



Underwater Acoustics Imaging: Introducing a New Solution

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ABSTRACT

Acoustic imaging systems utilising microphone arrays and beamforming algorithms are widely employed in diverse fields, such as product development, environmental acoustics, sound design, and surveillance. Although significant progress has been made in airborne sound detection, both in hardware and algorithms, underwater acoustic localisation continues to pose unique challenges due to the complexity of sound propagation and hardware constraints. This work presents recent advancements in underwater sound source localisation, addressing both the theoretical and practical challenges. A hardware and software concept is introduced, and measurement results are presented to demonstrate the system's capabilities and limitations. Potential applications are discussed, alongside with perspectives on future developments in underwater acoustic imaging.

1 INTRODUCTION

Acoustic imaging, which utilises beamforming techniques to visualise sound sources, is a well-established technology in terrestrial applications ranging from industrial diagnostics to aeroacoustics. However, adapting this technology for the marine environment presents unique and complex challenges, as variables like temperature, salinity, and boundary reflections significantly alter sound propagation. This paper explores the adaptation of acoustic imaging for underwater use, specifically addressing these unique challenges. We present a two-stage proof-of-concept project that begins with a known environment feasibility study and culminates in an open-water field validation. The core contribution of this work is the demonstration that a modified acoustic imaging system can reliably perform sound source localisation and separation in a dynamic underwater setting, thereby offering a powerful new tool for marine research and monitoring.

1.1 Acoustic Beamforming and Its Applications in Air

Acoustical beamforming is a spatial filtering technique that uses sensor arrays, commonly applied in Sound Source Localisation (SSL) and acoustic imaging (Merino-Martinez et al, 2019). Its use became widespread with the introduction of acoustic cameras. Beamforming exploits differences in signal arrival time and phase across sensors (e.g., microphones in air or hydrophones in water). Classic and conventional beamforming algorithms extend this principle to generate "acoustic maps," which allows to visualise the spatial distribution of acoustic energy. These maps are typically displayed as colormaps, where colours represent estimated Sound Pressure Levels (SPL), for example, red indicating high SPL and blue indicating low SPL, similar to how thermal cameras depict temperature.

While beamforming in air has been extensively studied and applied, for example in acoustic cameras used for machinery maintenance (Böck et al, 2015), train-noise visualisation (Kummritz and Movahed, 2021), wind-turbine noise studies (Bradley et al 2017), and aeroacoustic wind-tunnel measurements (Döbler et al, 2016), transferring these concepts to underwater environments introduces additional challenges.

1.2 Challenges of Underwater Acoustics

Unlike air, water is not a homogeneous propagation medium. Some main challenges for underwater 2D hydrophone arrays include (1) a variable propagation medium, (2) strong reflections and reverberations effects from surface and seabed, (3) frequency-dependent attenuation, and (4) ambient noise. Sound propagation is directly affected by water's physical properties, as sound speed depends on temperature, salinity, and pressure

(related to the depth). This relationship is commonly expressed as the Sound Speed Profile (SSP), which reflects these dependencies and varies seasonally (e.g., summer vs. winter) as well as geographically (e.g., equatorial vs. polar regions) (Kuperman and Roux, 2007). Consequently, spatial, and temporal variations in sound speed affect travel times and must be accounted for in signal processing.

Surface and seabed boundaries generate multipath effects that overlap direct arrivals and complicate signal processing; these effects are typically stronger in shallow water. Attenuation losses occur from both absorption losses and scattering losses, which increase with the frequency. Ambient noise arises from both human-made and natural sources (Kuperman and Roux, 2007). The dominant human-made influence is commercial shipping, although fishing activity and busy harbours in shallow waters can also elevate noise levels. Natural sources include biological sounds (e.g., fish, invertebrates, whales) (Dahl et al, 2007), wind and wave noise (Miksis-Olds et al 2013), ice cracking in polar regions [(Dahl et al, 2007), (Miksis-Olds et al 2013)], and geophysical events such as earthquakes or storms (Wenz, 1962). These sounds, elevate ambient noise and reduce the signal-to-noise ratio (SNR), therefore constraining detection and localisation capabilities.

