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TSC Technology Systems Corp.

Environment Coastal & Offshore Magazine ISSN # 2327-3445 is published 6 times a year by Technology Systems Corporation, 7897 SW Jack James Dr., Suite A, Stuart, FL 34997, Telephone +1-772-221-7720.

Editor's Welcome

Symphony of the Seas

Words by Kira Coley, Senior Editor

As we flock to the sandy shores, we breathe in the salty air and listen to the soothing sounds of waves lapping the beach. It's hard to imagine life beneath the surface to be any less tranquil. But, the ocean – both wild and calm - is a sea of contradiction.

As we begin to map the ocean's soundscape, we discover a cacophony of specialized hums, thuds, clicks, snaps, and whistles originating from the intricate world below. As it turns out, marine life often depends upon sound to navigate, forage, and socialize. These sounds can be vastly complex; often loudest at dawn and dusk, and ranging between high and low frequencies.

As humans continue to expand and increase our presence in the ocean, we begin to ask: How are we disrupting the ocean's soundscape? How does this impact marine life? How will the growing contribution of human-derived sounds affect different species in the future? And, what policies are needed to protect those most at risk?

These are not easy questions to answer. "Because scientists have measured the hearing capabilities of very few marine species, generalizing or producing how increases in sound levels affect all animals or marine ecology, beyond very broad statements about risk, is not yet possible," write the authors in our opening story.

While new acoustic technology is helping to fill some of our knowledge gaps, there is still a long way to go. Yet, the field of ocean sound is growing at an astonishing rate, and academics and industry are breaking new grounds each year.

We bring this special issue to you to showcase some of this work from around the world.

ECO Magazine is thrilled to partner with the **Scientific Committee on Ocean Research (SCOR)**, the **Partnership for Observation of the Global Ocean (POGO)**, and their new international research program called the **International Quiet Ocean Experiment (IQOE)**, along with all the sponsors that are helping us share the fascinating and essential work underway in this field today.

I would also like to welcome new readers to our leading international science magazine reporting from the frontline of ocean research and exploration. **To make the most of this digital issue, make sure your device's sound is switched on**. If you would like to **register for a free subscription** to ECO Magazine and receive future editions—print and digital—please visit ecomagazine.com/subscribe.

Whether new to our magazine or a loyal reader, I hope you enjoy reading – and listening to – this special issue on Ocean Sound.

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Editor's Welcome

Observing Sound

Discovery

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On the cover:

Humpback whale and her calf. Audio: CSA


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A WORD FROM OUR PARTNER

Introducing the International Quiet Ocean Experiment

New international research and observations of sound in the ocean and its effects on marine organisms

Words by members of the International Quiet Ocean Experiment (IQOE)

Ed Urban, Scientific Committee on Oceanic Research, Newark, Delaware, USA

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Sound in the ocean arises from a variety of sources. Since Earth's ocean formed early in the history of the planet, sound from geological processes such as subsea earthquakes, volcanos, and landslides has reverberated sporadically through the ocean. Physical processes such as wind, waves, rainfall, and ice movements and cracking add sound to the ocean incessantly, though with fluctuating intensity and geography. Finally, organisms have evolved many ways of producing sounds in the ocean. Marine life contributes sounds ranging from the clicking of snapping shrimps, which can dominate coastal acoustic habitats, to the complex songs of whales. The animal sounds have varied over time, differed in various locations, and probably waxed and waned over Earth's history as diversity, distribution, and abundance of different types of organisms have changed.

Very recently in terms of the history of sound in the ocean, humans have added new sounds. In the beginning, these sounds were concentrated near shore, extending into the open ocean as humans began to exploit marine resources and travel over the ocean surface for commerce and national defense, and explore and extract minerals on and beneath the seafloor.

Because hearing has evolved as the dominant sense in many marine animals, concerns have arisen over the potential for human-added sound to compete with natural sounds to which marine animals have adapted over their evolutionary histories. Since observations began around the time of World War II, scientists have observed that sound levels have increased, for example in the northeast Pacific Ocean. However, our knowledge of trends in ocean ambient noise is poor because we have measured sound over time in very few locations, and have not yet standardized procedures for measurement and analysis.

Frequency (or pitch) of sounds in the ocean is important to consider. Lower frequency sounds are absorbed less by seawater and travel further than higher frequency sounds. Different marine animals hear different frequencies, just as land animals, where dogs can hear sounds at higher frequencies and elephants at lower frequencies than can humans. In the ocean, dolphins, porpoises, and sperm whales are high-frequency specialists, and large baleen whales are low-frequency specialists. The way in which most fish sense sound limits their hearing to low frequencies, but some fish have specialized adaptations that enable high-frequency hearing. Because scientists have measured the hearing capabilities of very few marine species, generalizing or predicting how increases in sound levels affect all animals or marine, beyond very broad statements about risk, is not yet possible.

Development of the International Quiet Ocean Experiment

From 2000 to 2010, ocean scientists successfully carried out a coordinated international investigation of diversity, distribution, and abundance of marine life called the Census of Marine Life, involving hundreds of expeditions spanning near shore to mid-ocean, seafloor to sea surface, and microbes to mammals. As the Census came to a close, one of its founders, Jesse Ausubel (Rockefeller University, New York City), contended that studies of global change neglected sound in the ocean. Documenting what was known and needed to be learned about sound in the ocean would be timely, because ocean sound is increasingly regulated worldwide with meager knowledge. Ausubel helped raise funds to convene an international meeting of scientists who study sound in the ocean and its effects on marine organisms to explore what research and observations should be undertaken to improve our understanding. This meeting resulted in a plan for a new international research program called the International Quiet Ocean Experiment (IQOE).

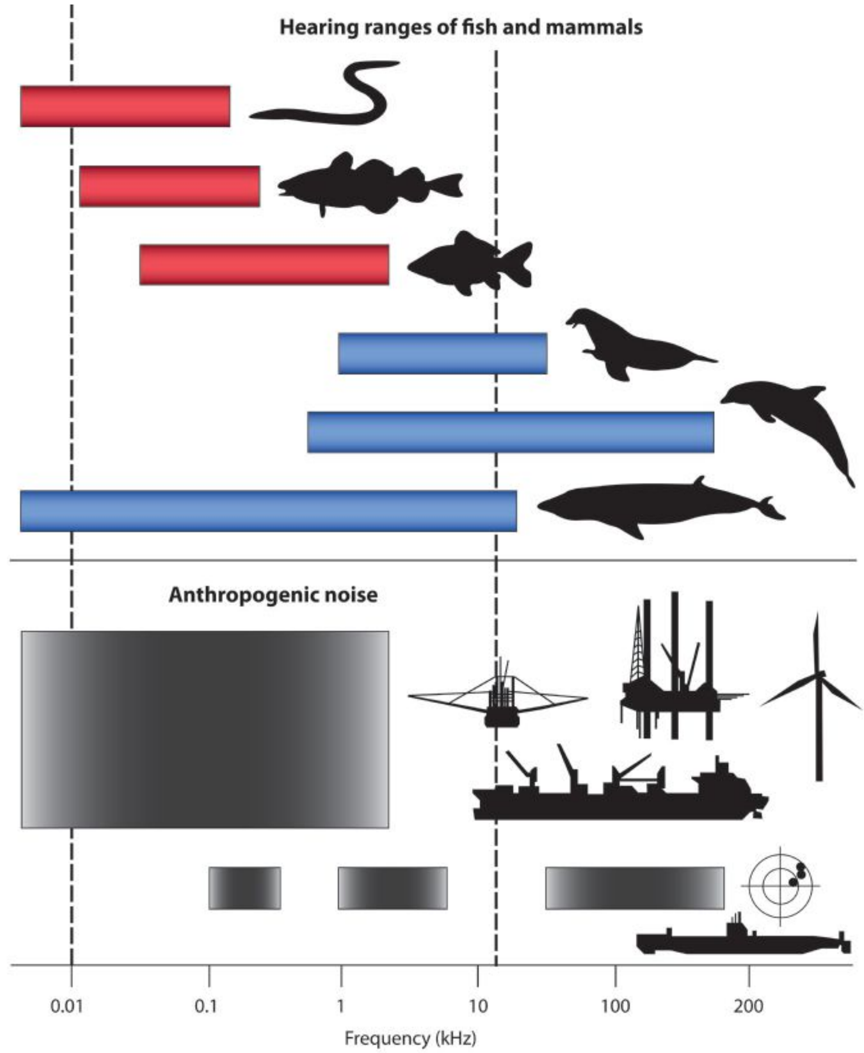


Figure 1. Diagrammatic representation of the overlap between the hearing ranges of different kinds of fish and mammals and the frequency of sound produced by different human-generated sources. Reproduced from Slabbekoorn, H., N. Bouton, I. van Opzeeland, A. Coers, C. ten Cate, and A.N. Popper. 2010. A noisy spring: The impact of globally rising underwater sound levels on fish. Trends in Ecology & Evolution 25:419-427.

Underlying IQOE are five fundamental questions:

1. How have human activities affected the global ocean soundscape compared with natural changes over geologic time?
2. What are the current levels and distribution of sound in the ocean?
3. What are the trends in sound levels across the global ocean?
4. What are the current effects of human sound on important marine animal populations?
5. What are the potential future effects of sound on marine life?

The Scientific Committee on Oceanic Research (SCOR) and the Partnership for Observation of the Global Ocean (POGO), who sponsored the meeting with the Intergovernmental Oceanographic Commission (IOC), agreed to incubate the IQOE and subsequently foster the program.

IQOE Implementation

SCOR and POGO formed a 10-person IQOE Science Committee, which met in 2016, 2017, and 2018 to begin implementation. Early action of the Science Committee formed working groups of experts on issues important across the project, such as data management and standardization of measurements, and groups made up of specialists for areas in which studies of ocean sound are particularly urgent, such as high-biodiversity areas and the Arctic Ocean.

The **IQOE Working Group on Acoustic Measurement of Ocean Biodiversity Hotspots** is reviewing the usefulness of sound as a tool to monitor diversity of animals in areas such as kelp forests and coral reefs. Hydrophones can continuously monitor these areas non-invasively to learn about cycles and patterns, complemented with visits by scuba divers and other kinds of survey teams to assess biodiversity visually. See the working group webpage at www.iqoe.org/groups/reefs.

The **IQOE Working Group on Arctic Acoustic Environments** is focusing its initial efforts on locating historical data on ambient sound in the Arctic Ocean, where climate is changing especially rapidly, and identifying observing systems that could be quickly and affordably enhanced with acoustic sensors. See the working group webpage at www.iqoe.org/groups/arctic.

The **IQOE Working Group on Standardization** will convene a workshop on "Guidelines for observation of ocean sound" to develop international guidelines for IQOE based on practices implemented by IQOE-endorsed projects and national committees. See the working group webpage at www.iqoe.org/groups/standardization.

The **IQOE Working Group on Data Management and Access** will cooperate with the other IQOE working groups to determine how best to create a global database of ambient sound to which it is easy to contribute observations, and which forms a reliable and accessible archive. See the working group webpage at www.iqoe.org/groups/data.

In 2016, IQOE began endorsing national and regional projects that contribute to the accomplishment of IQOE's objectives. Five projects have been endorsed so far:

ADEON: Atlantic Deepwater Ecosystem Observatory Network — ADEON is gathering time series of acoustic and environmental data (space-based remote sensing, hydrographic sensors, and biologic sensors) over multiple years to better understand how human, biologic, and natural abiotic components create the soundscape and ecosystem dynamics of the Outer Continental Shelf off the southeastern United States.

JOMOPANS: Joint Monitoring Program for Ambient Noise North Sea — JOMOPANS aims to develop a framework for a fully operational joint monitoring program for ambient sound in the North Sea to provide the tools necessary for managers, planners, and other stakeholders to incorporate the effects of ambient noise in their assessment of the environmental status of the North Sea, and to develop measures to improve it.

JONAS: A Joint Program for Ocean Noise in the Atlantic Seas — JONAS aims to assess the risks of sound on biodiversity, focusing on sensitive species in the northeast Atlantic Ocean by streamlining ocean noise monitoring and risk prediction. Cost effective, risk-based approaches to monitoring and modeling noise will be developed.

PHYSIC: Ports, Humpbacks, Y Soundscapes In Colombia — PHYSIC is performing a Before-After Control-Impact (BACI) study of ambient sound and humpback whale vocalizations related to port construction in Colombia.

TANGO: Rerouting shipping lanes in the Kattegat, effects on soundscape and ecosystem — Maritime authorities in Sweden and Denmark have proposed a rerouting of the main shipping routes into the Baltic, scheduled for 2020. This creates a unique opportunity to study the effects of ship noise in a shallow sea. A range of parameters will be measured in the existing shipping lane, the

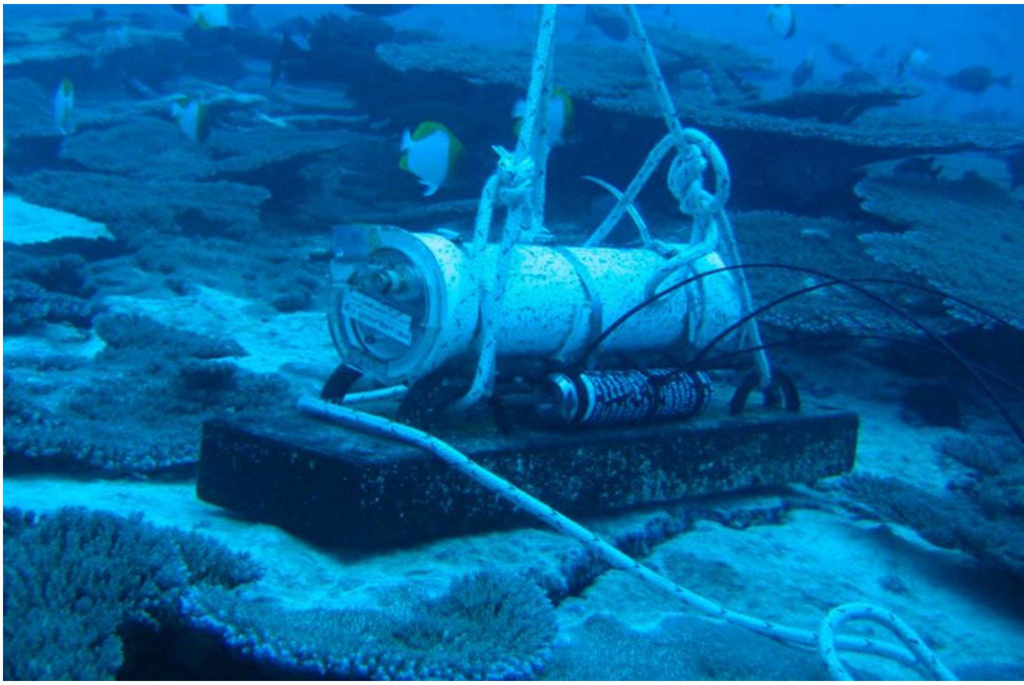


Figure 2. Ecological Acoustic Recorder (EAR). Such hydrophones form part of the tool kit of the IQOE Working Group on Acoustic Measurement of Ocean Biodiversity Hotspots. The U.S. National Oceanic and Atmospheric Administration deploys EARs at several sites around the Pacific Ocean to monitor the biology of reefs.

new shipping lane and reference areas away from the shipping lanes, for at least one year prior to rerouting, to establish a baseline, and at least one year after the change.

Selected IQOE Accomplishments

The first major accomplishment of IQOE was to bring together the ocean acoustics and bioacoustics communities in a large open science meeting in 2011 to determine what research, observations, and modeling would benefit from an international approach to improve our understanding of sound in the ocean and its effects on marine organisms. From this input and with extensive review, a leadership team developed the IQOE Science Plan and published it in 2015 with endorsements of POGO and SCOR (see www.iqoe.org/sites/default/files/files/IQOE_Science_Plan-Final.pdf).

Subsequently, IQOE worked with the Biology and Ecosystems Panel of the Global Ocean Observing System (GOOS) to develop specifications for an Essential Ocean Variable (EOV) for Ocean Sound. EOVs are being developed by the three GOOS panels to help national operators of ocean observing assets to implement observations in a coordinated and standardized manner. The POGO IQOE Working Group led the development of the Ocean Sound EOV, which GOOS approved in mid-2018. IQOE leaders have participated extensively in preparation of the acoustic dimensions of the OceanObs'19 conference, which aims to set priorities and increase resources for the next decade of ocean observing.

IQOE has developed a website that provides project information, as well as serving as a resource for the global community of ocean acousticians and bioacousticians (see www.iqoe.org/). The IQOE website includes a searchable database of publications related to ocean sound (currently with 4,689 references), an overview of international standards relevant for ocean sound monitoring, portals to databases of sound in the ocean and animal sounds in the ocean, observing systems, and meetings related to IQOE goals.

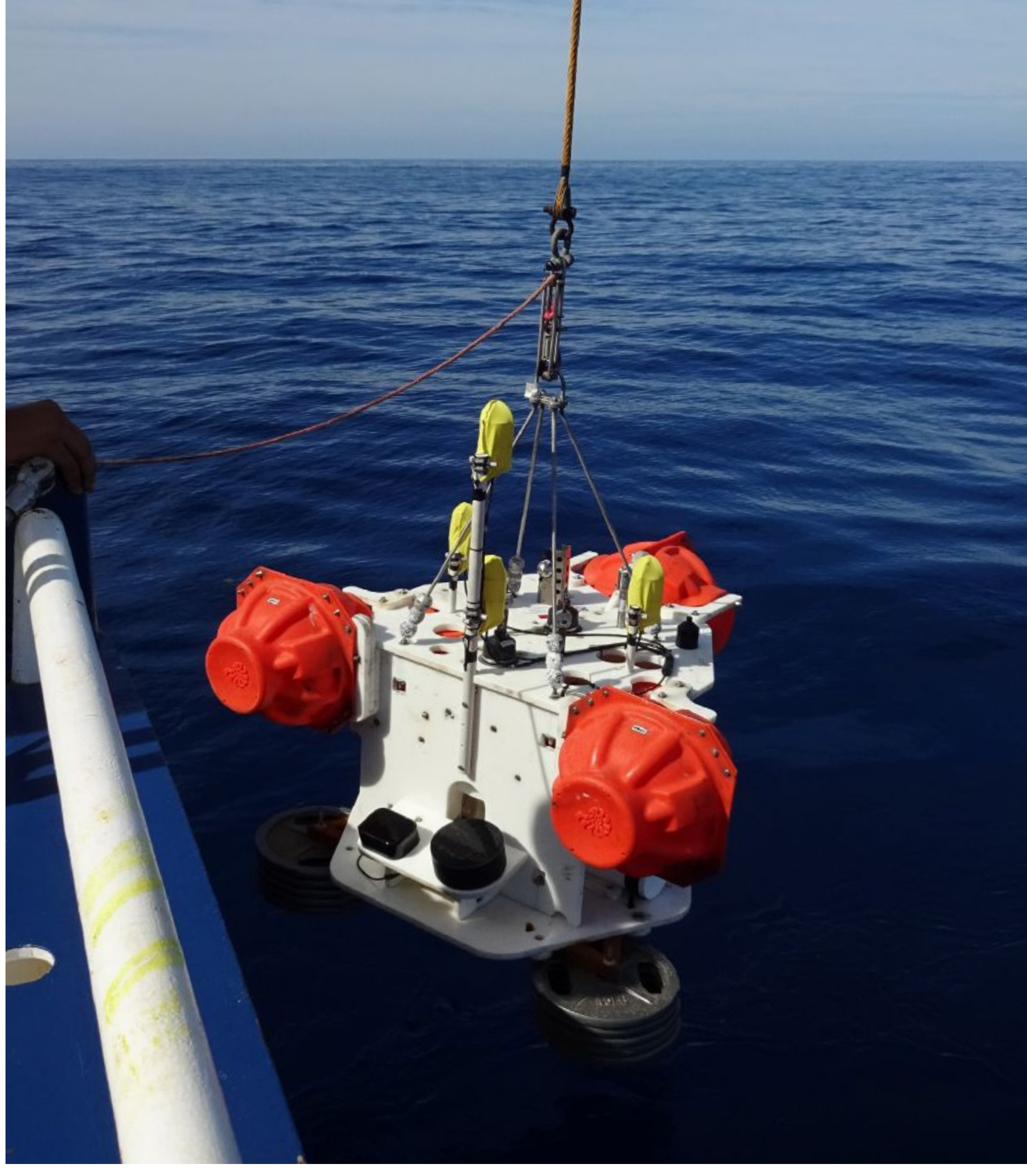
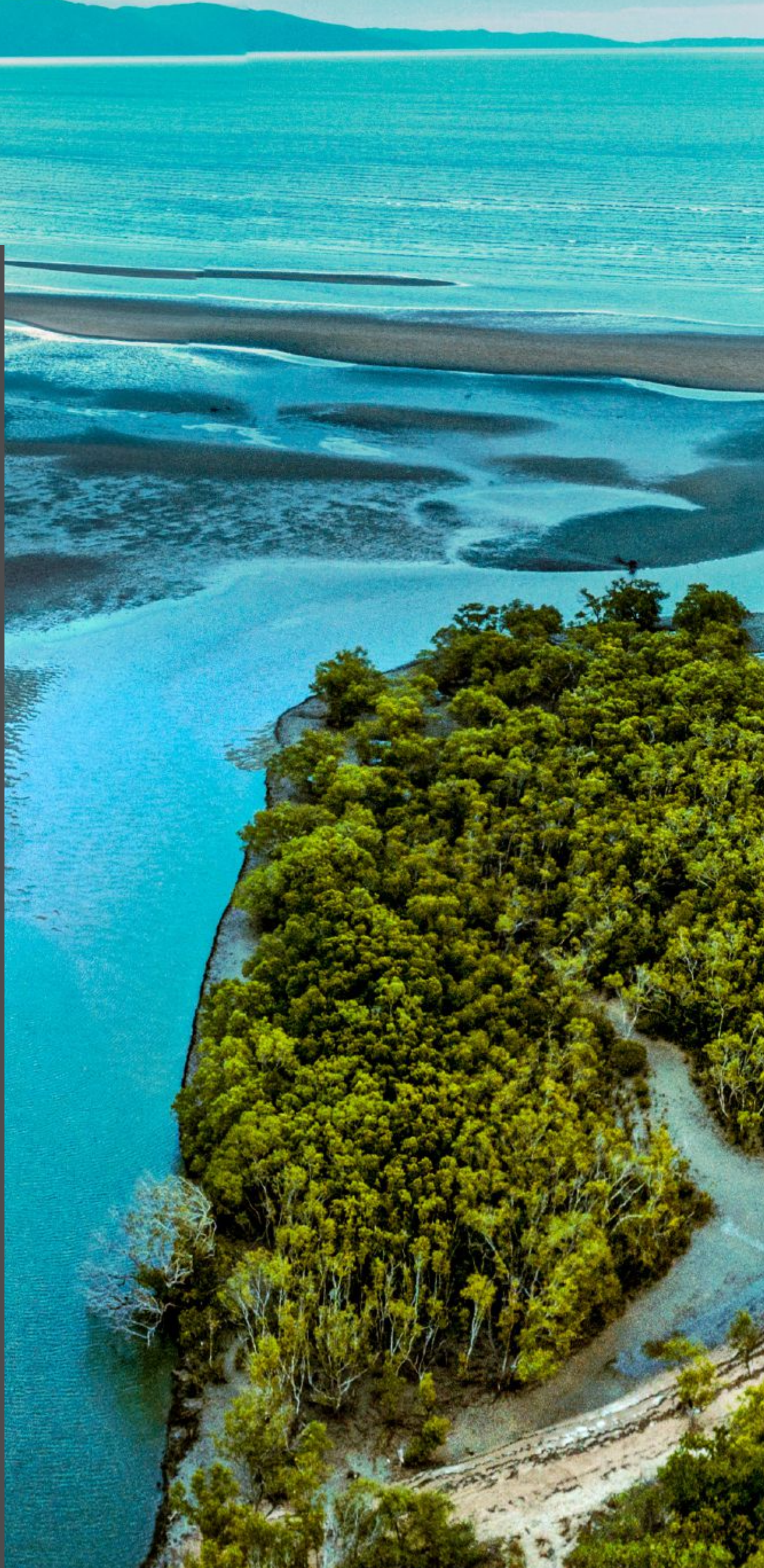


Figure 3. Deployment of ADEON bottom lander. Seven of these landers have been deployed along the Atlantic Coast, from Virginia to Florida, three in shallow waters < 400 m and four in deeper water > 400 m. All landers have passive acoustic and physicochemical sensors; the shallow landers also have been equipped with an Acoustic Zooplankton Fish Profiler system of echosounders. These landers will provide continuous data for ambient sound, sounds made by organisms, physical and chemical properties of seawater, and (for shallow landers), abundance of zooplankton and fish between the lander and the ocean surface.

Plans for the Future

Still early in its implementation, IQOE is building a foundation for its future activities and welcomes ideas and partners. During 2019, IQOE working groups will begin releasing publications related to their tasks and will build out their parts of the project. Where appropriate, the groups will create summaries for policymakers that will present the most current knowledge about ocean sound in non-technical terms. IQOE plans to hold a workshop during 2020 to continue implementation of the Ocean Sound EOV. IQOE will endorse additional projects which IQOE can help to grow and which help accomplish IQOE's scientific objectives.

Later in the program, IQOE's participants envision an unprecedented period of intense international attention to ocean sound research and observations, for example, an International Year of the Quiet Ocean, in which coordinated, standardized measurements are made worldwide, in quiet and noisy locations, to create a baseline global ocean soundscape.



SOUNDS OF THE COAST

PHOTO: Hans-Petter Fjeld

West Atlantic Cod

This species is widely distributed in a variety of habitats from the shoreline to well down the continental shelf, to depths over 600 meters, but is mostly found within the continental shelf areas from 150-200 meters. Source: FishBase

Oyster Toadfish

From Maine to the Caribbean Sea, Oyster Toadfish inhabit inner tidal areas in shallow water among rocky substrate. Their characteristic "boat whistle" is produced by oscillating muscles around the swim bladder, which they use as a resonator. These muscles are one of the fastest vertebrate muscles. Words: Ocean Conservation Research. Sound Source: CSA

Coastal Shipping

Due to the expansion of global shipping, ocean noise levels have increased anywhere from 4 to 15 times louder than what it was in 1958 (depending on location). Words: Ocean Conservation Research. Sound source: CSA

Manatee

Manatees live in warm waters and can be found along the coasts of Florida, Belize, Peru, Ecuador, Columbia, the Caribbean Islands, and West Africa. There are three species of manatees, including the West Indian (Trichechus manatus), West African, and Amazon manatee (Trichechus inunguis). Words: DOSITS. Sound Source: CSA

Silver Perch

Perch are shoaling animals found worldwide. It is hard to determine if these chorusing perch are synchronizing their pulses or interleaving them. The knocking characteristic indicates that sound production is probably by way of their swim bladders. Sound Credit: James Locascio and David Mann. Source: Ocean Conservation Research

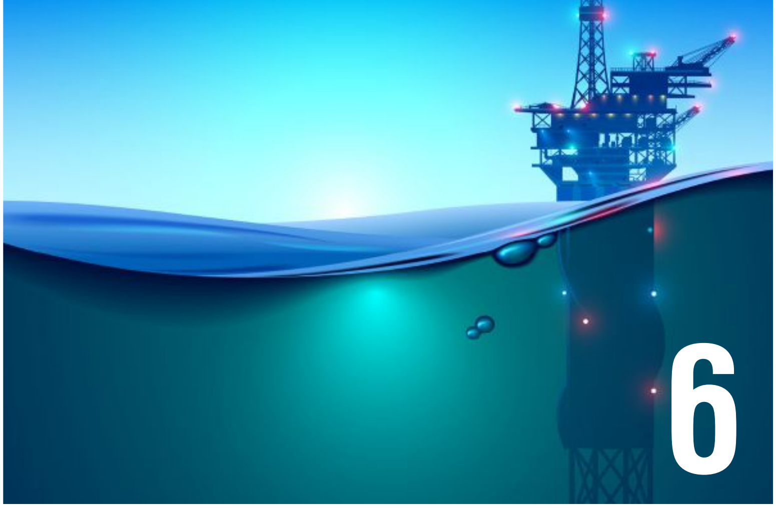
Thanks to the generous Gold Sponsors of ECO Magazine’s special issue: Ocean Sound

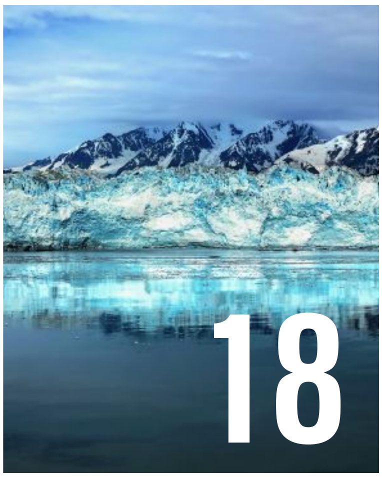
BOEM
Bureau of Ocean Energy Management

BOEM manages the responsible development of U.S. Outer Continental Shelf energy and mineral resources. BOEM’s environmental program covers the three major areas that it regulates: oil and gas, renewable energy, and non-energy minerals such as sand and gravel or hard minerals. Environmental protection informed by science and law is a foremost concern and an indispensable consideration in BOEM's decision-making, and since the 1980s, BOEM has invested nearly $90 million on protected species and noise-related research.

CSA
CSA Ocean Sciences Inc.

CSA, a marine environmental consulting firm founded in 1970, specializes in multidisciplinary projects concerning potential environmental impacts throughout the world. Headquartered in Stuart, Florida, with regional offices worldwide, CSA provides clients with field collected objective data and scientific research while maintaining an appreciation for the environmental, legal, and political sensitivities. CSA offers a wide variety of desktop and field survey surveys, with a keen focus on solutions for complex ocean sound issues.

