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COMPACT VOLUMETRIC ACOUSTIC SENSORS FOR STUDYING DEEP DIVING CETACEANS

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ABSTRACT

Deep diving cetaceans, especially sperm and beaked whales, are living in a world of their own. They are known to forage consistently at great depth where they spend a significant amount of time. Despite being wide ranging animals, sperm and beaked whales also show some preference to underwater canyons and sea mounts.

In summer 2021, three compact Volumetric Acoustic Sensors (cVAS) were placed in the vicinity of the Caprera Canyon, north-east of Sardinia in the Mediterranean Sea to monitor the presence of deep divers and to assess the acoustic environment these animals encounter while foraging in this habitat. The recorders were implemented as compact volumetric acoustic sensors using 6 hydrophones spaced by 69 mm in a volumetric configuration providing three-dimensional sound intensity estimation and direction-finding capabilities supporting the analysis of habitat usage of deep diving cetaceans.

The cVAS autonomous recorders were moored at water depths between 680 to 900 m and were sampling continuously the acoustic environment in the frequency band up to 48 kHz allowing the observation of echolocation clicks of deep divers, whistles and clicks of dolphins, in addition to broadband noise of passing ships due to close-by shipping lines and fishing activities.

Keywords: *deep divers, cetaceans, passive acoustic monitoring, volumetric sensor, autonomous recorder.*

1. INTRODUCTION

Deep diving cetaceans, especially sperm and beaked whales, are living in a world of their own. They are known to forage consistently at great depth where they spend a significant amount of time [1,2]. Despite being wide ranging animals, sperm and beaked whales also show some preference to underwater canyons and sea mounts [3,4]. This is mostly due to special underwater currents (upwelling) that are favorable for nutrient transport [5] and the development of a complete food chain attracting *inter alia* squids that are primary prey species of deep diving cetaceans.

It is of ecological interest to know if the dive behavior of different cetacean species differs in the presence or absence of other cetaceans, being them of the same species or not. Foraging at depth is energetically demanding [6] and one should expect that the cetaceans optimize their dive behavior, and this optimization may vary in presence or absence of other cetaceans. In other words, do foraging deep diving cetaceans forage independently from other animals, or do they coordinate the foraging behavior?

As sound propagates in water better than light [7], cetaceans use sound to navigate underwater, to search and hunt prey and to communicate. It is therefore appropriate to also use acoustic methods when studying underwater behavior of deep divers.

By listening to the whales and dolphins it is possible to infer some behavioral states by analyzing motion of the animals and the emitted sound. Cetaceans use during foraging activities specific short sound pulses to echolocate on prey.

The two species of interest in this work are sperm and Cuvier's beaked whales, both being deep divers. Sperm whales are well known for their loud echolocation clicks, but are not known to emit tonal sounds, like whistles that are characteristic for socializing dolphins, but use stereotyped click sequences, called coda, for intra species communication [8]. Social communication sounds have not yet conclusively been described for Cuvier's beaked

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whales, but there are indications of the presence of tonal sounds [9]. It seems therefore appropriate to concentrate on foraging activities when studying these cetaceans.

Traditional cetacean field work is very variable, but often oriented towards abundance or density estimation that are key quantities in ecology [10,11], where visual or acoustic methods are used to determine the total number of cetaceans that are present in a given area. Being based on statistical sampling methods, no specific attention to specific animals is permitted, as this would introduce biases into the abundance or density estimates, a requirement that explicitly excludes focus on individual cetacean behavior [10].

When the behavior of individual cetaceans is of research interest, focal follow methods are applied, where the activity of an individual is recorded in detail [12]. Ship based focal follow is for obvious reasons mostly restricted to visual observation and used during day hours and fair weather. Monitoring acoustic behavior of the focal animal is possible when using hydrophones [13]. However, using acoustics together with visual surveys is an added complexity as traditionally, this requires not only special hardware (cabled hydrophones and ultra-low noise electronics) and software (ultrasonic sound visualization) but also knowledge in sound signal processing (Detection, Classification and Localization (DCL)).

