. (Vachon et al., 2022) Different clans may have learned to optimize the exploitation of particular habitats, and they transmit this knowledge through social learning, spatially to other members of the clan and temporally from generation to generation.
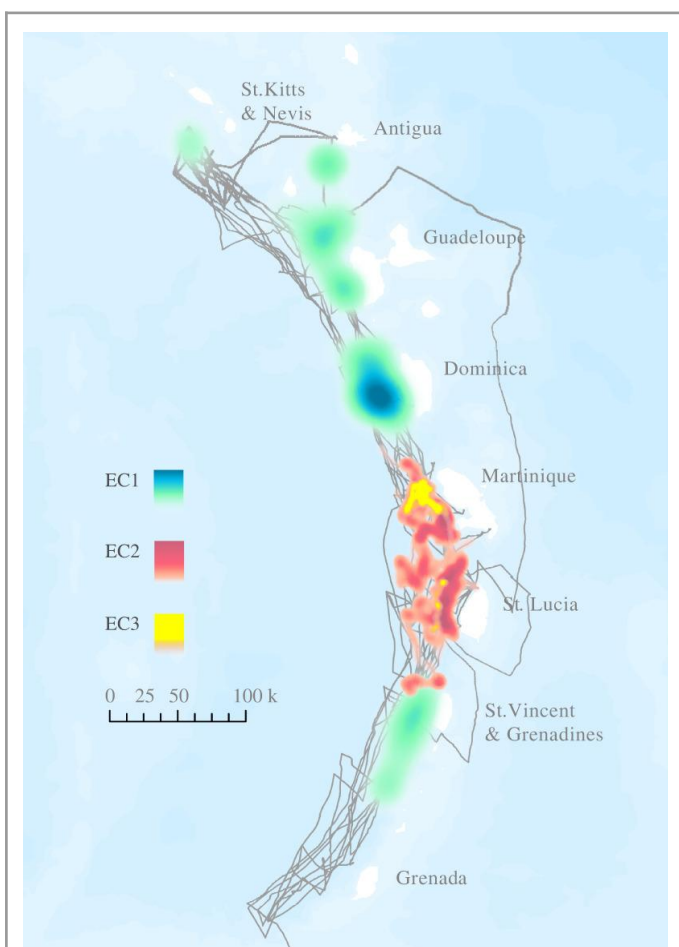

Figure 1.11: Heat map showing the distributions of three sperm whale vocal clans in the Eastern Caribbean. Though sympatric to the same general area, fine-scale resolution of habitats is clearly visible between groups EC1 and EC2, and less so between groups EC2 and EC3. (From: Vachon et al., 2022)

1.3.3. Migration patterns

16

Another notable example of sexual dimorphism in the species is the vast dichotomy in migration patterns between males and females. While, even after maturity, females remain with young in tropical, subtropical, and low-latitude temperate regions (Lefort et al., 2022), males migrate to progressively higher latitudes over their lifetimes, starting in temperate zones as "bachelor groups" of young adults (aged 3 - 15), then moving towards the poles in consecutively smaller groups until, finally, well into adulthood, they end up as lone bulls at the edge of the pack ice, returning to the tropics only for mating. (de Oliveira, 2014) This migration pattern implies that sperm whales, particularly males, travel immense distances over their lifetimes. Consequently, sperm whales have one of the most cosmopolitan distributions of all animals: they can be found in tropical, subtropical, temperate and polar regions; they are found in all the oceans of the world and in the Mediterranean Sea. (Whitehead, 2002)

The cryptic details of the migration patterns of sperm whales, particularly those of the adult males, have not been as well understood as those of other cetaceans, such as the baleen whales (Whitehead, 2002). With the advent of satellite-linked data transmitters ("tags") in recent decades, researchers have begun to fill in the missing picture. In a first-of-its-kind study for sperm whales in the Canadian Arctic, at the northern edge of the species' distribution in the Davis Strait, Kyle J. Lefort of the University of Manitoba in Winnipeg, Canada and his team affixed tags to three adult males and tracked their horizontal movements, including those of one as it migrated 5,556 km over a period of 56 days to waters in the Caribbean, making this one of the longest satellite-tracked sperm whale migrations ever documented. (See Figure 1.12.) The researchers used a state-space model, whereby actual observation data and their estimated errors are used to recursively refine the output of a position prediction model, in order to extrapolate the whales' positions based on fuzzy location data obtained from the ARGOS satellite network.[8] While transiting, the whale that migrated to the Caribbean traveled an average of 101.2 ± 39.7 km/day[9] (min = 9.6 km/day; max = 185.2 km/day) until contact was lost off the south coast of Bermuda while it was still in a transiting state, implying that it had not yet reached its final destination, perhaps breeding grounds in the Gulf of Mexico or the Caribbean Sea. (Lefort et al., 2022) The authors strongly urge the increased use of animal-borne telemetry as a key to gaining a better understanding of sperm whale spatial ecology.

---

[8] See https://www.youtube.com/watch?v=iS5xzcmhpW0 for an excellent overview of the use of state-space models to track animal movements.
[9] Mean ± 1 SD
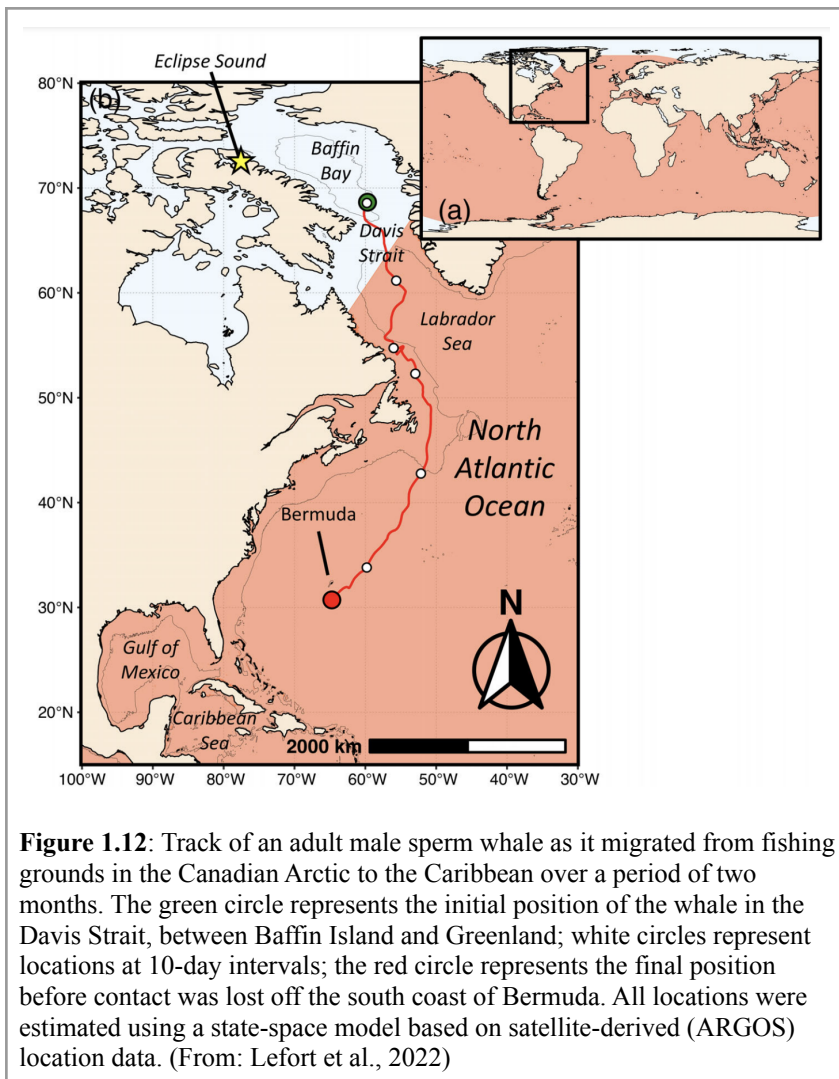
Figure 1.12: Track of an adult male sperm whale as it migrated from fishing grounds in the Canadian Arctic to the Caribbean over a period of two months. The green circle represents the initial position of the whale in the Davis Strait, between Baffin Island and Greenland; white circles represent locations at 10-day intervals; the red circle represents the final position before contact was lost off the south coast of Bermuda. All locations were estimated using a state-space model based on satellite-derived (ARGOS) location data. (From: Lefort et al., 2022)

1.3.4. Foraging behavior

Dive patterns

Whether as lone whales in high latitudes or females caring for young in tropical pods, deep foraging dives are the obsession of sperm whales, occupying around 75% of their time, both day and night. During these dives, the whale spends about half its time actively detecting and pursuing prey. (Irvine et al., 2017) Sperm whales tend to frequent deep (~1,000 m) offshore regions that are close to continental shelves, seamounts, submarine canyons and other bathymetric features where food is abundant, but they have been seen in shallow waters (< 300 m), including off the coasts of New York and Nova Scotia. (Whitehead, 2002, p. 1167)

In one well-known study, a female adult tagged with a time-depth recorder (TDR) off the coast of southwest Japan spent 80% of her total time over a 62-hour period in deep foraging dives. These dives were "U-shaped", typified by: a rapid (1.33 ± 0.24 min.), nearly vertical descent to the bottom; followed by an

extended period (17.5 ± 5.84 min.) foraging at depth; and finally, a quick (1.27 ± 0.26 min.), nearly vertical ascent to the surface. While foraging, the specimen's depth and velocity changed frequently, denoting an active search for food rather than a sit-and-wait approach. Maximum depths per dive ranged from 408 to 1192 m (844.1 ± 238.7 m), and surface resting times varied between 3.6 and 18.2 min (8.5 ± 2.23 min.). (Masao & Motoi, 2003) (See Figure 1.13.)

Figure 1.13: U-shaped foraging dives of a female sperm whale off the coast of Japan, characterized by a quick (~1.3 min.) descent to the bottom, a long period (~17.5 min.) of active foraging at depth and a quick (~1.3 min.) ascent to the surface, followed by a brief (~8.5 min.) resting period. (From: Masao & Motoi, 2003)
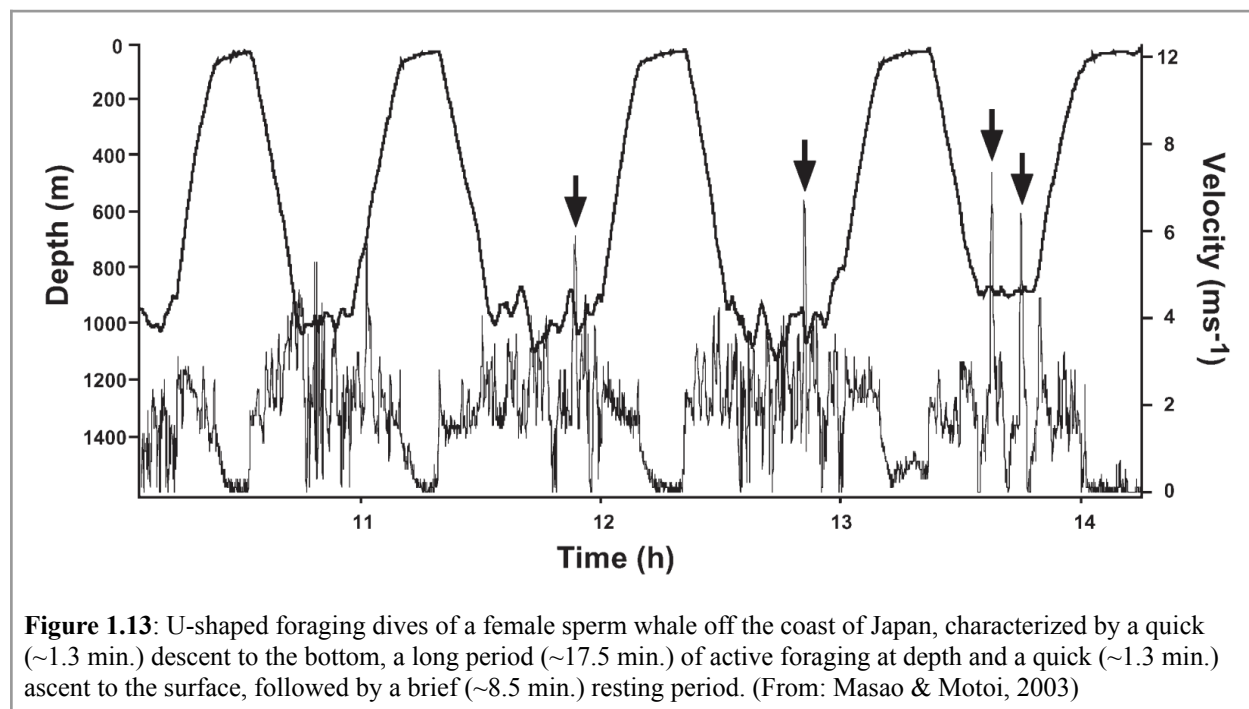
An updated study published in 2017 by Ladd Irvine of the Marine Mammal Institute of Oregon State University and his team used ADB (Advanced Dive Behavior) tags, which can continuously log data for periods of greater than one month at sampling resolutions of up to 1 Hz, to create detailed dive tracks of spe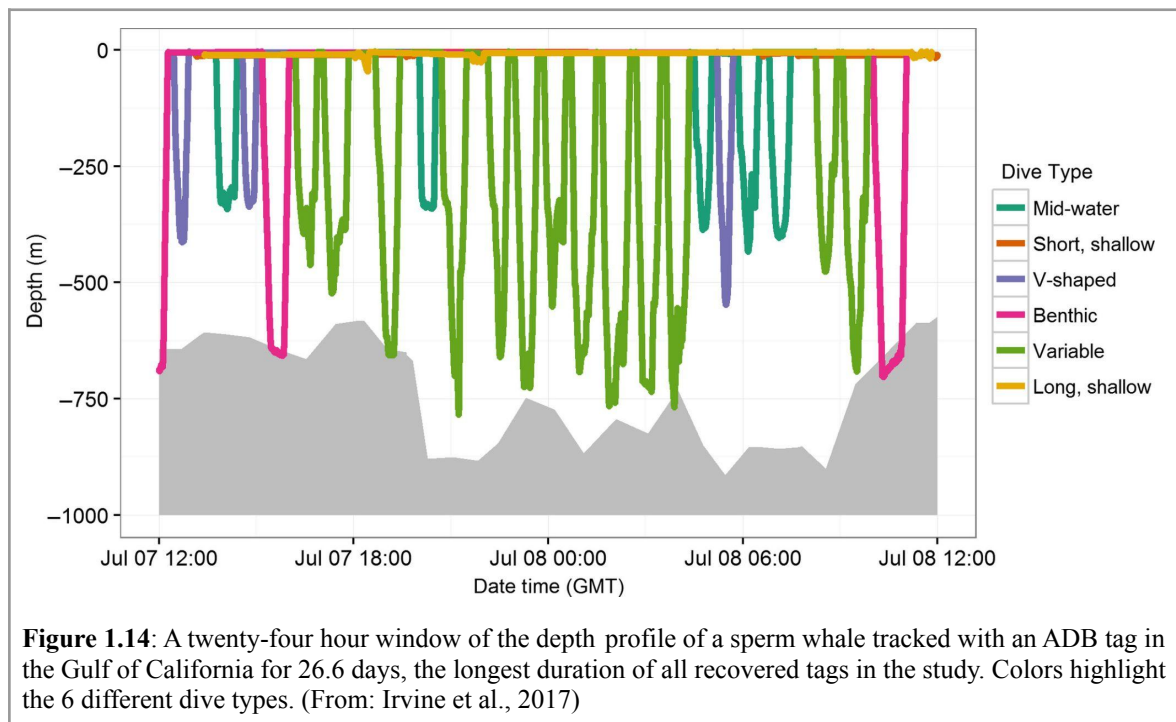rm whales in the central Gulf of California, Mexico. Tags affixed to 27 sperm whales tracked them for a median of 2.3 days (min. = 0 days; max. = 34.5 days), far longer than previous efforts, most of which used short-duration (<24 hr.) data loggers. From the raw data, twelve behavior-related variables were calculated, including maximum dive depth, dive duration, ascent / descent rates and bottom duration. The variables were then used to categorize dives into six dive types: four deep (Mid-water, V-shaped, Benthic, Variable) and two shallow (Short-duration, Long-duration). Deepwater dives (mean maximum dive depth > 290 m) are associated with foraging behavior, while shallow dives (mean maximum dive depth < 30 m) are attributed to socializing or resting. Analysis of the variables revealed that of 2,872 dives archived on recovered tags, 75.6% were deep dives with an average maximum dive depth of 413.8 m (Mid-water = 340 m, V-shaped = 290 m, Benthic = 457 m, Variable = 635 m) – though some reached as deep as 1,500 m – and an average duration of 30.9 min (Mid-water = 30.3 min, V-shaped = 21.4 min, Benthic = 45.8 min Variable = 33.1 min). (See Figure 1.14.) A somewhat surprising result was that a median of almost 30% of the whales' time was spent at or near the surface, an amount far greater than that reported in previous studies,

such as Miller et al., 2008 which placed the value at 7.1%. (Irvine et al., 2017; Miller et al., 2008) The relevance of this result to ship-whale collisions is self-evident.

Figure 1.14: A twenty-four hour window of the depth profile of a sperm whale tracked with an ADB tag in the Gulf of California for 26.6 days, the longest duration of all recovered tags in the study. Colors highlight the 6 different dive types. (From: Irvine et al., 2017)

Prey preference

The sperm whale's prey consists mostly of deep-sea squid, octopuses and demersal teleosts. Stomach contents analyses reveal a noted preference for the gelatinous squid of the Histioteuthidae family, such as the cock-eyed squid (*Histioteuthis* spp.), with a secondary preference for squid from other families, including the giant squid (*Architeuthis dux*) and the colossal squid (*Mesonychoteuthis hamiltoni*). (Cantor et al., 2019, p.265) Prey preference, however, has been shown to be influenced both by prey availability and geographical location. For instance, sperm whales in the Gulf of California showed an affinity for Humboldt squid (*Dosidicus gigas*). (Irvine et al., 2017) Prey are usually consumed whole, perhaps through suction feeding, as indicated by the fact that recovered stomach contents have few teeth marks, and total daily prey consumption is approximately 3% of the whale's body weight (Madsen et al., 2002a), amounting to 1.2 tons, or around 1,350 medium-sized squid and fish, for an average adult male weighing 40 tons.[10]

1.3.5. Sperm whale echolocation

It is now widely accepted that sperm whales use echolocation (biosonar) as an integral part of their foraging strategy, by emitting loud clicks and reading their echo responses, though this use of clicks has been

---

[10] Based on the statement in Madsen et al., 2002a that a 30-ton specimen consumes around 1,000 medium-sized squid and fish per day.

persistently questioned over the years. A recent study attempted to lay the issue to rest once and for all. By attaching sound and movement recording tags (DTAGs) to the tips of sperm whales' noses, Pernille Tønnesen and her team, based out of Aarhus University in Denmark and working in the Azores archipelago, were able to accurately record the echo responses (echograms) of clicks emitted by sperm whales during deep-sea dives. They determined that the distances from potential prey at which the clicks were emitted were consistent with their use in long-range and short-range echolocation while inconsistent with some other purpose, such as prey debilitation. (Tønnesen et al., 2020)

The sperm whale's clicks are produced in its enormous, asymmetrical, barrel-shaped head, one of the defining visual features of the species. This asymmetry is believed to aid echolocation by differentially focusing sounds depending on their angle of incidence. (Coombs et al., 2020) It also results in most of the cranial organs being focused on the left side of the head, leading to another distinct visible feature of the sperm whale: a single left-of-center blowhole, unique among odontocetes. The entire nasal complex sits atop and anterior to the skull, and is the locus of a number of organs which work in tandem to pneumatically generate the sperm whale's clicks, even at great depths where hydrostatic pressure compresses air to just 2% of its original volume. (Madsen et al., 2002b) These structures include the spermaceti organ, the "junk", two nasal passages and two air sacs (distal and frontal). (See Figure 1.15.)
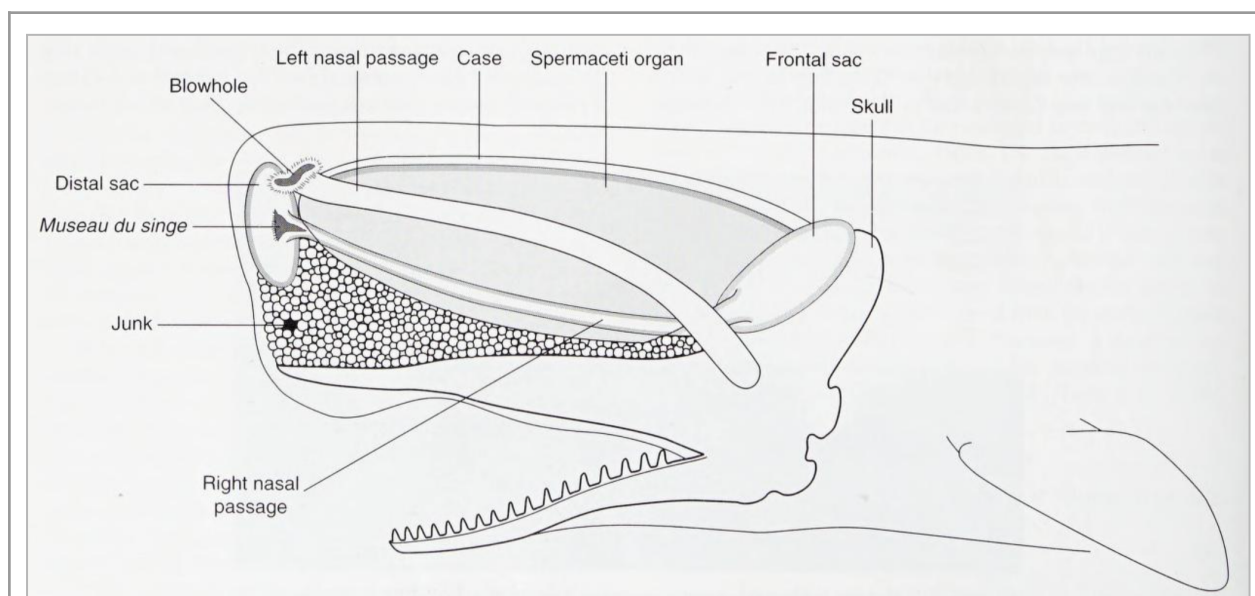
Figure 1.15: Diagram of a sperm whale's head, featuring its nasal complex in which clicks are generated. (From: Whitehead, 2002, p.1166)

The spermaceti organ is an ellipsoid-shaped structure made mostly of spongy tissue, which holds up to 1,900 liters of spermaceti oil, a mixture of wax esters and triglycerides that was highly valued by 19th century whalers for use in perfumes and candles, and originally mistaken for the whale's seminal fluid, hence the name of the species. Below this organ is the "junk" (so named because it was discarded by whalers, who

could not easily extract spermaceti oil from it), which consists of a series of vertically-oriented cartilaginous partitions containing lens-shaped pools of spermaceti oil. Analogous to the melon in other toothed whales, the junk acts as a sound lens, modulating and focusing the whale's vocalizations. A recent study applied structural engineering principles to show that the partitioned structure of the junk enables it to effectively absorb impacts, thereby allowing it to function also as a battering ram (Panagiotopoulou et al., 2016). This addresses a long-standing controversy dating back to the 1820 ramming and subsequent sinking of the whaling ship Essex by a sperm whale, the event on which Herman Melville's book Moby Dick is based.