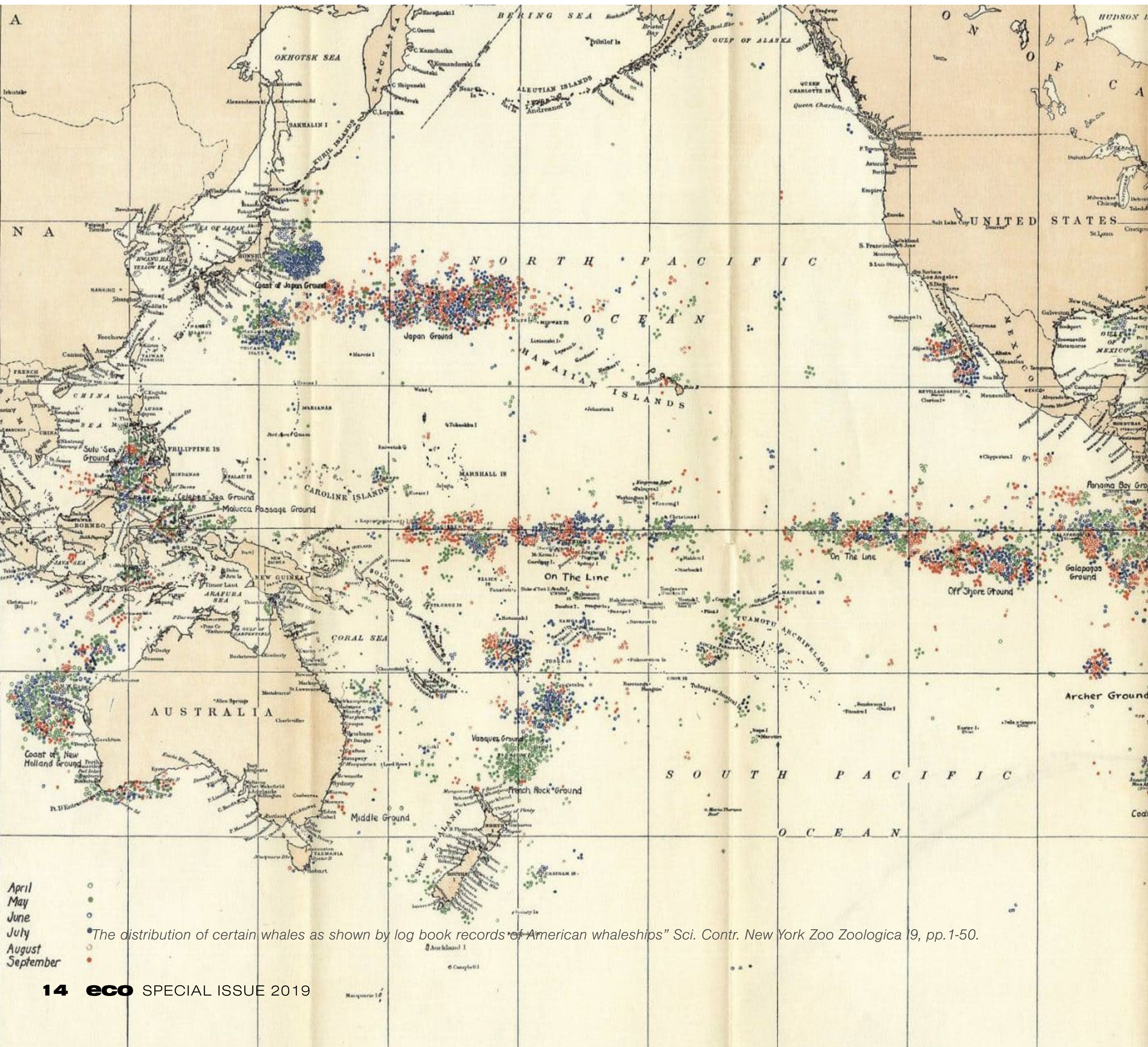




Observing Sound

Ocean Noise Regulation: A Brief History

Words by Michael Stocker, marine bioacoustician and founder of Ocean Conservation Research

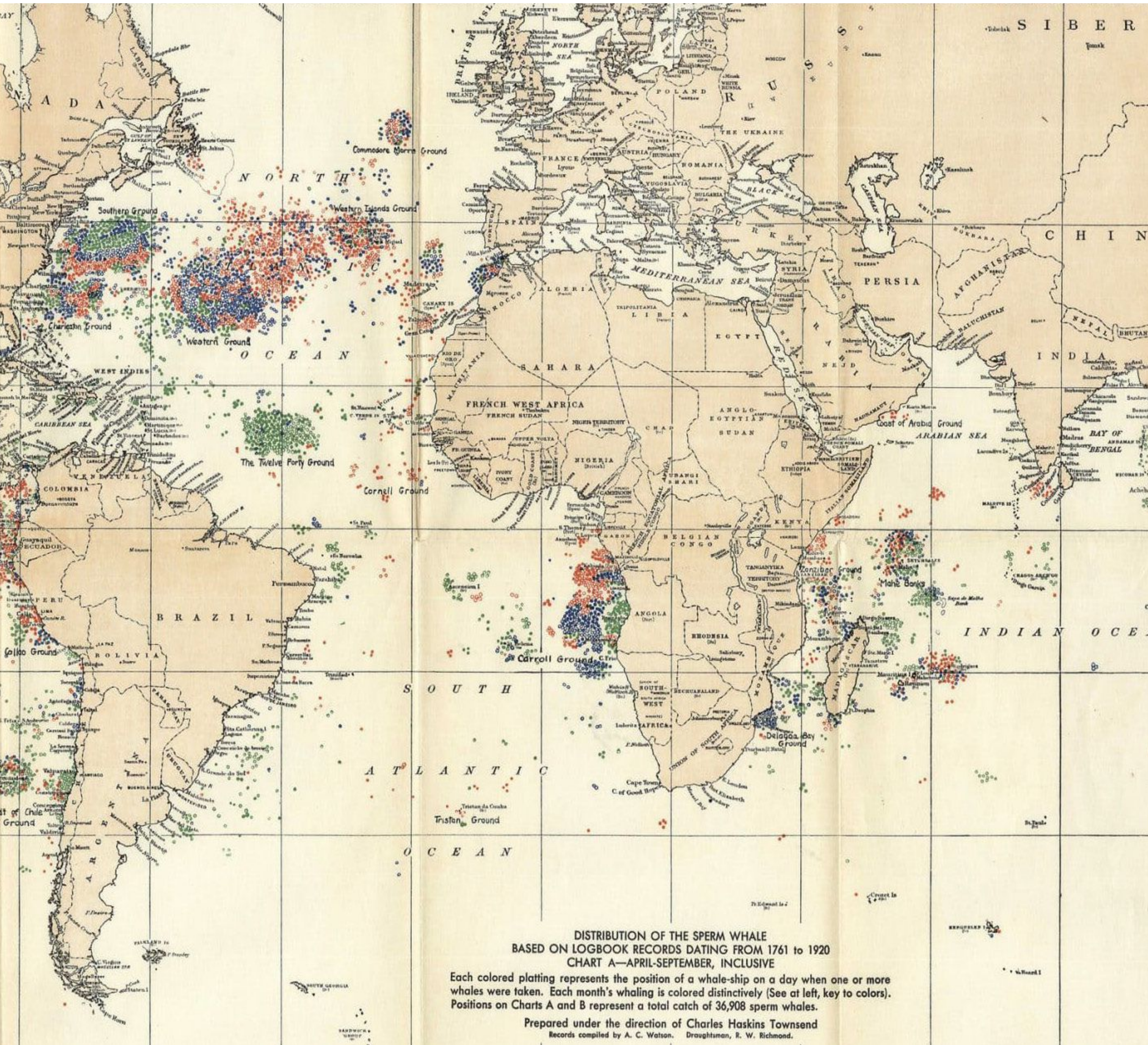


The distribution of certain whales as shown by log book records of American whaleships" Sci. Contr. New York Zoo Zoologica 19, pp.1-50.

In 1975, Donald Ross indicated a long term trend of low-frequency human noise increased by 0.55dB per year between 1958 and 1975. This trend in ocean ambient noise levels has been due to the expansion of global shipping and has yielded an increase in the ambient noise levels in the ocean that is anywhere from 4 to 15 times louder than what it was in 1958 (depending on location).

What was less known at the time was that Ross' baseline was laid down when the ocean was as quiet as it had been since the late Miocene period 10 – 15 million years ago, as the great whales grew into the largest creatures to inhabit the planet. Of course, there is no way to know for sure, but as some of the loudest whales have not otherwise changed morphologically since that time, it would be safe to assume that they have been making the same amount of noise throughout their natural history. And given the mass extirpation of these loud beasts in the course of industrial whaling, along with the collapse of their populations came the decrease in their noise.

Commercial whaling grew with the industrial revolution. Machines with gears and bearings needed lubrication – and whale fat offered a great resource for this. And sperm whale oil, with its negative thermal-to-viscosity coefficient (getting more viscous as it heats up), was an incredible boon to ever-faster machines. But when the famous oil gusher "Spindletop" burst forth in Beaumont, Texas, the gauntlet was thrown down in the industrial lubricant competition.



It was also fossil fuel that accelerated whale takes – powering up the whaling industry; replacing oars and sails with engines and propellers. Ironically it was Spindle-top that eventually saved the whales with an abundance of relatively inexpensive oil and fossil fuel that began driving the economy. But in a stunning effort to wring out the last profit from the whales, harvesting accelerated in the mid-50s to mid-60s – particularly by the Soviet whaling fleet, who were over-harvesting and under-reporting, by factors of ten, and literally, millions of whales were slaughtered in under a decade.

It was none-too-soon that the US led the efforts to put the brakes on commercial whaling during Richard Nixon's era of Federal Environmentalism. Due to several factors – from the TV series "Flipper," to the Roger Payne's *The Song of the Humpback Whale*, (the first gold album by animals) – marine mammal conservation became a priority for American citizens. In 1972, the Marine Mammal Protection Act (MMPA) codified our national relationship with marine mammals into a statutory context; defining things like "permissible takes," which at the time were graduate between "takes" for zoos and aquariums, "takes" for science, and "takes" for subsistence hunting. There was also the unintentional – or "incidental" – takes for navy exercises and offshore oil and gas operations for which "Incidental Harassment Authorizations" were devised.

...the MMPA did not originally consider acoustical "takes" in the context of behavioral disturbance.

It was this graduated idea of "takes" that codified an ambiguous term that has been a boon for conservationists, and a bane for the takers because the MMPA did not originally consider acoustical "takes" in the context of behavioral disturbance. Distinguishing the severity of the takes began flavoring the 1981 amendments of the MMPA, but the actual statutory definitions of "Level A" and "Level B" takes didn't show up until 1994, when the term "harassment" was statutorily defined under these distinctions.

A "Level A" take is pretty clearly defined as "any act of pursuit, torment, or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild." The acoustical exposure threshold for this can be determined by way of inferring (through auditory threshold testing) how loud a sound exposure would need to be to cause a permanent hearing threshold shift. I say "inferred" because empirically determining the threshold of hearing damage on a marine mammal would be unethical and immoral.

In the early stages of the "Level A Take" definition there was a bit of "push and pull" but was finally settled by the National Marine Fisheries Service (NMFS) as a "do not exceed" threshold below which physical injury would not occur. In cetaceans this was 180dB (re: 1μPa). In pinnipeds this was 190dB.

Level B exposure is defined as "any act that disturbs or is likely to disturb a marine mammal or marine mammal stock in the wild by causing disruption of natural behavioral patterns, including, but not limited to, migration, surfacing, nursing, breeding, feeding, or sheltering, to a point where such behavioral patterns are abandoned or significantly altered." But defining what constitutes "disruption" is itself fraught with threshold vagaries – given that behavior is always contextual, and the weight of the biological significance of the disruption hinges on a human value scale. How biologically significant is it when Bowhead whales change their vocalization rates in response to an airgun well below the Level B threshold? How biologically significant is it when a sea lion risks exposure to loud (above Level A) "Acoustic Harassment Devices" (AHD) to predate on fish pens in a behavioral relationship known as "the dinner bell effect," i.e., associating AHD signals with "dinner?"

Regulatory Metrics

Regulations work best when they are unambiguous. Regulators are not fond of nuance. Dichotomous decisions of Yes/No, Go/No-Go are their stock and trade. It was for this reason that until just recently the marine mammal exposure guidelines were really simple:

- Noise exposure above 180dB = Level A exposure
- Noise exposure above 160dB = Level B exposure (for impulsive sounds)
- Noise exposure above 120dB = Level B exposure (for continuous sounds)

But it was clear that these regulatory thresholds were actually too simple. When dolphins were riding the bow waves of seismic survey vessels – frolicking in a Level A noise field, it was apparent that the regulatory thresholds did not reflect common field conditions. This was addressed in what became known as "Southhall 2007" which eventually informed the current NOAA Fisheries noise exposure guidelines. These guidelines more accurately reflected the noise exposure criteria relative to the hearing ranges of a range of marine mammal species; Low-Frequency Cetaceans, Mid-Frequency Cetaceans, High-Frequency Cetaceans, Sirenians dugongs and manatees, Phocids (seals), Otariid (eared seals) and other non-phocid marine carnivores such as otters.

While this new standard more accurately reflects the frequency-defined hearing ranges of the exposed animals, it still falls short of addressing the complexity of the noise exposures in terms of sound qualities, as well as in terms of the complexity of the sound environments - or "soundscapes"- in which the exposures typically occur.

Increasingly complex subsea operations are introducing ever-increasing complex noises into the ocean soundscape.

Increasingly complex signals are being used in the sea for underwater communication and equipment control. These communication signals include sounds that can be rough or "screechy," and more disturbing than equal energy-level pure tones used to derive the regulatory thresholds. They can also be more damaging.

Additionally, sounds presented in the typical Environmental Impact Statements (EIS) are shown as single sources of sound, and while there is some consideration for cumulative impacts, the accumulation period "resets" after 24 hours, so the metric only reflects accumulated noise exposure and does not address the impacts of a habitat completely transformed by continuous, or ongoing noise. Given that typical seismic airgun surveys (for example) run around the clock for weeks to months at a time, and have an acoustical reach of hundreds to thousands of kilometers, the activity is likely to have much greater behavioral impact than what is reflected in accumulating and dumping of a noise exposure index every 24 hours.

Furthermore, operations such as seismic survey, or underwater extraction industry operations typically have a lot of different, but simultaneous sound sources. Seismic surveys may include seafloor profiling with multi-beam or side-scan sonars – for example. It was, in fact, the seafloor profiling sonars that were estimated to be the cause of a mass-stranding incident in Madagascar in 2008, not the seismic surveys.

Underwater extraction industries such as seafloor processing for hydrocarbon extraction, or seafloor mining operations will also necessarily have multiple sound sources – with equipment, along with acoustical communications for status monitoring, and remote and autonomous control of the equipment. These concurrently-operating compliments of noise sources can create a very complex soundscape. And even if the specific pieces of equipment don't in-and-of-themselves exceed regulatory thresholds, they may nonetheless create acoustically-hostile soundscapes likely to have behavioral and metabolic impacts on marine animals.

So far there is no qualitative metrics for compromised soundscapes, but modeling for concurrent sound exposures is possible, and in this context, many concurrent sounds in a setting would constitute "continuous sound," thereby qualifying the soundscape as a whole under the Level B continuous sound criteria of 120dB. Additionally, while sound sources in the near-field may be considered "impulsive sounds," and thus regulated under "Level B' criteria for impulse sounds, due to reverberation and multi-path echoes, louder sounds which have a long reach could be considered as "continuous sound sources" in the far field and thus be regulated under the Level B continuous sound criteria of 120dB.

So while underwater noise regulation has come a long way since the implementation of the Marine Mammal Protection Act in 1972, as human enterprise in the ocean becomes increasingly more complex, yielding ever-more complex soundscapes, we have a long way to go before our noise exposure regulations reflect that complexity.

The Arctic
A Natural Sound Sanctuary

Words by Melanie Lancaster and Peter Winsor, WWF Arctic Programme

By placing an oar into Alaska's cold ocean waters and listening to sounds under the surface, Indigenous hunters can track animals like bowhead whales and seals[1], much like a doctor uses a stethoscope. The Arctic's Indigenous Peoples have relied upon the ocean for thousands of years. But climate change and the growing impact from increased industrial activities like shipping and oil and gas development threatens the future survival of hundreds of species of marine animals that call the Arctic home.

When it comes to sound, the Arctic is unique. Sound travels further in the cold waters of the Arctic Ocean than in warmer regions, and at shallower depths, which coincide with depths at which whales and seals swim and dive. Sea ice blankets the water's surface from wind and wave noise, so in many places, the Arctic Ocean is quiet – a natural sound sanctuary. In contrast, many of the world's oceans are plagued with a growing man-made acoustic footprint, evidenced by a doubling of noise intensity every decade from 1950 to 2000[2]. Our understanding is also increasing on the breadth of harm underwater noise causes to ocean life – from commercially important fish stocks, to marine giants like blue whales, to tiny krill[3].

The Science on Underwater Noise Impacts in the Arctic

The Arctic is ground zero for climate change. As sea ice melts, shipping, oil and gas exploration and military activities push further into Arctic waters, exposing sea animals to growing underwater noise pollution to which they are largely naïve. The changing composition of Arctic ice cover is also affecting

Hubbard Glacier in Alaska. Audio: CSA

sound. For instance, thicker and older ice is rapidly vanishing from the Arctic Ocean. This ice is typically characterized by a rough and jagged underside, which acts as an effective sound dampening baffle, like what you find in music studios. The newer, thinner ice that is prominent now is smoother. Moreover, the increasing length of the open water season is transforming the soundscape, allowing a more direct transfer of noise.

The Arctic's remoteness and extreme environmental conditions make it a challenging natural laboratory for research, so the science on how Arctic sea mammals respond to underwater noise is patchy. But researchers have found that the sound of an icebreaking ship can be heard by beluga whales from 85 kilometers away. At 35-50 kilometers away, the belugas panic, form herds, make alarm calls and ultimately flee the area. In contrast, narwhals – the beluga's cousin – "freeze" and become silent when exposed to ship noise[4]. In response to seismic surveys for oil and gas, seals and whales try to escape the area. Long-term and more severe impacts are not yet documented for the Arctic but in other regions, seismic has caused barotrauma, essentially, ear damage, in humpback whales, and military sonar has been associated with mass stranding events and deaths of whales all over the world[6,7].

Acoustics in the Arctic – Closing Knowledge Gaps on Noise

Acoustic monitoring of the Arctic's underwater environment is helping to fill some of our knowledge gaps. One example of new technology enabling real-time collection of acoustic data in the Arctic comes from the Chukchi Sea, north of Russia

and Alaska. Since 2013, a research group has performed annual deployments of autonomous underwater vehicles, so-called Slocum gliders. Each year, the gliders complete multi-month-long missions, "flying" autonomously from the Bering Strait area to the Alaskan village of Barrow along the length of the Chukchi Sea[8]. The gliders are equipped with a digital acoustic monitoring instrument to record and process in situ low-frequency (< 5 kHz) audio to characterize marine mammal occurrence and habitat as well as ambient noise off the northwest coast of Alaska. This kind of new autonomous technology opens a suite of possibilities to provide real-time information on ocean conditions, including the distribution of marine mammal species and ambient noise levels in a changing and challenging environment.

Action Towards Safe Noise Levels in the Arctic

While there are still many Arctic-specific gaps in our knowledge of underwater noise, impacts from around the world serve as a warning to unchecked expansion of noise-producing industrial and military activities in the region. Not only will effects be felt on wildlife, but on commercial fishing[9] and importantly, on the livelihoods of Indigenous Peoples and those living in Arctic coastal communities. Many have expressed concern over how shipping and seismic surveys will affect marine mammals[10] and the ability of people to hunt these animals for subsistence. Rather than waiting until the impacts have taken a toll – the "business as usual" approach – precautions must be taken in the Arctic now, while we still have a chance to get it right. Underwater noise is pollution, but it's pollution with a relatively easy solution: stop putting it in the ocean and it's gone. While we focus on learning what safe levels of noise are, there are several simultaneous actions that can be taken to manage it.

Firstly, Arctic states need to recognize underwater noise as pollution. The European Commission has already done so, and EU states are currently developing noise monitoring systems and targets to limit noise discharges into European waters.

Secondly, Arctic states must be bold and commit to holding underwater noise at current levels until safe levels for Arctic wildlife are known. This doesn't mean halting industrial development in the Arctic. Technology-wise, it means building new ships with quieting technology and ending seismic surveys for oil and gas to transition towards investment in (low noise) renewable energy sources. Operationally, it means keeping underwater noise out of important habitats at important times of the year for biodiversity. Finally, it means ensuring that risk and impact assessments explicitly incorporate underwater noise, including cumulative impacts from multiple sources. Ultimately, Arctic states may need to regulate and incentivize industry to step up with solutions – such a model has been successful in Germany for mitigating underwater noise emissions during installation of offshore wind farms[11].

Furthermore, Arctic states must look for new opportunities to assert their leadership and safeguard their biological assets in the face of growing interest and investment in the region by non-Arctic nations. Iceland is the new chair of the Arctic Council and has stated that the Sustainable Blue Economy and healthy oceans are priorities for its chairmanship. A strong resolution by Iceland and subsequent action by Arctic states to reduce ocean pollution – including plastics and underwater noise – is needed. Additionally, the International Maritime Organization – the UN regulator of global shipping – is gearing up to meet its ambitious emission reduction targets. Reducing ship speeds is the cheapest, fastest and only way to cut emissions in the short term. Serendipitously, slowing down usually reduces noise pollution from ships and inadvertently regulates underwater noise.

As the Arctic opens up, scientific understanding of the marine environment will take great leaps forward. But along with the science must come policy that safeguards Arctic ecosystems from underwater noise and maintains a resilient Arctic for people and wildlife.

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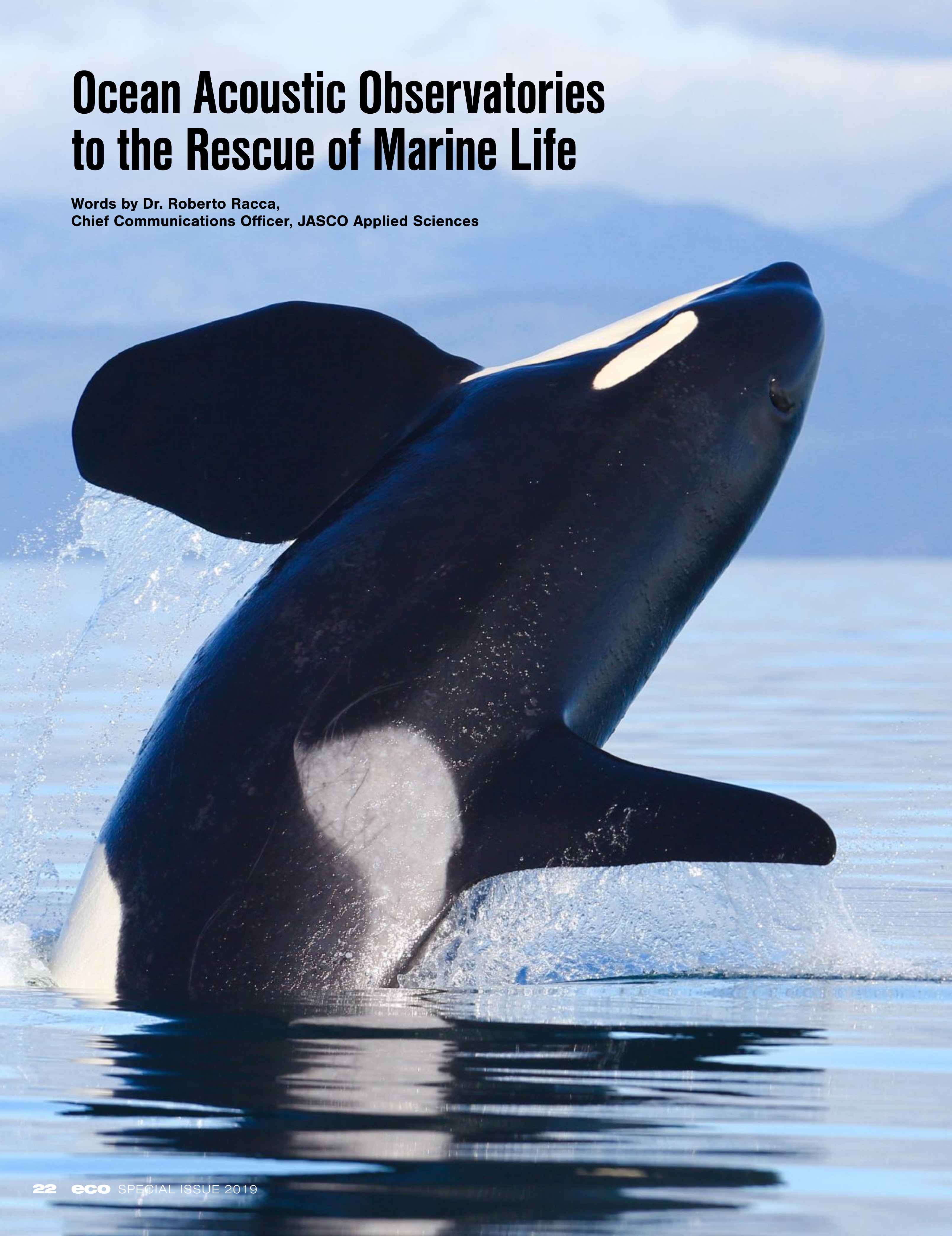
Beluga Whales in the Arctic

Ocean Acoustic Observatories to the Rescue of Marine Life

Words by Dr. Roberto Racca,
Chief Communications Officer, JASCO Applied Sciences



Vulnerable marine species and critical ecosystems worldwide are increasingly exposed to the risk of noise-related injury and disturbance from human activity. Because light travels poorly underwater, many aquatic animals rely far more on hearing than vision for critical life purposes including breeding, socializing, navigating, caring for young, and foraging. Their well-being is thus closely tied to living in a relatively undisturbed acoustic environment. Arguably the most globally widespread and persistent source of human-generated underwater noise is vessel traffic, ranging from transoceanic shipping to commercial fishing vessels to recreational watercraft, which in some regions of the world can reach surprisingly high concentrations.

Underwater acoustic observatories connected to shore stations by subsea cables or by wireless links enable long-term, real-time monitoring that can document trends in underwater noise levels and can simultaneously detect the presence of certain aquatic species in an area. JASCO Applied Sciences has long been a leader in implementing cutting edge solutions for fixed location acoustic monitoring with automated analysis. Over the years, the company has steadily adopted and developed new technologies for analyzing very large datasets from many years of recorded underwater sound, and for the immediate processing of real-time data such as audio streams produced by cabled acoustic observatories.

A prominent application of underwater sound observatory technology for ecological protection has been the effort to characterize the acoustic environment in the Salish Sea waters of British Columbia and Washington State. These waters are a critical habitat for endangered southern resident killer whales and other marine species. Intense maritime traffic occurs in these waters; several B.C. and Washington State ferries thread their ways daily between the gulf islands and across the Strait of Georgia. Container ships, tankers, bulk vessels and vehicle carriers traverse the main shipping lanes from Vancouver, passing through Strait of Georgia, Boundary Pass, Haro Strait, and the Strait of Juan de Fuca out to the Pacific Ocean. Commercial fishing boats, whale watching vessels, and pleasure motorboats add to the activity. All these sources contribute to a much higher level of underwater noise than the local species experienced historically; measurements of this sound and its correlation with vessel activities are essential for the development of mitigation solutions.

ECHO Program

To better understand and manage the impact of underwater vessel noise on local cetacean populations, the Vancouver Fraser Port Authority, with input and advice from numerous stakeholders, launched the Enhancing Cetacean Habitat and Observation (ECHO) program in November 2014 in which JASCO has been a major project partner along with Ocean Networks Canada. Under the aegis of ECHO, a cabled underwater listening station built on JASCO's technology was deployed in the Strait of Georgia on one of the shipping lanes leading into the Port of Vancouver. It operated continuously from September 2015 for about three years, monitoring the passage of vessels and their sound level, documenting ambient noise, and detecting and classifying marine mammal calls.

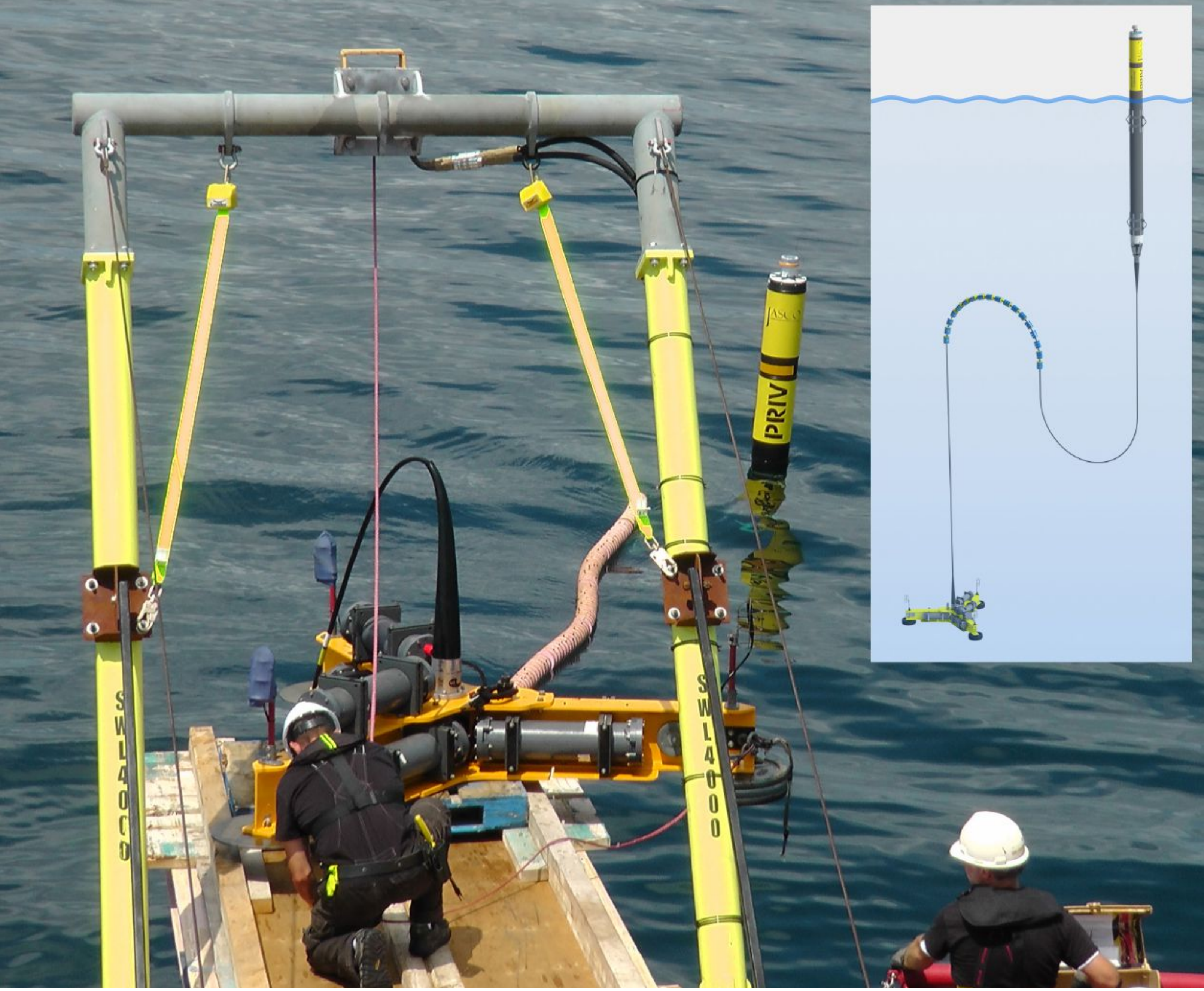
Map of the Salish Sea region where intense vessel traffic through critical killer whale habitat is being monitored by underwater acoustic observatories.

