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**Humpback
whales** 

Special Issue

Ocean Sound

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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.



The Forgotten Measurement:

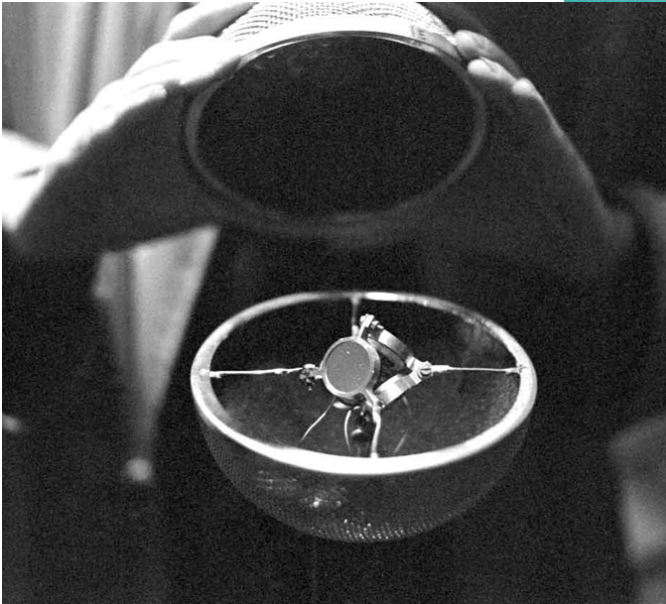
Sound Pressure and Particle Velocity

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.

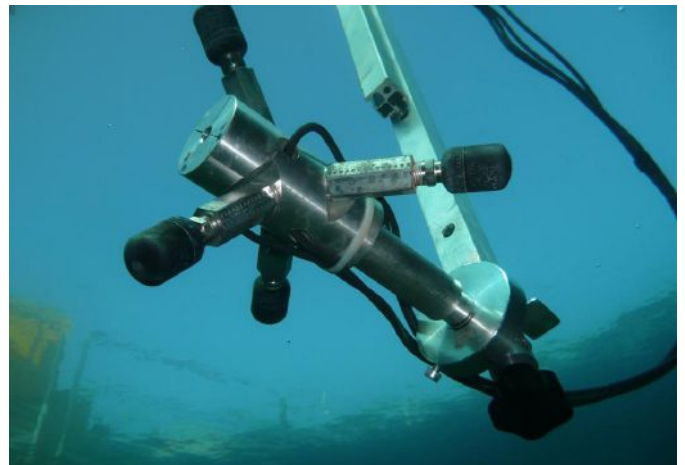
In such an example, pressure and velocity are related with a linear proportional law, but obviously, this case is as simple as unusual. In most cases of the real world, this relation is a lot different and much more complex. The same happens underwater and in particular close to the coastline, where 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 been 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).”

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.