Regarding the etiology of sperm whale clicks, they originate when the right nasal passage passes air into the distal sac through a pair of phonic lips known as the *museau du singe* (monkey lips). The sound pulse generated by the vibration of the lips reflects off the distal sac and is directed backwards through the spermaceti organ to the posterior of the head, where it strikes the frontal sac. At this point, the sound bifurcates: most of it is reflected downwards and forward through the junk, where it is focused and amplified, and passes out through the front of the animal; some of it, however, is reflected upwards and forward through the spermaceti organ towards the anterior of the animal, where it reflects off the distal sac once again, and the whole cycle repeats itself until the sound energy dissipates. (de Oliveira, 2014) Thus, a single sperm whale click consists of a series of progressively weaker sound pulses. Furthermore, the time interval between each pulse has been shown to be constant for a given animal and positively correlated to the total length of the animal, which makes intuitive sense given the above-described click production process. (Møhl et al., 1981) While most of the sound energy ultimately exits the sperm whale into the surrounding water, the air that produced it does not. Instead, it returns from the distal sac through the left nasal passage and is recycled for use in future clicks. (Madsen et al., 2002)

1.4. Sperm whale bioacoustics

In our project, it is the sperm whale's clicks that are used to localize the whale. It is to our great benefit, then, that significant progress has been made in recent years in understanding both the acoustic properties of sperm whale clicks and their associated behavioral contexts, as well as in applying these advancements to the acoustic processing of detected clicks. We therefore divide our survey of the state of the art of sperm whale bioacoustics into these two main areas.

1.4.1. Acoustic properties and behavioral contexts

Sperm whale clicks come in four main forms: the usual click, the creak (or buzz), the coda, and the slow click (or clang). Each of these click types has specific tonal features and each is believed to serve a specific behavioral purpose.

• "Usual clicks" are emitted every 0.5 - 1 sec. (Jiang et al., 2021)[11], usually for several minutes at a time in what are known as "click trains", and can reach sound levels exceeding 230 dB re 1 μPa at 1 m, making them the loudest sound of any animal on earth. They have centroid frequencies of 8 - 26 kHz, last 15 - 30 ms, are highly directional, particularly in the higher frequencies, and consist of a series of approximately 2 - 4 discernable pulses separated by an interpulse interval (IPI) of approximately 3 - 4 ms, with most of the sound energy focused in a single primary pulse. (See Figure 1.16, left.) Usual clicks are believed to be emitted while the animal is on the hunt for prey, initiating them 30 - 60 sec. into a deep dive at a depth of 50 - 250 m, and terminating them prior to the last few hundred meters of its ascent to the surface. (Madsen et al., 2002a) The directional nature of usual clicks causes their waveform and frequency content to be highly sensitive to the aspect between whale and receiver. Clicks received off of the axis connecting the two, by even a few degrees, can have an apparent source level of >40 dB less than their on-axis counterparts and a far less dominant primary pulse, characterized by a decay rate of only 20 dB to the subsequent pulse, as opposed to double that for on-axis clicks. (See Figure 1.16, right.) A train of usual clicks is generally followed by a 5 - 20 sec. period of silence or interrupted by a creak if the whale is ready to home in on prey.
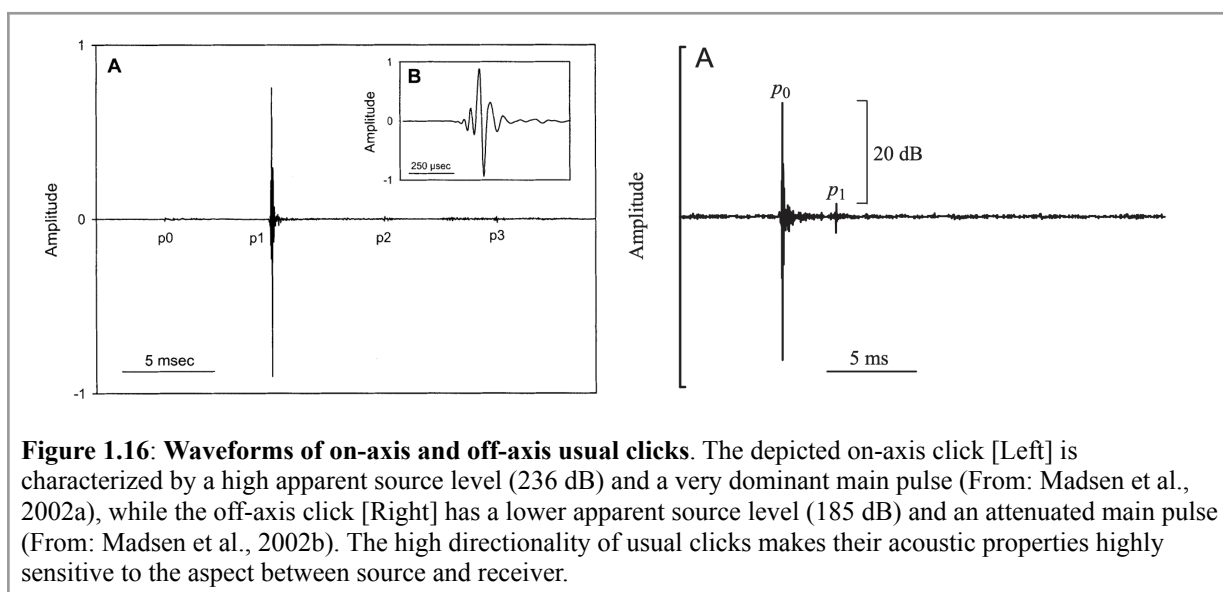
Figure 1.16: **Waveforms of on-axis and off-axis usual clicks**. The depicted on-axis click [Left] is characterized by a high apparent source level (236 dB) and a very dominant main pulse (From: Madsen et al., 2002a), while the off-axis click [Right] has a lower apparent source level (185 dB) and an attenuated main pulse (From: Madsen et al., 2002b). The high directionality of usual clicks makes their acoustic properties highly sensitive to the aspect between source and receiver.

• "Creaks", so named because they sound like a door creaking on its hinges, are initiated when the animal comes within close range of its intended prey, and are believed to be associated with the short-range biosonar necessary for prey capture. They consist of a rapid (every 5 - 100 ms) succession of shorter (0.1 - 5 ms), softer (205 dB[12]) high-directional clicks, the interclick interval (ICI) between which decreases as the whale moves in for the kill.

---

[11] Madsen et al. (2002a) places the range at 0.25 - 1.4 sec. and Skaroulis et al. (2022) at 0.5 - 2 sec.
[12] When not explicitly mentioned, all decibel levels in Section 1.4 are re 1 μPa at 1 m.

• "Codas" are produced almost exclusively by females and are believed to be related to intraspecies communication within and among pods. They occur in a series of 3 - 20 clicks with an ICI of 0.1 - 0.5 sec. Each click is characterized by a sound level of 160 dB, a lower centroid frequency (5 kHz) than usual clicks and low directionality. The decay rate (6 dB) between successive pulses in the coda is far less than that of usual clicks (20 dB), and hence the coda click contains more detectable pulses. (See Figure 1.17.)

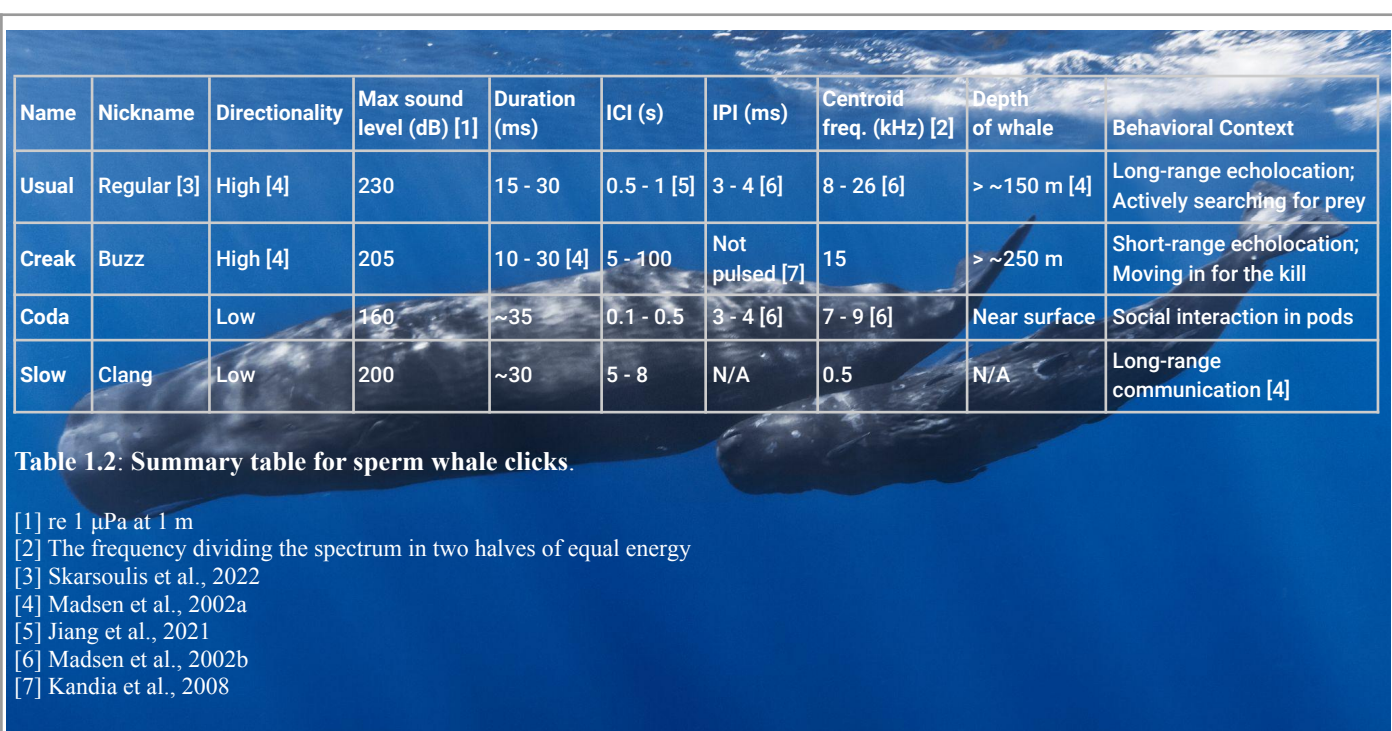**Figure 1.17**: Waveform of a coda click from a sperm whale recorded off the coast of Papua New Guinea. The primary pulse has a sound level of 165 dB and a decay rate of 6 dB to the next pulse, hence a greater number of pulses than the usual click before it dissipates. The interval between pulses, 3.4 ms, is similar to that of the usual click. (From: Madsen et al., 2002b)
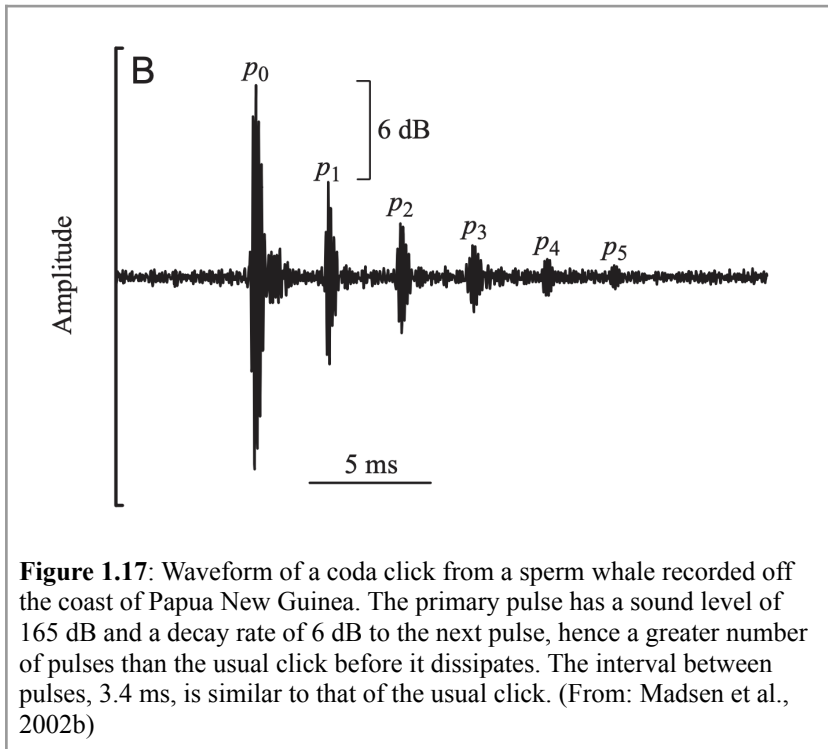
• "Slow clicks", which have a distinct reverberant metallic tone (hence their epithet "clangs"), are used by males for long distance communication (Jiang et al., 2021) and perhaps also as mating calls (Whitehead, 2002). It is unclear whether females produce these clicks at all. They are loud (200 dB), low frequency (500 Hz centroid), omnidirectional sounds which come in trains lasting up to ~24 sec. with far longer ICIs (5 - 8 sec.) than any other type of click, hence their name. A study led by Cláudia Oliveira of the Institute of Marine Research (IMAR) at the University of the Azores used acoustic and movement recording tags affixed to sperm whales to debunk the idea that slow clicks may be associated with echolocation or debilitation of prey, by showing that their acoustic properties and lack of temporal correlation with foraging behaviors make them incompatible with these functions. (Oliveira et al., 2013)

Name	Nickname	Directionality	Max sound level (dB) [1]	Duration (ms)	ICI (s)	IPI (ms)	Centroid freq. (kHz) [2]	Depth of whale	Behavioral Context
Usual	Regular [3]	High [4]	230	15 - 30	0.5 - 1 [5]	3 - 4 [6]	8 - 26 [6]	> ~150 m [4]	Long-range echolocation; Actively searching for prey
Creak	Buzz	High [4]	205	10 - 30 [4]	5 - 100	Not pulsed [7]	15	> ~250 m	Short-range echolocation; Moving in for the kill
Coda		Low	160	~35	0.1 - 0.5	3 - 4 [6]	7 - 9 [6]	Near surface	Social interaction in pods
Slow	Clang	Low	200	~30	5 - 8	N/A	0.5	N/A	Long-range communication [4]

Table 1.2: **Summary table for sperm whale clicks**.

[1] re 1 μPa at 1 m
[2] The frequency dividing the spectrum in two halves of equal energy
[3] Skarsoulis et al., 2022
[4] Madsen et al., 2002a
[5] Jiang et al., 2021
[6] Madsen et al., 2002b
[7] Kandia et al., 2008

1.4.2. Acoustic processing

Hand-in-hand with the progress that has been made in understanding sperm whale clicks are parallel advancements in their acoustic processing for use in detection, classification and localization tasks. As an example of progress on this front, Peter C. Bermant of Harvard University led an interdisciplinary team including computer scientists and biologists that used deep learning (DL) techniques pioneered in the study of human language processing, to automatically detect and classify sperm whale clicks. Deep learning is a machine learning paradigm whereby features are extracted from raw data and transformed across many layers (hence the word deep) of a neural network into progressively abstract representations, which can then be used to detect, discriminate and classify the original input. Bermant's team was able to develop a neural network which determined the presence or absence of sperm whale clicks in spectrograms, with 99.5% accuracy. Furthermore, they were able to use an increasingly popular paradigm called self-supervised machine learning, in which the neural network is primed with results imported from a similar but simpler task as a basis for learning new tasks, to (1) distinguish between different types of coda click patterns; (2) associate individual whales to vocal clans, and (3) distinguish between two individuals by their clicks, all with between 95% and 100% accuracy. The team sees these efforts as a fist step in developing next-generation systems which can intake and analyze sperm whale acoustic data from raw audio recordings in real time. (Bermant et al., 2019)
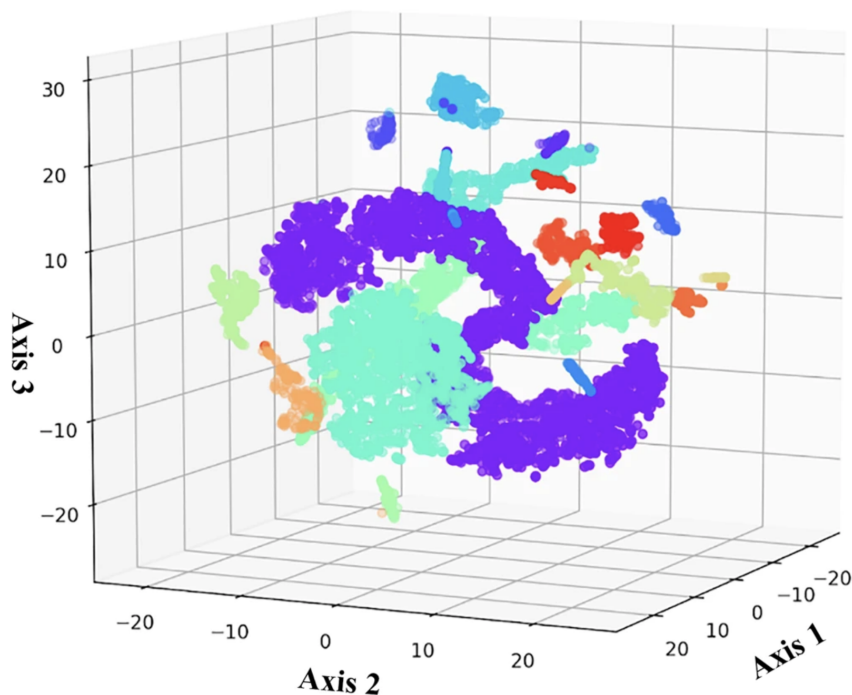
Figure 1.18: **Deep learning coda click type classifier**. Each color represents a different pattern of coda clicks. Patterns (click types) were identified and sorted using a deep learning (DL) paradigm called self-supervised machine learning. (From: Bermant et al., 2019)

1.5. Ship strike mitigation

We begin with a survey of some of the important projects currently taking place in the area of mitigation of ship strikes upon sperm whales, beginning with general efforts and then, later on in this section, focusing specifically on efforts involving PAM methods.

1.5.1. Rerouting ships around high-density sperm whale hubs in the Hellenic Trench

Dr. Alexandros Frantzis of the Greece-based Pelagos Cetacean Research Institute and his team have recently proposed that by slightly rerouting shipping lanes that pass through the Hellenic Trench (the same area where the SAvE Whales project is based), the risk of ship strikes on sperm whales can be reduced by approximately 70%, while adding only a maximum of 11 nautical miles (and around 5 miles in the vast majority of cases) to major shipping routes. (Frantzis et al., 2019) These detours would go a long way towards protecting the entire eastern Mediterranean sperm whale population since, as mentioned earlier (Section 1.2.2), the Hellenic Trench is a core habitat for the population. Based on data collated from previous observation surveys, Frantzis and his team have identified a 3 km swath on each side of the 1,000 m depth contour as an area of peak density for sperm whales, containing 74% of all sightings. This bathymetry, unfortunately, also happens to be highly suitable for shipping vessels in the area, which tend to

hug the southwestern coastlines of the Peloponnese peninsula and Crete while needing to maintain a safe distance from shore. Frantzis and his team have recommended two areas of exclusion, from which shipping should be prohibited (see Figure 1.19), and are petitioning the IMO[13] as well as working with local Greek authorities to implement their initiatives.

Figure 1.19: Proposed modifications in shipping routes in the Hellenic Trench off the coasts of the Peloponnesian peninsula and Crete. Areas inside yellow lines represent regions recommended for ship exclusion. Areas inside green lines are already partially protected under the Natura2000 (SCI - Sites of Community Importance) designation. Red dots represent sperm whale sightings. Purple lines represent ship traffic density. (From: Frantzis et al., 2019)

1.5.2. The use of automated thermal imaging systems to detect the presence of whales

Daniel P. Zitterbart of the Alfred Wegener Institute and Heather R. Smith of the Woods Hole Oceanographic Institution have evaluated the efficacy of using automated and semi-automated thermal imaging systems to detect the presence of whales. (Zitterbart et al., 2020) Land or ship-based thermal (infrared) imaging can be used to detect whales at the sea surface by elucidating patterns related to surface activities such as the breach, pectoral slap and tail slap. Of particular interest is the blow (ejection of air through the blowhole) of surfacing whales, which shows up as a warm, vertically-oriented column on the thermal image. (See Figure 1.20.)

---

[13] International Maritime Organization, a United Nations Specialized Agency, https://www.imo.org.

Figure 1.20: Thermal images, such as the one above showing the evolution of a humpback whale's blow over a 6 second period, can be analyzed by computer or in a hybrid setup (human observer aided by computer) to detect the presence of whales. (From: Zitterbart et al., 2020)
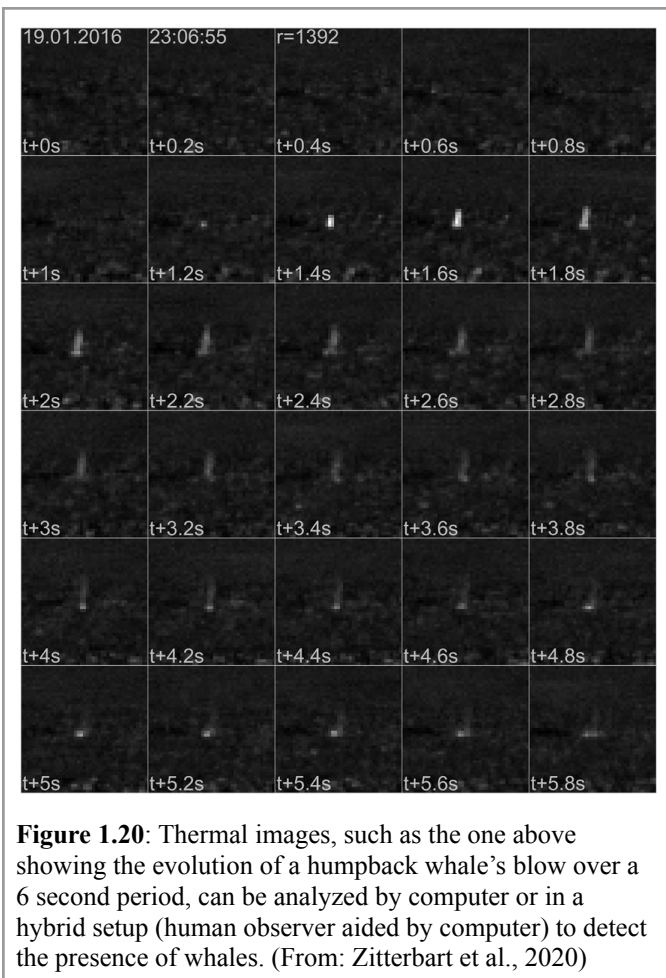
Zitterbart's team tested three platforms against each other: (1) eMMO: an experienced Marine Mammal Observer using only the naked eye and binoculars; (2) IR: an automated infrared system driven by a proprietary detection algorithm; and (3) aMMO: an assisted Marine Mammal Observer using the naked eye and binoculars, but with access to the simultaneous unverified outputs of the IR system, which he can refer to at will. The results showed that in most cases, a given method was able to pick up (recapture) only around 40% of the detections made (marked) by another method, although the IR platform performed best by this metric. (See Figure 1.21.) The authors suggest that an integrated approach, whereby the various systems work in complement with each other, might produce better results.
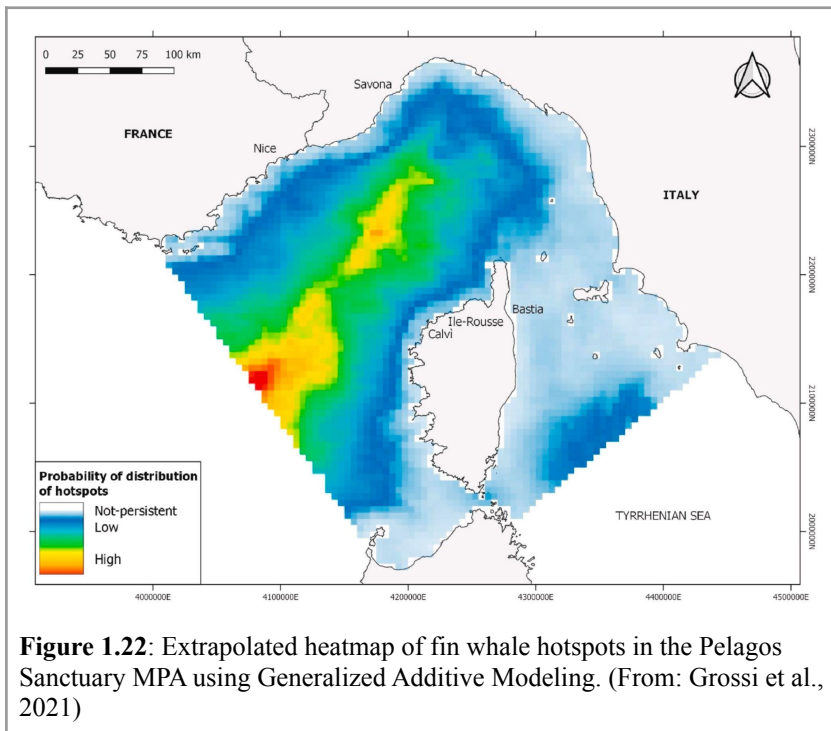
Figure 1.21: Results of three systems (eMMO, IR and aMMO) tested against each other. Each data point represents P(A|B), the probability that system A is able to recapture a cue marked by system B. (From: Zitterbart et al., 2020)
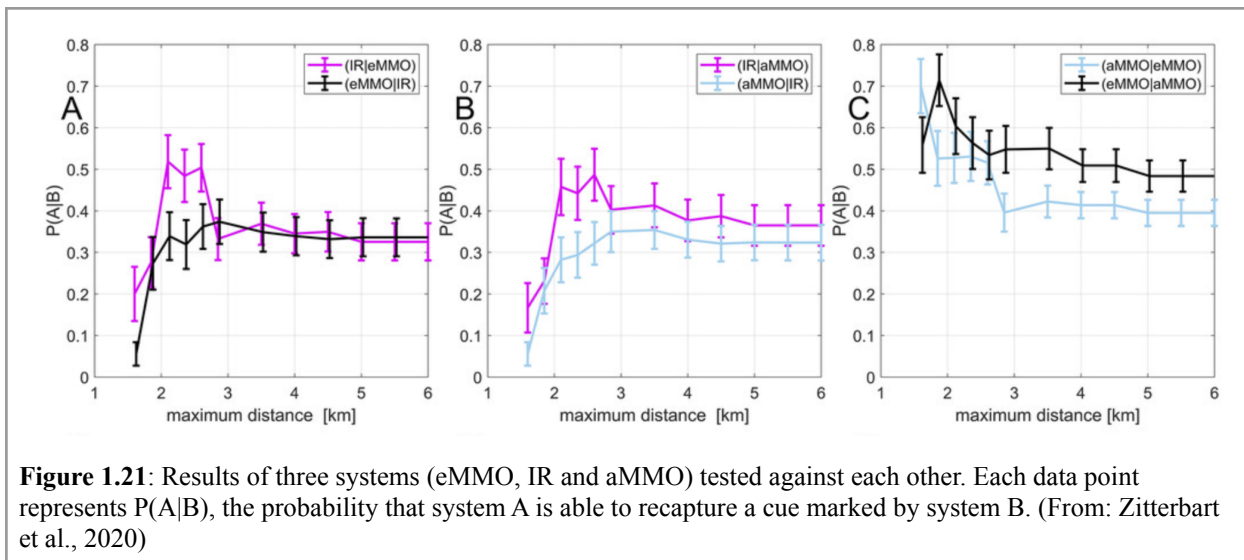
1.5.3. Other efforts