1.3 Statement of Contribution

This paper presents a two-stage proof-of-concept project demonstrating the successful adaptation of terrestrial acoustic imaging for underwater sound source localisation. The initial phase served as a preliminary feasibility study to confirm the technology's basic function in a known environment. The core of this work, however, is a second-stage measurement that validates the system's performance and reliability in an open-water setting. This work addresses the unique challenges of underwater sound propagation, offering a new tool for marine research and subsea monitoring. The subsequent sections will discuss the system's design, experimental methodology, and the key findings from our trials, highlighting the potential for future development in this field.

2 SYSTEM DESIGN AND METHODOLOGY

This section describes the hardware and software architecture adapted for underwater acoustic imaging, detailing the evolution of the system across the two-stage proof-of-concept project. The initial acoustic camera components were supplied by GFal e.V and gfai tech GmbH from Germany. The specialised hardware development, custom hydrophone array integration, and implementation of the system for the marine environment were performed by HW Technologies from Australia.

2.1 Hardware and System Architecture

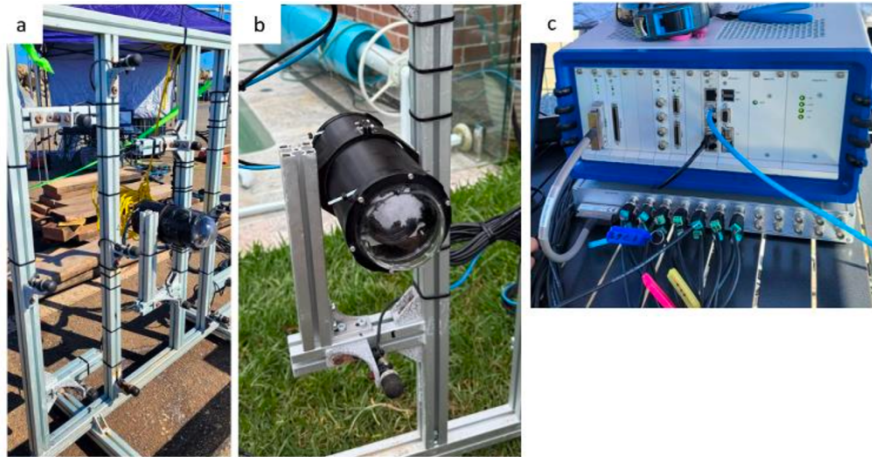
For this proof-of-concept project, the system's core hardware components were assembled and evolved across the two testing stages. The primary acoustic sensing element is a hydrophone array, integrated with an underwater camera and connected via specialised cabling to the data acquisition (DAQ) and analysis system. The DAQ hardware utilised was the 48 channel mcdRec data recorder from gfai tech (gfai tech GmbH, 2022). All hydrophone elements used in both stages were H2c-IEPE manufactured by Aquarian Hydrophones (Aquarian Audio & Scientific, 2025). While all underwater array components are rated to a depth of 80 meters, the current cabling has a validated depth restriction of approximately 25 meters. The system utilised the following specific hardware configurations:

2.1.1 Stage one: Known environment testing (feasibility study)

This initial prototype used a 6-Hydrophone array ($L=1.1\text{m}$, $H=1.0\text{m}$) mounted on a steel frame and utilised a GoPro Hero 10 camera (GoPro, 2025). The camera was carefully aligned using an existing acoustic camera array, Ring 48 from gfai tech (gfai tech GmbH, 2023) to ensure the recorded video image precisely matched the localisation of the acoustic map. To align the acoustic data with the video data, a modified clicker box with an integrated LED was used; the LED illuminated upon the start of acoustic recording, providing a visible marker in the GoPro video for precise time-frame integration of the acoustic maps.

2.1.2 Stage two: Open water testing (field validation)

The second prototype was constructed with a non-corroding aluminium frame and utilised a more robust Baumer industrial camera (model VLG 22C) (Baumer, 2023), which was integrated into a specialised underwater-proof housing. This setup featured a 14-hydrophone array, which was used for comprehensive field data acquisition. The key hardware components, including the array, camera, and data recorder, are illustrated in Fig. 1.



HW Technologies (Hugo Waibel, 2025)

Figure 1: Key hardware components. (a) The 14-hydrophone array in the aluminium frame; (b) Baumer industrial camera (VLG 22C) in the specialised underwater housing; (c) gfai tech mcdRec data recorder.