These functions are provided by a suite of acoustic monitoring tools developed by JASCO and branded as the PortListen® framework. At the time of this article, JASCO is leading a project funded by Transport Canada to install a new cabled underwater acoustic observatory off one of the small Gulf Islands between Vancouver Island and the mainland; it will monitor through PortListen® the critical habitat of southern resident killer whales in the busy Boundary Pass and Haro Strait corridor.

The applications and benefits of such an integrated infrastructure for underwater acoustic monitoring and analysis are multifaceted. The system can be used to generate automated real-time notifications of acoustic detection of marine mammals to vessels in the area, potentially allowing them to avoid deadly ship strikes through enhanced vigilance.

Enabling New World-Leading Policies

By enabling the collection of an unprecedented database of standardized acoustic source levels of thousands of



Deployment of an autonomous underwater observatory system suitable for use in remote locations. As shown in the inset, the instrumentation is housed in a lander assembly on the sea bottom connected to a spar buoy with satellite transmitter.

vessels - thanks to the extensive participation of merchant ships in a voluntary protocol whereby they transit at prescribed distances and speeds past the listening station in the Strait of Georgia - the program has also permitted the Port of Vancouver to incorporate the reduction of noise emission into a highly acclaimed, world-leading policy of incentivizing with reduced fees vessels that meet certain formal standards for environmental performance.

In Haro Strait and Boundary Pass, a multi-year program of voluntary slow-down trials is underway. In this stretch of water, different classes of vessels were asked to transit through an acoustically instrumented area at a prescribed lower speed still compatible with their commercial purpose. This has led to a unique understanding of how noise emission correlates with the operational regime for individual vessel types – a knowledge that can feed directly into better informed regulatory decisions.

As the enabling technology at the heart of studies and programs that ultimately inform and empower a movement toward the quieting of marine traffic, JASCO's PortListen® framework is contributing to an ecological benefit of global reach. The expansion of the paradigm to other centers of leadership around the world, which JASCO is pursuing through new collaborations, will compound this benefit and accelerate its propagation throughout the world's oceans.

Not Just for Noise

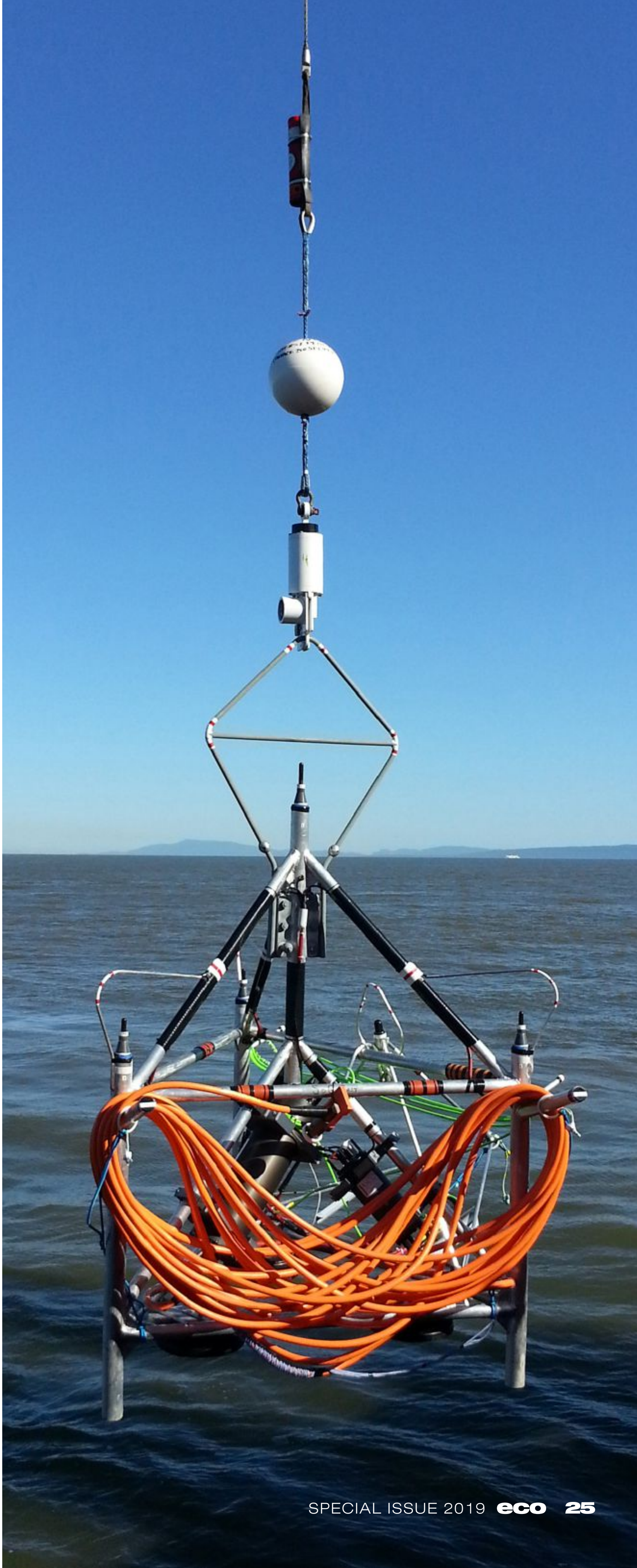
The enabling potential of real-time acoustic monitoring using fixed underwater listening stations is not limited to the assessment of noise levels. In a recent pilot project in collaboration with the Zoological Society of London (ZSL), JASCO evaluated and tested in British Indian Ocean Territory a proof of concept early warning system for illegal fishing in marine protected areas.

The pilot system, based on an autonomous mooring equipped with JASCO's underwater acoustic sensing and processing technology, would be integrated with ZSL's Instant Detect satellite communication infrastructure for wildlife and threat monitoring at remote locations worldwide.

The solution trialed in the Indian Ocean could be deployed in remote archipelagos and coral lagoons to listen around the clock to underwater sound and use JASCO's intelligent algorithms to detect engine tones from vessels encroaching into protected areas, triggering a warning through Instant Detect. Combined with independent analytics services such as OceanMind, providing verification and validation of at sea activities, this would give local enforcement teams a reliable tool to combat illegal fishing in ecologically sensitive areas.

Nor are the applications limited to fixed moorings. The current development of mobile instrumentation platforms including powered autonomous vehicles (underwater, surface and airborne) as well as ocean gliders and drifters, boosted by new low-power data processing and communications technologies, is expanding the concept of the acoustic ocean observatory to a sampling paradigm where entire regions of ocean can be monitored systematically over time by a fleet of 'crisscrossing' devices. JASCO has already adapted its underwater sound acquisition systems to be compatible with the payload capacity of several types of mobile platforms and is working on new challenges such as minimizing self-noise induced by the motion of sensors through the water. Parallel new developments in analytical methods will help tackle the meaningful interpretation and visualization of large volumes of acoustic data from multiple sites in constant relative displacement.

The science and technology of monitoring underwater noise grows more capable by the day, but so grow the threats on the aquatic environment related to noise from human activities. We have a finite window in which to apply our increasing knowledge of the problem to addressing and mitigating its causes.



An underwater listening station assembly for the ECHO acoustic observatory in the Strait of Georgia being lowered to the seafloor. The bright orange cable bundle will later be uncoiled by a Remotely Operated Vehicle (ROV) and connected at a junction box to the main subsea cable to shore operated by Ocean Networks Canada.

BOEM:
Understanding the Ocean Soundscape

Words by Dr. Rodney Cluck, Chief of Division of Environmental Sciences, and Dr. Jill Lewandowski, Chief of Division of Environmental Assessment, Office of Environmental Programs

Once considered silent, the seas are now known to be alive with sounds.

Some are from natural sources, such as storms, earthquakes, and waves. Other sounds are generated by animals that use acoustic signals to communicate and to navigate within their environment. Shipping, energy development, military operations, construction, and commercial fishing also introduce sounds into the ocean. When human-generated sounds are unwanted, they are generally referred to as "noise."

The Bureau of Ocean Energy Management (BOEM) was one of the first federal pioneers to sponsor research on ocean noise. By driving original research to fill knowledge gaps and overseeing environmental reviews, BOEM has played a key role in improving the overall scientific understanding of the potential effects of human noise on marine life and establishing requirements to protect marine life during noise-producing Outer Continental Shelf (OCS) energy and mineral development activities.

Background on BOEM Acoustics Research

BOEM began exploring the effects of industrial noise on large whales, seals and sea lions in the Pacific Ocean in the 1980s, followed by research offshore Alaska. Today it includes other geographic areas and examines impacts on species from plankton to fish. We use time-tested and new research methods and technologies like passive acoustic monitoring, autonomous platforms, animal tags, and acoustic modeling to collect and interpret the most accurate data. We partner with hundreds of researchers domestically and internationally. Recognizing the issue's importance, BOEM expanded its staff to include experts on marine acoustics, and regularly engages college and graduate students exploring marine acoustics careers.

Over the last three decades, BOEM has invested close to 90 million dollars on protected species and noise-related research by using four general research methods: 1) literature reviews, syntheses, and workshops; 2) field surveys; 3) empirical studies in the laboratory and in the field; and 4) sound source verification and modeling.

Partnerships

Some of our most significant research has taken place through partnerships with other federal agencies, academia, industry, and international groups. The U.S. Navy, NOAA Fisheries, and the National Academy of Sciences have been key federal partners, while the Joint Industry Programme (JIP) on Sound and Marine Life and countless academic institutions have led the way in collaborations outside of government. We share a need for baseline biological and acoustic data and a concern for better understanding the effects of noise on marine animals.

Photo: Scientists from Duke University and BOEM approach a sperm whale offshore North Carolina to attach a suction cup sound and motion tag for the Marine Mammal Passive Acoustics and Spatial Ecology Project (MAPS). Photo courtesy of Marine Conservation Research.

In 1987, BOEM sponsored a comprehensive literature review of the effects of noise, particularly focusing on the oil and gas industries. In 1992, the Office of Naval Research provided funding to convert this BOEM report into a book entitled, *Marine Mammals and Noise*, published by Academic Press (1995), and authored by Richardson *et al.*, which for nearly 25 years has been a key resource for scientists and regulators. In the 1990s, BOEM co-funded early scientific reviews by the National Academy of Sciences on noise. More recently, BOEM has co-funded research with the JIP on the effects of seismic surveys on migrating humpback whales, has gathered key biological data, and has developed new modeling approaches with NOAA Fisheries.

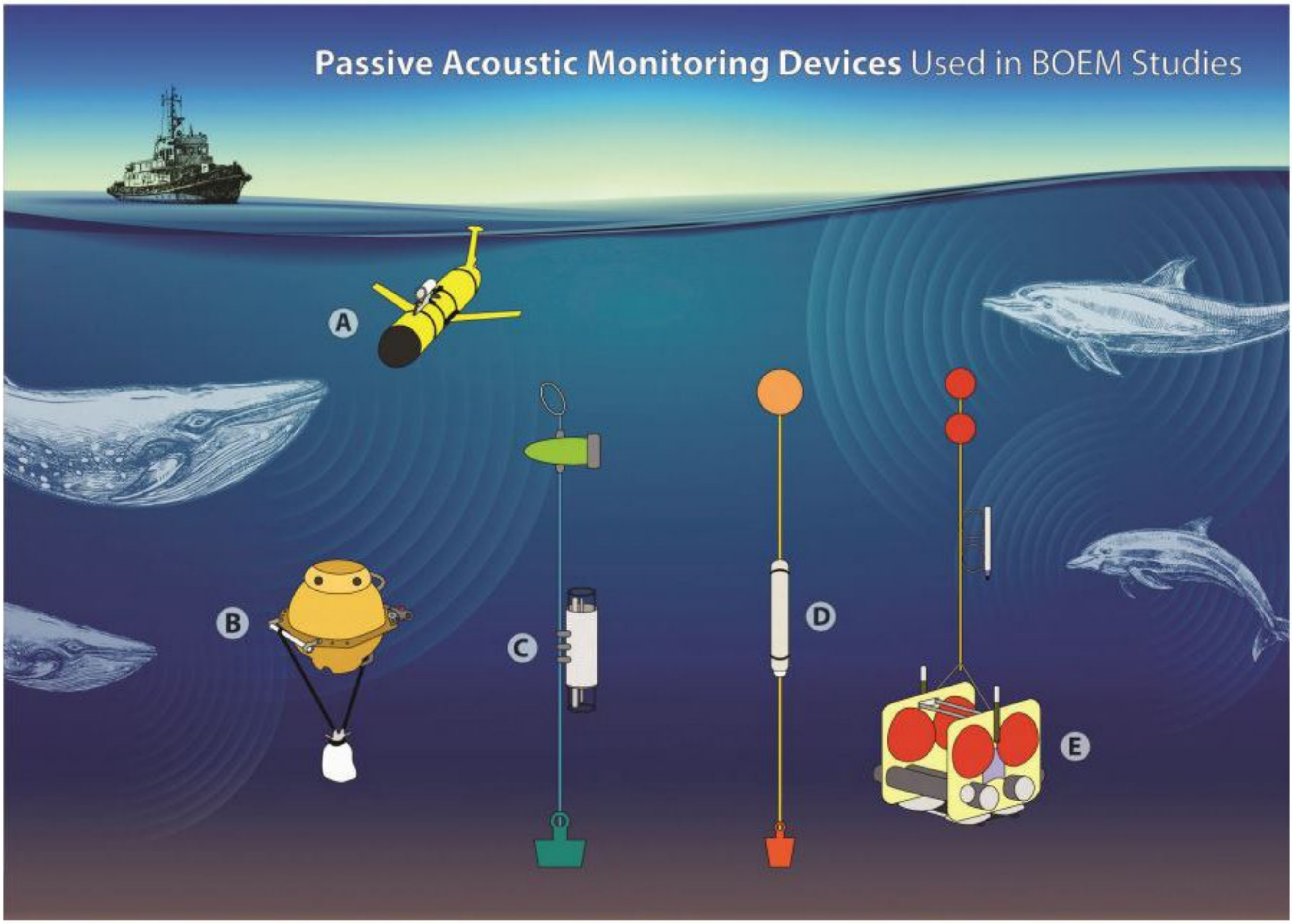
In a 2016 collaboration through the National Oceanographic Partnership Program (NOPP), BOEM is helping to fund investigators at the University of New Hampshire who are recording and analyzing patterns across entire acoustic environments (soundscapes). This project, known as the Atlantic Deepwater Ecosystem Observatory Network study (ADEON), also includes the U.S. Navy and NOAA Fisheries. The data will provide critical baseline information about ambient noise, oceanographic conditions, distribution of key marine species, and patterns in biodiversity across the deepwater regions of the Atlantic OCS. Potential changes in this baseline data could be useful if OCS energy and minerals activities proceed in these areas.

Keeping up with Acoustics Research

Expanding and sharing knowledge on new findings, research methods, and new technologies is critical to understanding and developing ways to reduce noise impacts. Consequently, BOEM regularly participates in and convenes numerous workshops and conferences.

BOEM's 2013 Quieting Technologies workshop convened U.S. and international experts to examine quieting technologies that could reduce the noise generated during offshore exploratory seismic surveys, pile driving, and associated vessel operations. Participants shared regulatory perspectives and efforts to minimize underwater noise. Besides evaluating technologies, the workshop report concluded that establishing standards or guidelines would assist in better managing noise, as would continued industry-BOEM dialog to help identify cost-effective changes.

Other workshops BOEM has co-sponsored since 2012 include: A Risk Assessment Framework to Assess the Biological Significance of Noise Exposure on Marine Mammals; the National Academies' Assessment of Cumulative Effects of Anthropogenic Stressors on Marine Mammals; The "Effects of Noise on Marine Life" conferences; The Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities Workshop; and the Cetacean and Sound Mapping Project and Symposium.



Passive acoustic monitoring devices used in BOEM studies: A) Slocum glider, B) Marine Acoustic Recording Units (MARU), C) Autonomous Marine Acoustic Recorder (AMAR), D) Cetacean Porpoise Detector (C-POD), and E) High Frequency Acoustic Recording Package (HARP)

Internationally, BOEM participated in a 2018 United Nations forum on Law of the Sea to raise awareness before the UN Ocean Conference in 2020. BOEM scientists participated in the Effects of Sound on Marine Mammals and JIP on Sound and Marine Life meeting in the Netherlands in 2018. BOEM's acoustics team plans to participate in the July 2019 Effects of Noise on Aquatic Life, where Dr. Lewandowski has been invited to deliver a keynote address on the international regulation of ocean noise.

Applying the Knowledge

BOEM applies its study and research results during offshore development project reviews to help evaluate the potential range of noise effects and identify measures that could reduce the impacts if a project moves forward. BOEM's studies also inform appropriate monitoring needs during operations to better understand actual noise impacts and mitigations' effectiveness.

The use of airguns during seismic surveys to identify offshore oil and gas resources can pose a noise concern and potentially harm marine mammals that are within the vicinity of operations. BOEM has studied and gathered independent data indicating the distance from airguns where noise might occur that is potentially injurious to marine mammals. Based on this information, BOEM requires the establishment of an exclusion zone, monitored by independent marine mammal observers, to ensure there are no marine mammals nearby both before and during airgun operations. This includes turning off airguns if a marine mammal appears within, or is about to enter, the exclusion zone. More information on the effects of seismic airgun noise on marine life and BOEM's mitigation requirements can be found in Programmatic Environmental Impact Statements for both the Atlantic and Gulf of Mexico.

Two recent BOEM reports shed light on mitigation effectiveness: Behavioral Response of Australian Humpback Whales to Seismic Surveys (BRAHHS), and Seismic Survey Mitigation Measures and Protected Species Observer (PSO) Reports in the Gulf of Mexico. The BRAHHS study showed that whales generally avoided the noise source, but that there was no significant difference in their response to ramp-up versus a full-scale seismic array. The PSO study looks at mitigation measures' effectiveness and, based on the results, will recommend potential changes to mitigation measures and modifications to protect marine mammals and sea turtles.

Another top concern for BOEM is the driving of large piles needed for offshore wind turbine foundations. For siting OCS wind facilities, we also apply knowledge gained from our studies. BOEM selects Wind Energy Areas to avoid known critical biological areas for endangered or threatened species to minimize impacts and develops best management practices to minimize the effects of noise-producing activities.

Since the Quieting Technologies workshop, we note that industry is looking to apply new technologies to mitigate the effects of airguns, and that companies submitting construction and operating plans for offshore wind turbines are seeking to adopt quieting technologies to offset noise from pile driving.

Looking Toward the Future

With increasing industrialization from many sources, ocean noise shows no signs of abating. To the extent BOEM-regulated activities may contribute to the noise, we continue to study new technologies as viable measures to reduce noise, including drawing upon industry and international expertise and partnerships. BOEM and many others have made substantial progress over the last four decades in improving our understanding, but we still have much more to do. BOEM remains committed to further enhancing the scientific knowledge on this issue and developing even stronger connections between science and regulation to ensure our OCS energy and minerals footprint is the least impactful as possible.

Australian Humpbacks. Photo Courtesy of the BRAHHS study

For more information:

Atlantic Geological and Geophysical (G&G) Activities Programmatic Environmental Impact Statement (PEIS)

www.boem.gov/Atlantic-G-G-PEIS/

Gulf of Mexico Geological and Geophysical (G&G) Activities Programmatic Environmental Impact Statement (PEIS)

www.boem.gov/GOM-G-G-PEIS/

Fact Sheet: Managing Impacts of Human-generated Noise on Marine Life

https://www.boem.gov/Fact-Sheet-on-Sound-Studies/

Assessment of Cumulative Effects of Anthropogenic Stressors on Marine Mammals (2017)

www.nap.edu/catalog/23479/approaches-to-understanding-the-cumulative-effects-of-stressors-on-marine-mammals

"Effects of Noise on Marine Life" conferences (Proceedings (Open Source) for 2010, 2013, and 2016)

asa.scitation.org/toc/poma/27/1?expanded=27

Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities Workshop (2013)

www.boem.gov/ESPIS/5/5361.pdf

Quieting Technologies for Reducing Noise During Seismic Surveying and Pile Driving Workshop (2014)

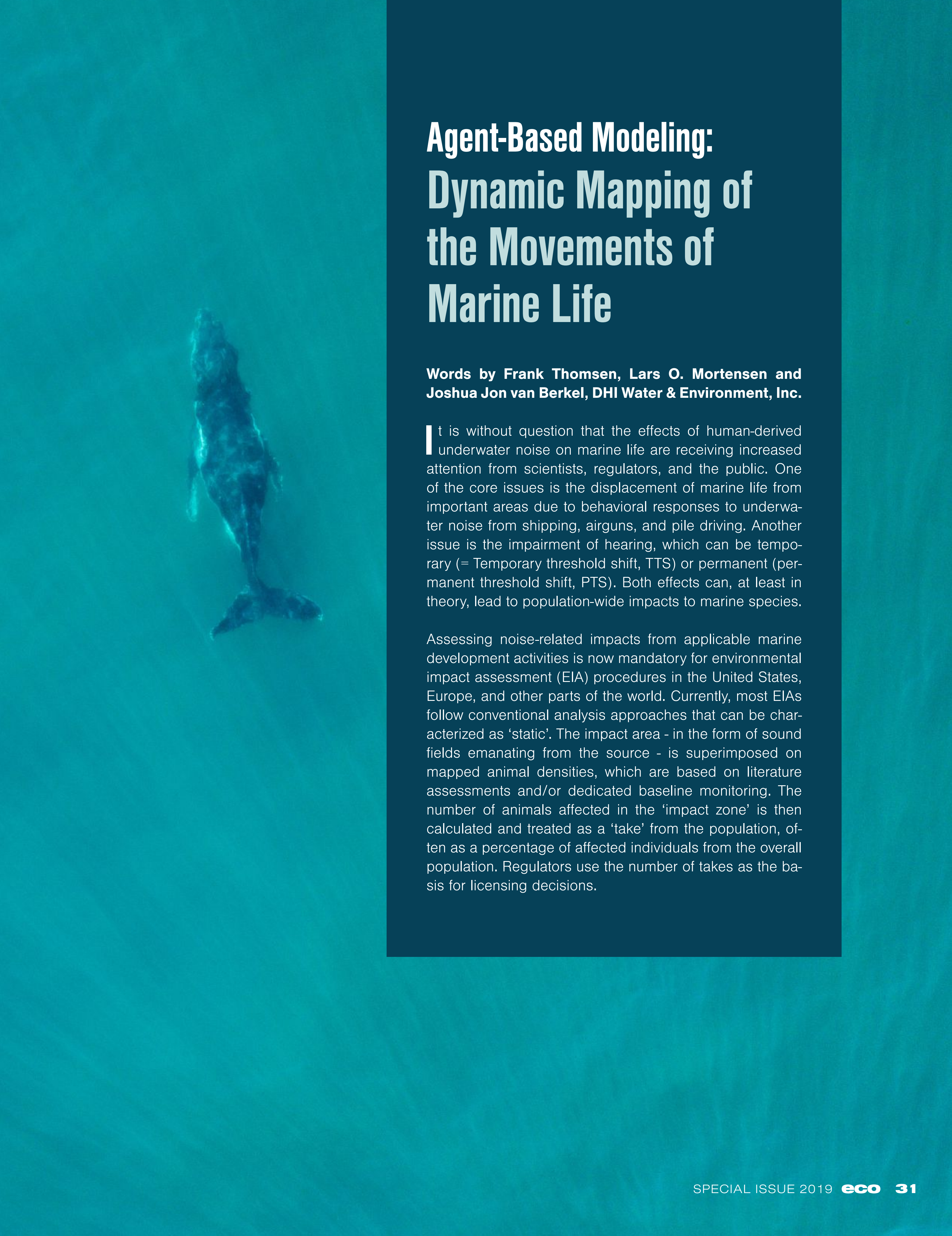
www.boem.gov/ESPIS/5/5377.pdf

Cetacean and Sound Mapping Project and Symposium (2012)

www.nefsc.noaa.gov/psb/acoustics/psbAcousticsCetSound.html

Seismic Survey Mitigation Measures and Protected Species Observer (PSO) Reports in the Gulf of Mexico.

www.boem.gov/Ocean-Science-Aug-Nov-2018/



Agent-Based Modeling: Dynamic Mapping of the Movements of Marine Life

Words by Frank Thomsen, Lars O. Mortensen and Joshua Jon van Berkel, DHI Water & Environment, Inc.

It is without question that the effects of human-derived underwater noise on marine life are receiving increased attention from scientists, regulators, and the public. One of the core issues is the displacement of marine life from important areas due to behavioral responses to underwater noise from shipping, airguns, and pile driving. Another issue is the impairment of hearing, which can be temporary (= Temporary threshold shift, TTS) or permanent (permanent threshold shift, PTS). Both effects can, at least in theory, lead to population-wide impacts to marine species.

Assessing noise-related impacts from applicable marine development activities is now mandatory for environmental impact assessment (EIA) procedures in the United States, Europe, and other parts of the world. Currently, most EIAs follow conventional analysis approaches that can be characterized as 'static'. The impact area - in the form of sound fields emanating from the source - is superimposed on mapped animal densities, which are based on literature assessments and/or dedicated baseline monitoring. The number of animals affected in the 'impact zone' is then calculated and treated as a 'take' from the population, often as a percentage of affected individuals from the overall population. Regulators use the number of takes as the basis for licensing decisions.

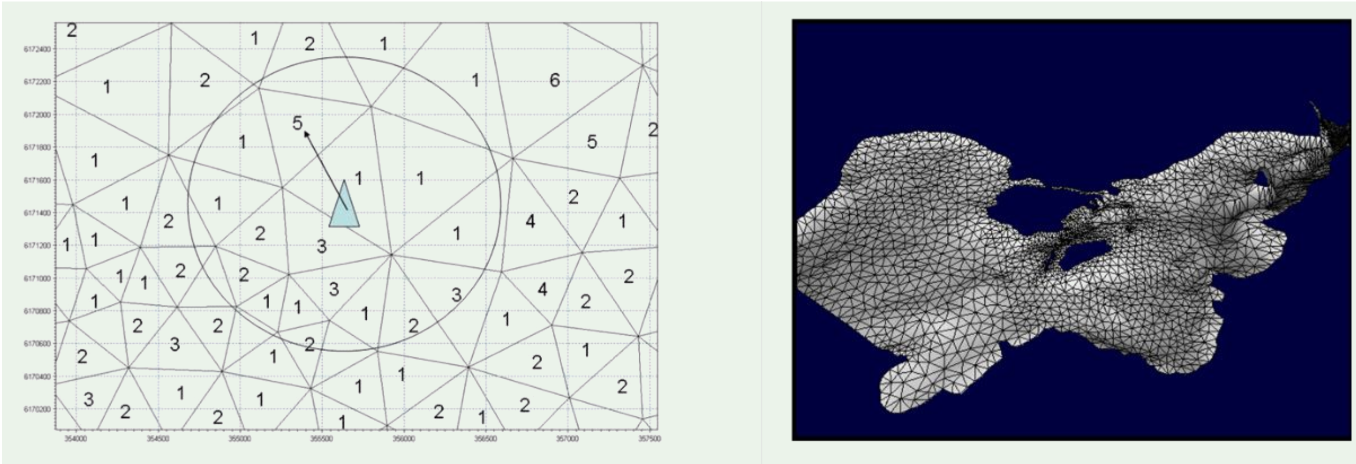


Figure 1: Example of an agent navigating grid cells (Right: full HD model for an ocean basin, left: details of the HD mesh. Agents in ABM lab can navigate in the same domain as the HD model, gathering information from the grid cell that the agent occupies and the surrounding cells).

Applying static assumptions, for example, assuming non-moving animals, can, however, lead to an overestimation of impacts. This can occur when the EIA analysis assumes – out of lack of inclusion of animal movements within the study area - that a new set of individuals is exposed to underwater sound events for each day of analysis. Also, if avoidance responses are not taken into account, it is possible that the estimated animal injury zone is larger than that of the behavioral reaction zone (i.e. the zone in which the animal moves away from the zone of danger {e.g. where TTS or PTS happens}). Such results can leave regulators with high levels of uncertainty of the actual effects and can thus lead to delays in permitting. They also do little to protect marine life from harm.

It, thus, appears necessary to include the movement of higher trophic levels of marine species in underwater sound impact analyses. This article describes the general concept of Agent-Based Models (ABM) and the attributes that make it ideally capable of replicating the movements of marine species. This is accompanied by an overview of example studies where it has been applied and, to conclude, a brief explanation of data gaps and research needs.