• Manuel Carillo of the Canarias Conservación Cetacean Research Society and Fabian Ritter of the Berlin-based MEER e.V. have assembled a list of urgent recommendations to reduce ship strikes around the Canary Islands, another hotspot for collisions between sperm whales and vessels. These include: (1) stationing dedicated marine mammal observers (MMOs) on board high-speed vessels; (2) rerouting ferries to keep their transects away from cetacean concentrations; (3) enforcing speed limits in areas of high risk for vessel-whale collisions; (4) creating an obligatory reporting system of whale-ship strikes; and (5) encouraging further research on the quantification of cetacean densities and shipping traffic patterns in the region. (Carillo & Ritter, 2010; Ritter et al., 2019)

• Francesca Grossi and her team at the CIMA Research Foundation in Savona, Italy have used Generalized Additive Models (GAMs)[14] to model fin and sperm whale ship-strike hotspots in the Pelagos Sanctuary MPA located in the Ligurian Sea, using data collected on only a subset of the area; namely, along major marine traffic corridors in the center of the sanctuary. (Grossi et al., 2021) First, fin and sperm whale observation surveys were carried out on major ferry routes over an 11-year period between 2009 and 2019. The distribution of whales was collated by year and mapped to a grid of 25km^2 cells, each of which received a yearly SPUE (sightings per unit effort) ranking. Cells which exceeded the year's mean SPUE by more than 1 standard deviation (> 1 SD) were designated as "hotspot" cells. To estimate the temporal tendency of a given cell to be a hotspot, each cell was assigned a "hotspot index" (HI) based on how many out of the 11 years it was designated a hotspot. Physiographic (static) data, such as distance to the continental shelf and bathymetry, and oceanographic (dynamic) data, such as sea surface temperature and Chlorophyll *a* concentration, were gathered for each cell. By cross-referencing these environmental variables with the

---

[14] Generalized Additive Models are statistical models in which the weighted sums of linear regressions are replaced with the sums of (potentially nonlinear) functions. In such a way, nonlinear data can be modeled in a more explainable way.

hotspot indexes, and then applying GAM modeling, the team was able to extrapolate a gridded map of hotspot probability over the entire Pelagos Sanctuary. (See Figure 1.22.)

Figure 1.22: Extrapolated heatmap of fin whale hotspots in the Pelagos Sanctuary MPA using Generalized Additive Modeling. (From: Grossi et al., 2021)

1.5.4. Passive Acoustic Monitoring (PAM) of cetaceans

We shall now survey a cross-section of important projects that use Passive Acoustic Monitoring (PAM) to study cetaceans, including sperm whales. PAM methods come with some distinct advantages and disadvantages. On the positive side, they provide far more versatility than traditional visual observation techniques, by allowing for the study of cetaceans at great depths and ranges, at night and in poor weather conditions (Klinck et al., 2012). Furthermore, they do so in a non-intrusive way since, unlike active acoustic methods such as sonar, PAM stations produce no significant sound of their own; in addition, they make no direct contact with their subjects. On the other hand, PAM systems depend on vocalizations from the animal, so when the animal is not phonating, they are non-operational. Furthermore, most applications require real-time transfer of large amounts of data to land-based processing stations, often from great depths and distances from shore. This problem is usually solved in one of two ways: either by wireless transfer through wifi or satellite links originating in sea-surface buoys, or through underwater sea-to-shore cabling. (Sanguineti et al., 2021b) Despite these limitations, passive acoustic monitoring has become an increasingly popular way to study the distribution, abundance and movements of cetaceans (Klinck et al., 2012), because of its overall effectiveness and recognized environmental friendliness.

1.5.4.1. Use of autonomous underwater gliders to monitor cetaceans

Seaglider™ underwater autonomous vehicles, originally developed at the University of Washington Applied Physics Laboratory (APL-UW), are able to make minute alterations in their buoyancy and convert the resulting vertical displacements into horizontal motion using wings, much in the same way that an airplane uses its wings to convert thrust to lift.[15] These gliders can dive to depths of 1,000 m or more and consume very little battery power, allowing them to remain autonomous for up to several months at a time, under a variety of light and weather conditions. When equipped with hydrophones, they constitute an autonomous, mobile, deep-diving PAM platform, suited to the investigation of mesopelagic and bathypelagic animals such as the sperm whale and the beaked whale. As a proof-of-concept, researchers from Oregon State University and APL-UW launched a single Seaglider equipped with a passive acoustic recording system, off the west coast of the island of Hawaii, where it followed a pre-programmed track skirting the 1,000 m and 2,000 m isobaths. During 85 glider dives, lasting an average of 4.3±1.3 hours each, a total of 194 hours of audio were recorded and immediately screened onboard by a cetacean click detection algorithm. Significant detection events were transmitted to shore by satellite whenever the glider resurfaced. Upon final recovery of the glider, the full set of audio recordings was manually screened by an experienced analyst, revealing that 50.4% of the (one-minute) sound files contained delphinid clicks, 11.8% contained sperm whale clicks and 1% contained beaked whale clicks. The automated detection system had been able to corroborate the presence of beaked whale clicks 72% of the time. The glider appears to have had three major encounters with groups of sperm whales, one lasting more than 24 hours. (See Figure 1.23.) The researchers view this pilot project as a test case for the expanded use of autonomous underwater vehicles (UAVs) in cost effectively carrying out marine mammal monitoring, remotely from shore, for extended periods of time. Such a system could potentially be used for ship strike mitigation, but first the time intervals between information transfers to shore would have to be reduced, perhaps by carrying out shorter dives or by surfacing as soon as sperm whales are detected. (Klinck et al., 2012)

---

[15] See page 5-4 of the "Pilot's Handbook of Aeronautical Knowledge", published by the U.S. Federal Aviation Administration, https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak.
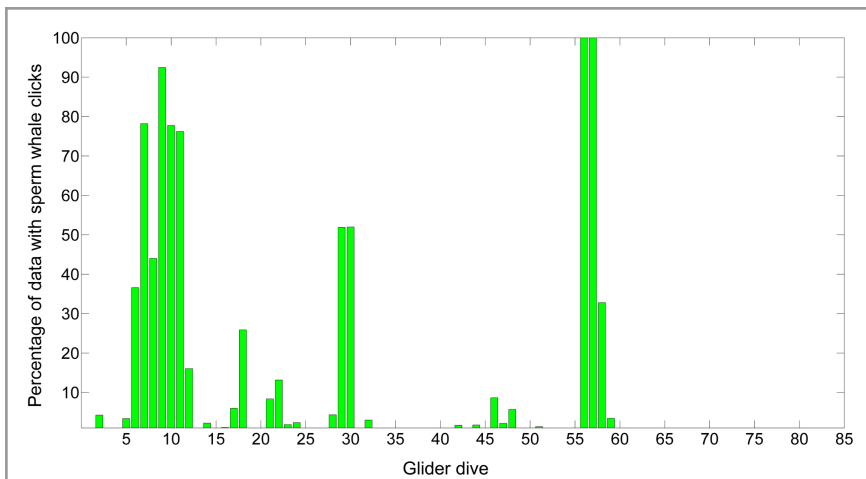
Figure 1.23: Of 85 dives conducted by the Seaglider™ underwater autonomous watercraft, sperm whales were acoustically detected during 31 (36.5%) of them, sometimes in as much as 100% of the one-minute audio files. Data reveal 3 main encounters with sperm whale groups and approximately 5 minor ones. Autonomous gliders could, in the future, be used to detect sperm whales in time frames small enough to be of use in deterring ship strikes. (From: Klinck et al., 2012)

1.5.4.2. Tracking movements of cetaceans around tidal energy turbines

Anthropogenic subsea structures often have moving parts that can cause injury and death to cetaceans. Passive acoustic monitoring can be used for risk assessment and abatement by carrying out fine-scale 3-D spatial and temporal tracking of marine animals around these structures. During a two-year period between 2017 and 2019, researchers from the University of St. Andrews in Scotland collected data from hydrophones placed in the Pentland Firth strait, at the base of an operating tidal energy turbine with 18 m rotor blades able to rotate at speeds of up to 14 rpm. The hydrophone array, which consisted of 3 clusters of 4 tetrahedrally-arranged hydrophones per cluster, was affixed to the support structure of the turbine to acoustically monitor harbor porpoises (*Phocoena phocoena*) in the area. Cetacean clicks were detected, and then localized using Time Difference of Arrival (TDOA) analysis, the same technique we use in our project. TDOA analysis estimates the location of a sound source by analyzing the differences in travel times of a sound as it propagates from its source along multiple paths (such as direct and surface-reflected routes) to one or more receivers.

The researchers used a sea-to-shore ethernet cable and open-source passive acoustic monitoring software (PAMGuard[16]) to automatically detect potential cetacean clicks, which were then manually screened to eliminate false positives. The human-verified clicks were analyzed to determine their TDOAs. A major obstacle that the team faced was similar to one we have come up against in our own research: assigning to the correct sound source (specific click from a specific animal) similar acoustic patterns repeated on

---

[16] https://www.pamguard.org

multiple temporal and spatial scales (i.e. received at different hydrophones) (See Figure 1.24, left.) The researchers attempted to solve this problem by arranging received clicks into groups, based on whether they could have originated from the same source sound: any pair of clicks received across two clusters at a TDOA less than a theoretical maximum – the distance between the clusters divided by the speed of sound – were deemed to have potentially come from the same source click, and were tentatively grouped together. The TDOAs of all click combinations within a group were compared against a theoretical model to determine possible source locations, and then a likelihood-based function was maximized to select the most probable one as the presumptive location of the source.

The researchers reported identifying 1044 porpoise and 31 dolphin transits consisting of a total of more than 172,000 clicks over the two-year period. While they were able to create accurate tracks for some of these events (for a sample track see Figure 1.24, right), the vast majority of events did not result in accurate tracks, due to limitations of the system when the animals pass at distances too great for accurate localization. Furthermore, the system did not operate in real time, and so is not appropriate for live tracking of cetaceans. Nonetheless, it is meant to serve as a prototype for future real-time PAM systems around artificial underwater structures. (Gillespie et al., 2020)
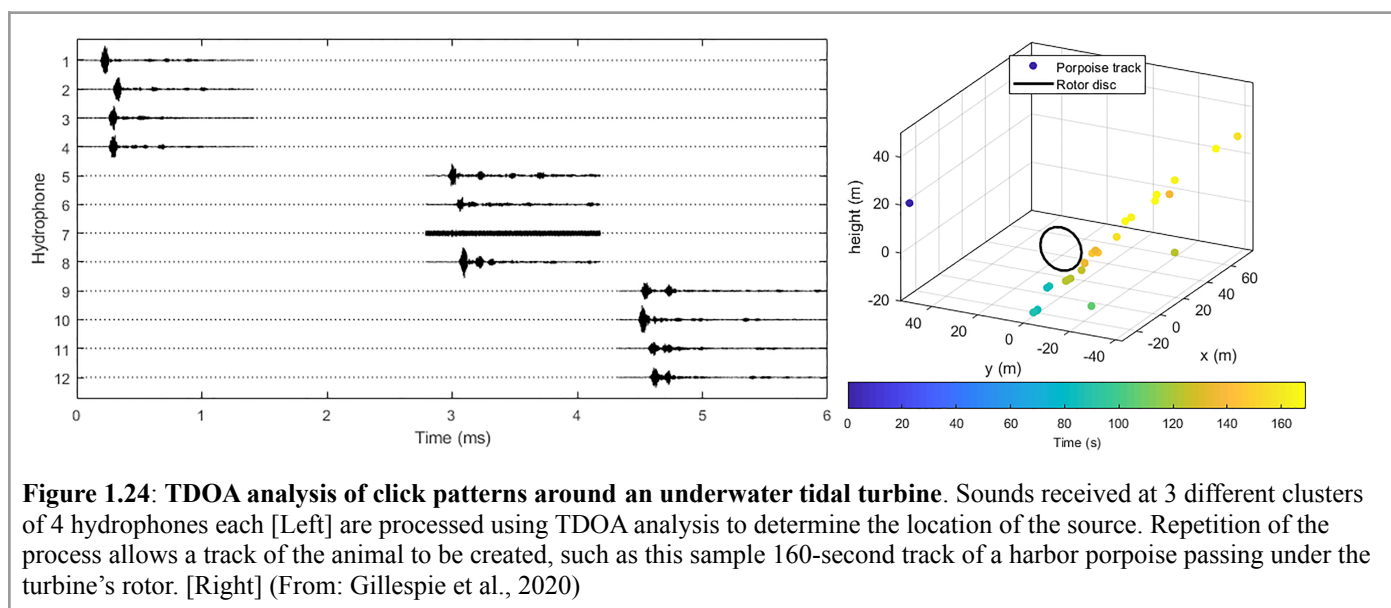

Figure 1.24: **TDOA analysis of click patterns around an underwater tidal turbine**. Sounds received at 3 different clusters of 4 hydrophones each [Left] are processed using TDOA analysis to determine the location of the source. Repetition of the process allows a track of the animal to be created, such as this sample 160-second track of a harbor porpoise passing under the turbine's rotor. [Right] (From: Gillespie et al., 2020)

1.5.4.3. Passive acoustic monitoring of cetaceans at neutrino telescope installations

Neutrino telescopes, used in the emerging field of neutrino astronomy to detect neutrino emissions from astronomical objects, are built deep underground or undersea in order to minimize interference from cosmic background radiation. Underwater installations consist of vertical chains of particle detectors anchored to the seabed at depths of over 2000 m. (Sanguineti et al., 2021b) Since these detector chains sway under the force of sea currents, acoustic emitters and hydrophones are embedded in the installation to monitor the positions

of its various components. The acoustic data gathered by these hydrophones are transferred to shore by electro-optical cables and, as a result, can be leveraged to aid in marine research. Such an approach has already been successfully used at the ANTARES neutrino telescope installation to study diel variations in the presence of sperm whales in the Ligurian Sea, and at the NEMO (NEutrino Mediterranean Observatory) collaboration's observatory off the coast of Sicily to detect a decrease in the presence of sperm whales between 2005 and 2012.

The KM3NeT (The Cubic Kilometer Neutrino Telescope)[17] is a next-generation neutrino telescope collaboration (*KM3NeT Opens a New Window on Our Universe*, 2022) that will incorporate the two aforementioned installations and add a third (NESTOR) near Peloponnese, Greece, a major hub of sperm whale activity. The potential to leverage the entire KM3NeT network as a continuously-online deep-sea acoustic marine observatory is very promising. To date, a number of pilot projects have already been implemented at KM3NeT, including a sperm whale and dolphin click identifier at the Toulon, France site. The identifier sequesters sounds that have an SNR ≥ 10 and computes their FFTs for further analysis in the frequency domain. Frequency curves in the range of 5 - 50 kHz are compared against reference curves for sperm whale and striped dolphin (*Stenella coeruleoalba*) clicks. Initial tests on data gathered from the 2,475-meter deep ORCA site have yielded excellent results, according to official spokespeople for the KM3NeT collaboration. Over 51,000 sperm whale clicks were detected between April, 2020 and June, 2021 (See Figure 1.25.) The future installation of additional hydrophones is expected to allow for reconstruction of sperm whale tracks. (Guidi et al., 2021)
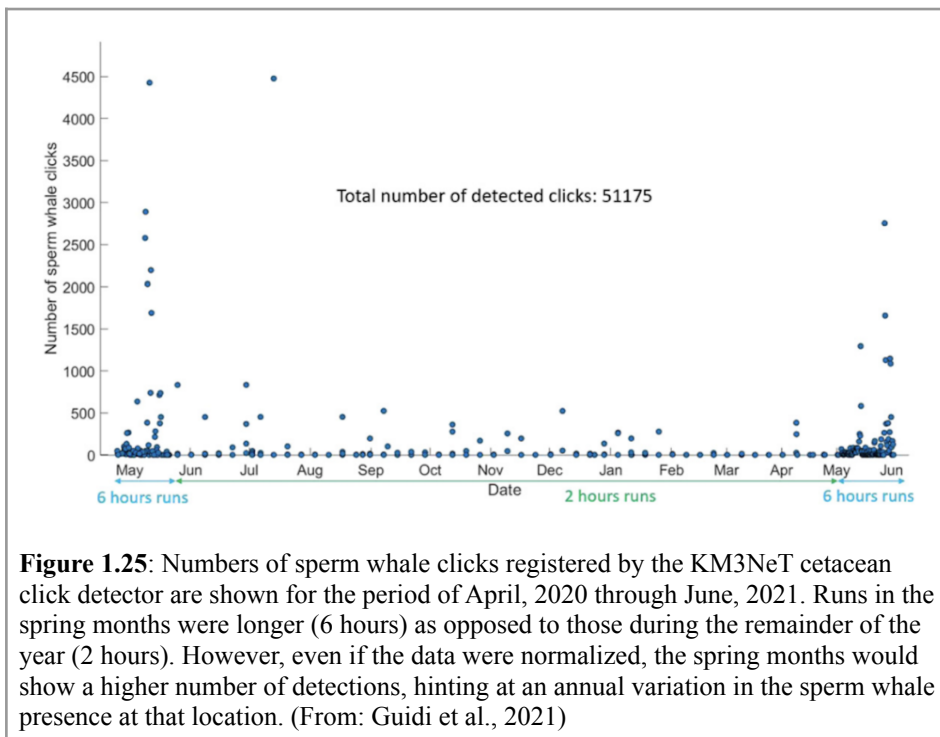
Figure 1.25: Numbers of sperm whale clicks registered by the KM3NeT cetacean click detector are shown for the period of April, 2020 through June, 2021. Runs in the spring months were longer (6 hours) as opposed to those during the remainder of the year (2 hours). However, even if the data were normalized, the spring months would show a higher number of detections, hinting at an annual variation in the sperm whale presence at that location. (From: Guidi et al., 2021)

---

[17] https://www.km3net.org

1.5.4.4. Passive acoustic monitoring to localize sperm whales in the Ligurian Sea

As part of the WHALESAFE Project[18], a Passive Acoustic Monitoring (PAM) system with some similarities to ours is being developed in the Pelagos Sanctuary for Mediterranean Marine Mammals, where 8% of sperm whales show evidence of rotor injuries from ships. This system uses a tetrahedral array of four hydrophones suspended from a buoy to a depth of 65 m, and can be deployed in a single-array or double-array configuration. Unlike the more complex ray tracing model underlying our system (see Section 2.2.1), the WHALESAFE system assumes straight-line sound wave propagation and a perfectly reflective sea surface. Nonetheless, the authors report accurate results for sperm whale localization and tracking, in both configurations. Computers mounted in the buoy perform primary processing tasks, such as initial identification of sperm whale clicks and determination of the array's spatial orientation. Secondary processing, including localization and tracking, is done on shore with data passed through a sea-to-shore wireless datalink. In the single-array configuration, arrival angles and time differentials between direct and surface-reflected paths are used to calculate source position. (See Figure 1.26.) In the double-array configuration, arrival angles and times of direct paths to each array are used. (Sanguineti et al., 2021a)
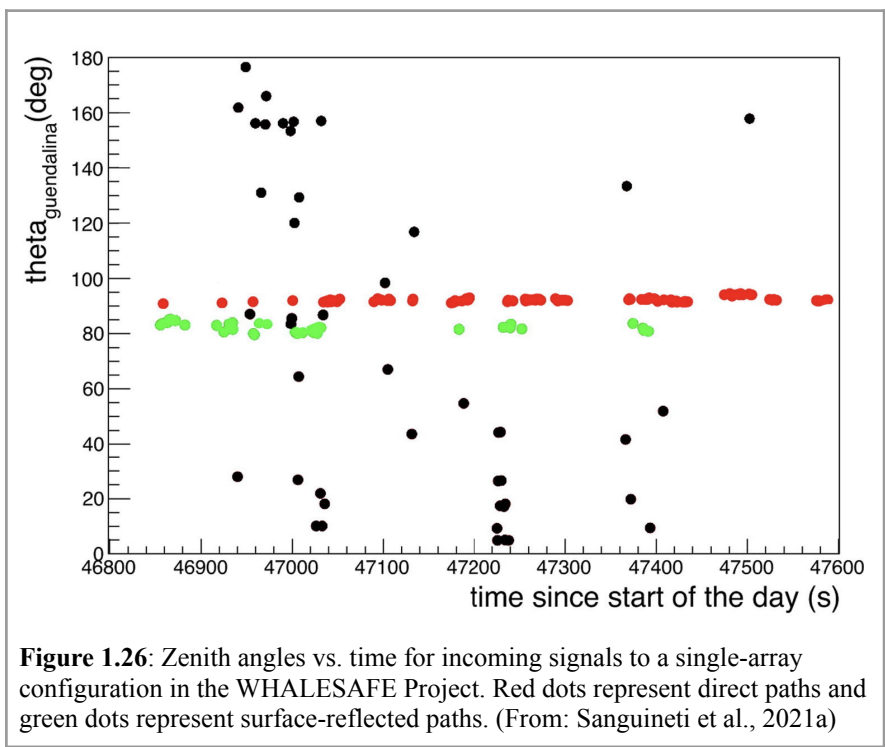

Figure 1.26: Zenith angles vs. time for incoming signals to a single-array configuration in the WHALESAFE Project. Red dots represent direct paths and green dots represent surface-reflected paths. (From: Sanguineti et al., 2021a)

1.5.4.5. The SAvE Whales project

---

[18] http://www.whalesafe.eu/index.php/en

Finally, we review the intermediate report published in May, 2022 by the SAvE Whales (System for the Avoidance of Ship-Strikes with Endangered Whales) project, with which I am associated through the Signal Processing Laboratory at the University of the Algarve (SiPLAB) headed by Professor Sérgio Jesus. The report details the results of a test deployment of the sperm whale localization system in the Hellenic Trench off the southwest coast of Crete, Greece. The Hellenic Trench, as mentioned earlier (Section 1.2.2), is one of the mainstays of sperm whale activity in the Eastern Mediterranean. It is home to about 20 pods of 5 - 15 individuals each, plus at least 30 mature solitary males. The SAvE Whales system is designed to be "a deep-water acoustic observatory for real-time detection and localization of vocalizing sperm whales." (Skaroulis et al., 2022) The whales are localized in real time and the localizations are fed into live marine traffic communications networks to provide nearby ships with timely updates of sperm whale activity in the area. Upon receipt of an alert, the receiving ships can respond by initiating evasive or mitigating actions such as altering course, throttling back engines or commencing visual searches for the whales.