Deploying autonomous acoustic recorders offers the advantage that acoustic data are collected in absence of human presence and therefore can be considered for studies that cover longer periods and can be implemented in remote areas. However, the material cost is increased due to added cost for power supply (batteries), disk storage, and release mechanism that is needed to recover the recorder. Deep-sea autonomous recorders need further implemented to sustain increased ambient pressure (100 atm at 1000 m depth).

In summer 2021, three compact Volumetric Acoustic Sensors (cVAS) were placed in the vicinity of the Caprera Canyon, north-east of Sardinia in the Mediterranean Sea to monitor the presence of deep divers and to assess the acoustic environment these animals encounter while foraging in this habitat. The recorders were implemented as compact volumetric acoustic sensors using 6 hydrophones spaced at 69 mm in a volumetric configuration providing three-dimensional sound intensity estimation and direction-finding capabilities supporting the analysis of habitat usage of deep diving cetaceans.

The cVAS autonomous recorders were moored at water depths between 680 to 900 m and were sampling continuously the acoustic environment in the frequency band up to 48 kHz allowing the observation of echolocation clicks of deep divers, whistles, and clicks of dolphins, and broadband noise of passing ships from close-by shipping lines and fishing activities.

Here we present the concept of the cVAS and illustrate two use cases, tracking of sperm whale clicks and sound intensity estimation of passing ships.

2. COMPACT VOLUMETRIC ACOUSTIC SENSORS (CVAS)

For this research activity a compact and smart acoustic research tool had been implemented that extends cetacean research into the deep-sea, acoustic domain of cetacean behavior. This research tool augments the available information of deep-diving cetaceans and allows science to relate the cetacean behavior to the acoustic soundscape the animals are living in.

Smart acoustic cetacean observation is best executed using 3D directional acoustic sensors where the compact designs allow easy handling and simplified signal processing.

There are a variety of hydrophone geometries possible. The smallest 3D directional (volumetric) design uses 4 hydrophones in tetrahedral configuration. A more robust direction estimate is obtained by using 6 hydrophones in octahedral configuration. To this goal, the cVAS, a 6-hydrophone compact acoustic sensor has recently been developed at CMRE and was the basis for this project.

2.1 cVAS hardware

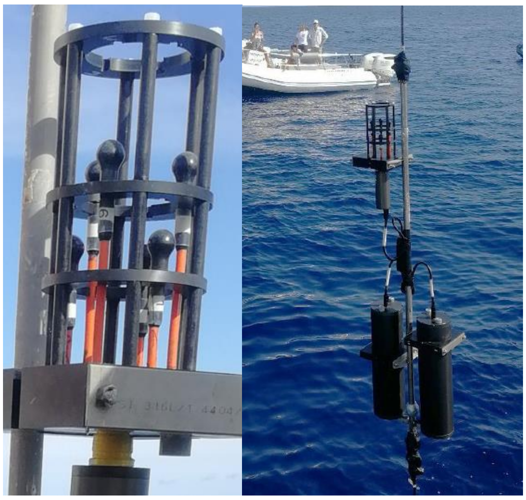

Figure 1. cVAS acoustic array (left) and together with attached electronics container and two battery packs during deployment (right).

The novelty of the cVAS hardware is the compact 6-hydrophone volumetric array, which is shown in Fig. 1 on the left that allows not only three-dimensional (3D) direction finding using traditional time delay of arrival estimates, but, due to its compact nature also the estimation of 3D sound intensity vectors, a method that like beamforming requires closely spaced hydrophones. Due to hydrophone spacings of 69 mm phase-based (coherent) processing is possible up to a frequency of about 10 kHz.

A low-cost Inertial Measurement Unit (IMU) provides the necessary data to establish the orientation of the recorder and its hydrophones.

The other particularity of the cVAS is the use of a commercially available micro controller (MCU), a NXP-IMXRT1062 based USB development board[1], that, being Arduino compatible, can be programmed easily without the need of a real-time operating system.