How does ABM work?

Ecosystem modeling has traditionally been conducted using top-down approaches, such as species distribution models. These models generally assume individuals behave identically to each other. The ABM is an alternative bottom-up population model where the focus is on the individual. ABMs allow fundamental traits of the individual (referred to as agents) to be modeled at random, which allows room for trait variance between individuals.

In ABM, the movement of the agents is modeled using a Lagrangian object-oriented model which allows for the distinct modeling of an activity. This model is then coupled with a classic Eulerian framework which simulates the hydrodynamics of the aquatic system. The simulated agents within the model domain are capable of reacting to Eulerian gradients such as water temperature or flow velocities. It is thus possible to investigate the potential effects of hydraulic and environmental cues on the movement of aquatic organisms on a complex spatial scale over time.

ABM allows for the definition of a sensory sphere around each agent that can potentially stretch across several Eulerian grid cells (Figure 1). This enables the agent to detect the gradient of Eulerian variables and/or the presence of other Lagrangian agents, for example, conspecifics, within the radius of its sensory sphere. The size of the sphere can be defined through a user-specified radius together with the angle of the agent's field of view, meaning that, if needed, an agent can be specified to only sense variables ahead of its direction of orientation.

A general ABM consists of a series of steps, wherein each agent makes a series of "decisions". Agents are released into the domain, and each agent attains the traits and states defined by the model. The traits of the agent are the basic properties that define elements of an agent's behavior, such as swimming speed or response thresholds. While the trait remains constant during the life of the agent, the stochastic selection process of the ABM allows for a pre-set degree of variance around the trait. For example, the average swimming speed of a humpback whale (agent) can be set at 1.14 meters per second. However, as whales do not swim at a constant speed all the time, the swimming speed can vary from time step to time step, depending on the desired variance in swimming speed.

States, such as weight and distance traveled, will change over the course of the agent's life. Ultimately, decisions made by the agents are based on their traits, combined with external variables such as noise, and internal states, which will result in a range of behaviors. This decision process takes place in the form of a decision tree where the yes/no answer leads to a new decision, and when the end of the decision tree is reached behaviors are executed, state variables are updated, and the process cycles to the next time step.

Assessing noise impacts using ABM

DHI has been involved in the development of ABMs for marine mammals, seabirds, and fish since 2013. As a first step in the analysis of noise related impacts, it's important to calibrate the model by making sure the movements of the agents are replicating natural behaviors. In one of our first investigations, we modeled bowhead whales *(Balaena mysticetus)* in the Chukchi Sea and calibrated the model using observations of whales passing several landmarks during their migration. The results were then validated using independent data. In the case of the bowhead whale, information obtained using radio telemetry was used (Figure 2).

In one of our more recent studies, a fully validated ABM of mackerel movements in the Norwegian Sea was developed to investigate the effects of noise from a 3D seismic survey on the population. This was achieved by adding a seismic vessel agent to the model, to represent the transect movements at four knots and simulating the related air gun pulses. The mackerel agents then made decisions in relation to the calculated direction, distance, received sound pressure level (SPL in dB re 1 μPa) and received sound exposure level (SEL, cumulative SEL in dB re 1 μPa2·s) from the active air gun at each time step of the overall ABM simulation. Using this procedure, it was possible to estimate the cumulative SEL of any agent at any time step and ultimately, the percentage of impacted agents as a function of received SEL.

Conclusions and ways ahead

DHI's studies illustrate the significant potential of ABM to replicate the movements of marine species in both natural and sound impacted circumstances. ABMs are, however, only as good as the required input data. In this regard, gaps in marine species movement data are apparent. While Telemetry datasets, which are the gold standard for this input, are becoming more available for an increasing number of marine life (see https://www.movebank.org/), additional research is warranted. This is also the case for behavioral responses of marine mammals and fish to noise, where data is particularly sparse. Among the datasets that have emerged, one study details responses in the form of dose-response functions examining the intensity of response as a function of the acoustic dose received.

It is evident the analysis paradigm is shifting towards dynamic approaches when assessing noise effects. This is an important consideration for industry, as well as regulators when making decisions on the most comprehensive and reliable technology. ABM is a proven and more holistic and dynamic option to that of the static approach and provides EIA regulators with a range of outcomes and scenarios, including uncertainty quantification. Thus, as applicable data becomes available, it may be apparent that static approaches are gradually phased out to make room for more validated animal response models.

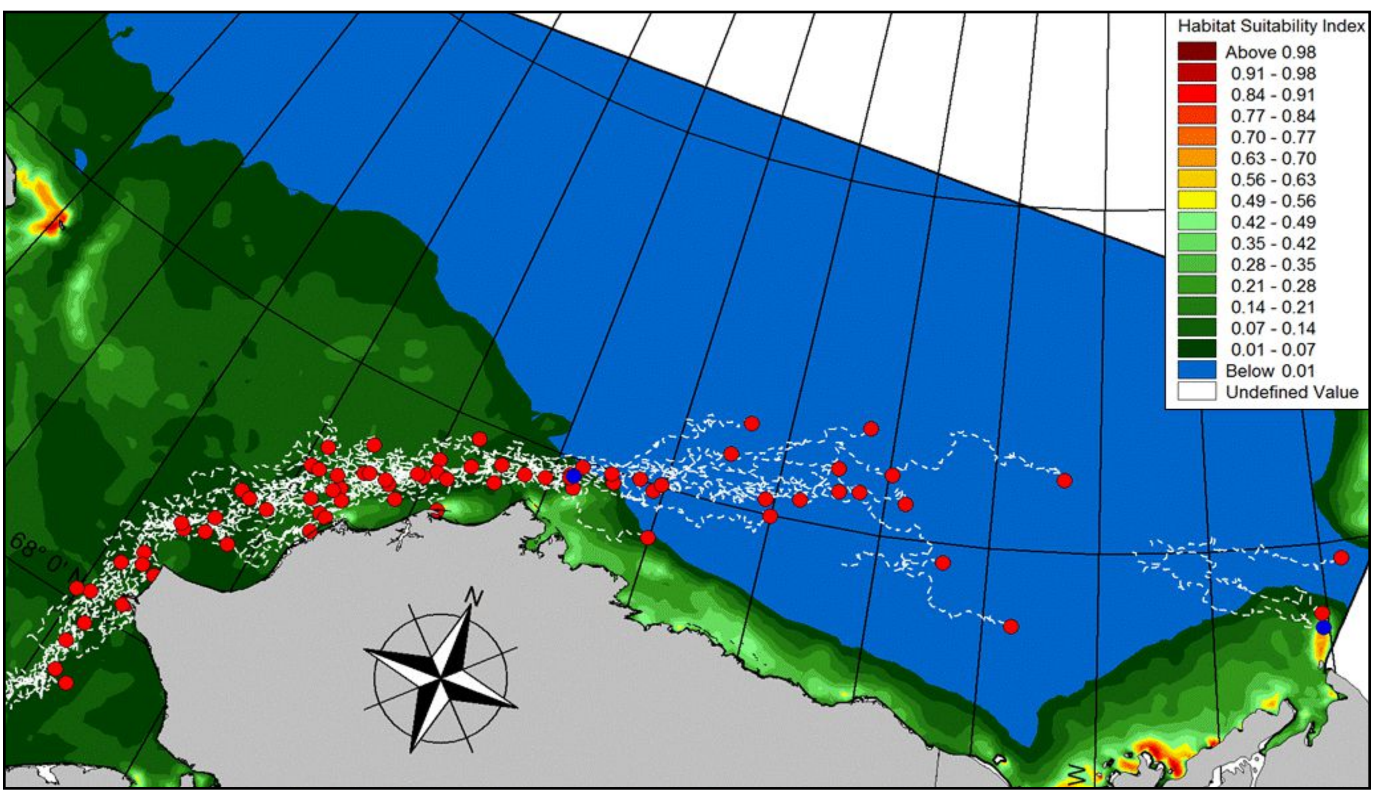


Figure 2: Example of a baseline ABM for bowhead whales in the Chukchi Sea (Snapshot of predicted spring migration {May 1, 2009}. Red agents are in a migratory study state, while deep blue agents have gone into a foraging mode. Background shaded areas indicate predicted habitat suitability; Thomsen et al., 2013) supported by Equinor ASA.

SOUNDS OF THE REEF

Snapping Shrimp

Probably the most ubiquitous sound in shallow temperate waters and thus the curse of all marine life sound recordists is the sound of the snapping or "pistol" shrimp. They produce an extremely loud pop (source level 220dB re 1 uPa or 80 kPa at 4 cm). This pop stuns their prey, which they can then dismember and eat without further ado. Words: DOSITS. Sound Source: CSA

Sergeant Major

Named from the military stripes they resemble, the sergeant majors school in groups of hundreds for feeding, but during the spawning season, the male will aggressively guard his nest. It is found worldwide in warm waters and abundant in Caribbean reefs as well as around islands in the mid-Atlantic region. Sound source: Steve Simpson

Outboard Motorboat

On smaller boats, like a zodiac, the small propeller produces a cavitation noise which is at higher frequencies than larger vessels. The smaller propellers also produce higher rotation rates, which also causes the propeller to make higher frequency noises. A zodiac, for example, can produce frequencies as high as 6300 Hz. Words: DOSITS. Sound source: Steve Simpson

PHOTO: Jon Hanson

Black Grouper

Black Grouper are found in the Western Atlantic from Massachusetts to Brazil. They are particularly associated with the southern Gulf of Mexico, Florida Keys, Cuba, the Bahamas, and throughout the Caribbean. Sound source: CSA

PHOTO: Monica Gagliano Martial Depczynski

Ambon Damselfish

Occurs mostly on coral reefs in the Western Pacific. Research has shown that if constantly threatened by predators, these small fish can grow a larger false 'eye spot' on the rear of the dorsal fin – and even more astounding, can also reduce the size of their real eyes. They are also able to recognize the UV facial patterns of individual Ambon Damselfish. Sound source: Eric Parmentier

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Ocean Sound

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IQOE
International Quiet Ocean Experiment

The International Quiet Ocean Experiment (IQOE) was launched in 2015 by the Scientific Committee on Oceanic Research (SCOR) and the Partnership for Observation of the Global Ocean (POGO). IQOE promotes new research, observations, and modelling related to levels, distribution, and trends of sound in the ocean and the effects of sound on marine organisms. IQOE brings together expertise from acousticians and bioacousticians to address these topics.

JASCO
APPLIED SCIENCES

JASCO Applied Sciences is a world leader in the analysis of underwater sound and its effects on marine life. From offices in Canada, the US, Europe and Australia we provide support for all aspects of environmental reviews and assessments of underwater sound impacts for the oil and gas, marine construction, energy, fisheries, and defence sectors. We design, develop and manufacture state-of-the-art oceanographic data acquisition systems to meet project demands for quality, endurance, reliability and performance.

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Noise from pile driving can harm fish and other aquatic wildlife. Marine Construction Technologies, PBC has developed a novel noise mitigation technology, a self-attenuating pile, that removes 80-90 percent of the underwater noise energy (20dB) during pile driving by reducing vibration. The company's piles are installed with standard equipment, simplify project implementation, and are ready for deployment in commercial projects.

OCEAN
SONICS

Ocean Sonics designs and manufactures icListen, the world's first smart digital hydrophone. Compact and easy to use, icListen's small size makes it the perfect tool for sound data collection. Listen in real-time to improve decision making or use as an acoustic recorder for long term deployments. Reliable, accurate and easy to use, icListen will improve the quality and success of your underwater sound measurements.

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Quiet-Oceans, European leader in the impact of underwater noise on marine species, offers unique solutions to the offshore industry and governments around the world to combine offshore projects with the protection of marine life.

To achieve this goal, Quiet-Oceans develops innovating technologies such as: modelling of real ambient underwater noise including its natural and anthropogenic components, and detection in real time of marine mammals. Quiet-Oceans has track records on all oceans.

The Scientific Committee on Oceanic Research (SCOR) was created in 1957 as an international non-governmental organization focused on ocean science. SCOR provides mechanisms for the global ocean science community to develop new research projects, solve methological problems that hinder ocean research, provide coordination needed to advance a variety of topics ocean science, and develop capacity for ocean science worldwide. National SCOR committees in 31 countries provide financial and management support for SCOR.

Seiche specializes in underwater acoustics and provides sound measurement, modeling and mitigation solutions to the oil and gas, renewables, construction and marine science sectors. Seiche is also the market leader in the provision of Passive Acoustic Monitoring (PAM) equipment to clients worldwide. Seiche offers full environmental service provision as well as baseline surveys, sound characterization services, modular buoy solutions and unmanned surface vehicles (USVs) for PAM in addition to a portfolio of analogue and digital regular and miniaturized hydrophone arrays.

For over 40 years, the Teledyne Marine brands have provided the industry with a broad range of high-quality, dependable hydrophones. Our offerings now span five Teledyne brands: RESON, Benthos, Geophysical Instruments, RTS, and AG Geophysical. From oceanographic research, to seismic operations, to monitoring industrial processes, Teledyne Marine has a range of hydrophones for reference measurement, reference projectors, passive arrays, positioning systems and tracking systems. For those with specialized requirements, custom-engineered solutions are available.

The University of Louisiana at Lafayette goes to great lengths – and depths – to understand the Gulf of Mexico, a dynamic ecosystem in its backyard. Its researchers build partnerships across campus, and across the globe, to examine the complex challenges the Gulf presents to the people who live along it and the animals that live within it. The University has research centers that serve as multidisciplinary hubs where this vital work occurs.

Discovery

Marine Robots for Passive Acoustic Monitoring

Words by Phil Johnston, AutoNaut USV

At its simplest, listening to the sounds of the sea involves nothing more than lowering an underwater microphone over a pier. However, new technologies for passive acoustic monitoring (PAM) emerge all the time and the field is now set to be revolutionized by marine robots.

A range of autonomous underwater vehicles (AUVs) and unmanned surface vessels (USVs) can now be fitted with hydrophones and sent to sea independently. It is even now possible for an unmanned aerial vehicle (UAV) to fly out to sea, dip in a hydrophone and return to shore with acoustic data.

The technology is impressive, but what does it actually offer in terms of data quality, data quantity, and crucially, is it cost-effective?

There are many methods already available for conducting PAM surveys – and many challenges. Selecting the right method for a particular mission may often involve compromise. A big question is always on balancing data quantity against data quality. For example, towing a cabled array from the stern of a conventional boat gives great mobility and acquires plenty of raw data through excellent spatial coverage, but high “self-noise” from the vessel engine impacts audio quality. A static sensor, whether mounted on the seabed or suspended from a buoy, cannot provide the same spatial coverage but will tend to result in a higher signal-to-noise ratio. The simplest answer might be to deploy a suite of sensors but this adds serious expense, and knotty issues of storage and management of data quickly emerge. Unless data can be safely received in real-time, the use of autonomous recorders will very likely involve dilemmas on the optimal sampling rate to conserve data storage space - and the worry that device failure risks losing all that valuable data to the blue depths. The challenges of successfully completing a comprehensive PAM survey involve the physical logistics of deploying and recovering these sensor packages. Reliance on a support boat often brings cost, time delays and safety concerns.

Given these challenges, what are these "marine robots"? And what solutions do they offer?

"Robot" is perhaps an unhelpful term. Marine autonomous systems (MAS) are undoubtedly becoming smarter and more self-sustaining, but most essentially follow waypoints with a human operator providing guided oversight. The various craft come in many shapes and sizes and offer varying capabilities for PAM:

Operating beneath the waves, the most widely used to date are buoyancy gliders, such as the Teledyne Slocum. Subsea gliders are able to collect data at depth for many weeks, cruising along at speeds of up to 1 knot.

Powered AUVs vary greatly in size and complexity, from EcoSub's uAUV to the Remus 600. With the addition of powered propulsion these mini-submarines offer more speed and manoeuvrability – but less endurance.

At the surface, there is now a wide range of proven USVs. Larger powered USVs, such as the L3 C-worker can readily tow a cable and essentially share the pros and cons of PAM from a conventional vessel – albeit with the safety advantage of no humans working offshore.

Renewable-energy-powered USVs derive energy from the waves, sun and wind, enabling longer, continuous missions at sea of many weeks' duration. The lack of engine and ability to safely tow a cable should also mean pristine sound recordings. The Liquid Robotics Wave Glider has led the way in marine science, but AutoNaut, SailDrone and other USVs have now matured.

As for those UAVs, range is limited by battery life, but the concept is for a 'copter drone to fly out to sea, dip in a hydrophone – and obtain short, sharp recordings.

While UAVs may still be in the test stage, AUVs, Buoyancy Gliders and USVs for PAM are now well advanced.

Ambitious programs such as the National Oceanographic Centre's (NOC) MASSMO program have really pushed forward the development of such marine autonomous systems for PAM. Lessons continue to be learned and a vital area of development is refining the integration of hydrophones. This is of particular relevance in addressing the knotty issue of self-noise. On most MAS, the acoustic sensor is by necessity, located close to the moving parts of the vehicle and is prone to electrical interference and engine noise from the platform itself. The simplest response is to extend a PAM cable to distance the sensor away from all this but, especially in an autonomous system, undue entanglement risk and technical capability may preclude this. Smart operation also has a role to play, by detecting potential hazards, carefully managing the use of backup thrusters in tune with the aims of the mission. Crucially, deeper integration is key, and this is the subject of ongoing activity in various combinations of sensors and platforms.

Development continues apace but full-scale projects remain at a pioneering stage. A recent mission by a wave-propelled AutoNaut USV offers an example: A 5-meter AutoNaut was launched directly from a remote beach and transited independently to the study area. In missions of up to four weeks, the USV conducted pre-set transects at an average of 1.5 knots. A 25-meter long cable of two hydrophone sensors was towed from the stern of the craft. Raw data was recorded onboard throughout and diagnostic checks – demonstrating that the data were safe – were relayed to land via a satellite link. Crucially, the mobility, low self-noise and unobtrusiveness of the USV achieved the aim of recording the underwater vocalizations of whales and dolphins. The mission provided substantial cost and safety advantages over conventional methods – which, in this instance, would have involved significant deployment challenges.

A similar story is emerging with the deployment of other such MAS for PAM. The combination of mobility, low self-noise is key – but good mission and operational planning remain vital. The exact cost-effectiveness of MAS is yet to become fully clear however. Capital cost may be coming down but is often still high. The sums can be compared only on a project-by-project basis - with the inclusion of all the personnel, logistic and vessel costs involved in a complex study program. Mission specifics will determine whether this diverse range of new technologies offer advantages or disadvantages relative to existing techniques.

The challenges of successfully completing a PAM survey are significant. Key to acquiring good quality underwater acoustic data is placing the sensor in the right place and at the right time. In choosing the best method of doing so, the simplest method may still be the most cost-effective. For a more ambitious PAM project, a suite of methods may be necessary. Increasingly, unmanned technology is being deployed to extend capability or to replace traditional methods. This advance of marine autonomous systems is undoubtedly beginning to change the way PAM surveys are designed and completed – in science, defense and industry.

Making Waves in Acoustic Science

Words by Roxanne Holmes, Tim Gordon, Kieran McCloskey, Isla Keesje Davidson, Emma Weschke, Lucille Chapuis and Harry Harding, SouthWest Aquatic Group for Bioacoustics and Behavioural Ecology

Photo: Isla Keesje Davidson. Audio: Eric Parmentier

Over a decade of sound research

In the early 2000's a ground-breaking discovery was made about larval fishes: organisms, which were previously thought to passively disperse on ocean currents with no control over their distribution, were observed orienting towards reefs and swimming successfully against ocean currents. Speculation began about how these minute larvae could find their way back to reefs over such great distances in the featureless open ocean. Acoustic cues eemerged as a critical driver of navigation, since underwater sound travels more than four times faster in water than air, without disruption by currents or poor visibility as seen in chemical and visual cues. Steve Simpson of the University of Exeter and Andrew Radford of the University of Bristol were involved in much of the initial research on the role of sound in the ocean and have since built a vibrant research group. Here we provide a few stories about some of the diverse past and present research of the group.

Natural soundscapes

Soundscapes are the unique combination of all of the sounds in an area. In shallow-water environments, this can include a myriad of fish vocalizations and shrimp snaps set over a backdrop of the deep whir of waves, wind and sometimes rain. These little symphonies are loudest at dawn and dusk of the new moon and guide many larval fishes to the coastline to settle and begin their lives on reefs. Once settled, these soundscapes provide organisms with information about the habitat, predators and even the biodiversity of the area. Sound quality in an area is in many cases synonymous with habitat health. However, as areas succumb to mass coral bleaching and overfishing, they begin to go silent. Degradation has become audible, and the signal guiding these fish home is being lost.

'Choral reefs'

Acoustic communication plays a crucial role in the lives of underwater creatures — from the love songs of humpback whales to the violin squeaks of spiny lobsters — animals use sounds to communicate, attract mates and defend territories. All fishes have a sense of hearing, even when they cannot produce sound themselves, and over 800 species of fish are known to communicate acoustically. Damselfishes — small territorial coral reef fishes — use 'chirps' and 'pops', while aggressively chasing their enemies, as a way to defend their resources from intruders.

So much remains unknown about the use of sound for communication in many species. For a sound to be defined as a form of communication it must be produced by a signaller in a particular context (for example, a fish warning of an approaching predator), be detected by a receiver (a fellow fish), and trigger a response in the receiver (fish fleeing to safety). Some fish species are constrained by their anatomy and are not known to communicate acoustically, yet recent studies have been exploring the potential for them to produce sounds without vocalization.

Manta rays

Reef Manta rays, *Mobula alfredi*, are one of the largest ray species known, reaching up to 5.5 meters long and weighing several tonnes. These giants are known to conduct 'breaching behavior', in which they surge up above the water surface and flop back into the waves with maximum impact, making as loud a clap as possible. This sound can travel many kilometers underwater, potentially producing a characteristic signal. If mantas were breaching to produce an acoustic signal, who is the receiver of this signal and what is the context for such a signal? Could mantas be using their weight (similar to that of a young elephant) to be ocean drummers, using body percussion as a means of communication to induce cooperative feeding or to attract a mate? As the research continues we are reminded of how much remains to be discovered about the underwater acoustic environment.

A degraded coral reef following bleaching. Photo: Monica Gabell. Audio: Steve Simpson

A family of orangefin anomonefish (Amphiprion chrysopterus) living in a bed of branching Acropora coral. Photo: Monica Gabell

Human noise

Male oyster toadfish call for females with a special 'hum' during the reproduction season (a song compensating for their lack of beauty!), their mating success dependent upon their acoustic courtship performance. Thus, vocal behaviors are essential for these species, ensuring defense of their territories, maximizing reproduction and ultimately shaping survival. Unfortunately, most of the acoustic signals produced by fishes fall within the lower frequency range (100 Hz – 1 kHz) which overlaps with many man-made noise sources, including motorboat noise, construction work (pile-driving) and seismic surveys. As a result, noise pollution can have detrimental effects on aquatic animals. Close to the source, animals can suffer instantaneous death or physical injuries. Physiological effects include stress, reductions in growth rates and abnormalities in developing larvae. For instance, juvenile spiny chromis, a species of damselfish, show reduced survival when exposed to loudspeaker-playback of motorboat noise.

However, the most widespread disruption occurs at greater distances from the noise source, where the sound is quieter and behavioral effects are most prominent. Noise has been shown to affect foraging, parental care of young and orientation behavior when larvae are finding new places to call home. Man-made noise can disrupt acoustic communication by drowning out the calls of fishes, making them inaudible or less clear. This can be potentially damaging, if, say motorboat noise is prominent during the reproductive humming of the toadfish; intended signals may be completely masked, and therefore not detected by the females, and the reproductive success of these males compromised. These findings reveal that noise can have impacts on key life-history events for aquatic creatures, potentially threatening whole populations.

To date, much of the research investigating impacts of noise pollution has involved single-species responses. However, in order to understand fully the implications of this pollutant on aquatic ecosystems, we need to understand how entire communities might be affected. Not all species are born equal, with their ecology, life histories and hearing sensitivities dictating how they may respond to noise. As such, there are likely to be winners and losers in an environment filled with the sound of passing boats and offshore construction. Understanding these interactions will allow scientists to predict how ecosystems may change and function differently in an increasingly noisy world.

Nocturnal noises

Picture a coral reef. You're likely imagining a sunlit mass of vibrant busy fishes weaving amidst complex structures of diverse corals. But what many of us miss out of this mental picture are the mysterious nocturnal fishes that lurk in the shadows of overhanging coral plates or dwell in gloomy caves, seeking solitude for sleep; hidden from the prying eyes of predators. After dark the reef undergoes a dramatic transformation. The vibrant fish community of the sunlit world flees to sleep in alcoves within coral branches. A frantic fog of invertebrates rises from the sea bed to feed on plankton, and the signature invertebrate 'crackling' and fish 'chirps' and 'grunts' of the daytime reef soundscape transitions into a night-time roar of 'snaps'. These invertebrates are an abundant and reliable food source for

Boat damaging a reef. Photo: Monica Gabell.

the awakening nocturnal fish, the near absence of light forces these fishes to rely heavily on sounds and smells. *Holocentrids* are nocturnal fish with a specialized adaptation linking their swim-bladder to their ears. Much like when you stand too close to a speaker and you feel your lungs vibrate, *Holocentrids* use their vibrating swim bladders to detect faint waterborne soundwaves through their body, likely allowing them to communicate, navigate the reef and hone in on prey in the darkness.

In the 21st century, motorboat noise increasingly dominates coral reef soundscapes. Much of the work on noise pollution has only explored the influence of noise on fishes active during the day. Much like their surroundings these fishes have been left in the dark. If you rely on sound to survive, can you sleep in a piercingly noisy world?

Orangefin clownfish, (Amphiprion chrysopterus). Photo: Isla Keesje Davidson

A ripple of hope

In a time when we are inundated with stories about the tragic status and outlook for our planet, success stories could be the key to igniting action and inspiring hope. Fortunately, compared to other major environmental issues such as climate change, noise pollution is more approachable and can be immediately addressed. We can control when, where and how we make noise without majorly disrupting day-to-day life. Vessels can be made quieter by redesigning propellers and promoting the use of electric engines, ships can approach ports more slowly and shipping lanes can be re-routed around known migration routes. Coastal construction can be conducted outside of breeding seasons or farther away from breeding grounds, and quieter, alternative approaches to pile-driving and seismic surveys can be used. These noise-conscientious changes can have a tremendous impact on the sounds we are introducing into natural environments, limiting subsequent effects on marine life.

These practices can, and already are being implemented. For example, when restoring Dorset's Swanage Pier in the UK, construction management and environmental agencies successfully cooperated to plan construction around the breeding season for protected resident short snouted and spiny seahorses. Furthermore, the construction utilized 'vibro-piling', a quieter, less damaging method than standard impact-hammer pile-driving. Cooperation allowed for the successful reduction in consequences for two protected species without hindering the necessary restoration of a historic pier. Success stories such as this one can have a knock-on effect, where one small win leads to another. These accomplishments are already happening, and if we can shift the narrative to focus on how we, as a society, are successfully improving our relationship with the natural world, we can then inspire backing from all corners of our planet.

New Insights

The Latest Discoveries in Science

Ocean Sound Research in
Frontiers in Marine Science

Sound is an integral part of ocean habitats: the calls of marine life, the roar of wind and waves, and – increasingly – the buzz of boats, the bang of oil rigs and the pings of seismic airguns, echo sounders and navy sonar.

This noise from motorized vessels, industrial development, and surveying can affect both habitat-use decisions and communication by fish, marine mammals, and birds – which in turn affects overall distributions of both prey and predator species. However, as most of the following articles published in *Frontiers in Marine Science* point out, large gaps remain in our understanding of the effect of anthropogenic noise on many marine species. Sound could also help us to better understand ocean life, as one study in this selection explores in a novel way – by making music from animal migration.

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frontiers
in Marine Science

Greenland Sharks: Protecting the Natural Soundscape

The Greenland shark *(Somniosus microcephalus)* is the world's longest-lived vertebrate, but many questions remain regarding its biology, physiology, and ecology. A gap analysis aiming to guide research and management priorities for this species notes the potential impact of increasing noise from vessels and industrial development the Arctic, including needing to adapt to changes in prey availability in areas where seismic surveys are conducted. The article recommends that disturbances to the natural soundscape be considered in ecosystem-based management of the region.

Edwards JE, Hiltz E, Broell F, Bushnell PG, Campana SE, Christiansen JS, Devine BM, Gallant JJ, Hedges KJ, MacNeil MA, McMeans BC, Nielsen J, Præbel K, Skomal GB, Steffensen JF, Walter RP, Watanabe YY, VanderZwaag DL and Hussey NE (2019) Advancing Research for the Management of Long-Lived Species: A Case Study on the Greenland Shark. *Front. Mar. Sci.* 6:87.

doi: 10.3389/fmars.2019.00087

Petrels: Anthropogenic Noise a Knowledge Gap

Anthropogenic alterations on land and at sea have led to a poor conservation status for many petrels, a seabird group found in all the world's oceans. A gap analysis to identify the most important threats to petrels notes that increasing noise from urbanization and development may affect these birds. Although such effects have not been well-studied, it has been suggested that such noise may attract some individuals to dangerous areas, and may have a short-term negative effect on parental care and chick provisioning behavior in at least one species.

Rodríguez A, Arcos JM, Bretagnolle V, Dias MP, Holmes ND, Louzao M, Provencher J, Raine AF, Ramírez F, Rodríguez B, Ronconi RA, Taylor RS, Bonnaud E, Borrelle SB, Cortés V, Descamps S, Friesen VL, Genovart M, Hedd A, Hodum P, Humphries GRW, Le Corre M, Lebarbenchon C, Martin R, Melvin EF, Montevecchi WA, Pinet P, Pollet IL, Ramos R, Russell JC, Ryan PG, Sanz-Aguilar A, Spatz DR, Travers M, Votier SC, Wanless RM, Woehler E and Chiaradia A (2019) Future Directions in Conservation Research on Petrels and Shearwaters. *Front. Mar. Sci.* 6:94.

doi: 10.3389/fmars.2019.00094

Whales and Seals: Losing Communication Space

Underwater noises from motorized vessels overlap in frequency, space, and time with marine mammal sounds – which may hinder effective communication between individuals. Modeling of vessel and natural ambient noise in Glacier Bay National Park, USA, indicates that typical summer vessel traffic in the park substantially reduces the communication space of singing whales, calling whales and roaring seals, especially during daylight hours and even in the absence of cruise ships. The study's metrics and visualizations create a common currency to describe and explore methods to assess and mitigate anthropogenic noise.