The test deployment consisted of a wide-aperture array of three hydrophones placed in a triangular pattern at distances of 1 - 2 km from each other, straddling the 500-meter isobath in the Bay of Sougia. The hydrophones are suspended from buoys to a depth of about 100 meters. Each buoy station has a small standalone CPU (Raspberry Pi 2), an embedded GPS receiver and a wireless communications modem. Initial processing of acoustic events occur at the buoys: arrival times and amplitudes of sounds with peaks surpassing 4 times the ambient noise level (SNR > 4) are captured for a period of one minute every 3 minutes, and transmitted wirelessly to the FORTH research center in Heraklion, Crete. There, arrival trains from all three hydrophones are combined and enter a detection algorithm which scans for the presence of sperm whale clicks at each hydrophone. A detection flag is raised when a series of arrivals within a train has a near-constant repetition rate within the boundaries expected for usual click ICIs (0.5 - 2 s), as determined by an examination of the histogram of differences in arrival times between each arrival and its temporal (within 2 seconds) neighbors. (See Figure 1.27.)
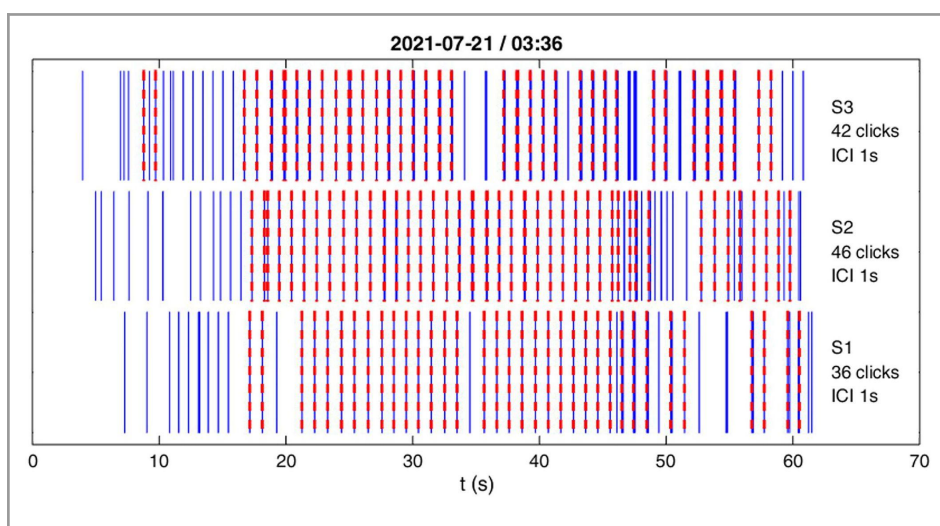
Once a detection event is marked, the extracted arrivals – those presumed to represent sperm whale clicks – enter a six-stage localization workflow to identify their source positions, as follows:

Stage 1 - *Time synchronization using PPS signals*: Precise synchronization of arrival streams to different hydrophones, necessary for accurate localization, is achieved using PPS signals[19] emitted by GPS satellites and picked up by the GPS receivers on the hydrophones. The signals are received in analog form, then digitally sampled and transmitted to the onshore processing station along with the arrivals data. There, the PPS signals are aligned and, along with them, the arrivals data. After synchronization, inter-hydrophone arrival time accuracy is reduced from a few milliseconds to on the order of 1 µs.

Stage 2 - *TDOA histogram analysis*: Each arrival selected by the detection algorithm as a sperm whale click is broken down further into direct and surface-reflected arrivals, and the time difference between them (TDOA) is plotted on a histogram. Since foraging sperm whales travel at speeds of only 1 - 2 knots (Skaroulis et al., 2022), the position of the vocalizing whale is not expected to change much in the one-minute window under consideration; therefore, the TDOAs should remain more or less constant (since TDOA in a given underwater environment is a function of the relative positions between source and receiver), and this will be visible as a peak in each hydrophone's histogram. (See Figure 1.28.) These TDOAs associated with these peaks are extracted and used in the next stage to make an initial estimation of the sound source's range (horizontal distance) from each hydrophone.

---

[19] PPS (Pulse per second) signals are electromagnetic signals emitted at a regular interval for purposes of timekeeping and synchronization. Each PPS signal is a 100-ms box-shaped pulse with a precise 1-sec. repetition period.
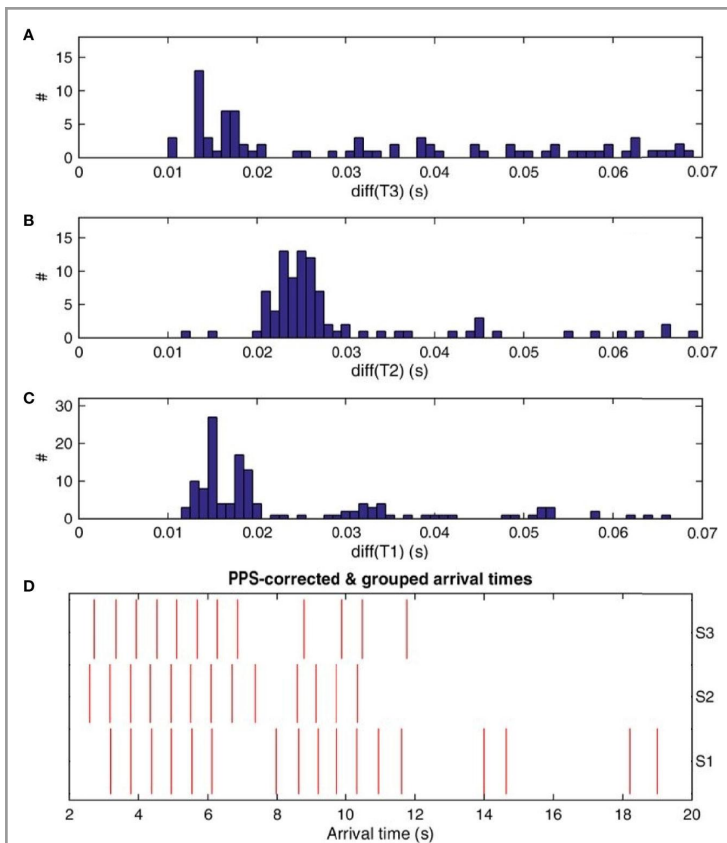
Figure 1.28: **TDOA histograms**. Time differences of arrivals (TDOAs) between direct and surface-reflected sound waves for each selected arrival are plotted on a histogram. The characteristic TDOA of the vocalizing source, a function of its current position, becomes visible as a peak in each hydrophone's histogram. These peaks are used to determine an initial localization of the whale on the horizontal plane. (From: Skaroulis et al., 2022)

Stage 3 - *Initial estimation of range and bearing*: The TDOA values (histogram peaks) extracted in the previous stage are compared against those determined by a theoretical sound propagation model, using an idealized underwater modeled environment (constant 1500 m/s sound speed), to produce a heatmap of potential 2-D locations (horizontal distance and azimuth angle) of the vocalizing source. (See Figure 1.29.) Depth is ignored at this stage. These initial estimates are refined in the following stages, however they serve as a fallback in cases when 3-D localization is not possible.

Figure 1.29: **Initial localization**. The diagram shows a heatmap of potential 2-D positions of the vocalizing whale, representing the initial estimation of its localization. This is achieved by comparing peak TDOAs extracted in the previous step with those determined by a theoretical sound propagation model. (From: Skaroulis et al., 2022)
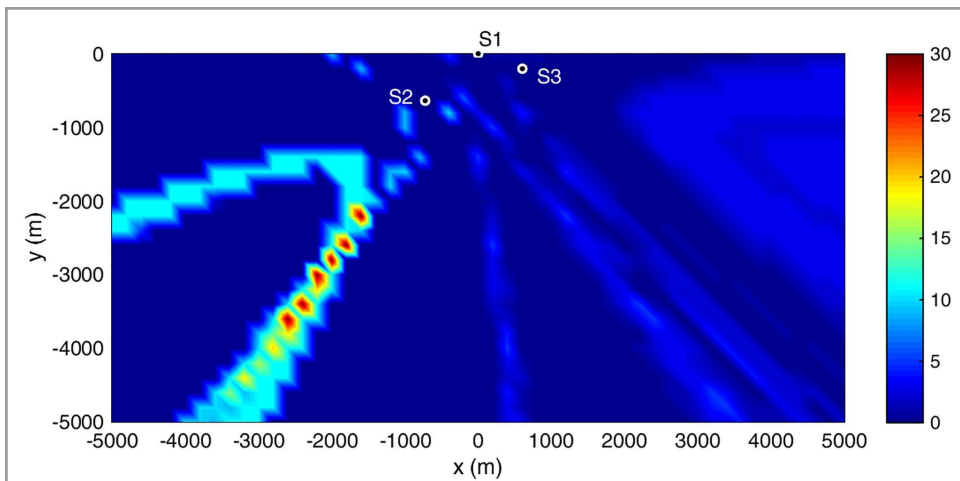
Stage 4 - *Cross-correlation of arrival streams*: The arrival patterns which were synchronized to a common clock in Stage 1 are now cross-correlated in an attempt to determine their time offsets from each other and thereby shift them into alignment. This is done by ascertaining the histogram peaks of the cross-correlations between all possible pairs of hydrophones, extracting the associated lag times, and then shifting all but one of the arrival patterns by the negatives of these time offsets. The resulting alignment is checked for geometric compatibility, i.e. that the theoretical sound propagation model provides at least one candidate source location resulting in time offsets equal to that particular alignment. (See Figure 1.30.) This process is complicated by the fact that when a hydrophone is distant from a sound source, two successive clicks may arrive at a closer hydrophone before the first one arrives at a more distant one. Nonetheless, it is necessary for full 3-D localization, which depends on the time differences between direct arrivals to distinct hydrophones in addition to the time differences between direct and surface-reflected arrivals to each individual hydrophone, which were calculated in Stage 2.
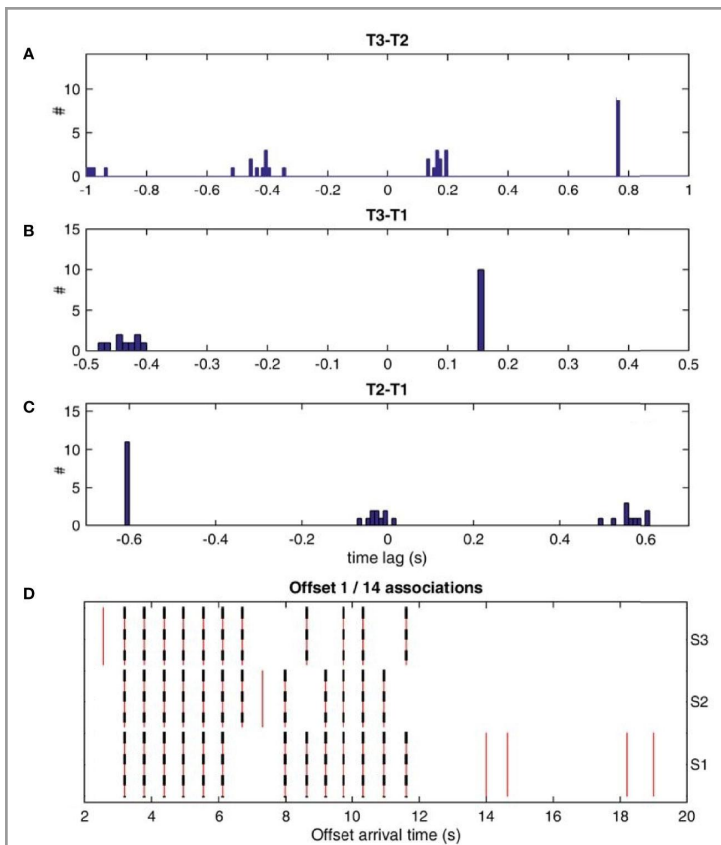
Figure 1.30: **Arrival stream pattern matching**. The above diagram shows the cross-correlation histograms for each hydrophone pair (panels A, B and C), and the resulting alignment of the click arrival patterns based on the histogram peaks (panel D). Note that alignment of the 3 time lags (0.75 sec. - 0.15 sec. + 0.6 sec.) results in a value of zero, showing their compatibility with each other. In addition, though not shown here, they were found to be geometriclly compatible with the sound propagation model. (From: Skaroulis et al., 2022)

Stage 5 - *Range and depth estimation*: Once the arrival patterns have been aligned, 3-D localization of the source can commence, in two stages. In this first stage, the source's range from each hydrophone and its depth are extrapolated by comparing the TDOA of the direct and surface-reflected arrivals at each hydrophone to those predicted by the sound propagation model, this time using a more realistic sound speed profile based on temperature measurements taken at varying depths in the water column. (See Figure 1.31.) Though the source's depth can be resolved from the TDOA at even a single hydrophone (as long as the hydrophone's depth is known), multiple hydrophones provide redundancy and a compatibility check. On the other hand, two or more hydrophones are necessary to provide any reasonable localization in the horizontal plane.

Stage 6 - *Azimuth estimation*: Using the GPS receivers embedded in the buoys, the precise horizontal locations (i.e. latitude, longitude) of the hydrophones can be combined with the ranges calculated in the previous step to estimate the azimuth angle of the source from each hydrophone. These angles, combined with the depth and range information from the previous stage, provide the final localization of the vocalizing

source. (See Figure 1.31.) This localization is defined by the intersection of a set of circles, each with its center at one of the hydrophones and a radius of the corresponding range. In the two-hydrophone case, these (two) circles intersect at two points[20], creating a left-right ambiguity mirrored across the extended line connecting the two hydrophones. This ambiguity can often be resolved by eliminating one of the points as improbable or impossible because it falls on land, in shallow water, below the seafloor, etc. In the three-hydrophone case, a third intersecting circle eliminates the ambiguity.
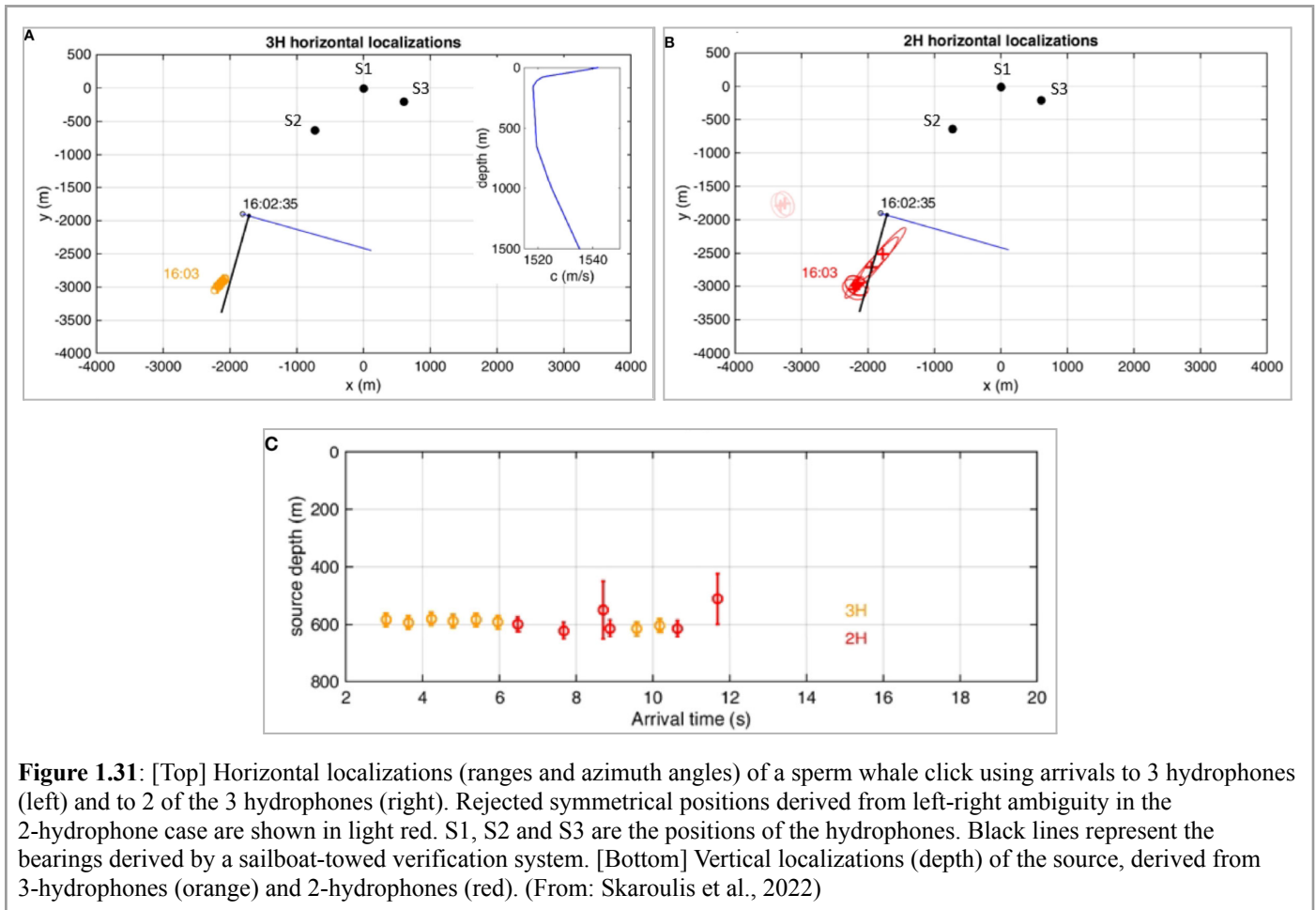
Figure 1.31: [Top] Horizontal localizations (ranges and azimuth angles) of a sperm whale click using arrivals to 3 hydrophones (left) and to 2 of the 3 hydrophones (right). Rejected symmetrical positions derived from left-right ambiguity in the 2-hydrophone case are shown in light red. S1, S2 and S3 are the positions of the hydrophones. Black lines represent the bearings derived by a sailboat-towed verification system. [Bottom] Vertical localizations (depth) of the source, derived from 3-hydrophones (orange) and 2-hydrophones (red). (From: Skaroulis et al., 2022)

Verification programs

Two verification campaigns were carried out to assess the effectiveness of the SAvE Whales system, one in the summer of 2020 and a second in the following summer. In both cases, a small-aperture array of 2 hydrophones (with a distance of 3 meters between them) was dragged behind a sailing vessel and the time differences of arrival between the direct paths of sperm whale clicks to each of the two hydrophones were used to estimate the bearings of clicks, much in the same way as described above in Stage 6. Left-right ambiguities (present since this was a two-hydrophone configuration) were eliminated by taking successive readings as the ship changed course or by visual observation of the animal's position. The small distance

---

[20] With the exception of the very rare case in which the circles are tangent to each other.

between the hydrophones allowed for very accurate bearing estimations, especially abeam of the array, which were compared to the horizontal localizations output by the primary system. A sample result, represented by the black lines in Figure 1.31 (top), shows close agreement with the primary system. The research team also reported being able to track a sperm whale for a period of almost 3 hours as it transited from east to west in the vicinity of the array. (See Figure 1.32.)
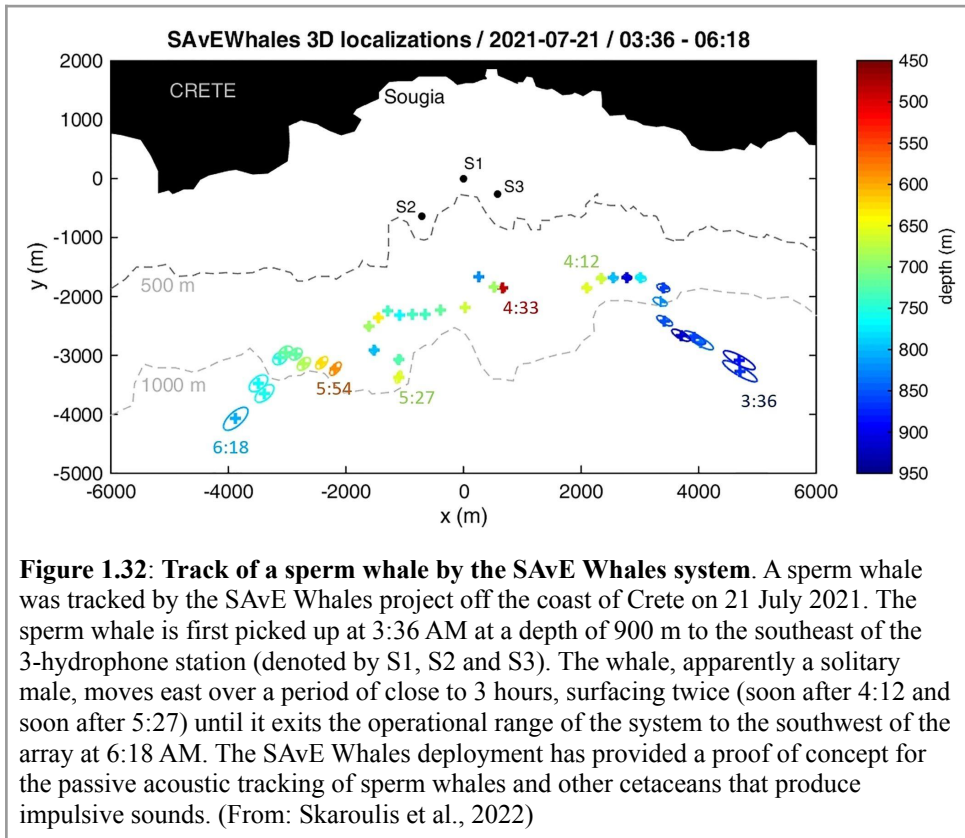

Figure 1.32: **Track of a sperm whale by the SAvE Whales system**. A sperm whale was tracked by the SAvE Whales project off the coast of Crete on 21 July 2021. The sperm whale is first picked up at 3:36 AM at a depth of 900 m to the southeast of the 3-hydrophone station (denoted by S1, S2 and S3). The whale, apparently a solitary male, moves east over a period of close to 3 hours, surfacing twice (soon after 4:12 and soon after 5:27) until it exits the operational range of the system to the southwest of the array at 6:18 AM. The SAvE Whales deployment has provided a proof of concept for the passive acoustic tracking of sperm whales and other cetaceans that produce impulsive sounds. (From: Skaroulis et al., 2022)

Overall, this pilot project sufficiently proved that the SAvE Whales observatory can be effective in detecting and localizing sperm whales, both in the three-hydrophone configuration and in the partial-data fallback scenario, i.e. the two-hydrophone configuration. Looking forward, a significant challenge will be to simultaneously localize individuals within a group of multiple sperm whales traveling in close proximity and in a coordinated fashion. A potential approach would be to take advantage of the fact that the click train of each sperm whale has a characteristic ICI, so clicks arriving from multiple individuals would be visible as multiple peaks on the click detection histograms. Another challenge will be determining the ideal depths to which to lower the hydrophones, in order to optimize two competing factors that greater hydrophone depths induce in the system: an increase in its effective range vs. the addition of extra arrivals (such as bottom-reflected sound waves) which obfuscate the ability to resolve TDOAs. More accurately modeling the underwater environment, such as by increasing the frequency of in-situ sound speed and sea state measurements, could help in surmounting this challenge.