2.2 cVAS software

The implementation of the cVAS as autonomous recorder requires in addition to the sensors (hydrophones) and disk storage (microSD cards) also a central processing unit (CPU) that has not only the task to capture the data from the sensors and to store them on disks, but also to interface with the user during system setup and after recording.

While the cVAS can be programmed within the Arduino development system, the software is refactored such that it can be developed completely outside Arduino.

The initial software features different recording modes:

- storing raw data
- loss-less compression

whereby the storage requirements are decreasing.

The data are stored on microSD cards using standard file systems to allow easy access to the data by inserting the microSD card to standard computers.

While still inserted in the cVAS, the microSD card can be accessed via USB using standard Media Transfer Protocol (MTP), the same protocol that is used to transfer pictures from cameras to PC. Using MTP transfer is, however, only suitable for a small number of files due to transfer speed limitation.

3. VOLUMETRIC SIGNAL PROCESSING

3.1 Sound Detection

Acoustic recordings contain a variety of sound types, tonal and transient sounds from cetaceans and other ocean fauna, but also broadband noise of passing ships due to close-by shipping lines and fishing activities.

Traditionally, one is interested in the detection of non-noise events, like cetacean echolocation clicks and considers ambient noise as nuisance that in most cases is described as a single RMS values. The cVAS provides a tool to obtain directional information on the directionality of both, the signal of interest and the ambient noise.

As the cVAS is designed to be developed into a smart acoustic recorder, all signal processing including sound detection is designed to occur without human interaction and validation. Consequently, the possibility of false detections is accepted and part of the concept that volumetric signal processing could help in eliminating false detections.

The volumetric processing is implemented in two steps, one being the classical time-delay based direction finding, the other one being the estimation of the three-dimensional sound intensity vector.

3.2 Time delay direction finding

The classical time-delay direction finding detects first the signal of interest, here sperm whale clicks, estimates the delays between pairs of hydrophones and calculates the angles of arrival.

Given a three-dimensional sound arrival vector $\vec{S}$ and a vector $\vec{d}$ that connects two hydrophones, then the cosine of the angle between the two vectors $\vec{S}$ and $\vec{d}$ is given by the relation

$$|d||S|\cos\beta = \vec{d}^T\vec{S} = d_xS_x + d_yS_y + d_zS_z \tag{1}$$

The left- hand side of Eq. 1, however, is proportional to the measured time delays [7]

Considering this equation for all 15 possible pairs of hydrophones that one can form with a 6-hydrophone octahedron, then one can easily estimate the direction of the sound arrival [7].

3.3 Sound intensity estimation

The concept of a compact volumetric acoustic sensor (cVAS) is based on the realization that ambient noise fields are best described by their two- or three-dimensional sound intensity vectors.

From basic acoustics follows that the sound intensity vector $\vec{I}$ is a time averaged quantity of the product of the omnidirectional sound pressure $p(t)$ and the directional sound particle velocity $\vec{u}(t)$:

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[1] Teensy® 4.1 (pjrc.com).

$$\vec{I} = \langle p(t)\vec{u}(t)\rangle_T \quad (2)$$

where $\langle \ldots \rangle_T$ denotes the time average.

While sound pressure is best measured by hydrophones, the measurement of sound particle velocity requires different sensor technologies. Although geophones could be used to directly measure the particle velocity, they are mostly applied to measure the earth motion and only recently, geophones are used to sense ambient sounds at very low frequency, i.e., < 50 Hz [14]. Most directional sound sensing devices (aka vector-sensors) use accelerometers that by temporal integration generate the desired sound particle velocity. Most notable, DIFAR sonobuoys use accelerometers to obtain the direction of arriving sounds.

The cVAS uses an alternative approach, where the sound particle acceleration is measured indirectly by measuring the sound pressure gradient, which is directly proportional to the sound particle acceleration. This method is based on the physical properties inherent to sound propagation. When sound propagates the water particles are accelerated proportionally to the sound pressure gradient:

$$\frac{d}{dt}\vec{u}(t) = -\frac{1}{\rho}\nabla\vec{p} \quad (3)$$

where ρ is the water density.