Gabriele CM, Ponirakis DW, Clark CW, Womble JN and Vanselow PBS (2018) Underwater Acoustic Ecology Metrics in an Alaska Marine Protected Area Reveal Marine Mammal Communication Masking and Management Alternatives. *Front. Mar. Sci.* 5:270.

doi: 10.3389/fmars.2018.00270

Omura's Whales: Particularly Vulnerable to Coastal Noise

In addition to masking communication, anthropogenic noise causes behavioral responses in whales, including changes in travel routes and distribution. The first compilation of global accounts of Omura's whales suggests this species – only described in 2003 – may be particularly vulnerable to such impacts, due to their predominantly near-coastal distribution and at least some populations being non-migratory with local, potentially restricted ranges. Furthermore, the shallow water nature of many populations could exacerbate the impact due to the propagation characteristics of low-frequency noise sources in shallow water.

Cerchio S, Yamada TK and Brownell RL Jr (2019) Global Distribution of Omura's Whales (Balaenoptera omurai) and Assessment of Range-Wide Threats. *Front. Mar. Sci.* 6:67.

doi: 10.3389/fmars.2019.00067

Elephant Seals: Turning Movements into Music

Understanding the movement of marine megafauna across the ocean is largely based on tracking individual animals. While this has led to major progress, understanding the collective movements of a group remains a challenge – in part due to the massive amounts of data required. As an alternative to visualizing more than 1 million positions from 321 elephant seals moving in four dimensions over 10 years, one group of researchers coded this data into sound. The harmony in this sonification suggests a remarkable degree of coherence in the seals' movements.

Duarte CM, Riker P, Srinivasan M, Robinson PW, Gallo-Reynoso JP and Costa DP (2018) Sonification of Animal Tracks as an Alternative Representation of Multi-Dimensional Data: A Northern Elephant Seal Example. *Front. Mar. Sci.* 5:128.

doi: 10.3389/fmars.2018.00128

Capturing Sounds to Capture Hearts:

Ocean Acoustics as a Tool for Science Engagement

Words by Tim Gordon, Lucille Chapuis, Isla Keesje Davidson, Harry Harding, Roxy Holmes, Kieran McCloskey, Emma Weschke and Steve Simpson, all from the University of Exeter and/or the University of Bristol

One of the authors (Tim Gordon) uses a hydrophone to record the sounds of ice movement in the Central Arctic Ocean image credit: Tegid Cartwright.

"I consider the sound of the sea to be part of my body." – Derek Walcott, winner of the Nobel Prize in Literature, 1992

Sounds define our mood and motivate our actions. Birdsong relaxes; crying toddlers can grate; sobbing demands empathy; laughter induces contagious smiles. The harsh edge of an irritated tone of voice completely subverts the infamous "I'm fine", while a simple "hmmm" can convey anything from disapproval or uncertainty through to curiosity, comfort or sympathy. We use music to control the mood of a room, we chant and clap to encourage, we boo and hiss to show disdain. From Mozart to Keating, from laughter to weeping, from cheering to shrieking; it is clear that our ears give us more than just banal information about the world around us. Sound is a communication channel for the most intense emotional moments in our lives.

And yet, we think of the underwater world as silent.

Most people have never heard anything under the sea. We spend most of our lives on land, and when we do venture into the ocean it tends to be on boats or ships. If we do plunge into the sea, we find that our ears don't work particularly well underwater, or the sounds that we would hear are drowned out by nearby boats or the flow of bubbles that we create with our body and SCUBA equipment. It's little wonder that most of us have no idea what ocean ecosystems sound like.

But when we do take a deep breath, clear our ears, pause and listen under the surface of the ocean, we discover a whole new world. Sound travels five times faster underwater than it does in air, and hearing is the dominant sensory modality for many sea creatures. Narwhals emit repetitive bursts of high-pitched 'pings' per second as they hunt fish by echolocation under sea ice; herring expel flatus to hear where each other are and maintain shoal cohesion on dark nights; baby fish navigate to far-away coral reefs by listening out for their tell-tale cacophony. In fact, ocean soundscapes are as full of curiosity, mystery and wonder as many other aspects of the deep blue. The constant crackles, pops and buzzes of healthy ecosystems reflect their diversity of life as much as any pictures. Clownfish chatter, cod grunt, shrimp click, damselfish whoop, dolphins whistle and the songs of whales reverberate for miles around. Many of these ocean sounds are unexpected and curious, and have been capturing imaginations for hundreds of years. Samuel Taylor Coleridge described some of the bizarre and awe-inspiring sounds associated with Arctic sea ice movement in his *Rime of the Ancient Mariner* in 1798:

"The ice was here, the ice was there,
The ice was all around:
It cracked and growled, and roared and howled,
Like noises in a swound!"

But today, with the help of advances in hydrophone technology, we can hear far more than could Coleridge's famous mariner through the wooden hull of his ship. And we can use the incredible sounds of the sea to spark interest, inspire awe and promote conservation of marine ecosystems.

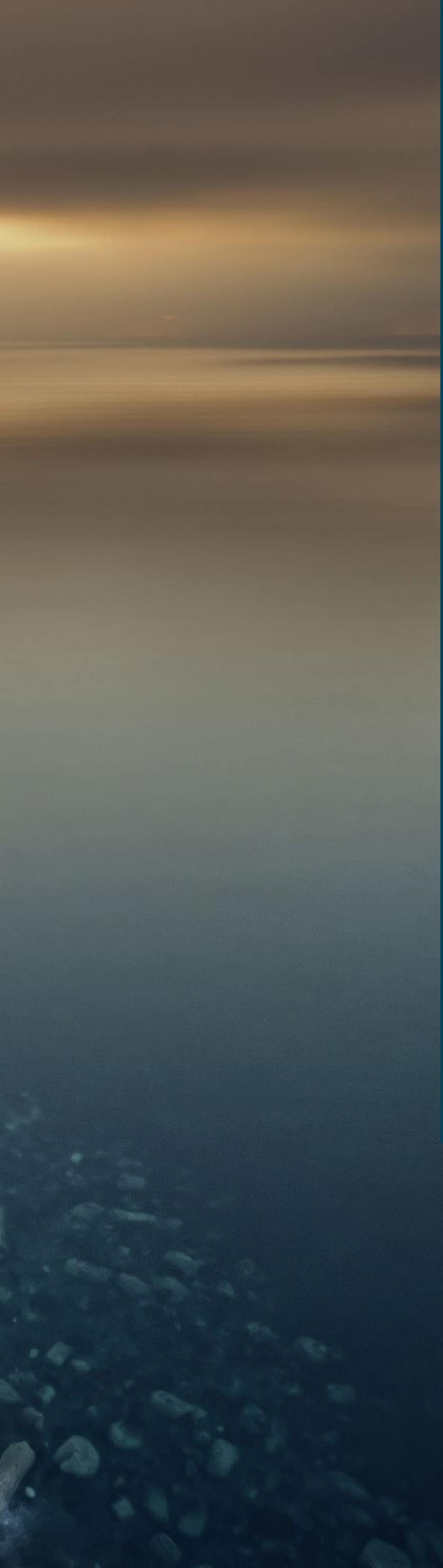
"Fish make those noises?! Woaaah, cool!" "What are they saying to each other? Can we talk to them?" "I want to sing like a whale!" exclaimed children at school science engagement events in Exeter, UK, 2018. The delighted exclamations of children discovering marine bioacoustics for the first time reveal the engagement power afforded by this discipline of research. Introducing children to underwater sounds offers a whole new dimension by which to understand the oceans. Adults can be equally astounded by the acoustic capabilities of many marine creatures. "Thirty years I've been keeping fish now, and I had no idea they could do *that*. Mind-blowing!" said an audience member at the Society of Experimental Biology Annual Symposium in Florence, Italy, 2018. Multisensory approaches to education appeal to a wide range of learning styles; the chance to interact with what we can hear, as well as what we see, inspires engagement from anyone who dares to listen.

A clownfish in its host anemone in Sulawesi, Indonesia. Clownfish are members of the damselfish family; fish in this family use their teeth and their swim bladders to make a range of chattering, popping and whooping sounds Image credit: Tim Gordon.

A coral reef at Heron Island, Great Barrier Reef. The constant clicks, buzzes, pops and chatter of fish and invertebrates make coral reefs some of the oceans' loudest ecosystems. Image credit: Tim Gordon

Exploring ocean acoustics also provides a new means to explore issues of marine conservation. If we can hear ecosystems living, then we can also hear them dying. And as human exploitation of the oceans increases, we leave our own acoustic footprint, or shadow, in the sea. The biological orchestra of the 21st century ocean is becoming quieter as animal populations decrease, while at the same time their acoustic space is being invaded by the deafening crescendo of industrial shipping, offshore construction and deep-sea mining. We've all seen the worrying transformation of our oceans from pristine natural environments to human-dominated degraded systems – but have we *heard* it happening? Understanding ecosystem change from an acoustic perspective provides an alternative angle through which to reinforce tired and increasingly-ignored conservation messages.

The oceans and the creatures that inhabit them are without doubt a visual spectacle. But we must not neglect what is at first not obvious. Adventuring beyond this immediate visual appeal gives us a more holistic, engaging and inspiring picture of marine life. Incorporating ocean acoustics into multisensory engagement programmes has the potential to capture imaginations, speak to different learning styles and inspire action at many levels. To reach people's hearts and minds, we should let the ocean sing.



The Forgotten Measurement:

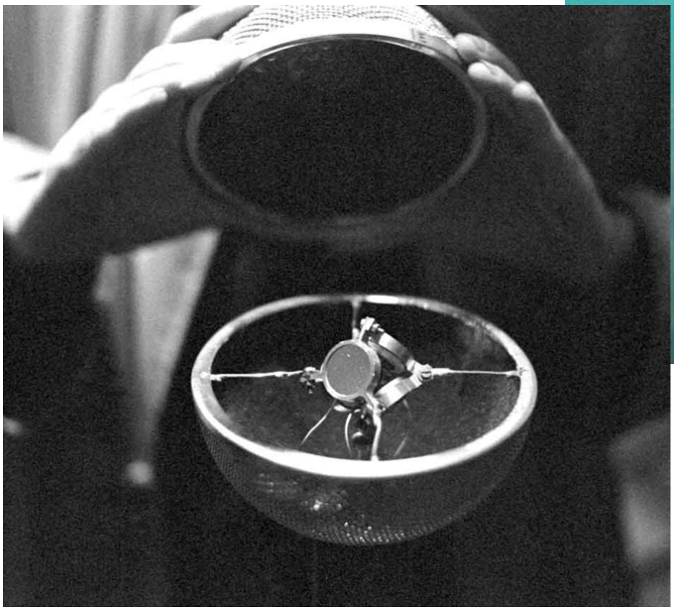
Sound Pressure and Particle Velocity

Words by Angelo Farina, Enrico Armelloni and Daniel Pinardi, University of Parma

In the last few years, the importance of assessing the environmental impact caused by underwater noise generated within human activities has grown significantly, mainly due to the effects found on the fishery industry and from the reduction of marine protected areas.

A large number of surveys and tests have been performed to evaluate the effect of noise on marine species. However, in most cases, the only physical quantity being measured was the sound pressure to which are typically sensitive mammals and birds. Conversely, there is a strong experimental evidence that most marine species do not have sound-pressure sensors. Instead, they are equipped with a sensorial system capable of detecting mostly kinematic quantities such as water particle velocity. This vector quantity carries the spatial information of the sound field, making it possible to distinguish the Direction-of-Arrival (DoA) of sounds, that is the capability of localizing sound sources.

Unfortunately, most acousticians, working either in air or underwater, seem to have forgotten these basic concepts, and assume that particle velocity is just proportional to sound pressure, which in general is not true.



The first prototype of the Soundfield microphone. Credit: Stephen Thornton

In this article we explain how it is possible to record sound pressure and particle velocity together underwater, thanks to an old theory developed in the seventies. Most studies made in the past on the effect of environmental noise pollution and on the sensitivity of marine species to underwater noise were, in fact, substantially wrong: limits specified only for sound pressure caused a systematic underestimation of the potential impact of noise, strongly biasing results.

Pressure and Velocity: From the Basics to Ambisonics Theory

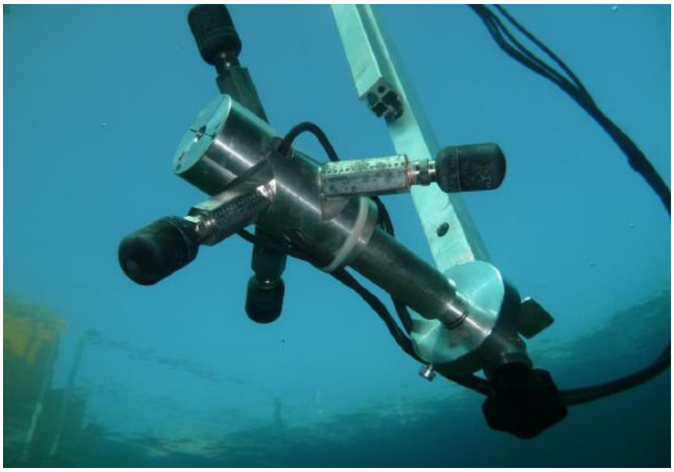
The dualism between sound pressure and particle velocity is usually introduced at the very first lesson of every good acoustics course. In general, it is presented as a cause-effect relationship: at the source, a vibrating body with a given velocity causes pressure fluctuations in the fluid in contact with it, which propagate in the medium to the receiver as acoustical waves. The simplest case to create this condition is a piston that moves in an infinitely long duct, generating the so called plane, progressive wave.

In such an example, pressure and velocity are related with a linear proportional law, but obviously, this case is as simple as unusual. In most cases of the real world, this relation is a lot different and much more complex. The same happens underwater and in particular close to the coastline, where for several reasons the particle velocity becomes substantially independent from sound pressure. Moreover, the sound pressure recorded by a normal microphone or hydrophone is an "omnidirectional" quantity without any directional information, while a particle velocity sensor is sensitive also to the Direction-of-Arrival of the sound wave. Hence, for fully describing the sound field in a point of space, a special probe capable of recording both pressure and particle velocity is required, and this has been made possible by the pioneering work of a British scientist, Michael Gerzon.

The tetrahedral array of four hydrophones. Credit: University of Parma

In the seventies, Gerzon successfully developed a complex theory known as Ambisonics for recording and playing back a three-dimensional sound field, employing a special set of mathematical functions called "spherical harmonics." He also built, with Peter Craven, a compact microphone array named Soundfield Microphone, capable of producing this spherical harmonics expansion. Unfortunately, the analog circuitry of that time showed poor performance, causing the initial failure of Ambisonics. Nowadays, thanks to digital electronics, Ambisonics is seeing a new wave of success for virtual reality applications, but still struggling to spread to other fields.

The first attempts of bringing the Ambisonics technology underwater date back to 2009, when a tetrahedral probe of four hydrophones, conceptually similar to the Soundfield microphone, was built. Since that time, several underwater hydrophone arrays, even more complex, were developed for studying underwater noise. Thanks to the spherical harmonics expansion, it has been demonstrated that "traditional" conversion of SPL into PVL based on the planewave assumption had resulted in a systematic underestimation of the underwater noise velocity signal. Combining the pressure and velocity signals properly, the trajectory of underwater noise sources like boats had been tracked over time too and, lastly, the usage of a panoramic camera system made possible to get underwater 360° video providing a realtime panoramic visual display of what happens around the probe.



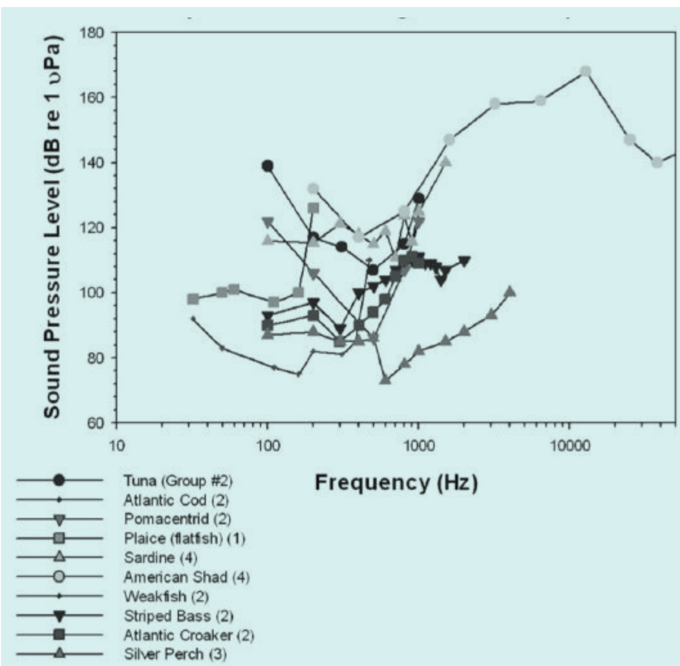
The tetrahedral array of four hydrophones. Credit: University of Parma

Sensitivity of Marine Species to Pressure and Velocity

It has only recently recognized by the scientific community the need to also record particle velocity (or particle acceleration) for assessing the effect of noise on marine species. We report here a short passage coming from the recent paper of Sophie L. Nedelec and others:

"Audiometric studies have long recognized the significance of particle-motion detection in fishes and invertebrates (e.g. Chapman & Hawkins 1973; Fay 1984; Popper, Salmon & Horch 2001), yet investigations of acoustic phenomena in the ecology of aquatic systems have previously focused on only one component of the sound field: sound pressure (see for exception Banner 1968; Sigray & Andersson 2011).

From an ecological perspective, there are several key reasons why we need to better understand the particle-motion component of underwater sound. First, while aquatic mammals use sound pressure, all fish and many invertebrates (i.e. most acoustically receptive aquatic organisms) detect and use the particle-motion component of sound (Popper, Salmon & Horch 2001; Bleckmann 2004; Kaifu, Akamatsu & Segawa 2008)."



Hearing threshold for a number of marine species. Credit: BOEM

The acoustic analysis of shelters and other nests employed by fishes presents another example of how the particle velocity evaluation could have provided a deeper understanding of their behavior. It had been suggested that some species choose shelters due to their acoustical amplification characteristic. However, this characteristic was assessed only in terms of sound pressure, neglecting the boost effect to particle velocity caused by the geometry of these cavities.

Many experiments for determining the sensitivity of fish and invertebrates to noise have been performed using water tanks equipped with a single underwater loudspeaker for generating the test sound, and then evaluating the behavioral response of the species under study. However, a single sound source inside a small tank drives the acoustic pressure quite linearly and does not excite properly the particle velocity field. This means that, when defining the threshold of sound level causing reactions from the marine species, the annotated value is that of sound pressure, and the particle velocity level is instead probably much smaller, and definitely unknown. This sheds a deep shadow on most studies performed under such controlled conditions.

A comprehensive analysis of known literature regarding fish sensitivity to noise is found in a public report of the U.S. Department of the Interior, published in 2014, which summarizes the known information obtained from such controlled experiments. We note that the hearing threshold of marine species is expressed in terms of Sound Pressure Level instead of Particle Velocity Level, which was generally unknown during those experiments, as no velocity transducers were employed. Only in very few studies, both in tanks and in situ, the problem of fish sensitivity to fluid motion and not to sound pressure is recognized, albeit the methods employed for addressing the issue are slightly questionable, as the values of particle velocity or particle acceleration were estimated theoretically, instead of being properly measured.

The conclusion is clear: underwater acoustical surveys for evaluating potential noise pollution effects should be made with proper equipment capable of recording both sound pressure and particle velocity. Nevertheless, studies on the reaction of marine species to noise should employ systems capable of controlling pressure and particle velocity with test sounds. Both goals can be achieved with the old Ambisonics theory applied to hydrophone or loudspeaker arrays, either to be installed inside a water tank or positioned around the fish shelter for in situ evaluations. This leads to the assertion that most of the work done in previous decades is fundamentally wrong, as wrong was the physical quantity observed. Now, it is time to collect new data on environmental noise pollution employing pressure-velocity probes and to repeat experiments aimed to establish the hearing threshold of fishes and other animals when stimulated by a combination of pressure and particle velocity waves.

COMPASS: Listening Between Borders

Dr. Denise Risch, an expert in underwater acoustics and marine mammal ecology, with the Scottish Association for Marine Science (SAMS), shares insights from her current work as part of an EU INTERREG VA funded programme. COMPASS will help to uncover some of the mysteries surrounding these very mobile species in the seas off Scotland and Ireland.

What is the COMPASS project, and where does your expertise in marine mammal acoustics fit into it?

The COMPASS project is a five-year multi-disciplinary project, aiming to establish a network of oceanographic and acoustic moorings within, and adjacent to, marine protected areas (MPAs) across the border region of Northern Ireland, Ireland and western Scotland. The EU funded project will produce new marine monitoring data for emerging areas of environmental concern, including ocean acidification and the long-term impacts of anthropogenic noise on marine life. We aim to develop a clearer understanding of what changes in the oceanographic climate have on underwater habitats, fauna, and flora. The ultimate goal of the project is the development of effective future monitoring programs for MPA networks.

Within the COMPASS project, I am leading the work package on passive acoustic monitoring of anthropogenic noise and vocalizing marine species such as marine mammals and fish. We will integrate oceanographic and sound data sampled at similar scales to investigate environmental drivers affecting the seasonal distribution of these highly mobile and often elusive species that are otherwise difficult to study. We will also assess the impact that underwater noise, from shipping, aquaculture or offshore construction can have on these species.

Why is your focus on the seas of Scotland and Ireland?

When it comes to highly mobile species such as marine mammals and migratory fish, there are no boundaries in the ocean. These species are far-ranging and inhabit vast stretches of the ocean. We need to learn more about their seasonal distribution and the underlying patterns for it so that we can minimize and mitigate conflict between human activities and important habitats. The border region between Scotland and Ireland is an important but understudied habitat for many marine mammals, as well as fish species. Funded by the European Union's INTERREG VA Programme, via the Special EU Programmes Body (SEUPB), the COMPASS project aims to better understand this important coastal environment, while also increasing collaboration and capacity across this remote region.

The wider North East Atlantic is a fascinating part of the world, with the North Atlantic current flowing through and the meeting of the Atlantic and Arctic oceans. What are the main challenges for marine mammals in this marine region, and how can COMPASS help to address these?

Coastal upwellings and tidally driven ecosystems provide ideal feeding grounds for several species of marine mammals in this region. The main challenges these species are facing include the issue of entanglement in fishing gear, the risk of collision with large vessels and acoustic harassment and injury from underwater noise (e.g., shipping, navy sonar, acoustic deterrent devices used in aquaculture and offshore construction work). COMPASS will provide better data (especially during winter months where data is mostly lacking) on the seasonal distribution of these species. This will help us to identify high-risk areas and times of the year where species overlap with human activity, a crucial step in mitigating human impacts. Also, we will be able to contribute data on the seasonally changing underwater noise environment and highlight hotspots where marine species and noise overlap with the aim to reduce such interaction in the future through better marine spatial planning and noise mitigation.

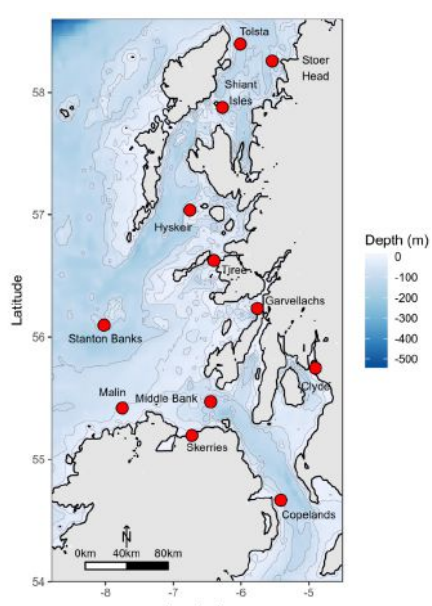
What do you hope to find out through the COMPASS project that you don't know already about marine mammals in the region?

Due to the difficulty in collecting visual sightings data at night and during adverse weather conditions, there is a general lack of data on the distribution of marine mammals in UK waters during winter months. The acoustic COMPASS array will, for the first time, provide year-round data on the distribution of marine mammals across the border region of Scotland and Ireland. We have already detected large baleen whale species such as humpback and fin whales, which are rarely seen during land-based visual surveys. These species tend to be further offshore, so this is a really exciting start to the project.

How would you define success in the project?

Success will be defined by the use of project results to shape and influence marine policy, such as the designation and management of MPAs in the region. First of all, to keep the project going, we are hoping not to lose too much of our equipment to storms or fishing activities! So far, a year-and-a-half into the project, we are doing quite well.

I would also think the project to be successful if the long-term collaborations and capacity developed during this project, could be maintained and further developed beyond the duration of the project. The ocean and the creatures living below its surface don't recognize national borders, so we must look at the ocean as a whole and work across nations to improve our knowledge of this vast ecosystem.



How can you build upon your own COMPASS work to help us understand marine mammals off the UK and Ireland?

Long-term data, collaboration, and data sharing is crucial to understanding the distribution and population dynamics of highly mobile species such as marine mammals and migratory fish. We are already collaborating with several other research institutes, non-governmental, and citizen science projects in the region to enhance the value of all our combined data sets and will continue to do so in the future. The multi-disciplinary approach of the COMPASS project is also key to its success and will help us to better understand the ecosystem that marine species depend on and the pressures they are facing.

You have used underwater acoustics to detect the elusive Minke whale. If funding allowed, what is the potential for underwater acoustics?

Yes, the discovery that we can use acoustics to reliably detect Minke whales in Scottish waters has been very exciting. However, there are many open questions about the vocal behavior of this species, including the question of whether both males and females are vocalizing, how often they are vocalizing and what the behavioral context is. Answering these basic questions about the acoustic ecology of the species would help us to use acoustic methods more efficiently in the future to better assess the human impact and develop methods for estimating animal abundance from acoustic data, which are currently limited.

Funding for the COMPASS project has been provided by the EU's INTERREG VA programme, which is managed by the Special EU Programmes Body (SEUPB), to the tune of €6.3m.

Partners in the project are SAMS, Agri-Food and Biosciences Institute, Inland Fisheries Ireland, Marine Institute Ireland and Marine Scotland.

Sounds in Japan's Deep: Long-term Monitoring of Fin Whales

Words by Mike van der Schaar, Serge Zaugg and Michel André, Laboratory of Applied Bioacoustics, Technical University of Catalonia, BarcelonaTech

Understanding the link between natural and human processes is essential for predicting the magnitude and impact of future changes of the ocean's natural balance. Amongst this wide variety of changes, the coming decades will see increasing levels of offshore industrial development that will almost certainly see a rise in noise pollution.

Definitive studies on the response of marine mammals to human sound are typically hampered by the short time spent at the surface and the deep-diving lifestyle of many vocalizing species. Implemented within the framework of the European Sea-Floor Observatory Network of Excellence (ESONET) in 2007, the "Listen to the Deep Ocean Environment (LIDO)" approach has developed and applied techniques for continuous noise measurement and passive acoustic monitoring (PAM) to world-wide cabled deep-sea platforms and moored stations, representing the first and only PAM system currently available online (http://listentothedeep.com).

LIDO uniquely offers the combination of real-time data management and passive acoustic monitoring with the use of the latest technological developments in underwater acoustic detection. This observatory has provided the scientific community with a hitherto non-available technology to reveal the daily behavior of deep-sea marine organisms, opening, for the first time, internet access to deep ocean sound information.

The software package behind LIDO has successfully validated the detection of many sound-types from fixed ocean observatories, including cetacean whistles, echolocation clicks, impulsive and tonal shipping noise, underwater explosions, echo sounders and pingers. In particular, the detection module for short tonal sounds has been successfully applied to detect dolphin calls and whistles as well as calls from orcas *(Orcinus orca)*, humpback whales *(Megaptera novaeangliae)* and right whales *(Eubalaena sp.)*.

Here, we looked at the contribution of fin whale calls to noise levels measured off Kushiro and Hatsushima in Japan from continuous recordings between 2011 and 2018.

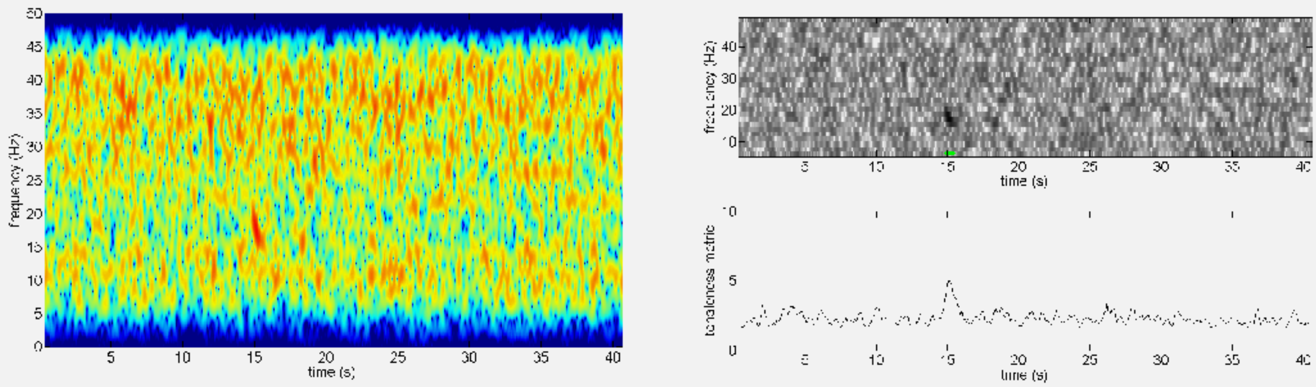


Figure 1: A segment with a fin whale call from the Kushiro observatory.. A high-resolution spectrogramme is shown on subfigure (a). The equalised spectrogram used by the detector is shown on subfigure (b). The tonaleness metric and the threshold used to identify the time stamps of the call are shown on subfigure (c). The automatically identified time stamp of the call is shown in green in subfigure (b). The segment shown in (a) was High-pass filtered at 6 Hz to improve plot contrast. See caption of Figure 2 for details.

