ARTICLE IN PRESS

Deep–Sea Research I xxx (xxxx) xxx

Contents lists available at ScienceDirect

Deep-Sea Research Part I

journal homepage: http://www.elsevier.com/locate/dsri

An autonomous hydrophone array to study the acoustic ecology of deep-water toothed whales

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ARTICLE INFO

Keywords:
Bioacoustics
Echolocation
Passive acoustics
Localisation
Hydrophone array
Source level

ABSTRACT

For vocal animals with distinctive calls, passive acoustic monitoring can be used to infer presence, distribution, and abundance provided that the calls and calling behaviour are known. Key to enabling quantitative acoustic surveys are calibrated recordings of identified species from which the source parameters of the sounds can be estimated. Obtaining such information from free-ranging aquatic animals such as toothed whales requires multi-element hydrophone arrays, the use of which is often constrained by cost, the logistical challenge of long cables, and the necessity for attachment to a boat or mooring in order to digitise and store multiple channels of high-sample rate audio data. Such challenges are compounded when collecting recordings or tracking the diving behaviour of deep-diving animals for which the array must be deployed at depth. Here we report the development of an autonomous drifting deep-water vertical passive acoustic array that uses readily available off-the-shelf components. This lightweight portable array can be deployed quickly and repeatedly to depths of up to 1000 m from a small boat. The array comprises seven ST-300 HF SoundTrap autonomous recorders equally spaced on an 84 m electrical-mechanical cable. The single-channel digital sound recordings were configured to allow for synchronisation in post-processing using an RS-485 timing signal logged by all channels every second. We outline how to assemble the array, and provide software for time-synchronising the acoustic recorders. To demonstrate the utility of the array, we present an example of short-finned pilot whale clicks localised on the deep-water (700 m) array configuration. This array method has broad applicability for the cost-effective study of source parameters, acoustic ecology, and diving behaviour of deep diving toothed whales, which are valuable not only to understand the sensory ecology of deep-diving cetaceans, but also to improve passive acoustic monitoring for conservation and management.

1. Introduction

Toothed whales are the largest toothed predators on the planet and rely on sound to mediate vital functions from foraging to courtship (Goldbogen and Madsen, 2018). However, relatively little is known about their acoustic ecology due to the challenges inherent to systematic sampling of the acoustic emissions of highly mobile free-ranging and deep-diving marine megafauna in offshore and pelagic environments. One approach to learn more about how these animals use sound is to tag them with sound and movement recording tags (*e.g.* Johnson and Tyack, 2003). While a biologging approach can provide unprecedented insights into the diving patterns, fine-scale movements, predator-prey dynamics and echolocation behaviours of individual animals, some toothed whale species are difficult to tag, and ethical issues can arise surrounding the tagging of protected species (Johnson et al. 2009). Additionally, audio recordings from tags on echolocating toothed whales cannot provide

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https://doi.org/10.1016/j.dsr.2020.103233
Received 23 August 2019; Received in revised form 27 December 2019; Accepted 7 February 2020
Available online 14 February 2020

Please cite this article as: Chloe E. Malinka, *Deep–Sea Research I*, https://doi.org/10.1016/j.dsr.2020.103233

information about the source properties of the biosonar signals of the tagged animal, because these signals are focused into a narrow forward-directed beam and yet are collected by a tag that is attached behind the head and so out of the main beam (Johnson et al. 2009). In order to quantify the source parameters (such as source level, bandwidth, duration, *etc.*) of such directional signals, it is essential that these are measured close to the acoustic axis, since both spectral content and signal amplitude vary with aspect (Au et al. 1986).