1.6. Conclusion

In this first general introductory section we have laid the groundwork for the necessity and efficacy of the research which will be presented in detail in Section 2, the journal article.

• We have shown the urgent need to minimize ship strikes upon sperm whales due to the dire situation of the worldwide and, in particular, Mediterranean sperm whale populations.

• We have explored the various causes of ship-whale collisions, including the exponential rise in commercial shipping density and, along with it, a similar increase in underwater anthropogenic noise pollution which has grave detrimental effects on the sperm whale's ability to evade oncoming ships, as well as the unique foraging behaviors of the sperm whale which result in its taking prolonged rests at the surface, often directly in shipping lanes.

• We have explored, in detail, the physiology, behavior and ecology of the sperm whale, with an eye towards keeping in mind that the better we know these elusive animals, the more effective will be the systems we can design in alleviating their untimely deaths.

• Finally, we have surveyed a cross-section of important ship strike mitigation efforts geared towards alleviating pressure on sperm whales and on cetaceans in general, eventually focusing in on PAM-related projects, which use a benign form of acoustic monitoring to detect, localize and track vocalizing cetaceans, particularly sperm whales.

• Last but not least, we have focused on the project under the scope of which my research has taken place – the SAvE Whales project – and presented some of the technical details and preliminary results of their implementation of a passive acoustic monitoring system for the localization of sperm whales.

Now, we are ready to dive into my current research. In doing so, I will present the research in the form of a journal article ready (or near ready) for publication. The article will detail the technical background and underlying theories behind the project, as well as the project's practical implementation, which I built from scratch on the Matlab platform. Please note that this project is very much a work in progress. In reality, one year is barely enough to scratch the surface of this fascinating and rapidly expanding area of research. Nonetheless, I hope that the presentation of my research will reveal new and interesting facets of this area of study which will contribute, in novel ways, to the overall conversation in this field.

References of the General Introduction

About SAvE Whales. (2019). SAvE Whales project. Retrieved December 27, 2021, from http://136.243.46.142/about/

André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., Schaar, M., Lopez-Bejar, M., Morell, M., Zaugg, S., & Houegnigan, L. (2011). Low-frequency sounds induce acoustic trauma in cephalopods. *Frontiers in Ecology and the Environment*, *9*, 489 - 493. doi: 10.2307/23034465

Arregui, M., de Quirós, Y. B., Saavedra, P., Sierra, E., Suárez-Santana, C. M., Arbelo, M., Díaz-Delgado, J., Puig-Lozano, R., Andrada, M., & Fernández, A. (2019). Fat Embolism and Sperm Whale Ship Strikes. *Frontiers in Marine Science*, *6*, 379. doi: 10.3389/fmars.2019.00379

Audoly, C., Gaggero, T., Baudin, E., Folegot, T., Rizzuto, E., Salinas Mullor, R., André, M., Rousset, C., & Kellett, P. (2017, April). Mitigation of Underwater Radiated Noise Related to Shipping and Its Impact on Marine Life: A Practical Approach Developed in the Scope of AQUO Project. *IEEE Journal of Oceanic Engineering*, *42*(2), 373 - 387. doi: 10.1109/JOE.2017.2673938

Baraniuk, C. (2015, October 16). *The noise we're creating in the sea can be deadly*. BBC Future: The Genius Behind - Ocean. Retrieved December 28, 2021, from https://www.bbc.com/future/article/20151016-the-noise-were-creating-in-the-sea-can-be-deadly

Bermant, P. C., Bronstein, M. M., Wood, R. J., Gero, S., & Gruber, D. F. (2019). Deep Machine Learning Techniques for the Detection and Classification of Sperm Whale Bioacoustics. *Scientific Reports*, *9*(1), 12588. https://doi.org/10.1038/s41598-019-48909-4

Bunyan, R. (2020, November 6). Mother sperm whale feeds its calf by injecting milk into the sea. *Daily Mail*. https://www.dailymail.co.uk/news/article-8920863/amp/Stunning-pictures-mother-sperm-whale-feeding-calf-injecting-milk-sea.html

Cantor, M., Gero, S., Whitehead, H., & Rendell, L. E. (2019). Sperm Whale: The Largest Toothed Creature on Earth. In B. Würsig (Ed.), *Ethology and Behavioral Ecology of Odontocetes* (pp. 261 - 280). Springer International Publishing. doi: 10.1007/978-3-030-16663-2_12

Carillo, M., & Ritter, F. (2010). Increasing numbers of ship strikes in the Canary Islands: proposals for immediate action to reduce risk of vessel-whale collisions. *Journal of Cetacean Research and Management*, *11*(2), 131 - 138. http://2k19.m-e-e-r.de/download/wissenschaftliche_publikationen/JCRM_ShipStrikes_Canaries_Carrillo_Ritter_2010.pdf

Clarke, M. R. (1979). The Head of the Sperm Whale. *Scientific American*, *240*(1), 128 - 141. https://www.jstor.org/stable/24965073

Collisions with Vessels a Deadly Threat For Whales. (2021, June 9). Friend of the Sea. Retrieved September 12, 2022, from https://friendofthesea.org/collisions-with-vessels-the-deadliest-threat-for-whales/

Coombs, E. J., Clavel, J., Park, T., Churchill, M., & Goswami, A. (2020). Wonky whales: the evolution of cranial asymmetry in cetaceans. *BMC Biology*, *18*(1), 86. doi: 10.1186/s12915-020-00805-4

de Oliveira, C. I. B. (2014, June). Behavioural ecology of the sperm whale (Physeter macrocephalus) in the North Atlantic Ocean. *PhD Dissertation in Marine Science, University of the Azores*. doi: 10.13140/RG.2.1.2461.6486

Díaz-Delgado, J., Fernández, A., Sierra, E., Sacchini, S., Andrada, M., Vela, A. I., Quesada-Canales, Ó., Paz, Y., Zucca, D., Groch, K., & Arbelo, M. (2018, October). Pathologic findings and causes of death of stranded cetaceans in the Canary Islands (2006-2012). *PLOS ONE*, *13*(10), 1 - 33. doi: 10.1371/journal.pone.0204444

Diving With Sperm Whales Can Be Painful or Deadly. (2021). For Scuba Divers. Retrieved January 19, 2022, from https://forscubadivers.com/marine-life-for-divers/diving-with-sperm-whales-can-be-painful-or-deadly/

Donn, N. (2022, April 15). 15-ton whale washes up on Almada beach. *Portugal Resident*. https://www.portugalresident.com/15-ton-whale-washes-up-on-almada-beach/

Frantzis, A., Alexiadou, P., & Gkikopoulou, K. (2014). Sperm whale occurrence, site fidelity and population structure along the Hellenic Trench (Greece, Mediterranean Sea). *Aquatic Conservation: Marine and Freshwater Ecosystems*, *24*, 83 - 102. doi: 10.1002/aqc.2435

Frantzis, A., Leaper, R., Alexiadou, P., Prospathopoulos, A., & Lekkas, D. (2019). Shipping routes through core habitat of endangered sperm whales along the Hellenic Trench, Greece: Can we reduce collision risks? *PLOS ONE*, *14*(2). doi: 10.1371/journal.pone.0212016

Frisk, G. (2012). Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. *Scientific reports*, *2*, 437. doi: 10.1038/srep00437

Gero, S., Gordon, J., & Whitehead, H. (2015). Individualized social preferences and long-term social fidelity between social units of sperm whales. *Animal Behaviour*, *102*, 15 - 23. https://doi.org/10.1016/j.anbehav.2015.01.008

Gero, S., & Whitehead, H. (2007, April). Suckling behavior in sperm whale calves: observations and hypotheses. *Marine Mammal Science*, *23*(2), 398 - 413. doi: 10.1111/j.1748-7692.2007.00113.x

Gillespie, D., Palmer, L., Macaulay, J., Sparling, C., & Hastie, G. (2020). Passive acoustic methods for tracking the 3D movements of small cetaceans around marine structures. *PLOS ONE*, *15*, 1 - 16. https://doi.org/10.1371/journal.pone.0229058

Grossi, F., Lahaye, E., Moulins, A., Borroni, A., Rosso, M., & Tepsich, P. (2021). Locating ship strike risk hotspots for fin whale (Balaenoptera physalus) and sperm whale (Physeter macrocephalus) along main shipping lanes in the North-Western Mediterranean Sea. *Ocean & Coastal Management*, *212*, 105820. https://doi.org/10.1016/j.ocecoaman.2021.105820

Guidi, C., Bou-Cabo, M., & Lara, G. (2021, October). Passive acoustic monitoring of cetaceans with KM3NeT acoustic receivers. *Journal of Instrumentation*, *16*(10), C10004. 10.1088/1748-0221/16/10/c10004

Hansen, G., Wensveen, P., & Cannon, J. (2022, June 7). Noise pollution spooks whales the way predators would, study finds. *Mongabay*. https://news.mongabay.com/2022/06/noise-pollution-spooks-whales-the-way-predators-would-study-finds/

Hildebrand, J. A. (2005). Impacts of Anthropogenic Sound. In S. Montgomery, R. R. Reeves, T. J. Ragen, J. E. Reynolds III, W. F. Perrin, & J. E. Reynolds (Eds.), *Marine Mammal Research: Conservation Beyond Crisis* (pp. 101 - 124). Johns Hopkins University Press. https://escholarship.org/content/qt8997q8wj/qt8997q8wj.pdf

Hurd, I. (2012, March 29). *Almost Saving Whales: The Ambiguity of Success at the International Whaling Commission*. Ethics & International Affairs. Retrieved August 1, 2022, from https://www.ethicsandinternationalaffairs.org/2012/almost-saving-whales-the-ambiguity-of-success-at-the-international-whaling-commission-full-text/

Injured beached sperm whale dies in Portugal. (2022, April 16). *The Animal Reader*. https://www.theanimalreader.com/2022/04/16/injured-beached-sperm-whale-dies-in-portugal/

Irvine, L., Palacios, D. M., Urbán, J., & Mate, B. (2017). Sperm whale dive behavior characteristics derived from intermediate-duration archival tag data. *Ecology and Evolution*, *7*(19), 7822 - 7837. https://doi.org/10.1002/ece3.3322

Jiang, J., Li, S., Wang, X., Li, C., Sun, Z., Liu, W., Duan, F., & Fu, X. (2021). Study of the relationship between sound signals and behaviors of a sperm whale during the hunting process. *Applied Acoustics*, *174*, 107745. https://doi.org/10.1016/j.apacoust.2020.107745

Jiang, W.-B., Han, J., Ma, X.-W., Liu, H., Yu, S.-B., & Sui, H.-J. (2021). Plastination of a sperm whale. *Journal of Anatomy*, *240*. doi: 10.1111/joa.13581

Jones, N. (2019). Ocean uproar: saving marine life from a barrage of noise. *Nature, 568*, 158 - 161. https://doi.org/10.1038/d41586-019-01098-6

Klinck, H., Mellinger, D. K., Klinck, K., Bogue, N. M., Luby, J. C., Jump, W. A., Shilling, G. B., Litchendorf, T., Wood, A. S., Schorr, G. S., & Baird, R. W. (2012, May). Near-Real-Time Acoustic Monitoring of Beaked Whales and Other Cetaceans Using a Seaglider™. *PLOS ONE*, *7*(5), 1 - 8. doi: 10.1371/journal.pone.0036128

KM3NeT opens a new window on our universe. (2022). KM3NeT home page. Retrieved August 23, 2022, from https://www.km3net.org/

Konrad, C. M., Frasier, T. R., Whitehead, H., & Gero, S. (2019, January / February). Kin selection and allocare in sperm whales. *Behavioral Ecology*, *30*(1), 194 – 201. doi: 10.1093/beheco/ary143

Konrad, C. M., Gero, S., Frasier, T., & Whitehead, H. (2018). Kinship influences sperm whale social organization within, but generally not among, social units. *Royal Society Open Science*, *5*(8), 180914. doi: 10.1098/rsos.180914

Lefort, K., Hussey, N., & Jones, J. (2022, January). Satellite-tracked sperm whale migrates from the Canadian Arctic to the subtropical western North Atlantic. *Marine Mammal Science*. doi: 10.1111/mms.12909

Lloyd, H., & Ross, G. A. (2015, June). Long-term trends in cetacean incidents in New South Wales, Australia. *Australian Zoologist*, *37*. doi:10.7882/AZ.2015.015

Madsen, P., Wahlberg, M., & Møhl, B. (2002a). Male sperm whale (Physeter macrocephalus) acoustics in a high-latitude habitat: implications for echolocation and communication. *Behavioral Ecology and Sociobiology*, *53*(1), 31 - 41. https://doi.org/10.1007/s00265-002-0548-1

Madsen, P. T., Payne, R., Kristiansen, N. U., Wahlberg, M., Kerr, I., & Møhl, B. (2002b). Sperm whale sound production studied with ultrasound time/depth-recording tags. *The Journal of Experimental Biology*, *205*, 1899 - 1906. http://groups.csail.mit.edu/drl/wiki/images/c/cc/spermwhaletagging.pdf

Masao, A., & Motoi, Y. (2003). Sperm whale diving behavior monitored using a suction-cup-attached TDR tag. *Marine Ecology Progress Series*, *258*, 291 - 295. doi:10.3354/meps258291

Millefiori, L. M., Braca, P., Zissis, D., Spiliopoulos, G., Marano, S., Willett, P. K., & Carniel, S. (2021). COVID-19 impact on global maritime mobility. *Scientific Reports*, *11*(1). doi: 10.1038/s41598-021-97461-7

Miller, P. J.O., Aoki, K., Rendell, L. E., & Amano, M. (2008). Stereotypical resting behavior of the sperm whale. *Current Biology*, *18*(1), R21 - R23. https://doi.org/10.1016/j.cub.2007.11.003

Miller, P. J.O., Isojunno, S., Siegal, E., Lam, F.-P. A., Kvadsheim, P. H., & Curé, C. (2022). Behavioral responses to predatory sounds predict sensitivity of cetaceans to anthropogenic noise within a soundscape of fear. *Proceedings of the National Academy of Sciences*, *119*(13). doi: 10.1073/pnas.2114932119

Møhl, B., Larsen, E., & Amundin, M. (1981). Sperm whale size determination: outlines of an acoustic approach. In *Mammals in the Seas: General papers and large cetaceans* (5th ed., Vol. 3, pp. 327 - 331). Food and Agriculture Organization of the United Nations (Rome).

Morell, M., Brownlow, A., McGovern, B., Raverty, S. A., Shadwick, R. E., & André, M. (2017). Implementation of a method to visualize noise-induced hearing loss in mass stranded cetaceans. *Scientific Reports*, *7*(1), 41848. doi: 10.1038/srep41848

Notarbartolo di Sciara, G., Frantzis, A., Bearzi, G., & Reeves, R. (2012). *Physeter macrocephalus*. The IUCN Red List of Threatened Species 2012: e.T41755A2955634. Retrieved 12 27, 2021, from https://www.iucnredlist.org/species/41755/2955634

Oceana: Sperm Whale. (2021). Oceana. Retrieved January 6, 2022, from https://oceana.org/marine-life/sperm-whale/

OceanCare. (2020, January 3). *Sperm whales need urgent protection from ship strikes in Greece*. International Fund for Animal Welfare. Retrieved December 26, 2021, from https://www.ifaw.org/international/people/opinions/sperm-whales-ship-strikes-greece

Oliveira, C., Wahlberg, M., Johnson, M., Miller, P., & Madsen, P. (2013). The function of male sperm whale slow clicks in a high latitude habitat: Communication, echolocation, or prey debilitation? *The Journal of the Acoustical Society of America*, *133*, 3135 - 3144. doi: 10.1121/1.4795798

Panagiotopoulou, O., Spyridis, P., Abraha, H. M., Carrier, D. R., & Pataky, T. C. (2016). Architecture of the sperm whale forehead facilitates ramming combat. *PeerJ*, *4*, e1895. doi: 10.7717/peerj.1895

Riedman, M. L. (1982). The Evolution of Alloparental Care and Adoption in Mammals and Birds. *The Quarterly Review of Biology*, *57*(4), 405 - 435. https://www.jstor.org/stable/2826887

Ritter, F., de Soto, N. A., & Martín, V. (2019). Towards Ship Strike Mitigation in the Canary Islands. *Paper submitted to the International Whaling Commission, SC/68A/HIM/15*. https://m-e-e-r.de/wp-content/uploads/2020/12/Towards-Ship-Strike-Mitigation-in-the-Canary-Islands_IWC.pdf

Rodríguez, O. C. (2008, June 13). *General description of the Bellhop ray tracing program* (Version 1.0). Physics Department, Signal Processing Laboratory, Faculdade de Ciências e Tecnologia, Universidade do Algarve. http://oalib.hlsresearch.com/Rays/GeneralDescription.pdf

Sanguineti, M., Alessi, J., Brunoldi, M., Cannarile, G., Cavalleri, O., Cerruti, R., Falzoi, N., Gaberscek, F., Gili, C., Gnone, G., Grosso, D., Guidi, C., Mandich, A., Melchiorre, C., Pesce, A., Petrillo, M., Taiuti, M.

G., Valettini, B., & Viano, G. (2021a). An automated passive acoustic monitoring system for real time sperm whale (Physeter macrocephalus) threat prevention in the Mediterranean Sea. *Applied Acoustics*, *172*, 107650. https://doi.org/10.1016/j.apacoust.2020.107650

Sanguineti, M., Guidi, C., Kulikovskiy, V., & Taiuti, M. G. (2021b, December 6). Real-Time Continuous Acoustic Monitoring of Marine Mammals in the Mediterranean Sea. *Journal of Marine Science and Engineering*, *9*(12), 1389. 10.3390/jmse9121389

Sarano, F., Girardet, J., Sarano, V., Vitry, H., Preud'homme, A., Heuzey, R., Garcia-Cegarra, A. M., Madon, B., Delfour, F., Glotin, H., Adam, O., & Jung, J.-L. (2021). Kin relationships in cultural species of the marine realm: case study of a matrilineal social group of sperm whales off Mauritius island, Indian Ocean. *Royal Society Open Science*, *8*(2), 201794. doi: 10.1098/rsos.201794

Schmidt, F. N., Delsmann, M. M., Mletzko, K., Yorgan, T. A., Hahn, M., Siebert, U., Busse, B., Oheim, R., Amling, M., & Rolvien, T. (2018, December). Ultra-high matrix mineralization of sperm whale auditory ossicles facilitates high sound pressure and high-frequency underwater hearing. *Proceedings of the Royal Society B: Biological Sciences*, *285*(1893). doi: 10.1098/rspb.2018.1820

Skarsoulis, E. K., Piperakis, G. S., Orfanakis, E., Papadakis, P., Pavlidi, D., Kalogerakis, M. A., Alexiadou, P., & Frantzis, A. (2022). A Real-Time Acoustic Observatory for Sperm-Whale Localization in the Eastern Mediterranean Sea. *Frontiers in Marine Science*, *9*. doi: 10.3389/fmars.2022.873888

Taylor, B. L., Baird, R., Barlow, J., Dawson, S. M., Ford, J., Mead, J. G., Notarbartolo di Sciara, G., Wade, P., & Pitman, R. L. (2019). *Physeter macrocephalus (amended version of 2008 assessment)*. The IUCN Red List of Threatened Species 2019: e.T41755A160983555. Retrieved 12 27, 2021, from https://www.iucnredlist.org/species/41755/160983555

Tepsich, P., Rosso, M., Halpin, P., & Moulins, A. (2014). Habitat preferences of two deep-diving cetacean species in the northern Ligurian Sea. *Marine Ecology Progress Series*, *508*, 247 - 260. doi: 10.3354/meps10851

Tønnesen, P., Oliveira, C., Johnson, M., & Madsen, P. T. (2020). The long-range echo scene of the sperm whale biosonar. *Biology Letters*, *16*(8), 20200134. doi: 10.1098/rsbl.2020.0134

Tournadre, J. (2014). Anthropogenic pressure on the open ocean: The growth of ship traffic revealed by altimeter data analysis. *Geophysical Research Letters*, *41*(22), 7924 - 7932. doi: 10.1002/2014GL061786

United Nations Conference on Trade and Development: Review of Maritime Transport 2019. (2020, January 31). https://unctad.org/system/files/official-document/rmt2019_en.pdf

Vachon, F., Hersh, T. A., Rendell, L., Gero, S., & Whitehead, H. (2022). Ocean nomads or island specialists? Culturally driven habitat partitioning contrasts in scale between geographically isolated sperm whale populations. *Royal Society Open Science*, *9*(5), 211737. doi: 10.1098/rsos.211737

Van Waerebeek, K., & Leaper, R. (2008, June 1). Second Report of the IWC Vessel Strike Data Standardisation Working Group. doi: 10.13140/RG.2.1.2020.2001

Wang, Z.-T., Supin, A. Y., Akamatsu, T., Duan, P.-X., Yang, Y.-N., Wang, K.-X., & Wang, D. (2021, December). Auditory evoked potential in stranded melon-headed whales (Peponocephala electra): With severe hearing loss and possibly caused by anthropogenic noise pollution. *Ecotoxicology and Environmental Safety*, *228*. https://doi.org/10.1016/j.ecoenv.2021.113047

Whitehead, H. (2002). Estimates of the current global population and historical trajectory for sperm whales. *Marine Ecology Progress Series*, *242*, 295 - 304. doi: 10.3354/meps242295

Whitehead, H. (2002). Sperm whale Physeter macrocephalus. In W. F. Perrin, B. G. Würsig, & J.G. M. Thewissen (Eds.), *Encyclopedia of Marine Mammals* (pp. 1165 - 1172). Elsevier Science. https://archive.org/details/encyclopediaofma2002unse/page/1166/mode/1up

Whitehead, H., Waters, S., & Lyrholm, T. (1991, December). Social organization of female sperm whales and their offspring: constant companions and casual acquaintances. *Behavioral Ecology and Sociobiology*, *29*(5), 385 - 389. doi: 10.1007/BF00165964

Zitterbart, D. P., Smith, H. R., Flau, M., Richter, S., Burkhardt, E., Beland, J., Bennett, L., Cammareri, A., Davis, A., Holst, M., Lanfredi, C., Michel, H., Noad, M., Owen, K., Pacini, A., & Boebel, O. (2020). Scaling the Laws of Thermal Imaging–Based Whale Detection. *Journal of Atmospheric and Oceanic Technology*, *37*(5), 807 - 824. https://doi.org/10.1175/JTECH-D-19-0054.1

Passive Acoustic Localization of Sperm Whales to Facilitate Ship Strike Avoidance

Michael R. Klosner[*] **& Sérgio M. Jesus**[a]

[a]*LarSys, Universidade do Algarve, Campus de Gambelas 8005-139 Faro, Portugal*

E-mail: `klosner.michael.r@gmail.com`

Abstract

Ship strikes are one of the leading causes of premature mortality among whales, accounting for the deaths of approximately 20,000 each year, with untold more being injured. Given the exponential increase in shipping traffic, estimated at 2 - 3% year-over-year, the potential for collisions continues to grow. Due to their large size, preferred habitats and sea surface behavior, the sperm whale is one of the species most vulnerable to ship strikes. In some populations, collisions with maritime vessels are the leading cause of death, premature or otherwise. This is particularly concerning considering that the sperm whale is listed on the IUCN Red List of Threatened Species as "Vulnerable" globally and "Endangered" in the Mediterranean region.