Detection of Fin Whales

The fin whale *(Balaenoptera physalus)* has a worldwide distribution and produces low-frequency calls, sometimes called pulses, in the range 15-200 Hz. The most frequently heard call-type is a frequency down sweep in the range 30-15 Hz with duration of around one to two seconds.

Fin whale calls were successfully detected by LIDO at three distinct geographical sites, where fin whales were known to occur: data from the West Atlantic through the fin whales 93 CD from Cornell University; data from the North Atlantic through the Mobysound database (www.mobysound.org); and data from the North-East Pacific through the Neptune observatory (now part of Ocean Networks Canada). These data were used to configure and evaluate the detectors obtaining false detection rates below 1%.

The detectors were then applied to the recordings at Japan with similar false detection rates below 1% (Kushiro: 0.71 %). Considering that data from the Kushiro observatory contained a significant amount of shipping noise and additionally intense narrow-band transients, the obtained false detection rate is very satisfying. The detector allowed to automatically select parts of a data stream that are most likely to contain fin whale calls, and return only these parts to second stage algorithms; thereby reducing the data volume to be processed in the second stage by a factor of at least 100.

Measuring Ocean Sound

The European Union's Marine Strategy Framework Directive (MSFD) includes two indicators concerning ocean noise aiming at quantifying the human contribution to the ocean's ambient sound. It has been an important first step to bring attention to the problem of marine acoustic pollution and to manage the introduction of sound into the ocean. The MSFD focusses on registering high impact impulsive sounds, and especially on computing yearly averages of third octave levels. Due to lack of long-term data, however, it does not enter into the interpretation or comparison of the levels.

One way to analyze the yearly averages is to look for changes over long time intervals where an increase in level can be a cause for concern and a threat for the local habitat. However, humans are not the only mammals producing sound and it will be important to try to separate human, biologic and natural sounds to identify the dominant contributors to the soundscape.

To illustrate this, this article shows data recorded through the Japanese earthquake detection system installed along its east coast in the deep sea between 2011 and 2018. The sea floor mounted hydrophones are sampling at 100 Hz, allowing to assess the lowest frequency sound levels. There was a special interest in the detection of fin whales, for which specific detectors were developed. While the sampling rate is limiting the noise bandwidth that can be studied, the availability of long-term data can give some insight in how the MSFD acoustic indicators can be used.

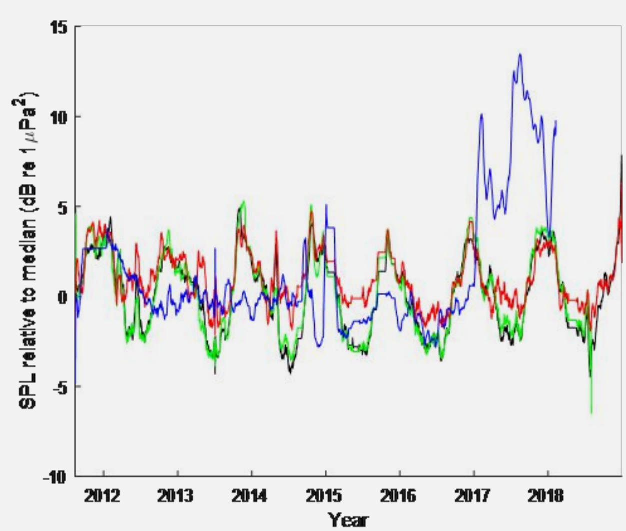


Figure 2: Sound pressure level in the 15 – 25 Hz band from Kushiro-Tokachi observatories 1 (green), 2 (black), 3 (red) and Hatsushima (blue).

Figure 2 shows the smoothed sound pressure level in the 15-25 Hz frequency band recorded at the three available Kushiro-Tokachi observatories (green, black and red) and Hatsushima (blue). The curves are plotted around their median level to allow comparison of changes and to be able to assess an overall change in the level over time. The platforms show a few different features of interest. The blue curve from Hatsushima shows some seasonality around 2012 and 2016, but is relatively constant during 2013 to 2015. From 2017, there is, however, a smooth consistent increase in the sound level (Figure 3). Manual inspection of recorded spectrograms suggests that there was increase in shipping in the area, although a change in hydrophone sensitivity cannot be entirely excluded. The gradual increase of the level does not indicate an unknown change in, for example, a change in the amplification of the acquired signal.

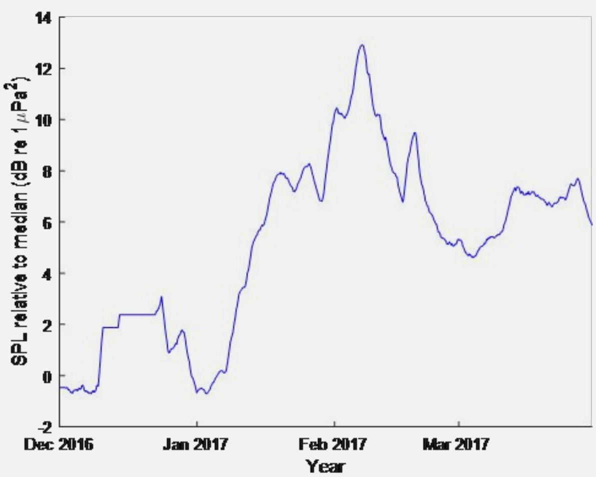


Figure 3: Zoom from Hatsushima showing a gradual increase in sound level during the second week of January 2017.

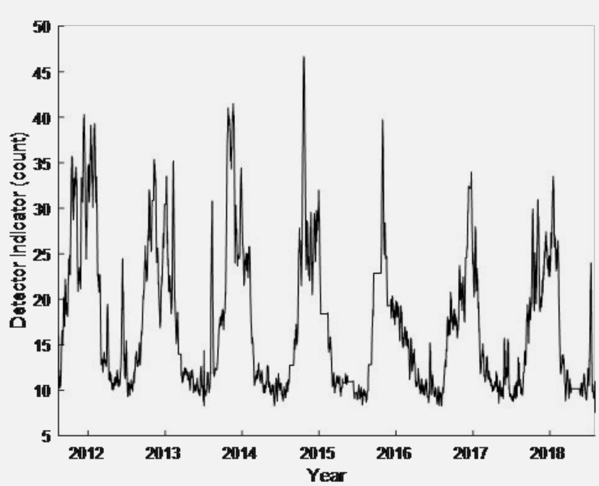


Figure 4: Seasonal pattern of the call detector between 15 - 25 Hz at Kushiro-Tokachi 2.

The other curves from Kushiro-Tokachi stations alternate around their medians in a seasonal pattern. The increase in level between January and August levels is around 6 dB, a considerable rise in the background sound level.

Figure 4 shows the output of the detector tuned to the fin whale calls at the second Kushiro-Tokachi station. There is a clear seasonal pattern that corresponds to a general increase in the sound level in the same band. Manual inspection of spectrograms (Figure 5) confirmed that the detector output was mostly correct and that the seasonal patterns in sound level are due to fin whale migration. In the figure, the top graph shows the output at the segment level (computed over 30 second data windows). The first spectrogram shows strong fin whale calls, where individual signals can easily be seen. The second spectrogram does not show individual calls, but a band of energy at the frequency of the most common fin whale call, explaining the overall increase in sound level.

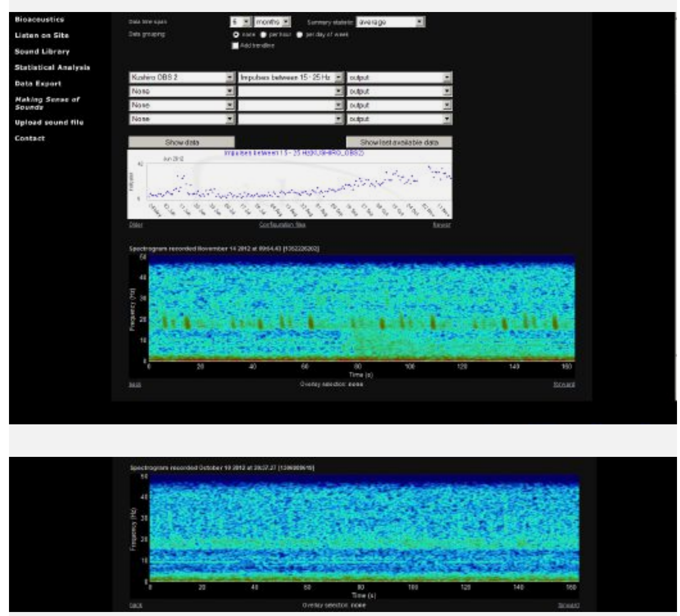


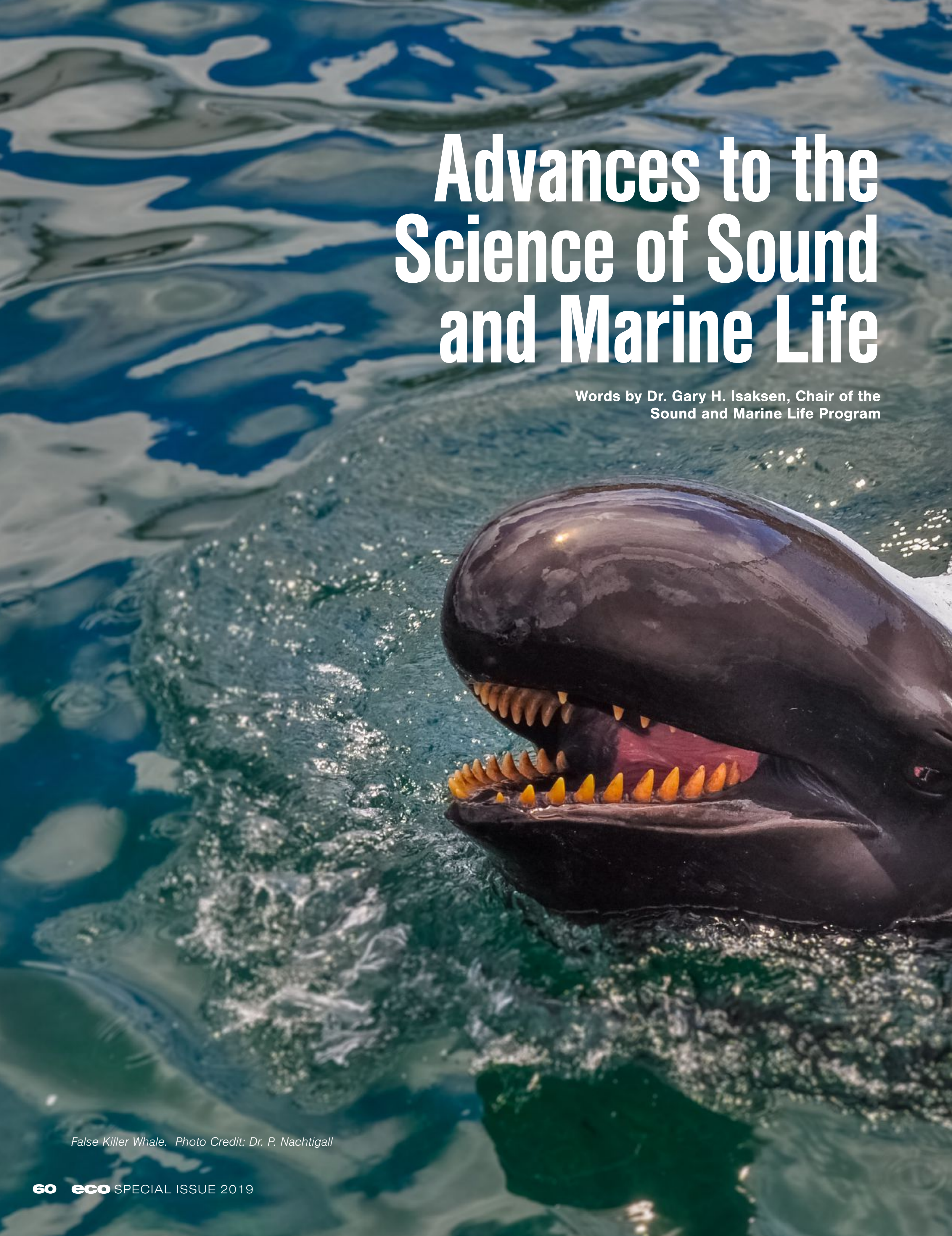
Figure 5: Illustration of the presence of fin whale calls in the 15 - 25 Hz frequency band at Kushiro-Tokachi 2 (LIDO interface).

Conclusion

The identification of the dominating sound sources is clearly important for the interpretation of the background sound level. At deep water stations, there is generally no strong contribution from fish, shrimp or crustaceans, but daily and seasonal patterns from such sources can be very common at shallow water stations. Reporting for the MSFD indicators should include an attempt to characterize the soundscape in order to understand the measured values. A single yearly value is not sufficient for this. Ideally the data is available at least at a daily resolution to investigate seasonal patterns. The value of long-term time series is obvious for the detection of a large deviation such as seen at Hatsushima.

Advances to the Science of Sound and Marine Life

Words by Dr. Gary H. Isaksen, Chair of the Sound and Marine Life Program



False Killer Whale. Photo Credit: Dr. P. Nachtigall

In May 2006, several of the world's leading oil and gas companies and industry associations embarked on a multimillion, multi-year research program with leading academics at universities and research institutions. The program is fully funded by the oil and gas industry. Its aim: to advance the scientific understanding of the effects of sound generated by offshore operations on marine mammals, fish and reptiles. This collaborative program is organized under the auspices of The International Association of Oil and Gas Producers (IOGP) and joined by The International Association of Geophysical Contractors (IAGC) representing the geophysical companies conducting seismic surveys. The Exploration & Production (E&P) companies include BHP Billiton, BP, Chevron, ConocoPhillips, ENI, Equinor, ExxonMobil, Santos, Shell, Total, and Woodside.

The program has been a massive success. It has not only advanced the science but has also built a solid reputation of scientific integrity for academic-industry-government cooperation. The Sound and Marine Life JIP is the largest non-governmental funder of research on this topic. To date, the JIP member companies have provided $55 million in research funds to understand a broad range of marine sound issues and enabled marine mammal observations at sea in many areas where few data previously existed. These combined efforts have greatly increased our understanding of sound and ocean conservation.

The collaborative program is divided into five categories, which are complementary and specially designed to understand potential effects associated with underwater sound from E&P activities:

- Sound Source Characterization and Propagation
- Physical and physiological effects and hearing
- Behavioral reactions and biologically significant effects
- Mitigation and monitoring
- Research Tools

Humpback tail. Photo credit: G. H. Isaksen

To date, the research partnerships have resulted in 126 peer-reviewed manuscripts published by independent scientists. Comprehensive program reviews in 2008, 2012, and 2018 enabled the researchers to present their work to peers, regulators, and stakeholders. Such research results help regulators and policymakers make decisions based on high-quality science and help the regulated industries develop effective mitigation measures. Information about the research, final project reports, and a list of peer-reviewed publications are available at www.soundandmarinelife.org

Behavioral Response of Australian Humpback Whales to Seismic Surveys

The most recently completed large-scale study investigated the Behavioral Response of Australian Humpback Whales to Seismic Surveys (BRAHSS). This was a multimillion-dollar, multi-year (2009-2019) Behavioral Response Study (BRS) examining how humpback whales respond to seismic sound in general and to the ramp-up procedure specifically[1]. The US Bureau of Ocean Energy Management (BOEM) also joined the program, thus forming an academia-industry-government partnership. The study was conducted on humpback whales off both the east and west coasts of Australia during their southward migrations in September and October of 2010–2014. The experimental design was relatively sophisticated with both treatment and control groups, a pre-trial statistical power analysis, a range of exposures with "before, during and after" analyses, and a four-stage ramp-up design[1, 2]. The experimental design progressed from using a single seismic source in 2010 to a fully operational commercial array with a ramp-up procedure in 2014.

In the first year of BRAHSS, behavioral reactions of humpbacks were assessed in response to the single 20 in3 source during 18 control and 16 active trials[3]. The source level was 199 dB re 1 μPa2·s sound exposure level (SEL) at one meter, and the received SELs were 105–156 dB re 1 μPa2·s. Humpback whales decreased both their dive time and speed of southward movement, but there was no evidence of a difference in orientation relative to the source vessel. This response was seen during both control and active trials, indicating that it was related to the presence of the vessel rather than the sound source itself[3].

Next, BRAHSS scientists measured humpback whales' responses to the ramp-up of the experimental array[5]. The control in this experiment was the same action as the source vessel without initiating the ramp-up procedure. Humpbacks slowed their speed of southward movement and deviated from their course in a manner that increased their distance from the source vessel. However, this potential avoidance behavior did not differ between trials when the ramp-up procedure was initiated and those in which the sources remained inactive, suggesting a reaction to the source vessel rather than the ramp-up procedure[5]. In most cases, the whale groups appeared to avoid the source vessel at distances greater than most exclusion zones, rarely coming within 600 meters of the source array.

Combined analyses of the 2010 and 2011 behavioral data led to the development of a model comparing the distance of the whale group to the source vessel, had they not deviated from their original path with their observed distance from the source vessel after the behavioral response, both relative to their baseline state[4]. The model was applied to a set of control trials in which the vessel was moving, but the sources were not operational versus two active trials, during which either the single 20-in3 source or the 140-in3 array was firing every 11 seconds. That model showed whales deviating from their predicted pathway in response to both control and active treatments and that this deviation could be either "avoiding" the source vessel or "approaching" it. Other whale groups did not respond at all. The scientists noted that additional variables are required, such as social context, proximity, and received level[4].

Detailed acoustic measurements were also made during the BRAHSS project using moored acoustic loggers, a moored hydrophone array, and drifting hydrophone buoys[1]. Data from this project were used in a larger study of 24 different seismic sources to define signal transmission around Australia[6]. Results of that study showed high variability in sound transmission among surveys, even for similarly sized sources; high variability within a seismic survey; and differences in transmission between the open ocean and continental shelf and slope waters. The whales did not experience any adverse impact (i.e. no physical injury), nor was there any adverse population-level effect. Rather "the response observed during both control and active trials, indicated that it was related to the presence of the vessel rather than the sound source itself" [3].

Results to date have been published in nine science journal papers, two book chapters and four conference proceedings. Two papers are in progress and two more are planned. Twenty papers have been presented at conferences, twelve internationally[7].

This study is also an example of the importance of experimental design when planning behavioral response studies. Research hypotheses need to be stated up front, and data collected without bias to ensure proper statistical power for any cause-and-effect statements. Furthermore, these types of study require a significant number of skilled people; in this case, over 88 field researchers, 122 volunteers, and 40 crewmembers on multiple vessels.

For any activities in the marine environment, key to the success of operating responsibly is making informed decisions and managing risk appropriately. Environmental risk assessments are important tools to understand the potential environmental hazards associated with activities and to assess any associated risks. Practical mitigation measures are then employed to reduce risks and operate in an environmentally safe and responsible manner.

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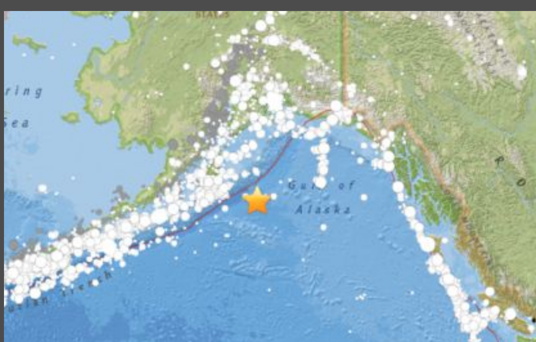
To download a PDF file of this report, click on the Environmental Studies Program Information System link on the US Department of the Interior, Bureau of Ocean Energy Management website at www.boem.gov/Environmental-Studies-EnvData/ and search on 2019-0002.
This report can be obtained from the E&P Sound & Marine Life Joint Industry Program at http://www.soundandmarinelife.org/library/project-reports.aspx.

SOUNDS OF THE OPEN OCEAN



Earthquake

Undersea earthquakes make low frequency sounds from the movement of the seafloor. The sounds they make can be heard far away from the earthquake location. In the Pacific Ocean, sounds from a volcanic eruption have been heard thousands of miles away. Words: DOSITS. Sound Source: CSA

Minke Whale

At 7 – 10 meters (23 – 33 feet) the Minke whale is the smallest of the baleen whales. One regional vocalization of the Minke from the Great Barrier Reef area is the "Star Wars" call. Another, called the "boing" was only recently associated with the North Atlantic Minkes. The chorusing sample provided here is from the West Indies; played back 10x speed the sound remarkably like crickets. Sound courtesy of Jay Barlow and Shannon Rankin, National Marine Fisheries Service. Source: Ocean Research Conservation

Sperm Whale

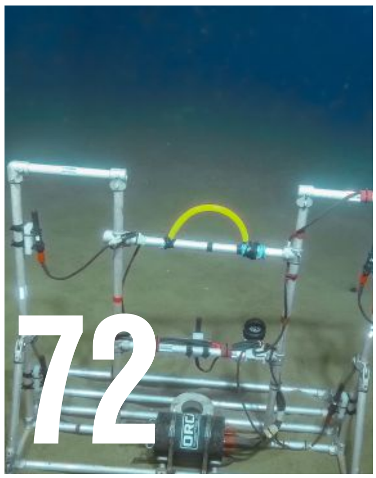
Often associated with feeding along the slope of the world's continental shelves, sperm whales are rarely found in waters less than 300 meters deep. The spermaceti organ has very complex acoustical features, allowing the focused transmission and reception of their characteristic bio-sonar. The sperm whale "clicks" when heard in aggregation sound like a busy team of carpenters hammering away on a job – giving them the colloquial name of "carpenter fish." Source: Ocean Research Conservation

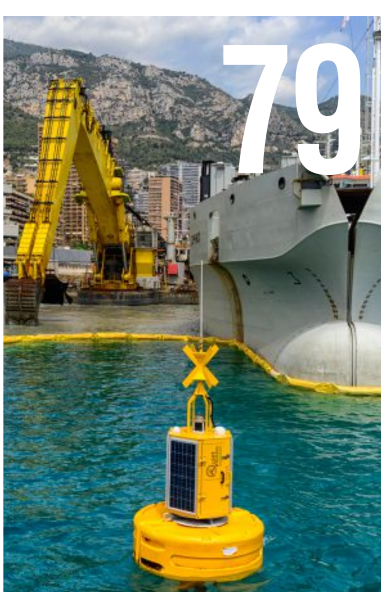
Humpback Whale

Humpbacks are best known for their vocalizations that are arranged in complex, repeating sequences with the characteristics of "song". Scientists have discovered that these songs are produced by males on the breeding grounds. Recent studies have found that humpbacks continue to sing on their feeding grounds. It is thought that singing may function as male breeding displays, male-male social ordering, or a means for spacing reproductively-active males. Source: DOSITS

Blue Dolphin

The dolphin's vocalization repertoire reflects their high-speed social and tactical adaptations. They use mid-frequency vocalizations for social interaction (within our human auditory band), and high-frequency bio-sonar to perceive their surroundings and "see" their prey. Source: Ocean Research Conservation





Technology

The Patagonia Puzzle:
Using Smart Acoustics to Explore Remote Regions

Words by Teledyne

Winding, steep-sided fjords peppered with islands comprise the Patagonia region in southern Chile. It's a sparsely populated area, largely untouched by humans and industry. This nearly pristine environment has made the region a sanctuary for many marine mammals, in particular, the secretive and endangered Sei whale. Because of its untouched nature and rich biodiversity, it is a researchers dream; however, its extreme isolation, which has allowed this protection, has also prevented its methodical inquiry. Now, Patagonia Projects, led by Keri Pashuk and Greg Landreth, is bringing teams of researchers onboard their sailing vessel, *Saoirse*, to shine a scientific light on the region.

Adventurers Keri and Greg are not researchers by trade: Keri is a photographer and Greg, a writer. The duo began sailing to Antarctica to climb untrodden paths and difficult to reach mountains. Over the years, they witnessed degradation of many of the places they visited. Among these troubling changes was the accumulation of trash in the oceans. This inspired them to re-invent their goals, pledging their vessel, *Saoirse*, as a platform for researchers to conduct query-based environmental research. They named the venture *Patagonia Projects.*

In 2015, while on a benthic dive mission with Dr. Vreni Häussermann, marine zoologist and the scientific director of the Huinay Scientific Field Station, in Patagonia, Keri and Greg found several beached whale carcasses. Since this initial finding, many more dead whales have been found washed ashore between Golfo Penas and Puerto Natales, where Patagonia Projects has their home base. Through this grim discovery, Patagonia Projects began their current ongoing project, to create a snapshot of the area before outside threats from illegal fishing, unregulated aquaculture and climate change alter the region forever.

Patagonia Projects invites researchers with different specialized skills and areas of research onboard *Saoirse*. The crew changes with researchers' schedules; however, they have found that acoustic recordings, combined with visual observations are proving to be the most effective tools to illuminate what cannot be seen in the depths of these remote channels. In 2018, they began using novel deployment methods to collect baseline data on the region. Using Ocean Sonics icListen Smart Hydrophones outfitted with Teledyne Reson

Hydrophone deployment

sensor tips, the team makes regular journeys down to Chile's southern coast to collect acoustic data on the many species that call the area home.

The researchers knew they wanted to collect sound data in two ways: opportunistically through strategic short-term deployments when Sei whales are actually sighted, to match the sounds with the individual animals; and via long-term soundscape recordings. To collect opportunistic data, Keri, Greg and team used visual identification to determine if there were marine mammals in the area. Then, a float with an icListen onboard was launched along with an Ocean Sonics Launch Box which provides a Wi-Fi link, providing real-time monitoring. Next, with the engine and a sonar equipment turned off, they silently maneuvered the vessel away from the hydrophone. Through this new deployment method, the crew were able to make recordings of the animals without interference; especially if the animals were feeding. Their drone hovered above, simultaneously recording video to make identification of the recorded animals easier.

Before the team set sail for home in December 2018, they deployed their long-term recording system. The system consisted of an Ocean Sonics icListen RB9 digital hydrophone with internal logging capabilities and Teledyne Reson omnidirectional sensor tip, connected to an Ocean Sonics battery pack. The battery pack is embedded in a secure mooring with the hydrophone attached directly to the top. The team installed the recorder at the mouth of a small gulf, visited often by marine wildlife. As this area has not yet been explored, and few acoustic recordings have been collected, the researchers hoped that a treasure-trove of data would be waiting for them on their return in three months' time.

When they returned in March, they were not disappointed. The data stored in the hydrophone revealed a number of discoveries for the Patagonia Projects team. Many vocalizing Sei whales can be heard throughout the data set, proving that the area is a key feeding ground for the endangered whales. They estimate that they may have increased the record of verifiable Sei whale calls by a large margin. Today, the team is busy combing through the data to identify the sounds of other marine mammals buried within the recordings.

The ultimate goal of these expeditions is to assist in identifying and securing marine protected areas in the Patagonia region. Capturing baseline data is the first, and most critical step in the process. Patagonia Projects is using the data collected from their icListen hydrophones to demonstrate the need to establish protected areas and ensure the safety and longevity of this rich environment.

Teledyne and Ocean Sonics:

The relationship between Teledyne Reson and Ocean Sonics began in 2010. Ocean Sonics had launched their 3rd generation smart hydrophones and needed reliable acoustic sensors with which to perform calibrations. This task was only trusted to the Teledyne Reson TC4034 acoustic sensor. Ocean Sonics enjoyed using the Teledyne Reson sensor so much, they chose to digitize it, becoming the digital solution for Teledyne Reson hydrophones. In 2015 Ocean Sonics launched their RB9 model smart hydrophone, a completely digitized hydrophone with a custom-made Reson sensor, TC4059. Through this Teledyne Reson sensor, Ocean Sonics was able to achieve low drift, low self-noise, reliable smart hydrophones with 900 meters depth rating. The collaboration between the two companies has been fruitful, pushing the bounds of underwater acoustic innovation. As Ocean Sonics launches their next generation Smart Hydrophones, beginning with the icListen Kayak, they trust Teledyne Reson to provide top quality acoustic sensors, ensuring simplicity, accuracy and reliability for users.