The core of the processing chain utilised NoiselImage (gfai tech GmbH, 2025), gfai tech's commercial acoustic camera software used for sound source localisation and visualisation. This specialised version was updated to incorporate algorithms that account for variables in the underwater environment, including water temperature, salinity, and depth, and included relevant sensor files.

3 EXPERIMENTAL SETUP

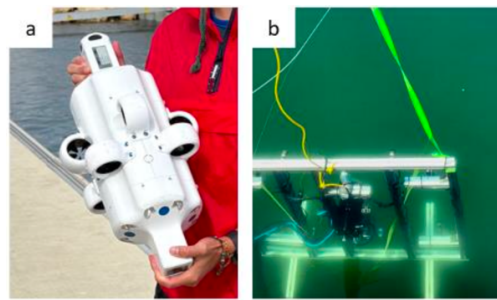
The project was conducted in two distinct stages to progress from a controlled environment to a real-world application.

3.1 Stage One: Known Environment Testing (Feasibility Study)

A preliminary feasibility study was conducted in a swimming pool in Sydney, Australia. The purpose of this stage was to confirm the fundamental functionality of the system, specifically its ability to localise a sound source underwater. An underwater pool cleaner fixed in position, served as the sound source for this initial trial. The hydrophone array was hung in the water, positioned approximately 1.0 meter below the surface. The array and the fixed sound source were separated by an approximate distance of 3.5 meters to observe localisation in the pool environment.

3.2 Stage Two: Open Water Testing (Field Validation)

The second stage took place in Fremantle Harbour, Western Australia. This was a crucial step to validate the technology's performance and reliability in a dynamic, open-water environment. This test was done in a collaboration with the Australian Navy's Centre for Innovation. The sound source was a Hydrus mapping drone supplied by Advanced Navigation, Australia (Advanced Navigation, 2025). The drone, which has seven thrusters, was launched from a wharf. The underwater acoustic camera was tethered and used to record the drone as it moved on all axes. The setup for the open-water field validation is shown in Fig. 2, where the acoustic array is submerged and the Hydrus drone is positioned for measurement. The depth of testing was approximately 1.0 - 1.5 meters. The reliability of the collected acoustic data was subsequently validated against the known operational parameters of the drone's thrusters.



HW Technologies (Hugo Waibel, 2025)

Figure 2: Open-Water Field Validation Setup. (a) Hydrus mapping drone used for source positioning; (b) Acoustic array submerged in the open harbour

4 RESULT AND ANALYSIS

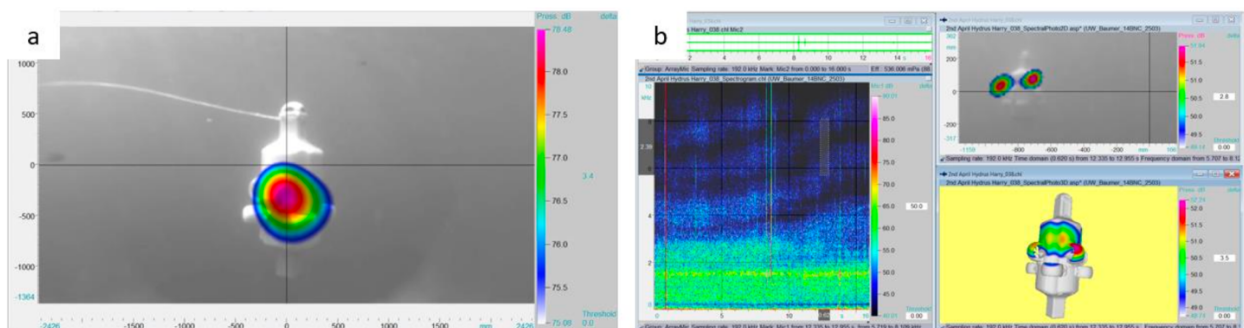
4.1 Stage One: Known Environment Testing (Feasibility Study)

The initial feasibility study in the swimming pool successfully confirmed the system's capacity for sound localisation. However, a significant early challenge was encountered due to strong sound reflections from the pool walls, which generated false data in the preliminary acoustic maps. This issue was resolved by fine-tuning the post-recording analysis. The analysis method focused on isolating and processing only the sound emitted prior to reverberation, using the high sampling rate of 192 kHz to target millisecond-long data windows. The successful mitigation of these reflections demonstrated a critical proof of concept for filtering boundary-related interference.