Passive Acoustic Monitoring, or PAM, is an environmentally non-intrusive method by which naturally generated underwater sounds, such as clicks made by sperm whales, are picked up by hydrophones (underwater recording devices) and analyzed to extract a variety of data, including the sound source's location. In the current research, we use a PAM methodology known as Time Difference of Arrival (TDOA) analysis, whereby divergent acoustic paths taken by sound waves from their source to a hydrophone are analyzed to extract the differences in time between their arrivals. Extracted TDOAs are compared to a theoretical model (in our case, the Bellhop ray tracing model) to extrapolate the source's localization, which can then be fed into a live marine traffic system such as MarineTraffic (marinetraffic.com) to alert ships in the area to the presence and locations of the whales, so that they may take preventative action. In this article,

I present, inter alia, a working prototype, developed on the Matlab platform, for the detection and localization of sperm whales based on their vocalizations (clicks).

2.1. Introduction

The sperm whale (*Physeter macrocephalus*) is a large, elusive, deep-diving cetacean with a complex social structure and a cosmopolitan distribution, found from tropical waters to near the polar ice caps, in all the oceans of the world and in the Mediterranean Sea. Sperm whale populations, which numbered a total of 2 to 3 million individuals in the 18th century, were decimated by intensive whaling in the 19th century, and by 1986, when the international moratorium on commercial whaling went into effect, sperm whale numbers had dwindled to just 200,000 worldwide. Populations never recovered as expected after the enactment of the moratorium (Hurd, 2012), and consequently, sperm whales are currently listed on the IUCN Red List of Threatened Species as "Vulnerable" globally (Taylor et al., 2019), and "Endangered, with Population Trend: Decreasing" in the Mediterranean region (Notarbartolo di Sciara et al., 2012), the locus of the SAvE Whales project, under the auspices of which this current research is being conducted.

One of the most tragic, and preventable, causes of premature sperm whale mortality is strikes by seagoing vessels. Typically, whales are nearly severed by the ship's bow or gashed by the propellers of its motor, the latter leaving a telltale series of parallel lacerations along their backs or sides. (See Figure 2.1.) This often leads to death, following which the whale carcass may drift out to sea or sink to the ocean floor, never to be seen or heard from again, making it difficult to assess the exact number of cetaceans killed by ship blows. (Ritter et al., 2019) Alternatively, it can lead to severe injury, following which the whale may strand itself. Vessel collisions are so common in certain regions of the world, such as the Canary Islands, that they account for more than 60% of total sperm whale deaths, natural or otherwise. (Arregui et al., 2019) A 2018 study by Díaz-Delgado et al. paints an even more dire picture: of 16 stranded sperm whales examined pathologically between 2006 and 2012, vessel collisions were the most probable cause of death for 11 of them (68.8%). Furthermore, among the 21 different cetacean species which were necropsied, comprising 224 animals, sperm whales were found to be, by far, the species most affected by ship collisions, accounting for almost half (11 of 24) of animals killed in this fashion. (Díaz-Delgado et al., 2018)

Figure 2.1: [Left] A stranded sperm whale almost severed in two from impalement by the sharp bow of a high-speed ferry in the Canary Islands. (From: Ritter et al., 2019) [Right] A stranded North Atlantic right whale carcass with clear signs of propeller gashes along its left side. (From: *Threats to Marine Mammals*, 2012)

Sadly, ship strikes upon sperm whales continue to increase at an exponential rate. (Van Waerebeek & Leaper, 2008) There are a number of identifiable reasons for this. The first is a corresponding exponential increase in shipping traffic. Total worldwide merchant ship numbers more than doubled in the 8 years between 2004 and 2012, and more than tripled between 1992 and 2012. (Tournadre, 2014) The second is the increase in anthropogenic undersea noise which, like shipping volume, has also grown exponentially – doubling in intensity every 10 years between 1950 and 2007 (Frisk, 2012) – and which has a profound effect not just on sperm whales, but on marine wildlife in general. Effects upon sperm whales include permanent impairment to their hearing (Wang et al., 2021), behavioral desensitization to the dangers associated with oncoming ships (Baraniuk, 2015) and disruptions in the availability and distribution of their prey (André et al., 2011).

An underlying cause behind collisions with ships is the sperm whale's distinctive foraging behavior. Sperm whales spend around 75% of their time, day and night, engaged in deep-sea hunting dives (Irvine et al., 2017) which can last for up to an hour and which take the whales well into mesopelagic and bathypelagic realms – generally to depths of around 1000 m, but sometimes as deep as 2,250 m. (Madsen et al., 2002) However, since sperm whales are mammals equipped with lungs and not gills, they must eventually return from the murky depths. Once resurfaced, the whales are exhausted from hunting, holding their breath, withstanding extreme pressures (which can exceed 100 atmospheres) and generating loud echolocation clicks of up to 230 dB re 1 μPa at 1 m. (*About SAvE Whales*, 2019) Therefore, they must rest, usually for a period of around 10 minutes, before commencing their next dive. It is during these repose periods that sperm whales are relatively immobile and particularly vulnerable to ship strikes. By an unfortunate coincidence, in certain areas of the world, such as the Hellenic Trench off the southwest coasts of the Peloponnese and Crete, sperm whales' preferred foraging grounds directly overlap busy shipping lanes, setting a course for disaster.

In response to this state of affairs, efforts have been underway for a number of decades to raise awareness of the issue, and to devise innovative ways to mitigate the frequency and severity of ship strikes. Ship rerouting, mandatory speed reductions in areas frequented by whales, and increased on-board lookouts, both human and automated, have all been recommended (Ritter et al., 2019) and implemented. One method which has gained increasing popularity in recent years is Passive Acoustic Monitoring, or PAM. Passive Acoustic Monitoring entails the positioning of underwater sound recorders (hydrophones) to detect and determine the locations of (localize) cetaceans by listening out for their calls. As the name implies, Passive Acoustic Monitoring is non-intrusive: it generates no sound of its own and it involves no direct contact with the animals; rather, it relies solely on the vocalizations of the target subjects. In the case of the sperm whale, these vocalizations are the aforementioned echolocation clicks, in particular the "usual click", the loudest of the sperm whale's repertoire, which it emits at a regular interval when scanning for prey. The usual click's regularity and unique triad of acoustic properties (it is broadband, impulsive and extremely loud) makes it ideally suited for detection and localization by PAM frameworks. Once localized, the animal's position can be fed into real-time ship-traffic monitoring systems, such as MarineTraffic (marinetraffic.com), which can, in-turn, send time-relevant warnings to ships in the vicinity of sperm whale activity so that they may initiate evasive or mitigative measures.

Though PAM has proven successful in reducing ship strikes, there are certain limitations to its effectiveness which must be addressed. One of the main impediments is that, as opposed to active acoustic methods such as SONAR, PAM systems must patiently "sit and wait" for the source to vocalize. A second obstacle is the identification of the target sound (i.e. a sperm whale click) among the many other pulsed sounds that pervade the subsea soundscape, such as those made by snapping shrimp, mussels, dolphins or boats (Skarsoulis et al., 2022). A third challenge is to properly identify a train of distinct sound snippets, arriving at different hydrophones and at slightly different times due to the multipath propagation of sound waves, as generated by the same source sound – an endeavor that is critical to successful localization. Finally, there exist boundaries on the operative depth and range of PAM systems because of the resolution limits of the system or because of divergence of the underlying mathematical models on which the localization protocol is based. (Skarsoulis et al., 2022)

Nonetheless, despite these appreciable challenges, PAM continues to show great promise for making a permanent dent in one of the leading causes of premature sperm whale mortality. Therefore, especially in light of the current acute threat to the species, there exists not only a necessity, but a sense of urgency, in promoting any and all effective PAM projects which might reduce vessel strikes on these and other cetaceans. The system that we plan to develop, test and deploy has the ability to do just that.

In this article, we present the theoretical underpinnings as well as the detailed workings of a prototype, built from scratch in the Matlab platform, for the passive acoustic localization of sperm whales. The system consists of a number of independently functioning modules, each of which performs a primary task necessary for localization, including the capture of sounds, the analysis of their waveforms and the comparison of parameters extracted from this analysis to a mathematical model predicting the source's position. To date, all development has taken place using computer simulations, with the intention to gradually migrate to a real-time system using live sounds recorded by hydrophones positioned in the Hellenic Trench off the coasts of the Peloponnese peninsula and Crete. So far, hundreds of simulations, covering a wide variety of scenarios, have been run, allowing for extensive testing of the platform, with overall positive results. Nonetheless, some serious obstacles have been encountered, which will be discussed in detail along with suggestions on how to potentially overcome them.

2.2. Materials and Methods

In the context of the SAvE Whales (System for the Avoidance of Ship-Strikes with Endangered Whales) project[21] and under the auspices of the Signal Processing Laboratory at the University of the Algarve in Faro, Portugal (SiPLAB)[22], a prototype has been developed from scratch on the MathWorks® Matlab platform using a Passive Acoustic Monitoring paradigm to test the localization of sperm whales in the Mediterranean Sea. Active development took place over a period of approximately four months, from March through June, 2022, using Matlab versions R2016b through R2022a on a Macintosh MacBook Pro with a direct network connection to Linux servers at the SiPLAB laboratory, where sample sounds and proprietary modules are stored. Efforts focused on developing a platform that followed best practices in software design, including modularity, clarity of code and computing time / memory considerations. The current version of the software (still very much in the alpha stage) consists of four independent modules: (1) TDOA database generation; (2) Sound generation / capture; (3) TDOA extraction from generated / captured sounds; and (4) Best matching of extracted TDOAs to the TDOA database. Since the system is still in the early phases of development – and not yet ready for a real-world test deployment – all sounds received at hydrophones were simulated *in silico* using, as source sounds, sample sperm whale clicks acquired from various online open-source repositories, with the exception of a one-minute non-simulated audio file from 14 June 2021 at 3:06 AM local time (.*wav* format, 100 kHz sampling rate) recorded by the SAvE Whales project's SWAN1 hydrophone which was positioned at a depth of 100 m below a surface buoy moored close to the 500-meter isobath in the Bay of Sougia off the southern coast of Crete. This recording features a heavy concentration of discernible sperm whale clicks which allowed us to test the system on data from a similar real-world deployment.

---

[21] http://136.243.46.142

[22] https://www.siplab.fct.ualg.pt

2.2.1. Ray Tracing and the Bellhop Model

The PAM system which we are developing is centered around an acoustic ray tracing model called the Bellhop model.[23] Ray tracing is an extremely efficient method for computationally modeling the propagation of energy – in our case, underwater sound waves. This is because, though it has applications to three-dimensional environments, it is built from a sequence of only one-dimensional curves. These curves emanate from the sound source and extend out into a surrounding plane which represents a vertical cross section of the modeled undersea environment. Each curve is discrete, constructed from a chain of small straight-line segments called rays, each of which propagates a small distance from the previous ray (or from the sound source), according to a set of underlying rules such as the law of refraction of energy waves (Snell's Law).

As opposed to full 2-D or 3-D wave-equation propagation models, ray tracing provides excellent computational efficiency without sacrificing the accuracy necessary for a large variety of applications, including localization. Though consisting of 1-D curves extending upon a 2-D vertical plane, Bellhop can be used to model 3-D environments by incorporating the real-world geometry of the scenario after the fact, using outputs generated by the model. This is precisely what we do in our system, as shall become clear.

The Bellhop model takes, as its input parameters, definitions for an impulsive sound source (frequency, depth, directionality, etc.), and for an idealized underwater environment (sound speed profile, bathymetry, surface reflective properties, etc.), and produces, as its output, the channel response of the sound, in the form of the above-described curves. Furthermore, it can calculate acoustic pressure, transmission energy loss and travel times from the source at points along the curves. (Rodríguez, 2008) Finally, one or more virtual receivers (hydrophones) can be positioned within the modeled underwater environment and Bellhop can trace only the curves which pass in their vicinity (eigenrays), further reducing computational complexity. (See Figure 2.2.)

---

[23] For further information on the Bellhop model, see: https://www.siplab.fct.ualg.pt/models/bellhop/manual/node2.html.
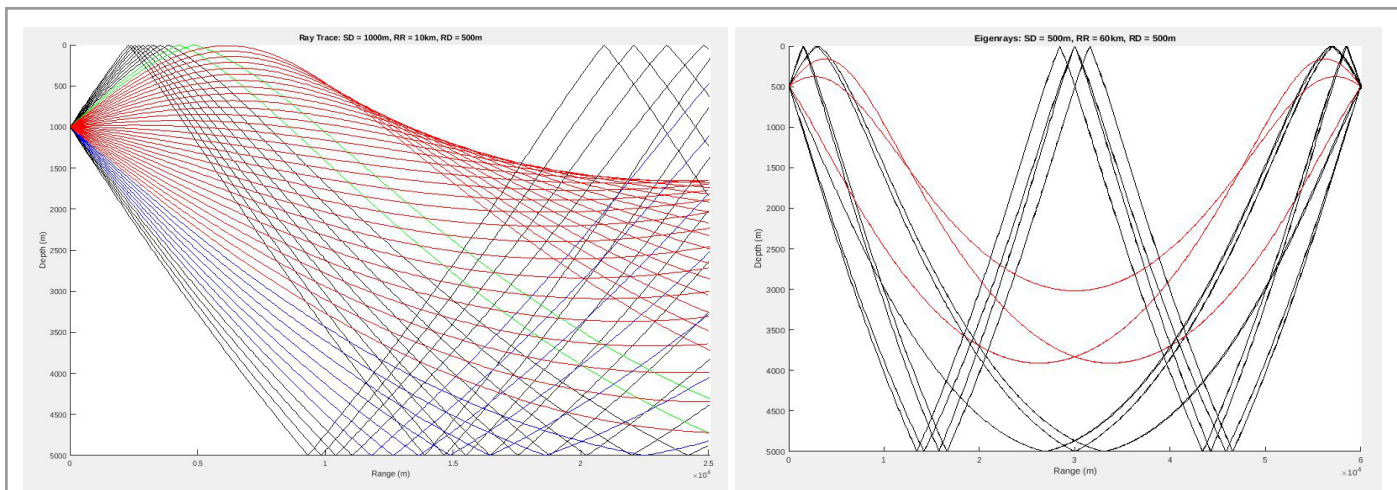
Figure 2.2: **The Bellhop Model**. [Left] Ray trace for a sound source located at a depth of 1000 m, out to a range limit of 25 km. [Right] Eigenrays connecting a sound source located at a depth of 500 m to a hydrophone located 60 km away at the same depth. Curves are color coded: red = direct paths, green = surface-reflected paths, blue = bottom-reflected paths, black = both-reflected paths. In both diagrams, the seafloor is flat with a constant depth of 5000 m and the sound speed profile is the Munk deep water profile.

2.2.2. Time Differences of Arrival (TDOAs)

In our case, it is the eigenrays of the system in which we are interested – more specifically, their travel times and amplitudes upon arrival at a hydrophone. We use these values to calculate the difference in travel times, called the Time Difference of Arrival (TDOA), between the surface-reflected path and the direct path to one or more hydrophones. When combined with the 3-D positions of the hydrophones *a posteriori*, full localization of the vocalizing source is achievable under optimal scenarios. Sperm whales' foraging clicks are particularly conducive to localization in this manner because of their unique acoustic properties among cetacean calls: they are loud, broadband and impulsive, a combination which provides excellent signal-to-noise ratios and sharp arrival peaks. "Usual" sperm whale clicks, emitted when the animal is on the hunt for prey, have a frequency spectrum which extends from 300 Hz to 30 kHz, a duration of 15 - 30 ms and they consist of a series of 2 - 4 distinct pulses with acoustic peaks lasting on the order of microseconds, the loudest of which can reach 230 dB re 1 μPa at 1 m. (Skarsoulis et al., 2022) On the other hand, they are highly directional, particularly in the higher frequencies, and thus their beneficial acoustic properties degrade significantly when the receiver is not on the axis of propagation of the click. (Madsen et al., 2002)

2.2.3. Overview of the localization system

The PAM system we have built consists of four independent modules, which work together as follows:

The first step is generation of the TDOA database using the Bellhop model, which is a preprocessing step that can be done in advance of the other steps. A single entry in the database maps a source location on the
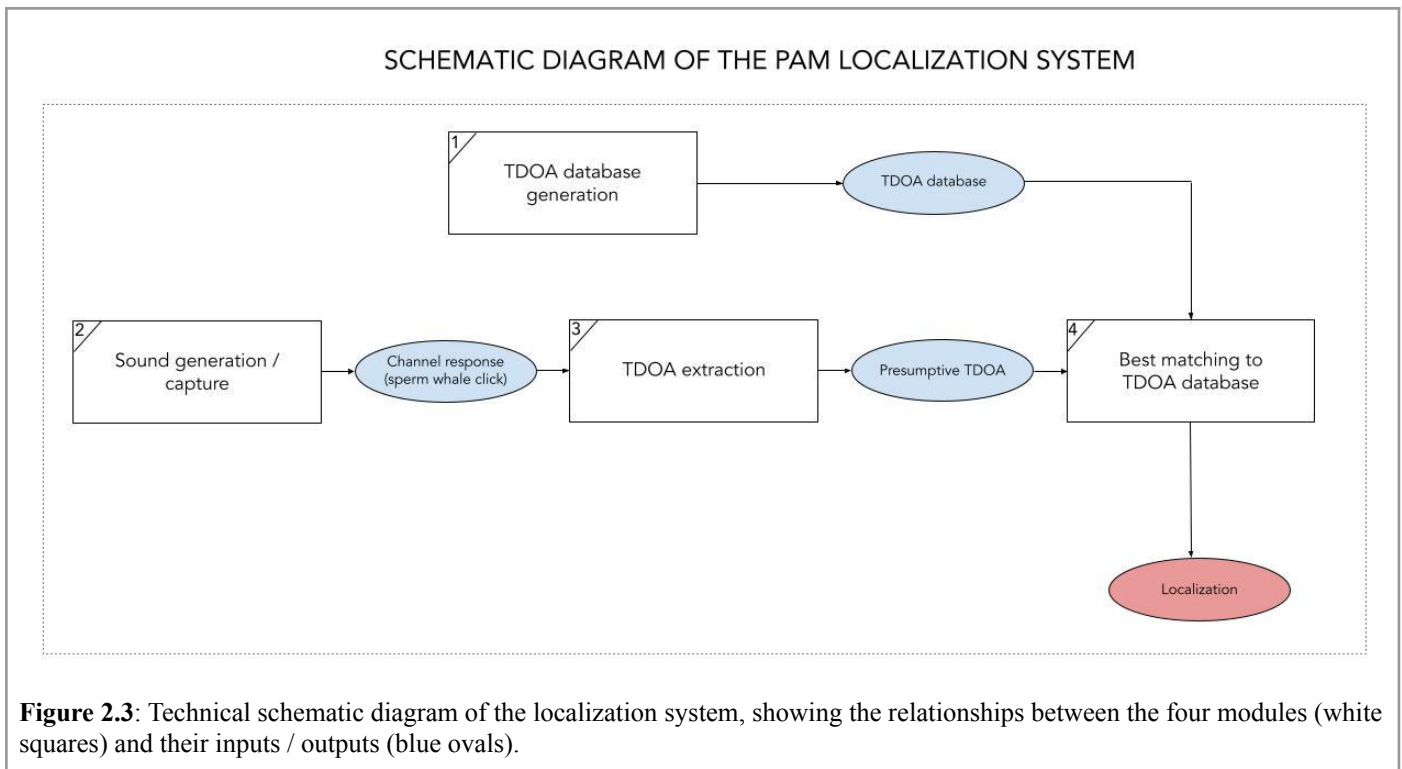
vertical plane, consisting of depth and range (*horizontal* distance between source and hydrophone), to the Time Difference of Arrival between the surface-reflected and direct ray from that source location to a hydrophone positioned at a designated depth. The entire database, therefore, consists of a matrix of such mappings encompassing the grid of all possible source locations, within the specified depth and range limits and with the specified granularity.

The sound generation / capture module captures the channel response of the source sound at the hydrophones, i.e. the sound that arrives at the hydrophones after the source sound propagates through – and is modulated by – the underwater environment. Currently, this is simulated by the Bellhop model using sample sperm whale clicks downloaded from the internet, but in the future this will be replaced with live sounds picked up by hydrophones situated in the water column. In that case, the module must distinguish between sperm whale clicks and other pulsed sounds such as those made by snapping shrimp, mussels, dolphins or boats, retaining the sperm whale clicks while filtering out the remainder. (Skarsoulis et al., 2022)

Once the channel response of a sperm whale click has been captured at a hydrophone – irrespective of whether the sound is simulated or live – the presumptive TDOA of the click must be extracted from it to determine the localization of the source. This is done by the TDOA extraction module using a pattern-matching algorithm based on autocorrelation, which will be described in greater detail below.

Once the presumptive TDOA has been extracted, it is queried against the TDOA database which was generated in the first step, for a best match. The source depth and receiver range associated with (inverse-mapped from) this best match are taken as the presumptive localization (depth, range) of the sperm whale. When this is done simultaneously at two or more hydrophones, localization can be reduced to two points or one point, depending on whether two or three hydrophones are used, respectively.

Below is a technical schematic diagram of the localization system, showing the four modules and their interfaces. (See Figure 2.3.)

Figure 2.3: Technical schematic diagram of the localization system, showing the relationships between the four modules (white squares) and their inputs / outputs (blue ovals).

2.3. Results

The localization system was tested on a variety of scenarios, with overall positive results, though many details still need to be worked out, which is to be expected in the early stages of development. We shall now go through a step-by-step example of the localization of a sperm whale click to demonstrate the workings of the system in detail.

2.3.1. Case study: localization of a sperm whale click

Step 1: TDOA database generation

Localization begins with the generation of the Time Difference of Arrival database. As mentioned above, this is a pre-processing stage, as the database needs to be regenerated only when the modeled underwater environment is updated. In their 2020 and 2021 tests of the SAvE Whales system off the coasts of the Peloponnese and Crete, in Greece, Skarsoulis et al. (2022), took water-column temperature measurements every two weeks to revise the underwater sound speed profile, and reported this frequency to be adequate. In future deployments, they intend to replace these biweekly readings with a thermistor chain and leverage the sea-to-shore communications capabilities of the hydrophone buoys to continuously update the sound-velocity profile. (Skaroulis et al., 2022). In such a scenario, the processing bottleneck would certainly be the time required to update the TDOA database, a computationally intensive operation which, in our case, can take a day or more when running on a single PC.