Using Smart Hydrophones to Monitor for Marine Mammals and Vessel Noise in the Bay of Fundy

Words by Rose Fisher, Ocean Sonics

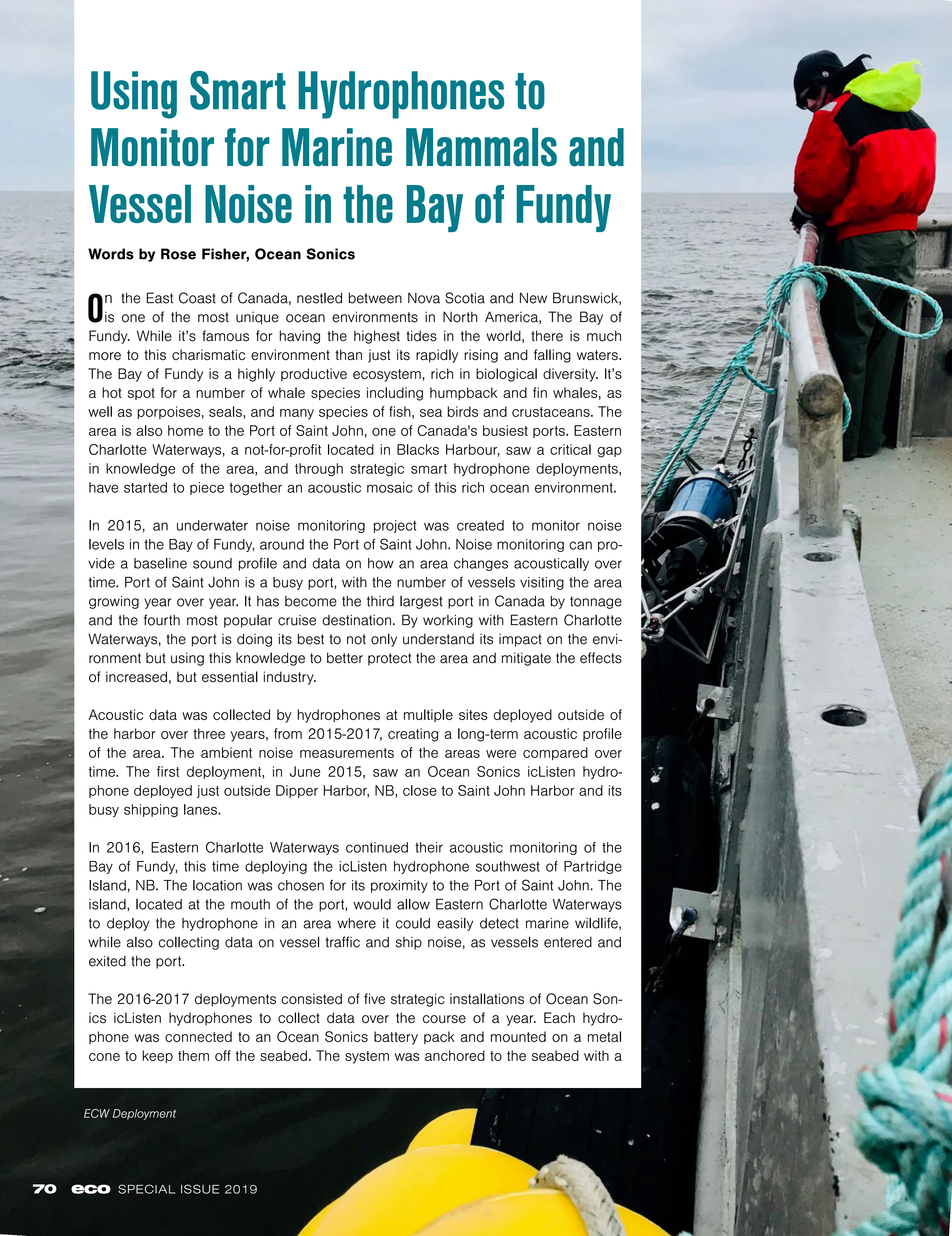
On the East Coast of Canada, nestled between Nova Scotia and New Brunswick, is one of the most unique ocean environments in North America, The Bay of Fundy. While it's famous for having the highest tides in the world, there is much more to this charismatic environment than just its rapidly rising and falling waters. The Bay of Fundy is a highly productive ecosystem, rich in biological diversity. It's a hot spot for a number of whale species including humpback and fin whales, as well as porpoises, seals, and many species of fish, sea birds and crustaceans. The area is also home to the Port of Saint John, one of Canada's busiest ports. Eastern Charlotte Waterways, a not-for-profit located in Blacks Harbour, saw a critical gap in knowledge of the area, and through strategic smart hydrophone deployments, have started to piece together an acoustic mosaic of this rich ocean environment.

In 2015, an underwater noise monitoring project was created to monitor noise levels in the Bay of Fundy, around the Port of Saint John. Noise monitoring can provide a baseline sound profile and data on how an area changes acoustically over time. Port of Saint John is a busy port, with the number of vessels visiting the area growing year over year. It has become the third largest port in Canada by tonnage and the fourth most popular cruise destination. By working with Eastern Charlotte Waterways, the port is doing its best to not only understand its impact on the environment but using this knowledge to better protect the area and mitigate the effects of increased, but essential industry.

Acoustic data was collected by hydrophones at multiple sites deployed outside of the harbor over three years, from 2015-2017, creating a long-term acoustic profile of the area. The ambient noise measurements of the areas were compared over time. The first deployment, in June 2015, saw an Ocean Sonics icListen hydrophone deployed just outside Dipper Harbor, NB, close to Saint John Harbor and its busy shipping lanes.

In 2016, Eastern Charlotte Waterways continued their acoustic monitoring of the Bay of Fundy, this time deploying the icListen hydrophone southwest of Partridge Island, NB. The location was chosen for its proximity to the Port of Saint John. The island, located at the mouth of the port, would allow Eastern Charlotte Waterways to deploy the hydrophone in an area where it could easily detect marine wildlife, while also collecting data on vessel traffic and ship noise, as vessels entered and exited the port.

The 2016-2017 deployments consisted of five strategic installations of Ocean Sonics icListen hydrophones to collect data over the course of a year. Each hydrophone was connected to an Ocean Sonics battery pack and mounted on a metal cone to keep them off the seabed. The system was anchored to the seabed with a



ECW Deployment

high-flyer buoy for easy retrieval. The hydrophones were set up to record the first two minutes of acoustic data every ten minutes, this allowed the battery packs to supply power to the hydrophones for two to three months

Eastern Charlotte Waterways multi-year noise monitoring project had two goals. One, to detect marine wildlife in the area, and two, to monitor vessel traffic and subsequent noise levels. Marine mammals rely on sound for many of their basic needs including finding food, avoiding predators, mating and rearing young. Vessel traffic introduces noise into the marine environment, so it is essential that the amount of noise and its effects on the environment are understood. Port of Saint John has taken a proactive approach to noise mitigation.

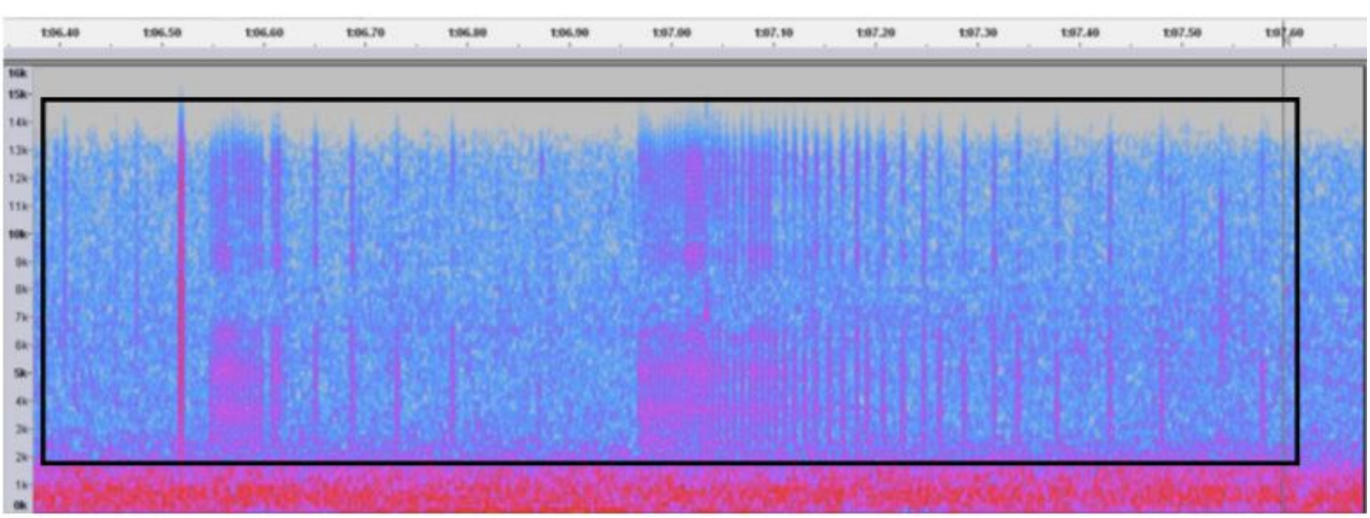
Many marine mammals were detected in the data throughout the deployments, the most common being dolphins, identified by their distinct clicks, buzzes and whistles. Year-round inhabitants of the area, harbor seals, were also detected frequently throughout the data set. In the 2015 recordings, there were many vocalizations from a number of different marine species including dolphins, harbor porpoises and seals. Many migratory species were detected including endangered North Atlantic Right whales and Sei whales, as well as Humpback whales and possible Blue whales. The 2016-2017 data confirmed the diverse nature of the area, with many of the vocalizing animals returning to the region. Humpbacks visited the area in November and December of 2016, and then returned again in September and October of 2017. Low-frequency baleen whale calls were recorded by the hydrophone, including Blue whales and Fin whales. And in the fall of 2016, potential calls from the endangered Sei whale were again detected.

While the abundance of marine mammal vocalizations is fantastic to hear, it's important to note that in nearly all of the recorded data, vessel noise was present. The noise came from a variety of sources such as ships entering and exiting the port, the nearby ferry, and distant vessels in the area. Larger vessels tend to increase noise levels for longer periods as the low-frequency noises travel further through the water. Smaller vessels increase noise in higher frequencies, but attenuation of these frequencies only allows the noise to travel short distances. The smaller vessels such as pilot vessels and ferries increase sound levels in higher frequencies from smaller propellers and increased speeds. The noise from these vessels attenuate much faster and do not affect low-frequency communication in baleen whales but can still have an impact on mid- and high-frequency communication from whales and dolphins as well as many marine organisms close to the vessel.

Because the ferry spends a lot of time in the area, there are increased noise levels in higher frequencies for longer periods and this affects marine organisms in the area. Further studies covering frequencies up to 200 kHz are needed to acquire full noise profiles of vessels which can then be used to assess the impact on marine mammals such as dolphins and harbor porpoise.

There is growing concern around the world about the effect of noise on aquatic life. Performing baseline studies like the one performed by Eastern Charlotte Waterways creates a snapshot of the ocean environment, allowing researchers and industry alike to monitor and mitigate the amount of noise introduced into an environment. Standards such as the European Marine Strategic Framework Directive are leading the way for responsible exploration and development of our aquatic industries while ensuring the protection and prosperity of essential ocean ecosystems.

Industry and environment can co-exist. Understanding the effect of anthropogenic noise in marine environments is the first step in creating a mutually beneficial system that allows the two to exist in harmony. The data collected by Eastern Charlotte Waterways between 2015 and 2017 clearly demonstrates the need for acoustic monitoring of the area, as numerous species of pinnipeds, cetaceans, fish and crustaceans inhabit or migrate in and out of the area every year. By taking proactive measures, the Port of Saint John has emerged as a leader in good environmental practice while maintaining thriving shipping and cruise industries.



Audacity Spectrogram: Dolphin Clicks

Pushing the Boundaries for Recording Underwater Noise

Words by Dr. Ryan Mowat, Director of Fisheries & Research, RS Aqua

The requirement for low cost, high specification passive acoustic recorders has increased in recent years, with multiple industries now measuring underwater noise. The stakeholders vary enormously, with marine mammal specialists, ecologists, oceanographers, offshore construction engineers, and defense experts – amongst others – all having passive acoustic monitoring (PAM) requirements.

This variety of users means a range of capabilities are required of any high-quality PAM recorder. Low-frequency recording can suffice for construction noise monitoring, whereas extremely high-frequency recording is necessary to hear the echolocation clicks of the protected Harbor Porpoise *(Phocoena phocoena)*. One hydrophone will suffice for ambient noise monitoring, whereas two or more are required if we want to have an idea of where a particular noise is emanating from. Another challenge is that recorded acoustic data is often extensive in size and requires lengthy processing to extract useable environmental information.

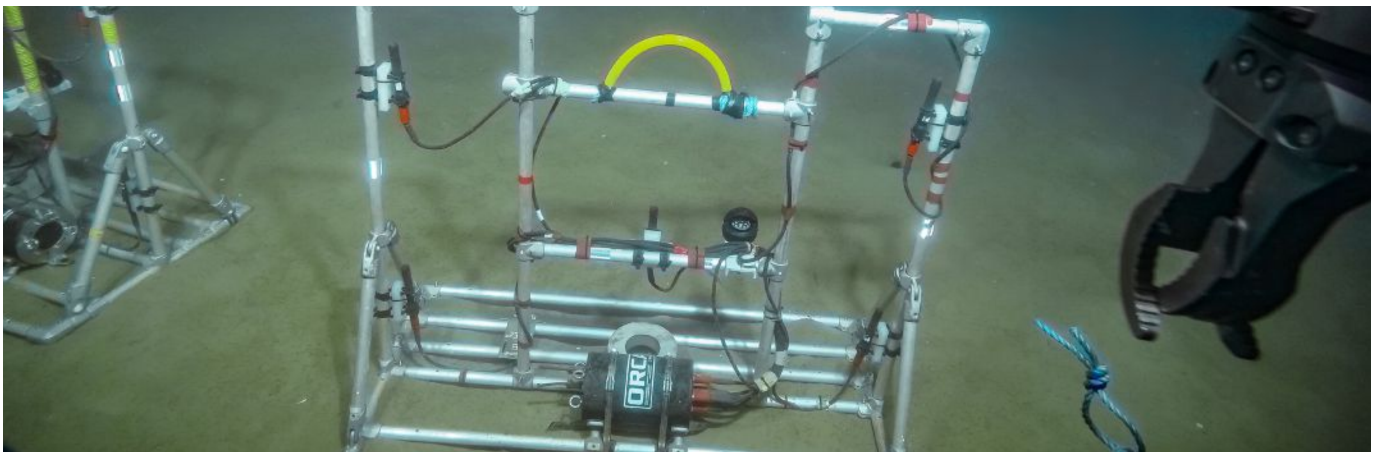
The lack of an encompassing solution to these issues led to the design of the Orca and Porpoise recorders by marine technology experts RS Aqua and Turbulent Research. RS Aqua is the UK's largest distributor of marine science instrumentation, and Turbulent Research is an acoustic engineering firm based in Nova Scotia. Both companies realized the need for a wide bandwidth, low power recorder that could fulfill a range of recording needs while offering the capability of extended deployments. In 2016, the multichannel Orca recorder was released, and there have now been over 60 deployments worldwide. The single channel Porpoise recorder followed in 2018 with over 50 of these now supplied internationally.

Both recorders offer sampling rates between 24 and 384 kHz, flexible gain settings, and duty cycle programming. Memory size is impressive, with the latest version of Porpoise capable of carrying 4 TB of SD card memory, and the Orca able to utilize both SD and SSD memory types. The Orca is also able to process acoustic data as it records, meaning information such as third octave band sound pressure levels can be cal-

Group of Harbor Porpoises off the coast of the Snaefellsnes peninsula in western Iceland culated and viewed in real time. Both recorders can stream recorded noise over Ethernet.

In terms of their size and versatility, the Orca and Porpoise really come into their own. For deep, long term deployments the Orca can hold up to 72 D-cell batteries (alkaline or lithium) and go to 3500 meters depth. For short projects, where size and ease of deployment are paramount, the Porpoise fits into the palm of your hand and can run on 12 AAA batteries. Both recorders can also mount external 36 D-cell battery packs for longer deployments.

They go even smaller, though! Unlike most recorders, the Orca and Porpoise can discard their pressure housings and still stream noise over Ethernet – all that is required is their internal PCBs, a connected hydrophone, and power. This has allowed us to integrate the Orca into Teledyne Slocum gliders for autonomous multiday recording missions, and even into a custom fin on a racing yacht. These deployments recorded underwater noise using ground-breaking methods and raised the bar for what can be expected of broadband subsea recorders. Expect to see more of this innovation from RS Aqua and Turbulent Research in the future.



Five Channel ORCA Recorder in the North Sea on the STEMM-CCS Carbon Capture Storage Project

Eavesdropping on the Gulf of Mexico

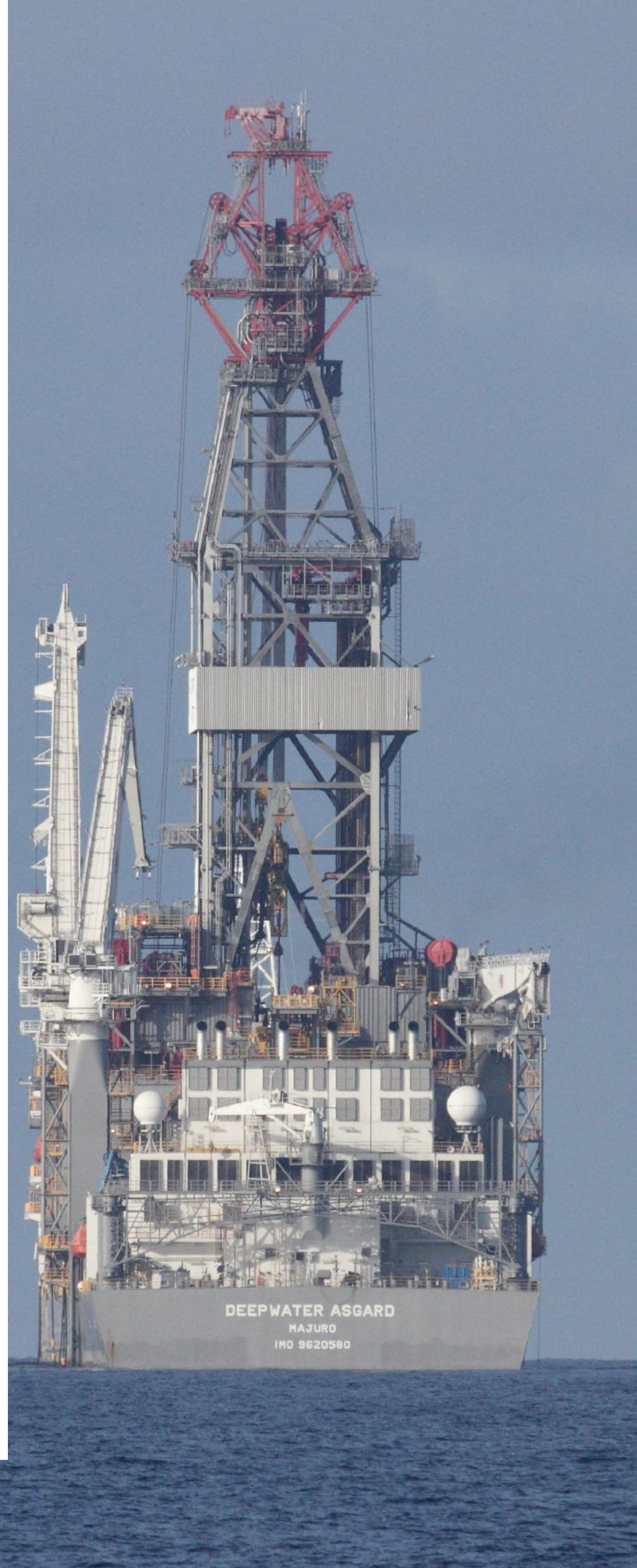
Words by Natalia Sidorovskaia, Director of LADC-GEMM Consortium, Department of Physics, University of Louisiana at Lafayette

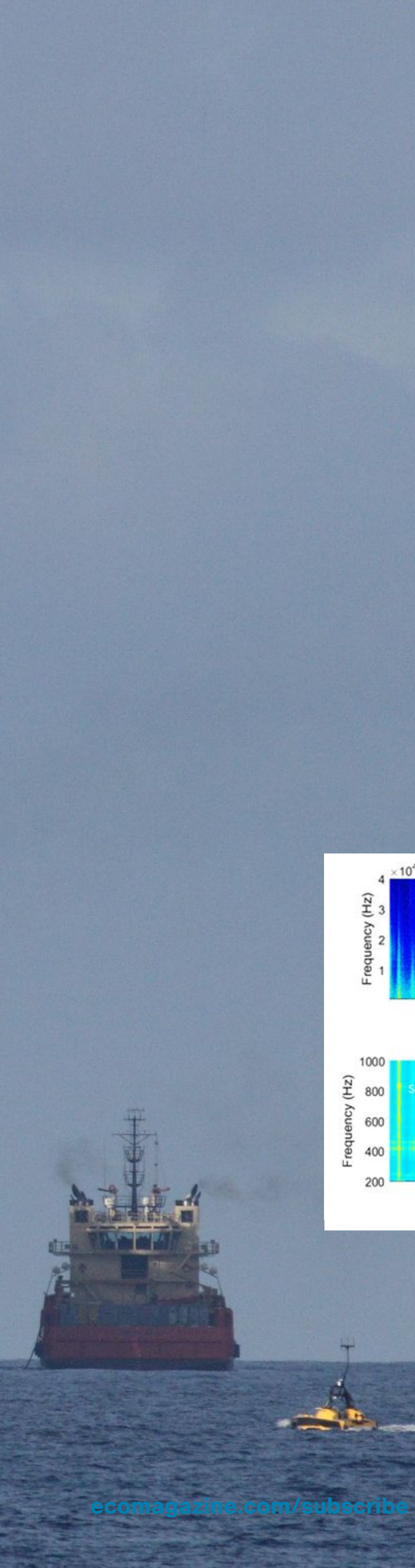
Over 70 percent of our planet is covered by oceans and yet less than five percent of it has been explored. Visible sunlight, which is about 40 percent of total solar energy received by our blue planet, doesn't penetrate below 200 meters deep in the ocean. As we descend beyond these depths, it is dark and cold, but it is certainly not quiet.

Sounds can travel for many hundreds of kilometers in water. Deep-diving sea creatures have learned to rely on sound to explore the deep, uninviting abyss. Scientists can learn a wealth of information about ocean health and its inhabitants just by eavesdropping. The cacophony of ocean sounds is becoming louder, and our charismatic marine friends and distantly related mammals (dolphins and whales) have been facing multiple challenges as humans expand natural resource exploration and extraction, and global warming has become an everyday reality.

In accordance with recent estimates, 26 percent of human-produced carbon dioxide (CO_2) gets absorbed by the ocean - over 2.5 billion tons go into the sea annually. Last month's CO_2 atmospheric concentration is at a record high and now consistently above 410 parts per million (ppm). As the ocean absorbs more CO_2, it becomes more acidic. More acidity means a lower pH and less absorption of low-frequency sounds. Changes in absorption combined with many other impacts of human activities raised concerns about increasing levels of ocean noise and its effects on a diverse ecosystem. For example, scientists from the Massachusetts Institute of Technology recently observed that sounds in the Arctic Beaufort Sea could now travel four times farther than just a decade ago.

It is critically important for society, researchers, and regulatory agencies to understand how humans impact ocean ecosystems and how we can mitigate these impacts in times of global warming. Acoustics provides an unsurpassed tool to answer these questions. However, such studies rely on long-term passive acoustic data collections and the development of advanced big data mining algorithms to extract relevant acoustic information about signals produced by particular species or physical events.





Gulf of Mexico: A Noisy Place

Marine mammals share their space with humans who use acoustics to find natural resources, navigate ships, monitor subsurface infrastructure, and create additional noise pollution through heavy shipping and construction.

The Littoral Acoustic Demonstration Center – Gulf Ecological Monitoring and Modeling (LADC-GEMM) consortium has been collecting passive acoustic data in the Gulf of Mexico since the early 2000s. Its goal is to understand how industrial activities impact the marine mammal population in the Gulf of Mexico (GoM) which is home to 28 species of marine mammals, including two endangered species: sperm whales and Bryde's whales.

About 200 offshore rigs are operating in the GoM, making it, after the North Sea, the second largest rig operating region in the world. Figure 1 shows a typical daily soundscape from the Gulf of Mexico visualized as a spectrogram. Frequencies of recorded sounds are shown on the vertical axis, time of the day is along the horizontal axis, and the color is related to the sound level.

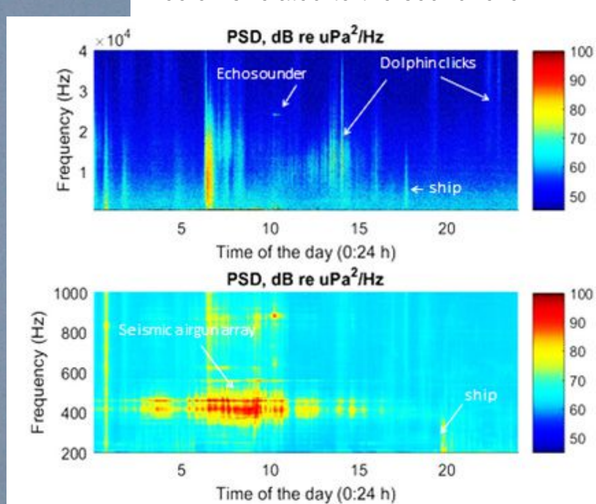


Figure 1. 24-hour soundscape from the Northern Gulf of Mexico.

Several acoustic events can be identified ("heard") on our deep-water autonomous recorders, the Environmental Acoustic Recording System (EARS) buoys, deployed in the Northern GoM: distant seismic exploration array, dolphin clicks, passing ship, and ship echosounder. The unique acoustic features in the signals of different species of marine mammals can be exploited by developing computer algorithms for the detection and classification of many different species. Figure 2 shows the calls of two different species of beaked whales encountered in the Northern GoM: Cuvier's and Gervais' beaked whales. We can easily discern the differences in signal patterns just by looking at the spectrograms (top row), and of course, we can train computers to do a much better job.

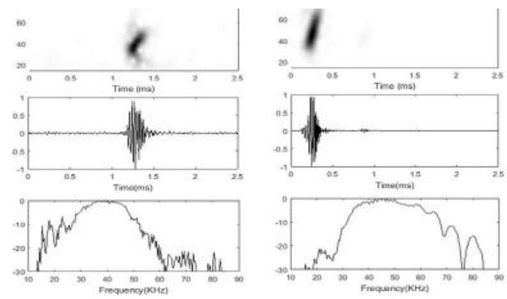


Figure 2. Cuvier's (left) and Gervais' (right) beaked whale clicks.

Marine mammals produce different types of signals depending on the purpose: communication amongst the group, echolocation clicks for orientation and prey search, and fast click trains moments before capturing prey. Once signals of a particular species or individual animals are detected, the data can be used in many different ways: to learn about the presence or absence of a particular species in the region, to mitigate the impact of human activities (ship strikes, seismic surveys), to measure feeding success rates, to discern the stock structure (gender ratio, size of animals), or to estimate regional population densities.

Improving Data Collection

Traditionally, the assessment of marine mammal stock population and a stock status report for the Gulf of Mexico is provided by the National Oceanic and Atmospheric Administration (NOAA). Systematic visual surveys provide information for offshore stocks and aerial surveys for coastal stocks. The visual observation efforts for offshore stocks are expensive, depend on daily weather conditions, cannot be conducted between sunset and sunrise, heavily rely on the expertise of human observers, and, at best, provide a single spatial population density snapshot in several years. Carefully designed passive acoustic monitoring efforts could be free of such shortcomings.

Rapidly developing Autonomous Underwater Vehicle (AUV) technologies and real-time machine learning algorithms open unprecedented opportunities for studying marine mammals and their interaction with the entire Gulf of Mexico ecosystem. AUVs and Autonomous Surface Vehicles (ASVs) can offer a considerable reduction of costs and risks, and add survey planning flexibility associated with automatic decision making. Passive acoustic data can simultaneously provide information on many acoustic events “heard” by a system. It can also be reprocessed in the future as more sophisticated algorithms get developed and synthesized with other oceanographic data, which are usually collected by the sensors placed on the same platform.

Deep Water Horizon: Listening for Impacts

In 2015, our consortium was funded by the Gulf of Mexico Research Initiative (GOMRI) to study impacts of the 2010 *Deep Water Horizon* oil spill on deep-diving marine mammals by using acoustic monitoring. As a part of the efforts, our research team was determined to advance Passive Acoustic Monitoring (PAM) approaches in the GoM. Although AUVs are widely used in oceanographic research, there have been very few projects which used acoustic systems on AUVs, and none until 2015 in the Gulf of Mexico.

Through partnerships between several universities and private industry, our consortium simultaneously operated three different PAM platforms in the region in 2015 and 2017 (Figure 3, Kongsberg’s Seagliders, C-Worker 5 ASV integrated with the Seiche Ltd. PAM system and hydrophone array, and autonomous bottom-anchored EARS buoys developed by NAVOCEANO).

Figure 3. Acoustic monitoring platforms: The C-Worker-5 Autonomous Surface Vehicle, Kongsberg’s SeaGlider, and EARS mooring snaked for deployment.

The Seiche monitoring system allows users to detect and classify the acoustic encounters from low-frequency calls of Bryde’s whales *(Balaenoptera edeni)*, the only baleen whale in the Gulf, to the high-frequency clicks of dwarf sperm whales *(Kogia Sima)* and pygmy sperm whales *(Kogia breviceps)*.

The real-time acoustic data-feed via a wireless link was available 24-hours to operators on the support vessel. The estimated maximum data transmission range exceeded ten kilometers, but the ASV was typically stationed three to four kilometers ahead of the support vessel. Based on the lessons learned from the first sea trial in 2015, the C-Worker 5 integrated with a Seiche acoustic monitoring system demonstrated an impeccable performance for the real-time detection and localization of marine mammals.

A few successes are worth mentioning. During the 2017 seven-day field work period, we had over 90 real-time acoustic encounters with marine mammals versus 28 visual observations. Sperm whales were often encountered in aggregations and were recorded more frequently than other species - the equivalent proportion of five-minute intervals with sperm whale detections in 2017 was 17 percent. The acoustic activity of sperm whales was mostly to the west of the spill site (Figure 4). Similar observations are corroborated by other studies and our acoustic observations on the stationary bottom-anchored moorings.

These observations may be indicative of considerable food web damage in the vicinity of the oil spill and to the east of the spill site where most of the oil was carried. One of our main objectives was to estimate the abundance of sperm whales in the study area. We were able to localize the positions of 26 sperm whales, some were over nine kilometers away from the ASV-towed array. Localization is an integral part of the statistical abundance estimators. The density estimate using ASV data was 7.3 whales per 1000 square kilometers, representing between 22 and 88 animals within the survey area. We are currently working on the density estimates based on data recorded by two other platforms. If similar numbers are obtained, it will provide a considerable confidence in our quantitative estimates based on acoustic data.