Given a pair of hydrophones, the projected spectral sound intensity is then estimated using the following relationship [15]:

$$I_{12}(\omega) = -\frac{1}{\rho}\frac{1}{2\pi}\frac{1}{d_{12}}\frac{\mathrm{imag}\left(P_1(\omega)P_2(-\omega)\right)}{\omega} \quad (4)$$

where d_{12} id the separation between hydrophones 1 and 2, $P_1(\omega), P_2(\omega)$ are the complex spectral power estimates at the hydrophones and ω is the circular frequency.

Following Eq. 4, the sound intensity estimation can easily be implemented using standard spectrograms.

To measure the sound pressure gradient, two closely spaced hydrophones are used along the direction of interest. As with the time/delay method, a minimum of 4 adequately located hydrophones are required to estimate three-dimensional sound directions, but more hydrophones may be useful to reduce the sound direction estimation error.

Both approaches to estimate the sound direction (directional sound particle velocity using accelerometer or pressure gradient method) have their disadvantages. Both methods suffer from the fact that the effective sensitivity decreases with decreasing frequencies. The use of accelerometers is typically limited to lower frequencies due to hardware constraints. Pressure gradient sensors are also limited in frequency as the minimal achievable separation between hydrophones limits the possibility for phase processing to lower frequencies. For the cVAS where the hydrophone separation is 69 mm, the maximal frequency for which pressure-gradient methods work is a little over 10 kHz. For higher frequencies spatial aliasing takes place, that is, the phase difference between the measurements of the two hydrophones is not uniquely related to a single sound direction.

Advantage of the pressure gradient sensor method is, however, that for higher frequencies, where estimation of the pressure gradient is impossible or unreliable, the individual hydrophones can still be used to obtain the direction of short impulsive sound that typically contain significant high frequency energy. This is achieved by the classical time difference of arrival (TDOA) method (See 3.2). This approach was indeed applied to another volumetric hydrophone array (CPAM) developed at NURC (STO-CMRE) [16].

4. FIELD WORK

4.1 Locations

In summer 2021, three compact Volumetric Acoustic Sensor autonomous recorders (cVAS-AR) were placed in the vicinity of the Caprera Canyon (Fig. 2), north-east of Sardinia in the Mediterranean Sea. The purpose was to monitor the presence of deep divers and to assess the acoustic environment these animals encounter while foraging in a typical habitat.

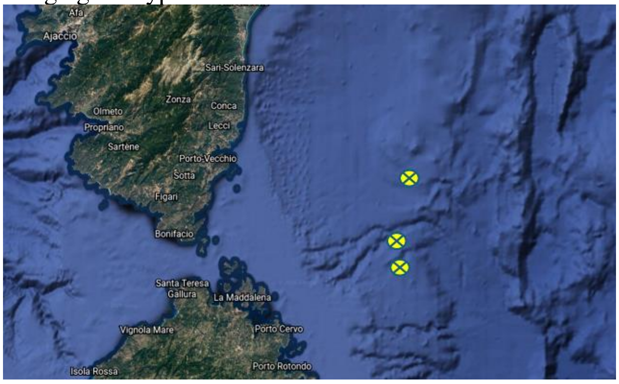

Figure 2. cVAS-AR locations in vicinity of Caprera canyon system north-east of Sardinia.

The cVAS-ARs were moored at water depths between 680 to 900 m and continuously sampled the acoustic environment in the frequency band up to 48 kHz thereby allowing the observation of echolocation clicks of deep divers, whistles and clicks of dolphins, broadband noise of passing ships from close-by shipping lines and noise due to fishing activities.

The northern location was close to the presence of an underwater seamount, while the other two recorders were placed closer to underwater canyons. The locations were chosen to maximize the encounter probability of deep divers, i.e., sperm whales and Cuvier's beaked whales.

5. RESULTS

5.1 Soundscape

Figure 3 shows a typical soundscape where one can note different types of sound arriving from different sources. Ship noise is typical low frequency noise extended over multiple minutes. The presence of Depth sounder sound (here at 30 kHz) is a sign that the associated ship is very likely a fishing vessel. Dolphin echolocation clicks are in general sounds in the high frequency range (typically >20 kHz). Dolphin whistles are in the low frequency range up to 10 kHz, but not visible in Fig. 3 due to masking.