4.2 Stage Two: Open Water Testing (Field Validation)

The field validation trials in Fremantle Harbour successfully validated the system's performance, achieving the core project goals of source localisation, separation, and modelling in a dynamic environment. A total of approximately 60 measurements were conducted using the Hydrus mapping drone as the primary sound source. The system successfully localised the drone as it moved on all axes and demonstrated the ability to operate in a noisy environment; noise from a passing fishing vessel was clearly localised, and once it passed, the drone became the dominant source for analysis (Fig. 3(a)).

Crucially, the system proved capable of differentiating between multiple noise sources from the same moving object. By analysing specific frequency ranges, the system achieved localisation and separation of the drone's seven thrusters down to a resolution of approximately 100 millimetres. The reliability of these acoustic measurements was confirmed by correlation against the drone's known operational parameters and thruster timing. Furthermore, the two-dimensional acoustic results were successfully integrated with a 3D model of the drone, which was overlaid onto the acoustic image for enhanced visualisation and data interpretation (Fig. 3(b)). The maximum measurement distance achieved during these initial tests was approximately five meters.



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Figure 3: Acoustic results: Localisation and Source Separation. (a) 2D Acoustic Map demonstrating source localisation; (b) 3D Acoustic Map overlaid on the model of the drone, showing source separation.

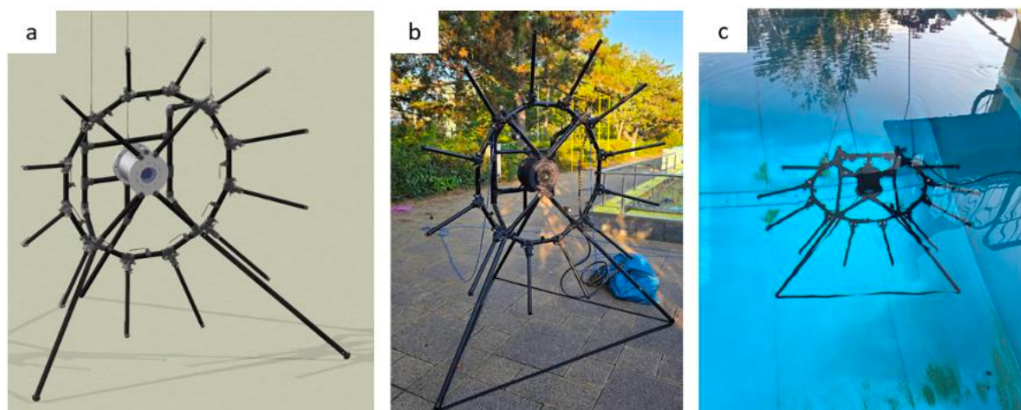
5 CONCLUSION AND FUTURE WORK

5.1 Summary of Contributions

This two-stage proof-of-concept project successfully validated the adaptation of terrestrial acoustic imaging technology for underwater sound source localisation. The initial feasibility study confirmed the system's fundamental functionality and its capacity to mitigate boundary-related interference through focused post-recording analysis. The core findings from the open-water field validation demonstrated the system's reliability in a dynamic environment, successfully achieving localisation and differentiation of multiple, closely spaced sound sources (seven thrusters, resolved to 100 mm) on a moving platform. The ability to integrate the acoustic data with a 3D model, alongside accurate correlation against known operational parameters, confirms that the technology can reliably map and visualise underwater sound. This work establishes a viable new tool for marine research and subsea monitoring, with potential applications including naval surveillance, offshore infrastructure inspection, and non-intrusive marine fauna monitoring.

5.2 Future Directions

Based on the findings of these initial tests gfai tech, together with HW technologies, produced a more advanced Underwater Acoustic Camera (UAC). This system is based on a newer model of data recorder and on an optimised array. 24 hydrophones, arranged in a double-ring geometry, are positioned on a foldable light-weight construction optimised to be submerged. The construction of this system has just been finished and the first underwater tests are conducted at the moment. The design and deployment status of this next-generation UAC are illustrated in Fig. 4 (a-c).



gfai tech GmbH (Benjamin Vonnrhein, 2025)

Figure 4: Next-Generation UAC Development. (a) CAD model of the UAC; (b) Physical prototype during testing; (c) Array prototype submerged for testing.