The database generation module takes, as its input, the acoustic properties of the source sound (frequency, directionality, etc.), a receiver depth (which is a known quantity based on the simulated or real-world scenario) and a 2-D grid of source locations with desired granularity. As its output, it produces the Time Difference of Arrival to the receiver between the surface-reflected ray and the direct ray, from each source location on the grid. (See Figure 2.4.) In cases where there is more than one surface-reflected path or more than one direct path, the highest amplitude ones of each type are chosen; in cases where either a direct ray or a surface-reflected path does not arrive, the result is recorded as null. For a grid of *m* depths and *n* ranges, generating the database amounts to calculating the arrival times of the eigenrays of the system *m·n* times. Examination of the resulting matrix shows that, for many scenarios, the TDOA database is a well-behaved function, i.e. that small deviations in source location will not result in large deviations in TDOA. Thus, once a sound source's TDOA is extracted, as will be done in Step 3, querying it against the TDOA database should can be expected to return a reasonable estimation of its localization, even if the extracted TDOA is slightly in error.
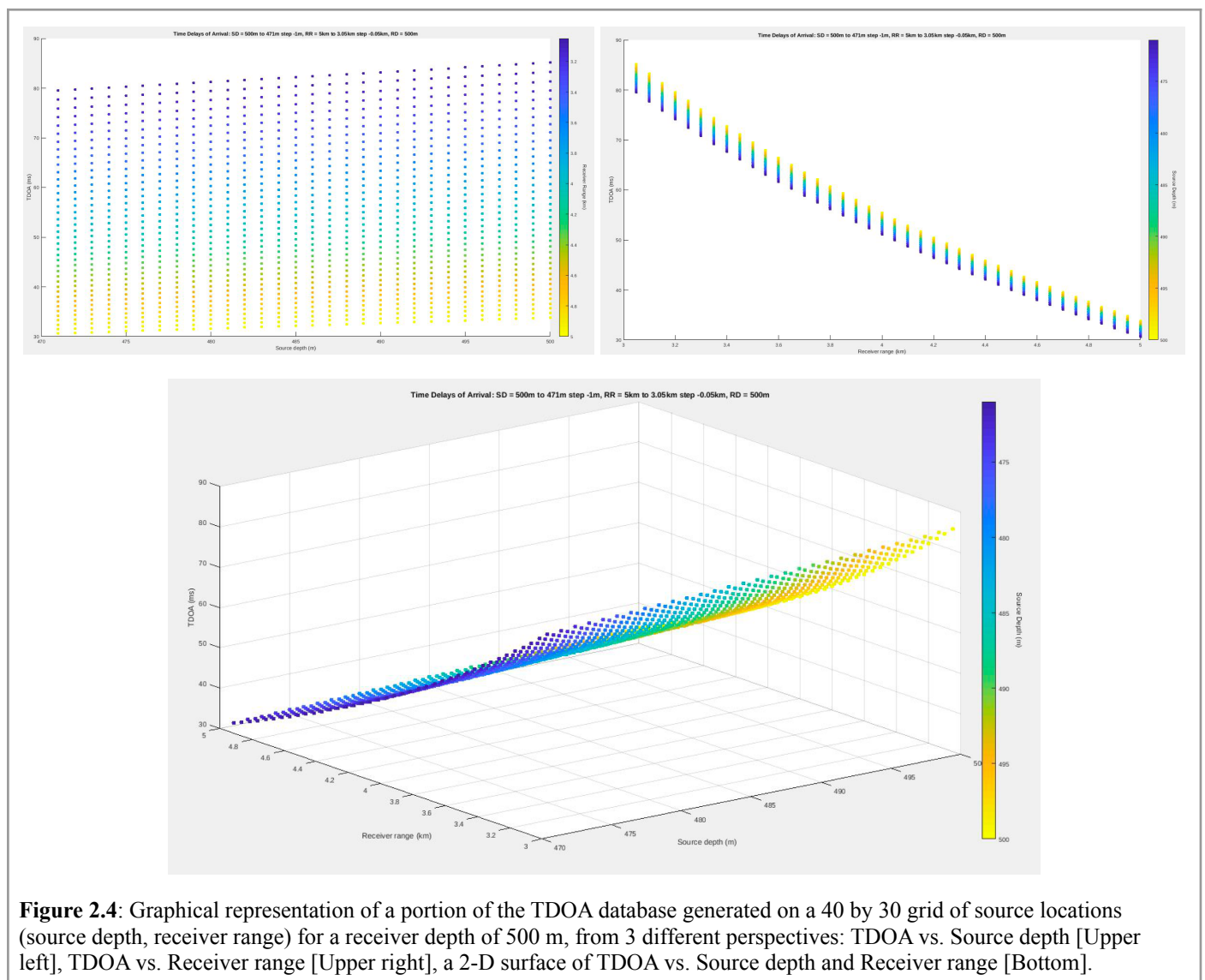

Figure 2.4: Graphical representation of a portion of the TDOA database generated on a 40 by 30 grid of source locations (source depth, receiver range) for a receiver depth of 500 m, from 3 different perspectives: TDOA vs. Source depth [Upper left], TDOA vs. Receiver range [Upper right], a 2-D surface of TDOA vs. Source depth and Receiver range [Bottom].

Examination of the plots shows that TDOA is a well-behaved function for this scenario.

Step 2: Sound generation / capture

The second step is to capture sperm whale clicks arriving at the hydrophones. At this stage, as mentioned earlier, all received sounds, with the exception of a one-minute recording by the SWAN1 hydrophone, were simulated, in the following manner: first, the channel response of an impulsive (instantaneous) source sound at the desired location (depth and range from the hydrophone) is computed by the Bellhop model to determine its paths to the hydrophones and their associated travel times. The channel response is then convolved with the original source sound to approximate the channel response of a whale click. (See Figure 2.5.) The resulting waveforms are passed onto the TDOA extraction module (Step 3). In a real-world scenario, the channel response would be recorded by physical hydrophones placed at known underwater positions, without any *a priori* knowledge of the sound source's location. In such a case, the addition of a sperm whale click detector is necessary to filter out unwanted sounds. For click detection, Skaroulis et al. (2022) used an energy detector with a time-variable threshold which is recalculated at one-second intervals based on the current background noise, and sequestered acoustic peaks with an SNR ≥ 4, each peak representing a potential click. This train of arrivals was then searched for interval regularity by examining the histogram of arrival time differences between each arrival in the train and all of its temporal neighbors up to the expected ICI for a usual click, 0.5 - 2 seconds. A recurring pattern is visible as a clear peak in the histogram, and each arrival that makes up that peak is construed as a confirmed click, based on the idea that the ICI for a particular individual will remain constant over time. (Skaroulis et al., 2022) Kandia et al. (2008) further suggest using a Teager-Kaiser energy operator[24] to suppress noise before searching for clicks in the acoustic stream. (Kandia et al., 2008)

---

[24] The Teager-Kaiser energy operator is a simple algorithm of the form $y_t = x_t^2 - x_{t-1}x_{t+1}$ used to enhance signal detection by augmenting acoustic peaks.
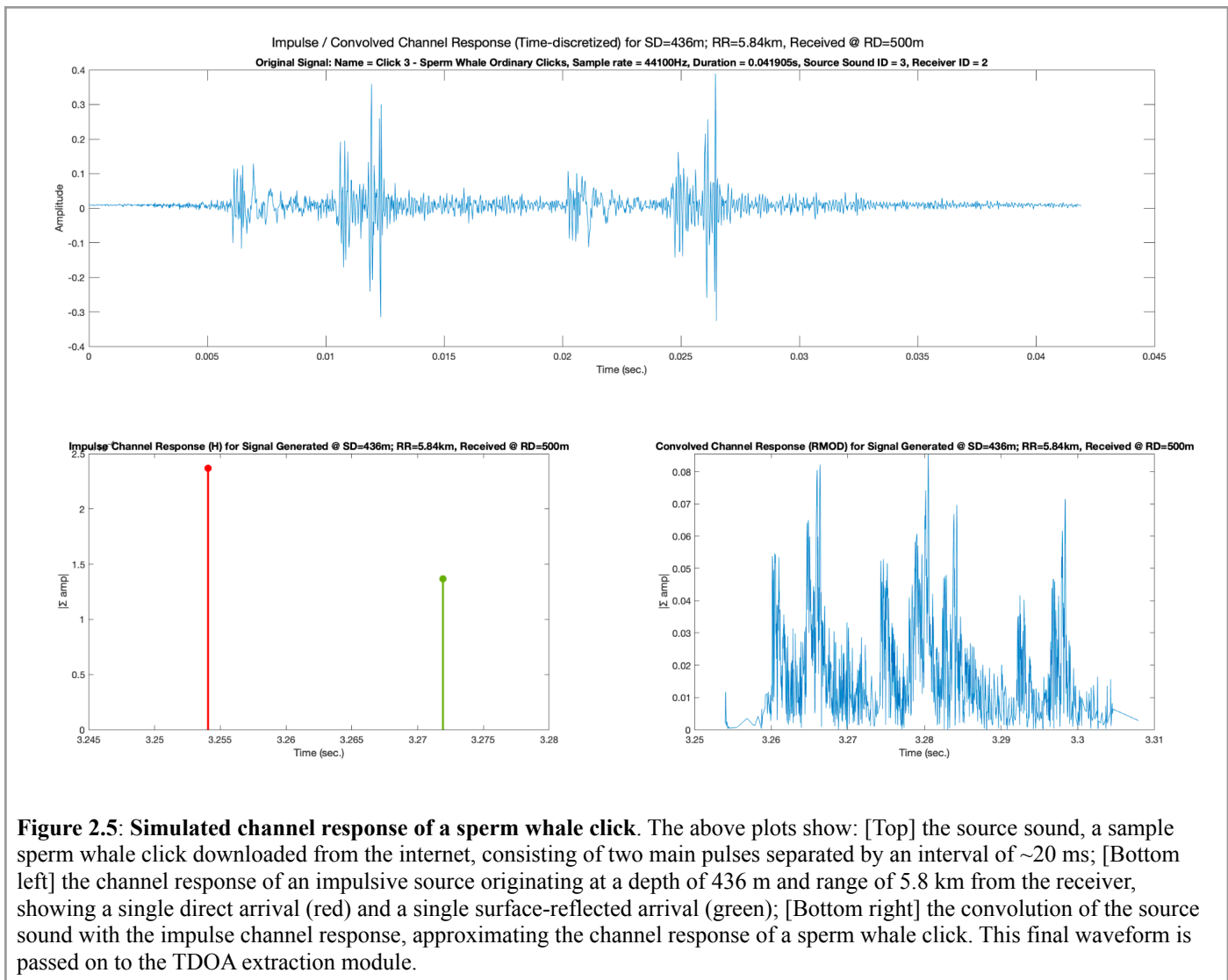
Figure 2.5: **Simulated channel response of a sperm whale click**. The above plots show: [Top] the source sound, a sample sperm whale click downloaded from the internet, consisting of two main pulses separated by an interval of ~20 ms; [Bottom left] the channel response of an impulsive source originating at a depth of 436 m and range of 5.8 km from the receiver, showing a single direct arrival (red) and a single surface-reflected arrival (green); [Bottom right] the convolution of the source sound with the impulse channel response, approximating the channel response of a sperm whale click. This final waveform is passed on to the TDOA extraction module.

Step 3: TDOA extraction from generated / captured sounds

The channel response waveform captured in the previous step is now analyzed to identify in it the highest-amplitude surface-reflected and the highest-amplitude direct path, and compute the TDOA between them. This is done in the time domain using autocorrelation, whereby an exact copy of the (amplitude vs. time) waveform is superimposed over the original, but offset in the horizontal (time) direction by an amount called the lag time. The products of the resulting overlapping amplitudes are summed together to produce a scalar quantity called the correlation, for that lag time. When lag time is varied (between -*t* and *t*, where *t* is the total duration of the original waveform), the resulting correlations can be plotted against lag time to produce the autocorrelation plot. (See Figure 2.6.) The expectation is, since correlations will be high when the "copy" is offset by a lag time that causes the waveform portions of the direct and surface-reflected paths to overlap, that this will be visible as a prominent peak in the autocorrelation plot. Prominence is a measure of how high a peak "sticks out" above the highest surrounding "significant" valley, or *col*, where a significant valley is defined as the lowest point on a path that connects it to a higher peak. We initially look

for the second most prominent peak, since the first one will always be formed by the waveform directly overlapping itself without a time offset, i.e. when lag time is equal to zero. The lag time corresponding to this second peak is taken as the presumptive TDOA of the channel response at the hydrophone. In the simulated case, we can test the accuracy of our extraction method by comparing the extracted TDOA to the TDOA of the impulsive source: if our extraction method is effective, the two should be a close match. Unfortunately, taking the second most prominent peak does not always produce the correct result. In our simulations, we observed that the second peak, at times, corresponds to the correlation between the direct paths of two pulses within a click, and not to the correlation between the surface-reflected and direct paths of the loudest pulse. In Section 2.4.3, we discuss some potential approaches to minimize this problem.
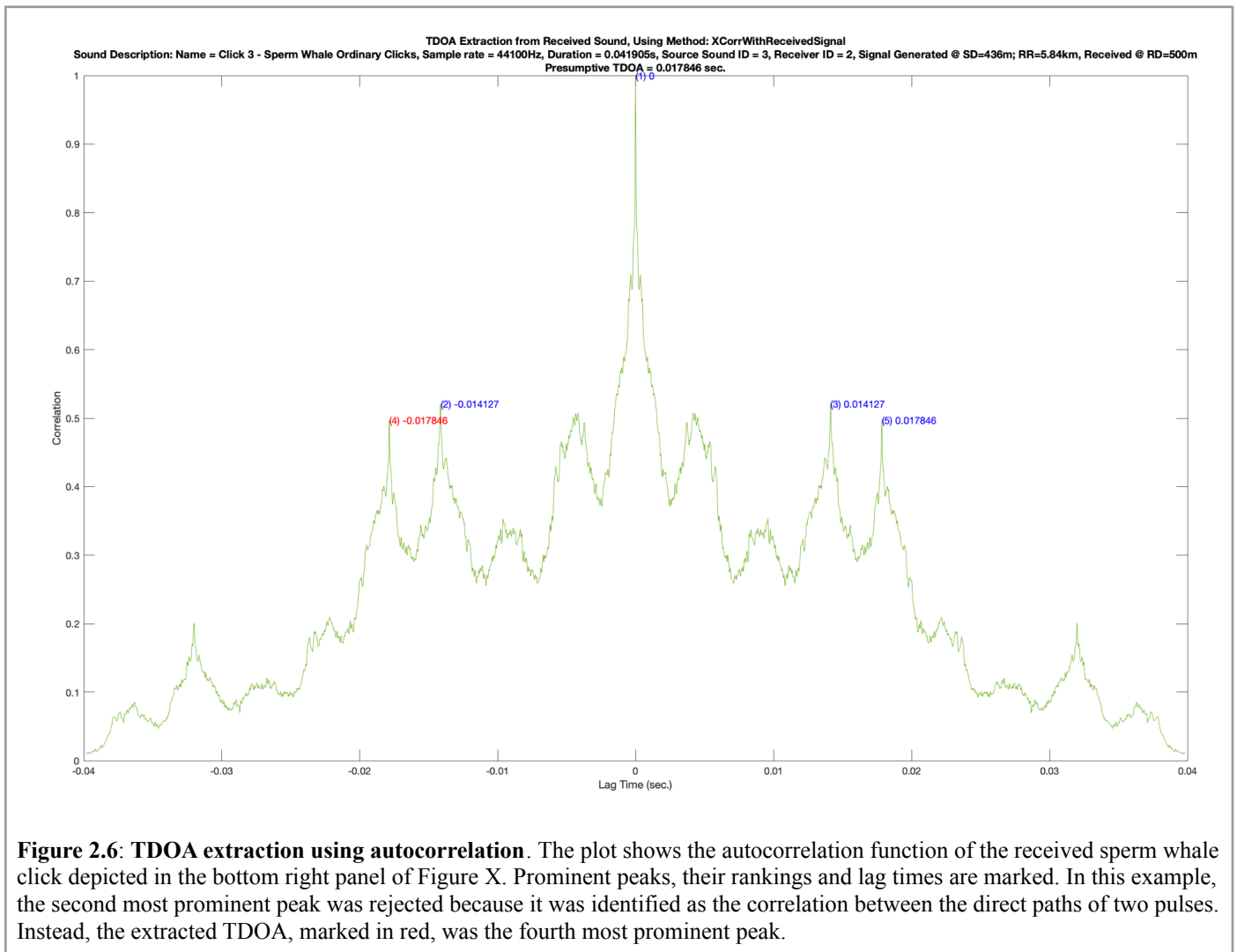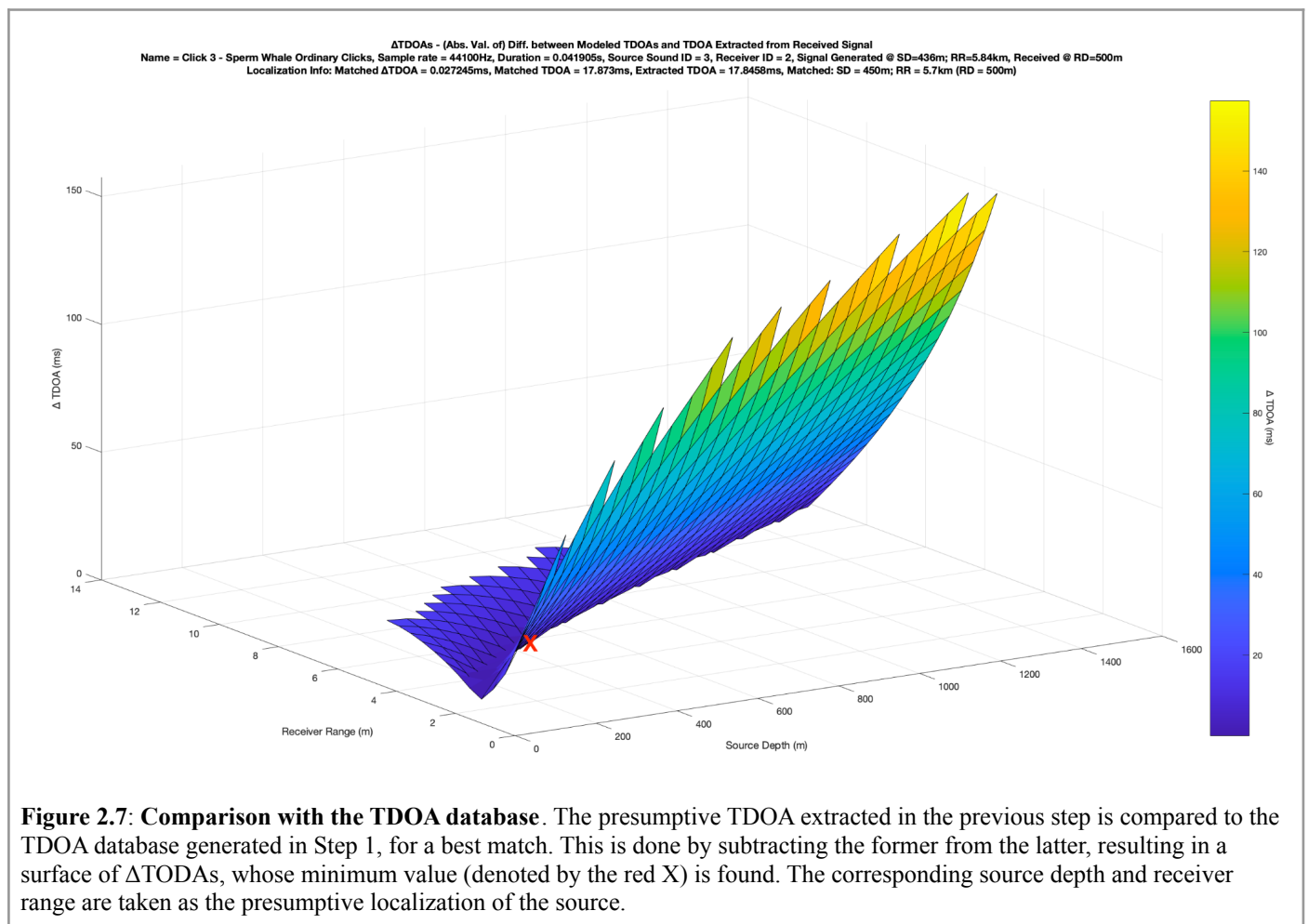

Figure 2.6: **TDOA extraction using autocorrelation**. The plot shows the autocorrelation function of the received sperm whale click depicted in the bottom right panel of Figure X. Prominent peaks, their rankings and lag times are marked. In this example, the second most prominent peak was rejected because it was identified as the correlation between the direct paths of two pulses. Instead, the extracted TDOA, marked in red, was the fourth most prominent peak.

Step 4: Best matching of extracted TDOAs to the TDOA database

Once the presumptive TDOAs of the received sounds have been extracted, the final step is to compare them with the TDOA database generated in the first step, in search of a best match. This is done by taking the absolute values of the differences between the TDOA database entries and the presumptive TDOA, leaving a
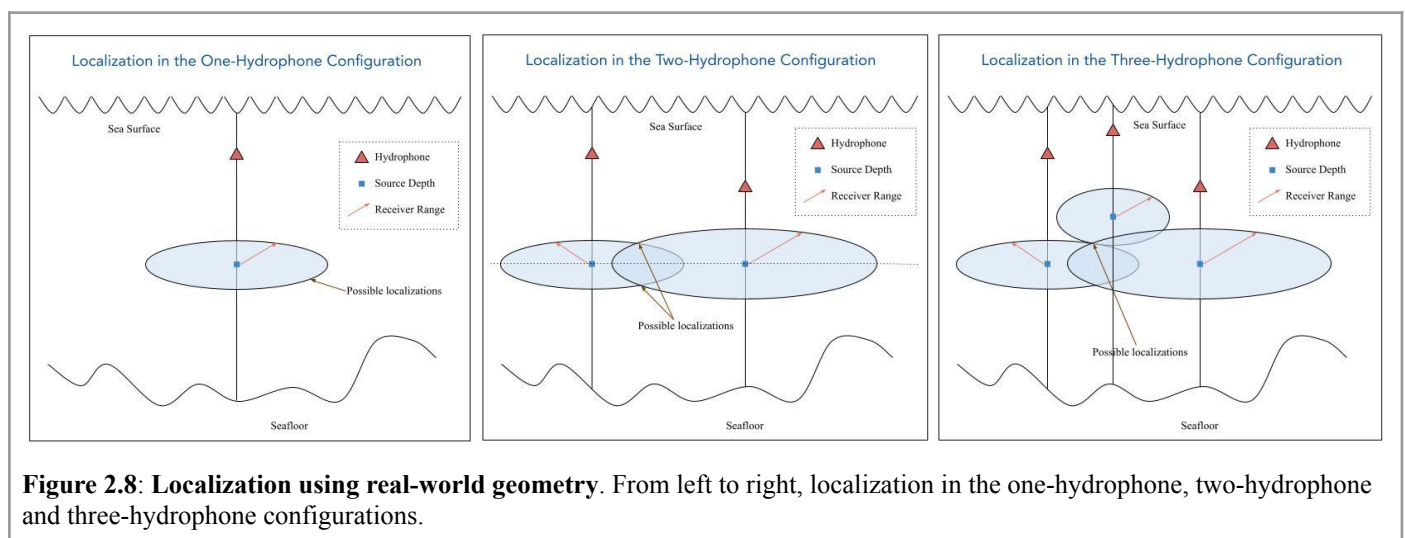
2-D surface of differences (ΔTODAs), then finding the minimum value on this surface. (See Figure 2.7.) The source depth (SD) and receiver range (RR) associated with (inverse-mapped from) this minimum are taken as the presumptive localization of the source sound, relative to the receiver. Since, as mentioned earlier, the TDOA database is a well-behaved function, in the sense that it contains no discontinuities for the depths and ranges usually under consideration, the ΔTODAs surface will, likewise, be well-behaved. We can therefore expect that even if the TDOA extracted from the channel response in the previous step is slightly in error, the resulting deviation in localization will not be great.

Figure 2.7: **Comparison with the TDOA database**. The presumptive TDOA extracted in the previous step is compared to the TDOA database generated in Step 1, for a best match. This is done by subtracting the former from the latter, resulting in a surface of ΔTODAs, whose minimum value (denoted by the red X) is found. The corresponding source depth and receiver range are taken as the presumptive localization of the source.

Step 5: Integrating the spatial geometry

When the 3-D undersea locations (depth and horizontal position) of the hydrophones are known, absolute localization can be achieved. In a real-world situation, the former is usually derived from the length of the cable tethering the hydrophone to a surface buoy, while the latter is generally acquired using a GPS receiver attached to the buoy. Since the previous step (TDOA database matching) returns the source depth (SD) and the receiver range (RR), even with a single hydrophone, source depth can be resolved. However, since RR is solely the horizontal distance between source and receiver, the resulting localization will be described by a horizontal circle with radius RR, centered at depth SD on the vertical line passing through the hydrophone.