Sperm whale echolocation clicks cover a frequency range from 5 to about 30 kHz. Cuvier's beaked whale echolocation clicks that like dolphin clicks also cover the frequencies >20 kHz are not present in this Fig. 3, but recorded in other occasions.

At lower frequencies there is also some electronic noise in the form of horizontal and vertical lines. These are mainly due to very small instabilities in the power supply to the hydrophone preamplifiers due to periodic load changes within the cVAS-AR.

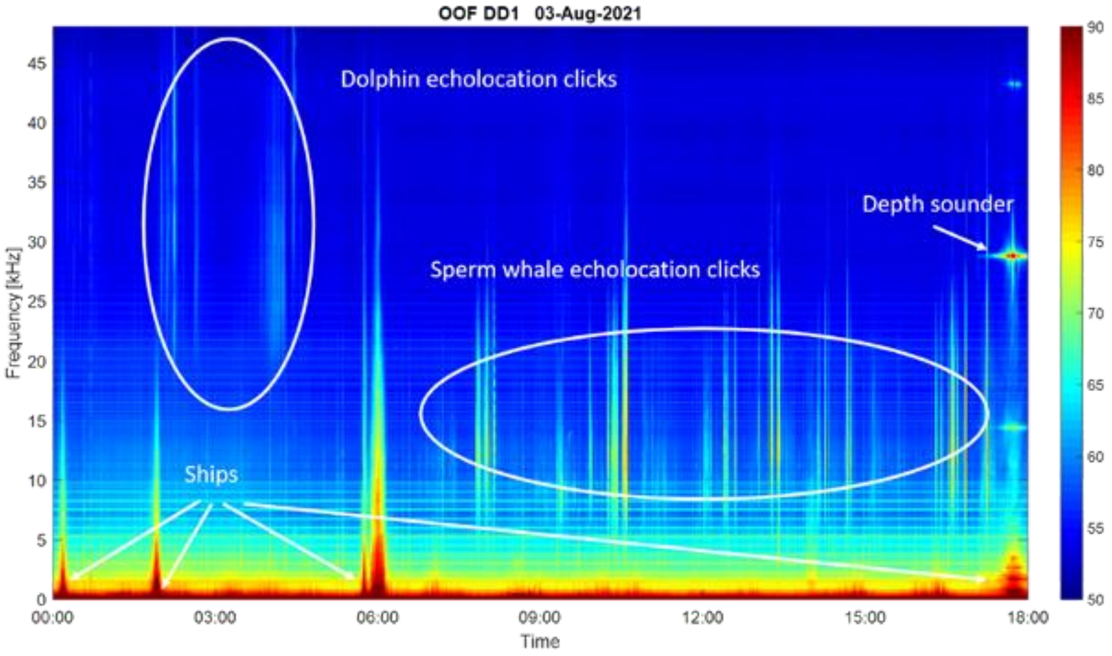

Figure 3. Deep Sea soundscape observed close to Caprera Canyon

5.2 Sperm whale clicks

To demonstrate the use of the volumetric array for direction finding, a single sperm whale click as received by all six hydrophones of the cVAS-AR is shown in Fig. 4. The left panel shows the direct arrival, the middle panel shows the sperm whale typical scull-related reflection (IPI), and the right panel shows a sea surface reflection. A careful inspection of the click arrivals shows that the clicks do not arrive at the same time. These time differences are a consequence of the volumetric arrangement of the hydrophones.

The observed difference is not very large due to the compact nature of the hydrophone array, but sufficient to estimate the arrival angles of the sound signal. Larger hydrophone spacings would show these delays more clearly but would also complicate computer-based signal processing. As with all signal processing, the precision of angle estimation depends on the signal to noise ratio. Weak signals embedded in noise give not robust results, independent of signal processing methods.