It is expected that this system generates more precision in mapping and is more versatile in the underwater usage. It can either be placed on the ground or hung at depths down to 25 m (momentarily restricted due to cable lengths). Future works will show more results from measurements with this system.

5.2.1 Customisation

As there is a wide range of applications to use UAC systems, it is expected that different array geometries, especially in regard of channel count and array size, will be explored and produced for different use-cases. Furthermore, different hydrophones and preamplifiers can be utilised to boost the signal to noise ratio, to obtain data in more challenging scenarios.

REFERENCES

- Advanced Navigation. 2025. 'Hydrus Micro AUV'. <https://www.advancednavigation.com/robotics/micro-auv/hydrus/>. [Accessed Oct 2025].
- Aquarian Audio & Scientific. 2025. 'H2C-IEPE'. <https://www.aquarianaudio.com/h2c-hydrophone.html>. [Accessed Oct 2025].
- Baumer. 2023. 'VLG 22C Industrial Camera Datasheet'. https://media.baumer.com/Baumer_VLG-22C.I_DE_20230718_DS.pdf. [Accessed Oct 2025].
- Böck, Magdalena, Benjamin Vorrhein, Marc Mehlhaff, and Ulrich Meyer. 2015. 'The Acoustic Camera as a tool for machinery maintenance'. In *44th International Congress and Exposition on Noise Control Engineering (Internoise 2015)*. 1 (8): 5815-5822. San Francisco, USA.
- Bradley, Stuart, Michael Kerscher, and Torben Mikkelsen. 2017. 'Use of the Acoustic Camera to accurately localise wind turbine noise sources and determine their Doppler shift'. In *7th International Conference on Wind Turbine Noise*. Rotterdam, Netherlands.
- Dahl, Peter H., James H. Miller, Douglas H. Cato and Rex K. Andrew. 2007. 'Underwater Ambient Noise'. In *Acoustics Today*. 3 (1): 23-33. New York, USA.
- Döbler, Dirk, Jörg Ocker and Dr. Christof Puhle. 2016. '3D-Beamforming in the Wind Tunnel'. In *Proceedings on CD of the 6th Berlin Beamforming Conference*. Berlin, Germany.
- gfai tech GmbH. 2022. 'mcdRec Data Recorder'. <https://www.gfaitech.com/products/acoustic-camera/data-acquisition/data-recorder>. [Accessed Oct 2025].
- gfai tech GmbH. 2023. 'Ring 48 Microphone Array'. <https://www.gfaitech.com/products/acoustic-camera/microphone-arrays/2d-beamforming-microphones>. [Accessed Oct 2025].
- gfai tech GmbH. 2025. 'NoiseImage Software'. <https://www.gfaitech.com/products/acoustic-camera/software-noiseimage>. [Accessed Oct 2025].
- GoPro. 2025. 'HERO10 Black Camera'. <https://gopro.com/de/be/shop/cameras/hero10-black/CHDHX-101-master.html>. [Accessed Oct 2025].
- Kummritz, S, and A. Movahed. 2021. 'Visualisation of train noise with Acoustic Cameras'. In *27th International Congress on Sound and Vibration 2021*. 1 (6): 4188-4195. Online.
- Kuperman, William and Phillip Roux. 2007. 'Underwater Acoustics'. In *Springer Handbook of Acoustics* :149-204. 1st ed. New York : Springer.
- Merino-Martínez, R, P. Sijtsma, M. Snellen, et al. 2019. 'A review of acoustic imaging methods using phased microphone arrays'. In *CEAS Aeronaut J* 10 (1), 197–230. doi:10.1007/s13272-019-00383-4.
- Miksis-Olds, Jennifer L., David L. Bradley, and Xiaoyue Maggie Niu. 2013. 'Decadal trends in Indian Ocean ambient sound', In *Journal of the Acoustical Society of America*. 134 (5): 3464–3475.
- Wenz, G. M. 2013. "Acoustic ambient noise in the ocean: Spectra and sources", In *Journal of the Acoustical Society of America*. 34 (12): 1936–1956.