(See Figure 2.8, left.) This result is not very useful, so a second hydrophone must be added to achieve any meaningful localizations. In the two-hydrophone configuration, pseudo-range[25] trilateration can be used to reduce the localization to the intersection of two such circles, both at depth SD (which serves as a redundancy check), and each one centered on the vertical line intersecting its respective hydrophone and with a radius of the corresponding RR. The resulting localizatination consists of two points, mirrored across the extended horizontal line at depth SD connecting the vertical lines passing through the hydrophones (left-right ambiguity). (See Figure 2.8, center.) A third hydrophone can resolve this ambiguity with the addition of a third intersecting circle, and any additional hydrophones can be used for redundancy and verification. (See Figure 2.8, right.) Alternatively, localization in the two-hydrophone configuration can be resolved by rejecting one of the two points due to its incompatibility with the topography, such as when it falls on land, in shallow water or below the seafloor (Skarsoulis & Kalogeraki, 2005), or due to its inconsistency with previous recent localizations of the same animal. The geometry creates localization uncertainties that are dependent on the azimuth angle of the source with respect to (the midpoint of) the horizontal line (at depth SD) connecting any two hydrophones. When the angle is small (i.e. the source is to the broadside of the line), range and depth uncertainties are large and azimuth uncertainties are small; when the angle is large (the source is to the endfire of the line), range and depth uncertainties are small and azimuth uncertainties are large. (Skarsoulis & Dosso, 2015)

Figure 2.8: **Localization using real-world geometry**. From left to right, localization in the one-hydrophone, two-hydrophone and three-hydrophone configurations.

2.4. Discussion

2.4.1. Why the sperm whale?

---

[25] Pseudo-range refers to the fact that the ranges are measured indirectly through times of arrival of energy waves, in contrast to true-range trilateration in which ranges are measured directly by instruments. The former creates greater accuracy errors.

An elephant (or whale) in the room that must be addressed, and which has only been alluded to thus far is, "Why the sperm whale?" Sperm whales are not the only species to be negatively affected by deaths and injuries from ship strikes. According to some estimates, as many as 20,000 whales, constituting a wide variety of species, are killed each year by impacts from ships. (*Collisions With Vessels a Deadly Threat For Whales*, 2021) Yet, an inordinate percentage of PAM projects focus on the sperm whale. Why? There are a number of reasons for this, some of which have already been touched upon: the vulnerable (endangered in the Mediterranean Sea) conservation status of the species, the high rate of ship collision deaths among all causes of death when compared to other cetacean species. (Díaz-Delgado et al., 2018) But perhaps the main reason is the distinctive acoustic properties of sperm whale echolocation clicks, properties which make them ideally suited for PAM-based projects. It can be claimed that no sound made by any other marine animal (or, one could argue, any other terrestrial animal) provides the same nexus of loudness, impulsiveness and frequency range that the sperm whale usual click (and to a lesser degree, creak click) does. All of these factors combine to create an acoustic profile that has an excellent signal-to-noise ratio and distinct acoustic peaks, precisely what is required for high-quality acoustic detection and localization. Thus, the sperm whale is a case of picking the "low-hanging fruit": we localize sperm whales using PAM methods because they are the ideal species to localize using these methods (Kandia et al., 2008), not because they are the only species affected by ship strikes. Attempts to localize other species of marine mammals using PAM have been attempted, with some success. Gillespie et al. (2020) reported limited success tracking harbor porpoises (*Phocoena phocoena*) in the vicinity of underwater tidal energy turbines using clusters of tetrahedrally-arranged hydrophones affixed to the turbine's base, and Klinck et al. (2012) used autonomous underwater gliders equipped with hydrophones to detect beaked whales and delphinids, in addition to sperm whales, off the coast of Hawaii. (Gillespie et al., 2020; Klinck et al., 2012) However, the fact still remains that an inordinate amount of PAM-based detection and localization efforts are focused on the sperm whale. This is not necessarily a drawback: the technologies that are being developed today to track an amenable sound like the sperm whale click can be improved and refined over time to work with more intractable sounds such as the calls of other cetaceans. In the meantime, the sperm whale, because of its immense size, cryptic nature, renowned loud clicks and historical place in the popular lore (the title character in Herman Melville's 1851 novel Moby Dick was a sperm whale), continues to capture the public's imagination and therefore serves as an excellent flagship species[26] for getting the word out regarding the dangers to cetacean populations from ship collisions.

2.4.2. Software development methodology

---

[26] A flagship species is a species with a strong popular appeal that can be used to draw attention, and hence funding, to conservation efforts which may, incidentally, positively impact upon other less charismatic species.

In designing our PAM-based localization system, careful attention has been paid to adhering to accepted best practices in software development, including the principle of modularity and the optimization of algorithms to minimize computation time and memory requirements.

Modularity

Modularity is the design of a software system in such a way that allows it to be decomposed into discrete components (modules), each of which can be modified and improved independently of the others, and each of which exchanges information with other modules only through well-defined and fixed channels known as interfaces. As long as the interfaces remain unchanged, then the modules can be considered black boxes, and their internal workings can be improved independently of one another, unfettered by the effects of these modifications on the functioning of the other modules. Through such a paradigm, the entire system can be iteratively improved and enhanced. In the schematic diagram of our system (Figure 2.3), the rectangles represent modules while the ovals represent interfaces. Note that each module is connected to other modules only via the interfaces. As a concrete example of modular design in our system, the current version of the sound generation / capture module simulates received sounds at hydrophones using mostly sample sperm whale clicks downloaded from the internet; in future iterations, we can attempt to progressively confound the system by creating less-than-ideal simulated clicks and testing the response. Thus, we start with a clear signal, then add noise, reduce amplitude and create mismatches by slightly altering hydrophone locations or by modifying the modeled undersea environment away from that which is expected by the TDOA database. Ultimately, these simulated sounds will be replaced by actual sounds picked up by live hydrophones. However, as long as the sound generation / capture module outputs the received sounds in the format (interface) expected by the module that consumes them, the TDOA extraction module, then the method by which the sounds are generated and captured is irrelevant to the TDOA extraction module.
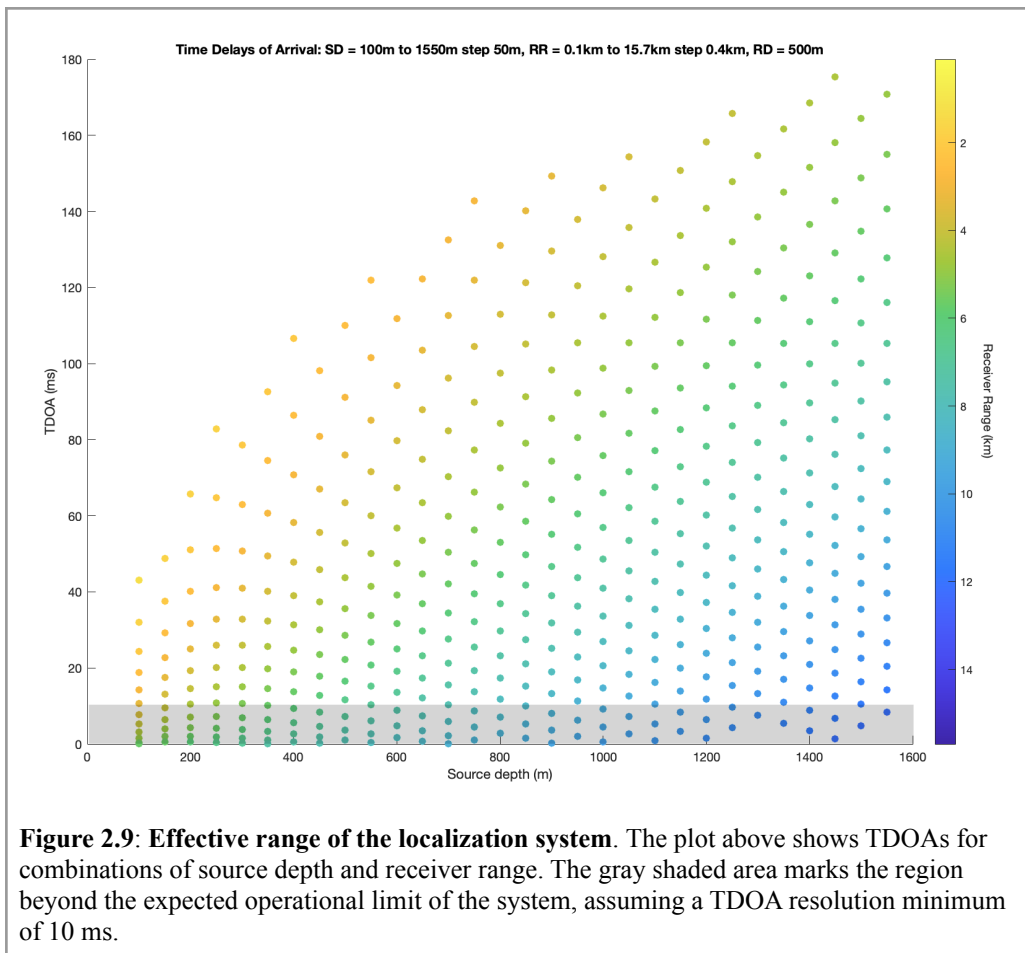
Optimization of algorithms

Careful attention has been paid to optimization of algorithms across the system, with an eye towards minimizing computational complexity, both in terms of time (CPU effort) and space (memory). As an example of time minimization, in the TDOA extraction module, after performing the autocorrelation operation, all correlations with a value below a defined threshold are removed from the results and only the remaining correlations are scanned for peak prominences. Since peak prominence calculation is a computationally intensive operation, searching for prominences among a subset of the original correlations significantly reduces computing time. As an example of optimization with regards to memory use, the sound generation / capture module features a completely redesigned arrival times calculation function which computes the channel responses one-by one for each source sound and then returns the results immediately –

after which they can be erased from memory – rather than processing all the sounds at once and storing the results in an in-memory data structure, as was done previously. Without a doubt, the main computational bottleneck in the system is the Bellhop ray tracing model itself, a computationally intensive module, the internal workings of which we are not privy to change at this point in time. This is the main factor behind why generation of the TDOA database takes so long, but, as mentioned earlier, this can be done in advance and recalculated only when the modeled underwater environment needs to be updated. The other modules rely minimally, or not at all, on running the Bellhop model; rather, they merely process outputs from it.

2.4.3. Limitations of the system

Effective range

There are a number of limitations of the system which must be addressed. The first is limits on the effective range of the system, due to the inability to make meaningful localizations when the horizontal distance between the source and the receiver becomes large. This is because, as range increases, TDOA decreases and along with it gradients to nearby TDOAs, resulting in more and more imprecise (fuzzy) localizations. The picture makes intuitive sense if one considers the geometry of the setup: when range is short relative to the difference in depths between source and receiver, then the apex angle of a triangle connecting the source, the receiver and any point on the sea's surface is small, and hence the sum of the lengths of the two legs adjacent to this angle (representing the surface-reflected path) is much greater than the length of the third leg (direct path), and the result will be a large TDOA. The reverse holds true when range is large: the apex angle is, likewise, large and therefore the sum of the lengths of the adjacent legs will be only slightly larger than the length of the third leg, resulting in a small TDOA. As range continues to increase, TDOA tends towards zero. Skarsoulis et al. (2022) reported that in the 2020-21 test deployment of their localization system, when the hydrophone was placed at a depth of about 100 m and whale depths were less than 500 - 600 m, the effective range of the system was 6 - 7 km, depending on the sound propagation conditions. (Skarsoulis et al., 2022) We note that in the most commonly used underwater environment in our simulations, for a receiver depth of 500 m the TDOA drops below 10 ms (which can be considered to be the resolution limit of the system) at a range of ~4 km when the whale is at a depth of ~200 m, at ~6 km when the whale is at a depth of ~500 m and at ~9 km when the whale is at a depth of ~1000 m. (See Figure 2.9.) Possible solutions to this problem include more precise and frequent modeling of the underwater environment and the placement of a larger network of hydrophones for more coverage area.

Figure 2.9: **Effective range of the localization system**. The plot above shows TDOAs for combinations of source depth and receiver range. The gray shaded area marks the region beyond the expected operational limit of the system, assuming a TDOA resolution minimum of 10 ms.

Spurious autocorrelation peaks

The next obstacle is that of contending with spurious autocorrelation peaks created by overlapping pulses within the same click during TDOA extraction, as described earlier (Section 2.3.1, Step 3). One possible solution is to exclude all autocorrelations with a lag time less than the maximum value for the duration of a sperm whale usual click, or approximately 30 ms. The reasoning behind this is that all pulses originating from the same click and following the same path must arrive within this time differential of each other, and therefore any correlations between them will be filtered out. Though this approach has the negative ancillary effect of decreasing the system's operational range, as can be seen by following the 30 ms horizontal line in Figure 2.9, (for example, a whale at a depth of 500 m would be detectable up to ~5 km instead of ~6 km), the tradeoff might be worth it. In addition to a lower boundary for putative TDOAs, an upper boundary can be imposed as well, namely, the minimum ICI of a usual click train, or approximately 500 ms (Jiang et al., 2021). Eliminating all lag times exceeding this limit would preclude autocorrelations between pulses from consecutive clicks from being confused with the target TDOA. Furthermore, this upper boundary can be imposed without sacrificing system range, since TDOA values for the maximum source depths and minimum receiver ranges we are interested in (when TDOAs are high) still remain well below this threshold. For instance, in the aforementioned scenario (a hydrophone depth of 500 m), a whale emitting a

click at a depth of 200 m and at a range of ~1 km from the hydrophone would produce a TDOA of approximately 65 ms, far below the 500 ms maximum. Kandia et al., (2008) reported encountering the same problem described here and suggested a different approach: using an all-pass filter[27] to create a minimum-phase signal which focuses the energy of the click in the first pulse, thereby eliminating the possibility of high correlations with other pulses. (Kandia et al., 2008)

A more general problem

The above problem is but one example of a more general issue which we have encountered again and again during the research and development phases of building our system. Consider that a single sperm whale usual click is composed of multiple pulses, separated by a time period of low amplitudes (the interpulse interval, or IPI). In turn, usual clicks are generated not in isolation, but rather in trains of multiple clicks separated by short periods of silence (the interclick interval, or ICI). Neither are sperm whales always found in solitariness. Females and young in pods or even lone bulls in fertile feeding grounds may forage near each other and may all be producing click trains simultaneously. All of these copious sounds spread out from their various source locations in three dimensions, taking multiple paths to each of several receivers (since PAM installations almost always consist of multiple hydrophones.) The end result is an inundation of similar sound patterns, in near simultaneity, at different receivers, originating from various source locations, all of which must be sorted out and assigned to a specific click from a specific sperm whale at a specific place. Needless to say, this may seem like an insurmountable set of problems to overcome. To get a taste for how solutions to this problem might be approached, consider the following example:

We note that the click of an individual sperm whale has an IPI which is characteristic of that individual; likewise does its click train have a characteristic ICI. These can be thought of as an acoustic "signature" of that particular whale. In the case of the IPI, duration has been correlated positively to the length of the animal (Møhl et al., 1981) If the IPI of a click can be picked out of the incoming audio stream, then it can be used to assign the click to an individual whale. Once a click has been assigned to a whale, the whale's associated localization can be compared with previous recent localizations of the same whale, and if they are within a plausible distance of each other, based on the fact that sperm whales move at speeds of 1 - 2 knots while foraging (Skarsoulis et al., 2022), then the new localization can be added to the track of the whale; otherwise it can be discarded. Moving forward, finding innovative solutions to problems such as these will be one of the main engineering challenges in transitioning from a simulated to a real-world scenario.

---

[27] An all-pass filter is a filter which neither amplifies nor attenuates any part of the frequency spectrum; rather, it alters the phase based on frequency.

2.5. Conclusion

Herein we have presented a prototype for a Passive Acoustic Monitoring system to localize sperm whales based on their clicks, with an eye towards facilitating ship strike reductions. Though very much in the initial stages of development, the prototype shows great promise for eventual use in real-world applications. Careful attention to software design principles such as modularity and algorithm optimization have allowed for the creation of an efficient system which can be improved iteratively in order to move from the current simulation-based alpha release to an eventual production-level release using live hydrophone to produce real-time localizations. In addition, potential limitations and their possible solutions have been discussed. The need for such a system is acute, as stagnation in the recovery of sperm whale populations combined with an exponential year-over-year rise in shipping volume continue to contribute to an unsustainable increase in the probability of tragic and unnecessary sperm whale deaths by ship impalement.

References

About SAvE Whales. (2019). SAvE Whales project. Retrieved December 27, 2021, from http://136.243.46.142/about/

André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., Schaar, M., Lopez-Bejar, M., Morell, M., Zaugg, S., & Houegnigan, L. (2011). Low-frequency sounds induce acoustic trauma in cephalopods. *Frontiers in Ecology and the Environment*, *9*, 489 - 493. doi: 10.2307/23034465

Arregui, M., de Quirós, Y. B., Saavedra, P., Sierra, E., Suárez-Santana, C. M., Arbelo, M., Díaz-Delgado, J., Puig-Lozano, R., Andrada, M., & Fernández, A. (2019). Fat Embolism and Sperm Whale Ship Strikes. *Frontiers in Marine Science*, *6*, 379. doi: 10.3389/fmars.2019.00379

Baraniuk, C. (2015, October 16). *The noise we're creating in the sea can be deadly*. BBC Future: The Genius Behind - Ocean. Retrieved December 28, 2021, from https://www.bbc.com/future/article/20151016-the-noise-were-creating-in-the-sea-can-be-deadly

Collisions with Vessels a Deadly Threat For Whales. (2021, June 9). Friend of the Sea. Retrieved September 12, 2022, from https://friendofthesea.org/collisions-with-vessels-the-deadliest-threat-for-whales/

Díaz-Delgado, J., Fernández, A., Sierra, E., Sacchini, S., Andrada, M., Vela, A. I., Quesada-Canales, Ó., Paz, Y., Zucca, D., Groch, K., & Arbelo, M. (2018, October). Pathologic findings and causes of death of stranded cetaceans in the Canary Islands (2006-2012). *PLOS ONE, 13*(10), 1 - 33. doi: 10.1371/journal.pone.0204444

Frisk, G. (2012). Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. *Scientific reports*, *2*, 437. doi: 10.1038/srep00437

Gillespie, D., Palmer, L., Macaulay, J., Sparling, C., & Hastie, G. (2020). Passive acoustic methods for tracking the 3D movements of small cetaceans around marine structures. *PLOS ONE*, *15*, 1 - 16. https://doi.org/10.1371/journal.pone.0229058

Hurd, I. (2012, March 29). *Almost Saving Whales: The Ambiguity of Success at the International Whaling Commission*. Ethics & International Affairs. Retrieved August 1, 2022, from https://www.ethicsandinternationalaffairs.org/2012/almost-saving-whales-the-ambiguity-of-success-at-the-international-whaling-commission-full-text/

Irvine, L., Palacios, D. M., Urbán, J., & Mate, B. (2017). Sperm whale dive behavior characteristics derived from intermediate-duration archival tag data. *Ecology and Evolution*, *7*(19), 7822 - 7837. https://doi.org/10.1002/ece3.3322

Kandia, V., Stylianou, Y., & Dutoit, T. (2008). Improve the Accuracy of TDOA Measurement Using the Teager-Kaiser Energy Operator. In *Passive '08: An IEEE Workshop & Exhibition on New Trends for Environmental Monitoring Using Passive Systems (Final Program)* (p. 85). IEEE. 10.1109/PASSIVE.2008.4786987

Klinck, H., Mellinger, D. K., Klinck, K., Bogue, N. M., Luby, J. C., Jump, W. A., Shilling, G. B., Litchendorf, T., Wood, A. S., Schorr, G. S., & Baird, R. W. (2012, May). Near-Real-Time Acoustic Monitoring of Beaked Whales and Other Cetaceans Using a Seaglider™. *PLOS ONE*, *7*(5), 1 - 8. doi: 10.1371/journal.pone.0036128

Madsen, P. T., Payne, R., Kristiansen, N. U., Wahlberg, M., Kerr, I., & Møhl, B. (2002). Sperm whale sound production studied with ultrasound time/depth-recording tags. *The Journal of Experimental Biology*, *205*, 1899 - 1906. http://groups.csail.mit.edu/drl/wiki/images/c/cc/spermwhaletagging.pdf

Møhl, B., Larsen, E., & Amundin, M. (1981). Sperm whale size determination: outlines of an acoustic approach. In *Mammals in the Seas: General papers and large cetaceans* (5th ed., Vol. 3, pp. 327 - 331). Food and Agriculture Organization of the United Nations (Rome).

Notarbartolo di Sciara, G., Frantzis, A., Bearzi, G., & Reeves, R. (2012). *Physeter macrocephalus*. The IUCN Red List of Threatened Species 2012: e.T41755A2955634. Retrieved 12 27, 2021, from https://www.iucnredlist.org/species/41755/2955634

Ritter, F., de Soto, N. A., & Martín, V. (2019). Towards Ship Strike Mitigation in the Canary Islands. *Paper submitted to the International Whaling Commission*, *SC/68A/HIM/15*.

https://m-e-e-r.de/wp-content/uploads/2020/12/Towards-Ship-Strike-Mitigation-in-the-Canary-Islands_IWC.pdf

Rodríguez, O. C. (2008, June 13). *General description of the Bellhop ray tracing program* (Version 1.0). Physics Department, Signal Processing Laboratory, Faculdade de Ciências e Tecnologia, Universidade do Algarve. http://oalib.hlsresearch.com/Rays/GeneralDescription.pdf

Skarsoulis, E. K., & Dosso, S. E. (2015). Linearized two-hydrophone localization of a pulsed acoustic source in the presence of refraction: Theory and simulations. *The Journal of the Acoustical Society of America*, *138*(4), 2221 - 2234. https://doi.org/10.1121/1.4930937

Skarsoulis, E. K., & Kalogerakis, M. A. (2005). Ray-theoretic localization of an impulsive source in a stratified ocean using two hydrophones. *The Journal of the Acoustical Society of America*, *118*(5), 2934 - 2943. doi: 10.1121/1.2041267

Skarsoulis, E. K., Piperakis, G. S., Orfanakis, E., Papadakis, P., Pavlidi, D., Kalogerakis, M. A., Alexiadou, P., & Frantzis, A. (2022). A Real-Time Acoustic Observatory for Sperm-Whale Localization in the Eastern Mediterranean Sea. *Frontiers in Marine Science*, *9*. doi: 10.3389/fmars.2022.873888

Taylor, B. L., Baird, R., Barlow, J., Dawson, S. M., Ford, J., Mead, J. G., Notarbartolo di Sciara, G., Wade, P., & Pitman, R. L. (2019). *Physeter macrocephalus (amended version of 2008 assessment)*. The IUCN Red List of Threatened Species 2019: e.T41755A160983555. Retrieved 12 27, 2021, from https://www.iucnredlist.org/species/41755/160983555

Threats to Marine Mammals. (2012, February 8). Georgia Marine Mammal Stranding Database. Retrieved September 5, 2022, from http://marinemammal.uga.edu/index.php?page=information/threats

Van Waerebeek, K., & Leaper, R. (2008, June 1). Second Report of the IWC Vessel Strike Data Standardisation Working Group. doi: 10.13140/RG.2.1.2020.2001

Wang, Z.-T., Supin, A. Y., Akamatsu, T., Duan, P.-X., Yang, Y.-N., Wang, K.-X., & Wang, D. (2021, December). Auditory evoked potential in stranded melon-headed whales (Peponocephala electra): With severe hearing loss and possibly caused by anthropogenic noise pollution. *Ecotoxicology and Environmental Safety*, *228*. https://doi.org/10.1016/j.ecoenv.2021.113047