5.2.1 Sperm whale size estimation

The presence of a reflection that follows with a constant delay the primary direct arrival allows us to estimate the size of the sperm whale [17]. The observed 5 ms delay between the direct arrival and the skull-related signal corresponds then to an overall body size of 12 m [18].
The presence of skull related reflections is indeed characteristic and diagnostic for sperm whales and cannot be found in other cetaceans [19].

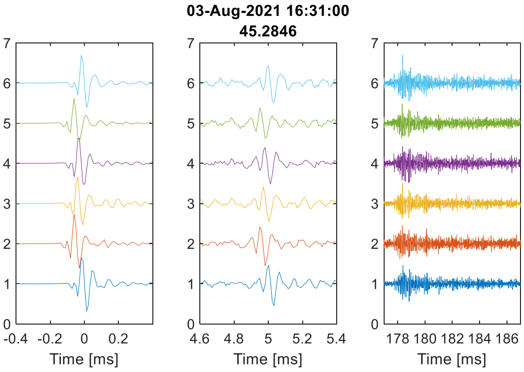

Figure 4. Sperm whale clicks as recorded by the cVAS-AR on all hydrophones, numbered 1 to 6 on the vertical axis. Left: direct arrival, middle: reflection from whale scull, right panel: surface reflected signal.

5.2.2 Surface reflection

About 178 ms after the direct arrival, another signal is found, which is very long (> 10 ms), unlike the very short direct arrival (~0.1 ms) indicating multi-point reflections on a sea boundary. As in this case the sperm whale is echolocating close to the bottom, the only plausible reflection location is the ocean surface. The observed extended reverberation is then an indication of significant sea surface roughness. No further analysis has so far been carried out in correlating the see surface roughness (wind speed) with reverberation of echolocation clicks.

5.3 Three-dimensional direction estimation

Upon detection of the individual sperm whale clicks, the three-dimensional sound direction is estimated following the methods described in [7,16]. Fig. 5 shows the resulting estimation of azimuth and elevation angles.

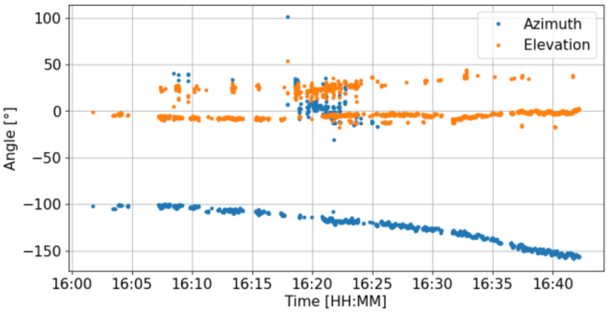

Figure 5. Azimuth and elevation angle estimation of a Sperm whale click train.

There are a couple of observations to be made:
The azimuth estimations of most detections are very well aligned and vary slowly from -100° to -150°; most elevation angles are just below 0°, but some elevation angles are significantly positive >20°. As the hydrophone depth is about 150 m over the sea bottom, a negative elevation angle indicates that the sperm whale is foraging between hydrophone depth and bottom. Positive elevation angles are indicative for surface reflected sound.
Finally, around 16:20 there are additional detections with different azimuth and no related negative elevation angle. These detections are not from the deep diving sperm whale but from another animal close to the surface.

5.3.1 Ranging

The detection of sea-surface reflections in combination with the knowledge of the hydrophone depth and the elevation angle of the direct arrival allows in theory the estimation of range and depth of the sperm whale [16].
Fig. 6 shows an example of the range and depth estimation of the foraging sperm whale. One can easily see that the sperm whale is indeed foraging close to the bottom in the canyon area. For this case, i.e. the click that is shown in Fig.4, the direction angles were 356.4° and -4.10° for the azimuth and elevation angle of the direct path. The elevation angle of the surface reflected path turned out to be +25.0° for a 179.8 ms delay of the surface reflected click.
The resulting range to the whale was 2606 m with a whale depth of 693 m, which is just above the bottom.
However, the uncertainty of the exact arrival of the surface reflected signal is very high due to the increased reverberation, so precise motion estimates are difficult to obtain. Consecutive range and depth estimates may be too noisy to be used for instantaneous speed estimation without additional filtering. Kalman filters have been shown to be

suitable in such cases to smooth the instantaneous speed estimations of the sperm whale [7].