It was an exciting event to record Kogia and beaked whale clicks on the ASV array. Acoustic detections of Kogia and beaked whales are rare on towed surface arrays because of the high-directionality of their clicks which are mostly produced at feeding depths. It was encouraging to detect these animals with the ASV monitoring system the first time in the Gulf of Mexico. Through simultaneous visual and acoustic detections, we added a new species of dolphin to the Gulf of Mexico acoustic library database, the Clymene Dolphin (*Stenella clymene;* Figure 5)

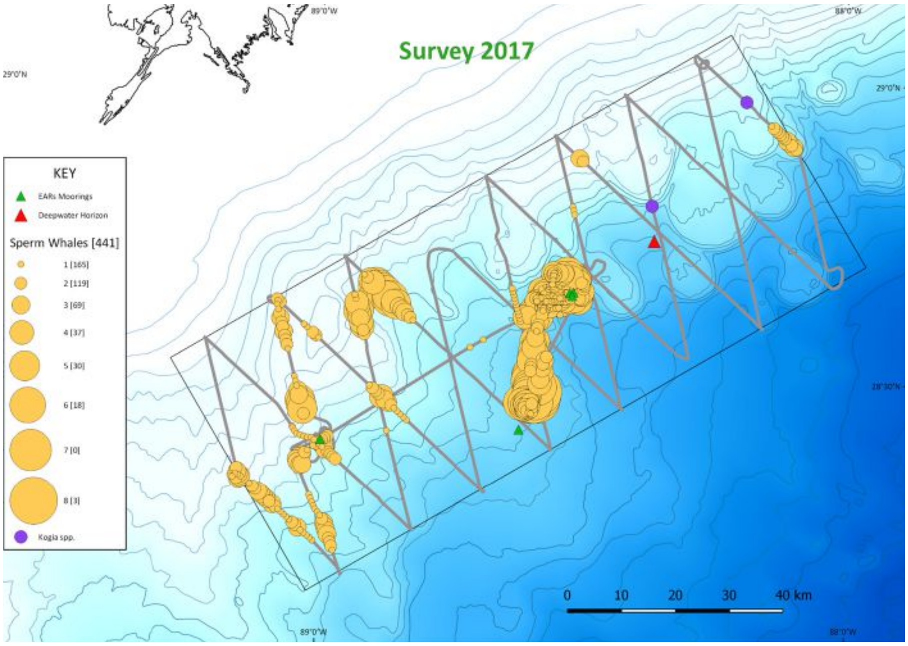


Figure 4. Sperm whale detections along the Autonomous Surface Vehicle tracks. Circle size represents the number of whales simultaneously phonating in a group. (Research results by Chris Pierpoint, Seiche Ltd.)

Learning for the Future

Through utilizing high temporal and spatial resolution data from 2015-2017, we already learned a great deal of new information on how marine mammals use the habitat. For example, we see much higher acoustic activity of Gervais' whales at the shallower, 1000 meter site, whereas the Cuvier's species dominate in deeper water (1500 to 2000 meters). Much more information will be potentially extracted from already collected datasets in the near-future, unveiling the acoustically vibrant world of the Gulf. Especially as we further utilize Artificial Intelligence and Machine Learning techniques to mine the information contained in hundreds of terabytes of collected data.

In addition to direct studies of the oil spill's impact on marine mammals via acoustics, several ecosystem monitoring projects were simultaneously conducted in the region to quantify the changes in the lower trophic layers supported by the GOMRI program. Synthesis of acoustic data with oceanographic and prey distribution data will advance our understanding of the Gulf ecosystem connectivity. New research initiatives supported by NOAA, the Bureau of Ocean Energy Management, and the oil and gas industry are also emerging in the Gulf of Mexico. As the GOMRI program is wrapping up by the end of 2020, we, the researchers, are determined to keep the marine mammal acoustic studies in the Gulf continued. Passive acoustics has a bright future for our understanding of the food web and ecosystem connectivity in the Gulf, and on how past and future oil spills may impact long-lived top predators and what relevant mitigation and conservation methods should be considered. As we collect and process these valuable datasets, we also provide the baseline information for future research on ocean changes at a time of global warming.

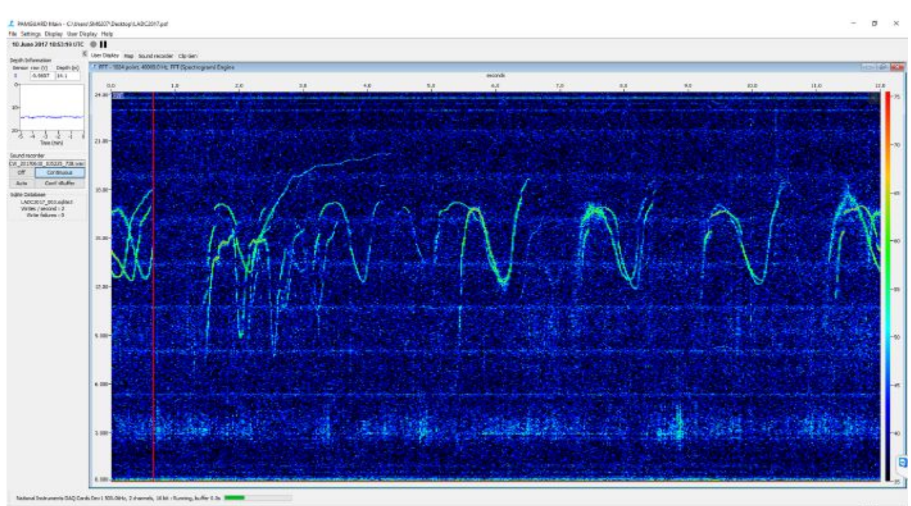
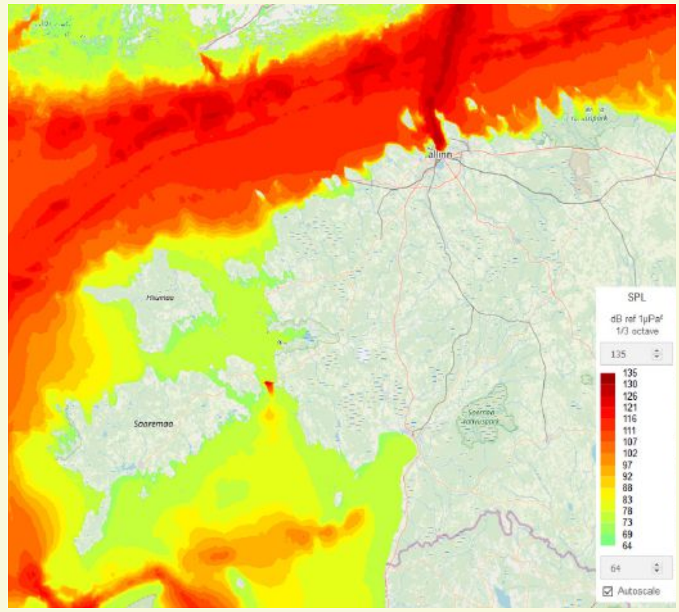


Figure 5. Clymene Dolphin whistles – new addition to the Gulf of Mexico acoustic library.

Modeling to Assess the Impact of Noise on Fish Stocks

Words by Carl Bois, Quiet-Oceans

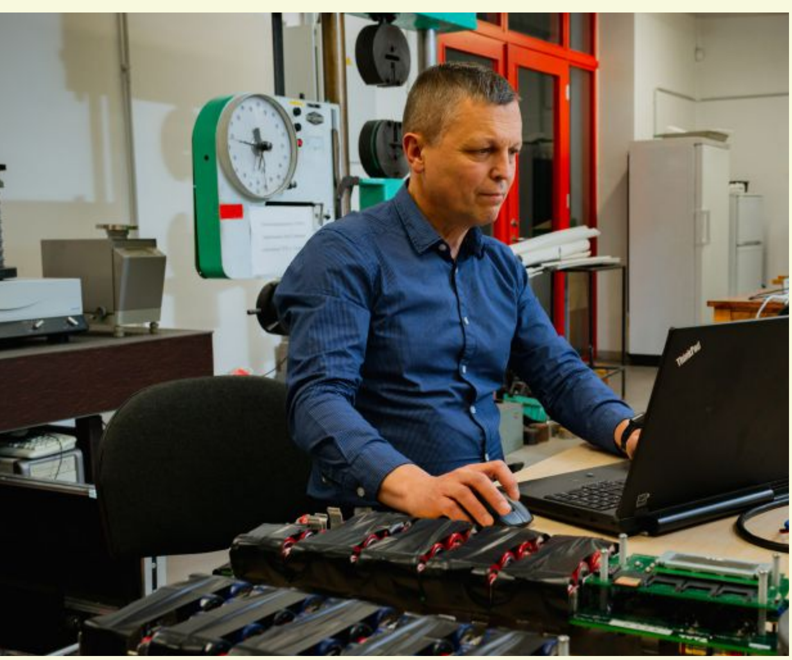
What is the correlation between underwater noise and the distribution of fish stocks? This is the subject of the research project led by Professor Aleksander Klauson of the Department of Civil Engineering and Architecture at the Tallinn University of Technology (Taltech), jointly with the fish biologists from Estonian Marine Institute of the University of Tartu. This three-year project, managed by the Estonian Ministry of the Environment and funded by the European Maritime and Fisheries Fund (EMFF), focuses on the Estonian Exclusive Economic Zone (EEZ).



EEZ Estonia, June 2018

The methodology used in the project consists of comparing the evolutions of underwater noise levels and of the presence of fish. The results of trawling campaigns on the two main impacted species - European sprat *(Sprattus sprattus)* and Atlantic herring *(Clupea harengus)* - have been gathered to have comprehensive data for the Gulf of Finland and the Gulf of Riga, the two areas of interest.

Onsite measurements of underwater noise have also been performed for this study. But underwater noise is very volatile, measurement is expensive, data processing can be time-consuming, and getting extensive data requires a huge number of hydrophones in many positions over a long period. To dispose of comprehensive noise data for every point of the Estonian EEZ and over the duration of his study, Taltech research group uses modeling. They have chosen Quonops Online Services, a web-based platform that offers the modeling of ambient noise (historical and near real-time) including natural and anthropogenic components of noise and the prediction of the noise footprint of a complete range of human activities, taking into account the auditory range and sensitivities of species. Quonops Online Services, which recently released its two millionth map, is based on Quonops©, one of the most validated underwater noise modeling tools with around 2,000 days of onsite measurement. The choice of the modeling option relies on the fact that Quonops© has been used for the underwater noise mapping of the Baltic Sea as part of the European BIAS project. Hydrophones were implemented in 37 positions during a full year in 2014 by Governmental agencies and universities of countries bordering the Baltic Sea to calibrate the outputs of Quonops©.



Prof. Klauson

Professor Klauson and his team now compare the results of the ongoing modeling with the BIAS map atlas and the measured data. He appreciates the easy and efficient way the propagation of underwater noise is modeled and some features like the insertion of noise sources based on measured spectrums and the weighting functions, taking into account the sensitivities of species. “A good point,” he says, “is the adaptability of the platform to new conditions in the context of fast developing environmental underwater acoustics.” He decided to use this platform for the assessment of the acoustic impact on seals and fish of the construction of the Baltic connector pipeline. The interim results of the study, which will be issued next year, show that modeling tools now really help to achieve a good understanding of the acoustic impact on species. This improved capability is especially important as more regulations and requiremented to consider the impact of anthropogenic noise.

Real-Time Acoustic Impact Avoidance at Portier Cove in Monaco

Words by Carl Bois, Quiet-Oceans

Smart-PAM buoy monitoring Jan De Nul operations in Monaco. Picture: Jan De Nul.

Monaco is expanding into the Mediterranean Sea. The ongoing $2.3 billion Portier Cove project aims at offering 650,000 square feet of luxury apartments, commercial spaces, an expanded conference and cultural center and a landscaped park on 15 acres of land reclaimed from the sea as well as a splendid new marina with 30 berths for yachts.

Conceived as an eco-district, this major land reclamation project is built by the European civil engineering firm Bouygues TP Monaco. The construction consists of watering 18 concrete chambers filled in with over 21 million cubic feet of sea sand on a previously leveled seabed. Launched in 2017, the development of the maritime infrastructure should be completed in 2020.

Protection of the environment is the key point of this project. Under the leadership of Prince Albert II of Monaco, a dedicated marine environmentalist, this project has been entirely designed to make certain marine species and water quality are protected. A comprehensive impact assessment study has allowed the conception of a specific environmental strategy, which includes the relocation of protected seaweed, Neptune grass, and noble pen shells among other species.

Underwater noise is an important issue in this project. According to the impact assessment's outcomes, an acoustic risk area for marine mammals is monitored in real time before the beginning of each noisy workshop to check the presence of mammals. If no individual is detected during a 30-minute period, a green light is given to begin the work. To ensure this important step in the protection of mammals, Bouygues TP Monaco is backed by Quiet-Oceans, a European specialist in the assessment and avoidance of the impact of underwater noise on marine species.

Quiet-Oceans has adapted a real-time noise measurement and species detection buoy called Smart-PAM. Smart-PAM was first developed on request by the French Agency for Biodiversity for the real-time underwater noise monitoring of Marine Protected Areas in partnership with Sonsetc, a spin-off of the of Bioacoustics Applications Laboratory the Polytechnic University of Catalonia.

In Monaco, Smart-PAM electronics are inserted into a large mark buoy and are operated remotely from Quiet-Oceans' headquarters, which communicates in real-time with the team and the contractors of Bouygues TP Monaco according to a precise methodology. For more than two years now, Smart-PAM has been continuously used for noise monitoring and detection of marine mammals in the acoustic risk area of the diverse construction activities, including the operations of companies like Jan De Nul, Saipem, Van Oord, and Intrafor.

The avoidance of acoustic risk on marine mammals using this methodology and technology has recently been chosen by major wind farm installation and Oil & Gas companies convinced by the efficiency and the easy implementation of Smart-PAM. Passive acoustics better detection of cetaceans than visual observation as mammals are most of the time swimming under the sea level and as it can be operated anytime, even at night and by low visibility conditions. The possibility to remotely operate this buoy keeps the cost low. In addition to mammal detection, this buoy also offers real-time underwater noise level measurement and recording.

With the implementation of Smart-PAM and other solutions, the land reclamation project of Portier Cove is a very interesting laboratory of new technologies and methodologies to protect the marine environment, is well worth studying.

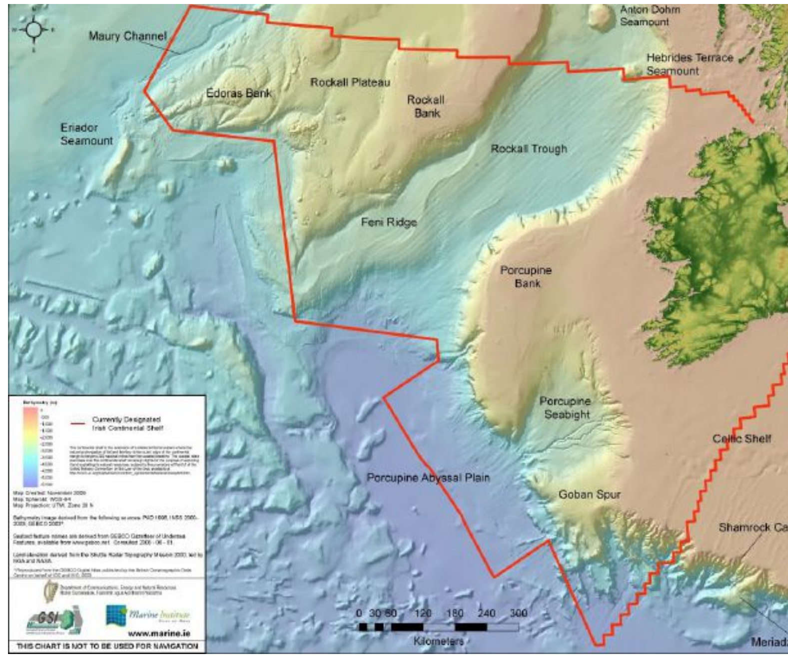
Listening to Ireland's Ocean Floor

Words by Chris Bean, Senior Professor of Geophysics Secton of the School of Cosmic Physics, Dublin Institute for Advanced Studies (DIAS)

The *In situ* Marine Laboratory for Geosystems Research (iMARL) is a network of sensors located on the ocean floor, hosted by the Dublin Institute for Advanced Studies (DIAS), that provide direct long-term observations of the interaction between the ocean and solid earth. The equipment will facilitate the integration of solid earth and marine geoscience, leading to a better understanding of how the land and the deep ocean interact with one another, far offshore.

Ireland has an ocean territory ten times larger than its terrestrial landmass. Geological, oceanographic, and biological processes interact daily in this vast territory, but until now, have been poorly understood due to; (a) a lack of observational infrastructure, and (b) a need for more interaction between marine sciences and geoscience disciplines.

Funded by Science Foundation Ireland (SFI) with support from the Geological Survey Ireland (GSI), iMARL comprises of broadband Ocean Bottom Seismographs (OBS), broadband acoustic sensors, and sensors for measuring absolute water pressure and temperature on the seabed. A system capable of detecting tsunamis also forms part of the infrastructure. The sensor pool is largely mobile and can, in principle, be deployed around the world. However, iMARL's 18 OBS are currently being used in the project *Structure, Evolution And Seismicity* of the Irish offshore (SEA-SEIS) to better understand the Irish ocean territory. Scientists from DIAS have deployed these seismometers at the bottom of the North Atlantic Ocean. The network covers the entire Irish offshore, with a few sensors also in the UK and Iceland's waters. Another OBS is in the process of been developed and will ultimately become a real-time sensing offshore element of the Irish National Seismic Network (www.insn.ie).



Map indicating Ireland's internationally designated vast marine territory (Marine Institute and Geological Survey Irelad 'Real Map of Ireland')

Strapped to seabed landers and deployed on the seafloor, iMARL will allow for the detection of offshore earthquakes and storms, as well as noise in the ocean and biologically generated acoustic signals (e.g. from cetaceans). Benefits from this program will include natural resources quantification, natural hazard estimation, environmental and baseline climate-related *in situ* ocean monitoring, and the monitoring of marine noise pollution.

Ocean Bottom Seismographs being deployed

RBR bottom pressure recorder

The ocean-bottom seismometers were deployed between September 17 and October 5, 2018, and will collect valuable data until their retrieval. Currently, this is the smallest broadband seismometer for long-term deployments. The instrument has four channels (three components of the ground displacement and one broadband hydrophone) with 32-bit recording at 250 samples per second. It has 300 miliwatt total power consumption, including its 120s broadband Trillium Compact seismometer, manufactured by Nanometrics (Canada).

The hydroacoustic network can be used for locating and tracking sound sources in the ocean, including whales, dolphins, environmental noise, and acoustic noise due to ocean-atmosphere interaction. It is comprised of a set of ten RS-ORCA3000 high specification underwater acoustic data recorders and signal processors capable of supporting multiple input channels. Each ORCA3000 recorder is capable of supporting five synchronously sampled hydrophone inputs with flexible sampling rates ranging from 1500 Hz to 384 kHz. We have ten broadband acoustic hydrophones with possible applications. One such application could be the study of wave-generated continuous background seismic noise, called microseisms, which is useful for seismic imagery and marine resource mapping, seafloor stability, ocean wave climate studies, and wave energy potential estimation. The ten medium to high-frequency hydrophones have other possible applications in wildlife studies such as monitoring whale and dolphin vocalizations covering lower frequency calls of fin and blue whales (approx. 10Hz to 31kHz) and studying the sources and effects of marine noise pollution.

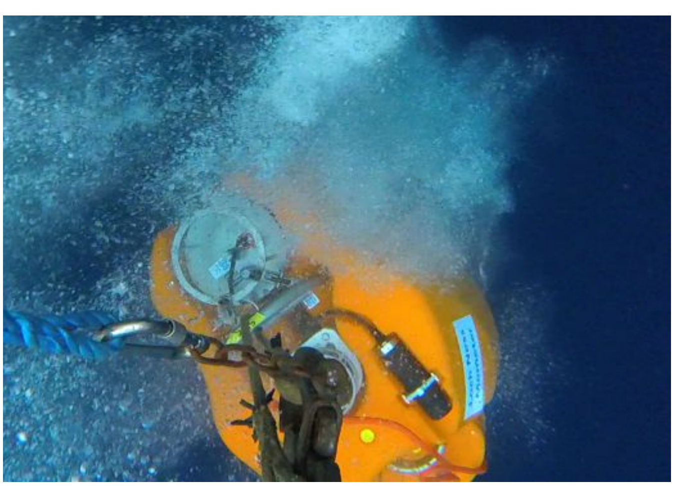
The ocean pressure network allows the measurement of absolute water pressure, down to depths of 7,000 meters. Low-frequency variations in this pressure field can also be measured. This allows an estimation of the absolute loudness of low-frequency sound, and insights into how atmospheric driven sound variation in the water influence the sea floor. The data betters the understanding of microseism generation by measuring the energy transfer from the ocean acoustic wavefield into the seabed.

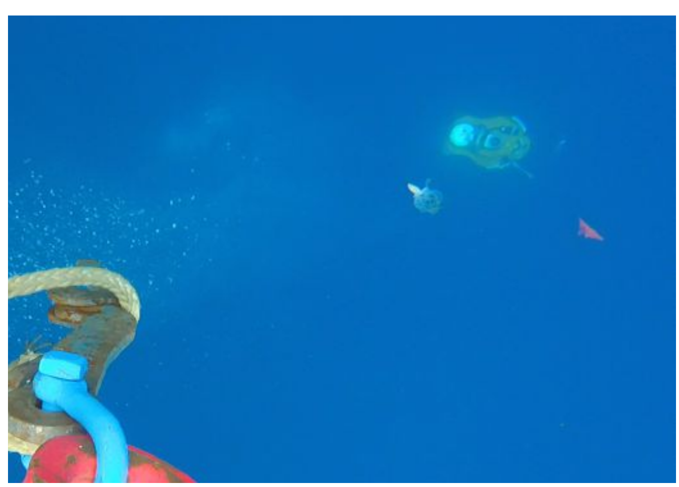
Absolute measurements of ocean floor pressure are the only reliable means of determining if a tsunami is actually propagating offshore. This pool comprises shallow and deep water instruments with six Enduro absolute pressure, temperature and tilt sensors; one Seabird Scientific SBE54 Tsunameter and five RBR*quartz*³BPRs (bottom pressure recorders) suitable for short and long-term studies.

RS Aqua ORCA Acoustic data recorder.

iMARL will include a fixed seismic, hydroacoustic and absolute pressure instrument set for long term monitoring at a single site. The construction of this OBS is well underway by Guralp Systems Ltd.

The aim is to monitor seismic signals from a wide range of sources especially from microseisms and local and distant earthquakes and detect and measure tsunamis. The system will be able to communicate through an acoustic link to a buoy moored in the vicinity of the underwater module. The buoy will be equipped with a satellite communication system to allow near real-time communication between the seafloor station and the onshore national data center at DIAS.





Ocean Bottom Seismographs meeting local wildlife on its autonomous descent to the bottom of the Rockall Trough, offshore Donegal, Ireland

Reducing Underwater Noise from Pile Driving

Words by Marine Construction Technologies

Marine Construction Technologies, PBC is a for-profit Delaware public benefit corporation established in 2012 to develop and commercialize noise mitigation technology for use in marine and other aquatic construction, specifically pile driving

Piles are hollow steel tubes that are driven deep into the seabed or substrate. They are essential for construction of bridges, ferry terminals, docks, port facilities, and other offshore and nearshore structures. Underwater noise from impact pile driving is a pressure wave, which can harm fish, marine mammals, and other sensitive wildlife by compressing and expanding gas-filled organs and hearing structures resulting in temporary or permanent injury or even death. To protect marine life, regulators limit cumulative noise, impose timing restrictions, and require use of noise attenuation technologies and extensive monitoring. As a result, permitting can be difficult and project implementation and scheduling can be complicated.

Most noise attenuation technologies encapsulate the piling to isolate installation noise from the surrounding environment. Many of these technologies demonstrate variable performance, because they only mitigate noise within the water column, not the noise that reflects back out of the seabed.

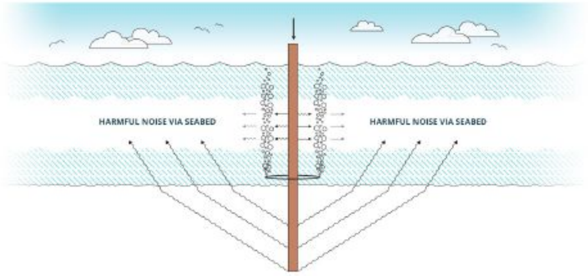


Illustration of how sound from the seabed is transmitted unhindered by a sound shield surrounding the pile in the water, e.g. a bubble curtain.

The Solution: Quiet Piles

Marine Construction Technologies (MCT) has developed a double-walled pile that can be installed more quietly, offering reductions of over 20dB. Noise is measured on a logarithmic scale, so a 20db reduction removes 80-90 percent of the noise energy associated with pile driving. This reduction falls below the regulated or scientifically recognized injury thresholds for most sensitive species and results in substantially smaller ensonified areas during construction.

Our double-walled pile consists of a smaller diameter inner pile sleeved inside of a larger diameter pile with an air gap

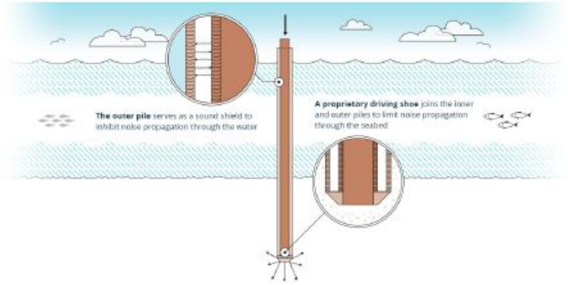


Illustration of double-walled pile.

maintained between the two. The inner pile is the only pile struck or vibrated by a hammer to advance the pile into the substrate. The air gap between the two piles buffers the noise, or pressure wave generated by striking the inner pile, from entering the surrounding environment along the entire length of the pile – addressing both in-water and in-sediment noise. The two piles are connected with our special driving shoe. MCT piles can be driven using standard impact or vibratory hammers and are self-attenuating.

Illustration of double-walled pile.

The company has completed two full-scale tests of its technology in Puget Sound, both sponsored by Washington State Department of Transportation and the U.S. Department of Transportation's Federal Highway Administration. These tests demonstrated effective noise mitigation and drivability. Noise data from the initial full-scale test are summarized below for a standard pile with bubble curtain versus the two versions of MCT piles.

Metric	Standard Pile w/ Bubble Curtain	MCT Double Walled Pile	MCT Mandrel Driven Pile (Reusable Inner Pile)
Peak Reduction	-6	-21.2 dB	-23.2 dB
SEL Reduction	-5	-17.2 dB	-18.0 dB
RMS Reduction	-5.5	-19.1 dB	-20.7 dB

SOUNDS OF THE POLAR REGIONS

Belugas Hunting

These Arctic odontocetes have a very cheery and colorful sounding social vocalization repertoire. They also have a very plastic melon that can change shape to "mind-blowing" degrees. Given that the melon is associated with bio-sonar and hearing, this indicates a very complex relationship with sound. Source: Ocean Conservation Research

Bearded Seal

Male bearded seals are found in the Arctic and have a complex vocal repertoire which they bring out during breeding season during the Arctic Spring (March through July). They also have very pronounced and thick vibrissae, or "whiskers" indicating that they also have a deep physiological investment in perceiving particle motion in their habitat. Source: Ocean Conservation Research

Bowhead Whale

This cousin of the Right Whale resides exclusively in the Arctic. They follow the advance and retreat of the lead ice, can break through 12" of ice, and are often accompanied by belugas. The bowhead whale could live to over 200 years, growing up to 20 meters (66 feet). Source: Ocean Conservation Research

Weddell Seal

Found in the Antarctic, the Weddell seal's complex descending sweeps and chirping calls are produced by the males during breeding season, evidence that this vocalization probably has something to do with courtship, advertising breeding fitness, and/or territorial announcements. Signals are complex in frequency, amplitude, and time domain. Sound source: Ocean Conservation Research

Arctic Cod

Also known as the polar cod, it is a hardy fish that survives best at temperatures of 0–4 °C, but may tolerate colder temperatures owing to the presence of antifreeze protein compounds in its blood. Arctic cod group in large schools in ice-free waters, feeding on plankton and krill. It is, in turn, the primary food source for narwhals, belugas, ringed seals, and seabirds. Sound source: Fishbase

Editorial Calendar 2019

eco
environment coastal & offshore

January/February

Editorial Focus	Products & Services Focus	Deadlines	Show Distribution	
Deep Sea	Laboratory Equipment and Clothing Benthic Sampling Tools and Services	**Editorial:** December 14 **Ads:** January 03	**Oceanology International Americas**	February 25-27
			World Ocean Summit	March 5-7

March/April:

Editorial Focus	Products & Services Focus	Deadlines	Show Distribution	
Polar Science	Polar Field Equipment and Clothing Expedition Consultation and Logistics	**Editorial:** February 06 **Ads:** February 14	**Ocean Business**	April 9-11
			EarthxOcean	April 26-28
			EOMAP SDB Day	May 14-16 💻

May/June:

Editorial Focus	Products & Services Focus	Deadlines	Show Distribution	
Marine Ecosystems	Diving Equipment Underwater Cameras and Lights	**Editorial:** April 24 **Ads:** May 02	**Dredging Summit & Expo**	June 4-7
			Clean Pacific	June 18-20 💻
			Africa Blue Economy Forum	June 25-26 💻

July/August:

Editorial Focus	Products & Services Focus	Deadlines	Show Distribution	
Fisheries and Aquaculture	Fisheries and Aquaculture Equipment and Services Environmental Impact Assessment Services	**Editorial:** June 25 **Ads:** July 03	**OceanObs'19**	September 16-20
			ICE Coastal Management	September 24-26

September/October:

Editorial Focus	Products & Services Focus	Deadlines	Show Distribution	
Coastal and Estuaries	Oil Spill Cleanup Remediation Product and Services Processing and Analysis Software	**Editorial:** August 28 **Ads:** September 05	**Teledyne Marine Tech Workshop**	October 6-9 💻
			Arctic Circle Assembly	October 10-13
			OCEANS '19	October 27-31
			Clean Gulf	October 28-30
			CERF	November 3-7
			WOC SOS	November 20-22

November/December:

Editorial Focus	Products & Services Focus	Deadlines	Show Distribution	
Ocean Exploration	Pelagic Sampling Tools PAM/MMO Tools and Services	**Editorial:** October 30 **Ads:** November 07	**TBD**	

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