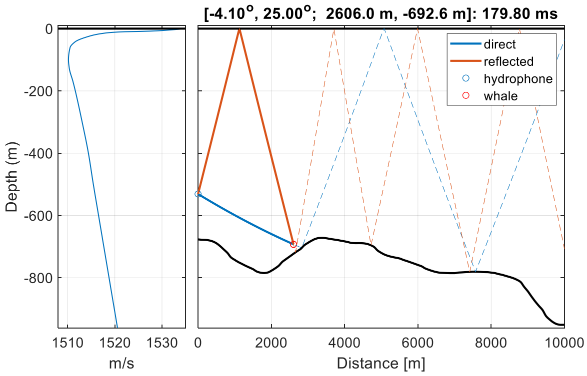

Figure 6. Sperm whale range estimation. Left: sound speed profile, right: ray traces for direct and surface path.

6. SOUND INTENSITY ESTIMATION

One of the design features of the cVAS is the compact arrangement of the hydrophones to allow the estimation of directional sound intensity.
Fig. 7 shows an example of the spectral intensity vector for two passing ships. The spectral extent is limited to 10 kHz due to the physical limitations imposed by the hydrophone separation. One notes that the first ship passes from left-behind to right-forward and the second ship passes in front of the receiver from right to left.

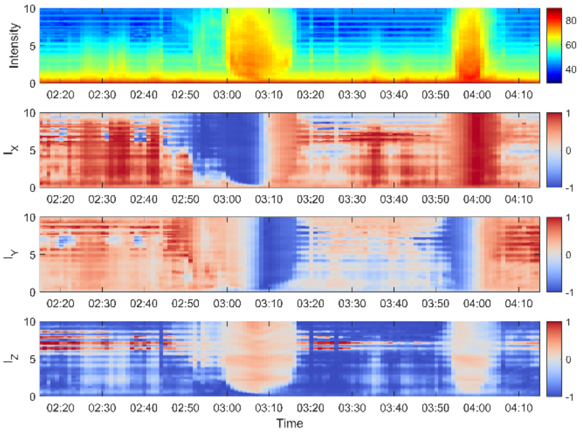

Figure 7. Spectral sound intensity vector of two passing ships. Top: Sound intensity, remaining panels show relative directional components.

The spectral representation of the sound intensity vector allows more detailed investigation of spectral characteristics of the detected signal, but to describe the proper sound intensity vector, which is an average quantity, spectral integration is required.

7. SUMMARY

The cVAS implements a compact Volumetric Acoustic Sensor that can be used to obtain three-dimensional sound field estimations. By using hydrophones and not accelerometers to estimate the sound field vector, both standard time-delay based, and phase-based direction-finding methods can be used. In particular, the estimation of wide-band sound intensity vectors calls for closely spaced sensors like the ones that are implemented in the cVAS.
The cVAS recordings obtained from the Caprera Canyon system NW Sardinia, Italy, demonstrate *inter alia* the presence of deep diving sperm whales that forage close to the bottom and the capability for tracking passing ships.
Dolphin whistles and clicks and possible Cuvier's beaked whale echolocation clicks were detected but lack clear multipath signals that is necessary for range estimation and are therefore not further discussed in this publication.
The apparent lack of clear multipath signals for Cuvier's beaked whale signals merits further analysis as this observation differs significantly from previous ones where clear surface reflections were recorded using a volumetric array towed close to the sea surface [16].
Despite the difficulties to easily obtain detailed motion estimates of distant cetaceans, the cVAS autonomous recorders enable long term soundscape analysis and allow the study of the acoustic behavior of deep diving cetaceans and other marine fauna in relation to anthropogenic sound, especially passages of ships and boats.
The cVAS hardware is finally flexible and powerful enough to be developed further into smart, possibly AI based, real-time marine soundscape analysis systems.

8. ACKNOWLEDGMENTS

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