The quantification of animal sounds is important for several reasons. Passive acoustic monitoring (PAM) methods to study the occurrence, distribution, density and relative abundance of vocal animals rely on descriptions of species-specific sounds in order to classify detections (Zimmer, 2011). Estimates of source parameters can be used to calculate maximum detection ranges and infer the acoustic detection function (Marques et al. 2009), both of which are essential for the planning and interpretation of data from PAM surveys (Zimmer et al. 2008). Knowledge about an echolocator's beamwidth is useful for informing optimal hydrophone array configurations (Zimmer et al. 2005), indicating the volume over which their biosonar system can operate to detect prey (Madsen et al. 2007; Jensen et al. 2018), estimating acoustic detection probabilities, and inferring density (Fraiser et al. 2016). Also, the directionality of a biosonar beam reveals the acoustic field of view of echolocating animals, providing insight into their sensory ecology (Madsen et al. 2013).

Recordings from moored, drifting, or boat-deployed hydrophones are typically used to characterise the powerful clicks produced by echolocating toothed whales. Single hydrophone recordings can be used to quantify the occurrence rate and general characteristics of biosonar sounds, but rarely give unambiguous information about the range to the clicking animal, or whether the sound was recorded close to the animal's acoustic axis. Both of these are needed to estimate the source level and therefore infer the detection range of biosonar sounds. By using an array of synchronised hydrophones at known locations it is possible to calculate the location of the animal, and therefore its range, from the time-difference-of-arrival (TDoA) of signals at each hydrophone (Watkins and Schevill, 1972; Spiesberger and Fristrup, 1990; Wahlberg et al. 2001). With this set-up it is also possible to distinguish on-axis clicks by comparing the relative amplitudes of clicks recorded on different receivers. As animals manoeuvre, they occasionally scan their biosonar across the array giving rise to recordings of sequences of clicks with increasing and then decreasing amplitude; the highest amplitude click in these sequences is then the closest exemplar of the on-axis click (Au, 2004; Madsen et al. 2004a, 2004b). The source level of the clicks can be estimated using the range to the animal and the received level of putative on-axis clicks combined with known transmission properties of the medium (Møhl et al. 1990). Thus, accurate identification and quantification of the spectral and temporal properties of on-axis clicks requires the deployment of a calibrated and time-synchronised hydrophone array in front of the echolocating animal (Madsen et al. 2004a; Madsen and Wahlberg, 2007).

It is critical to quantify biosonar sounds produced by animals in their natural habitat. Sonar signals recorded in small tanks in captivity have been shown to be of lower amplitude and lower frequency than those recorded from wild cetaceans (Au, 1993; Wahlberg et al. 2011; Ladegaard et al. 2019). However, when recording at sea it can be difficult to obtain on-axis clicks from animals vocalising at depth with a hydrophone array near the surface, because animals may rarely point upwards towards the array. This problem is relevant when using arrays that must be closely tethered to a vessel to both power the recording system and digitise the sound. The use of tethered hydrophone arrays to study marine animals was pioneered by Whitney (1968), Dunn (1969), and Watkins and Schevill (1971), amongst others. These authors used linear hydrophone arrays suspended from a boat or sonobuoy to localise toothed whales and to investigate the spectral content, intensity, and duration of echolocation clicks, as well as to quantify inter-click intervals (ICIs). Using a 4-hydrophone array, Watkins (1980) reported the depths at which sperm whales start clicking, and inferred their vertical dive angles and swim speeds during dives. Towed linear arrays have also been used to identify the vocal individual in a group of diving whales using beam-forming (*e.g.* Miller and Tyack, 1998; Zimmer et al. 2005), or to identify the range and bearing of vocal whales in acoustic surveys. Such tethered arrays, often in a star configuration, are useful for studying shallow-swimming wild odontocetes and, in particular, species that are prone to approach vessels. They have been used to quantify the source properties of echolocation clicks and to investigate how animals adjust their biosonar signals as they approach targets (*e.g.* Rasmussen et al. 2002; Au and Herzing, 2003; Au and Benoit-Bird, 2003; Au et al. 2004; Ladegaard et al. 2017). More recent tethered arrays have also reported on the beam pattern of biosonar clicks (*e.g.* Koblitz et al. 2016).

An alternative to maintaining recording synchrony on a hydrophone array, while relieving the constraint to be tethered to a boat, is by distributing the array and synchronising it with a universal timing signal. This approach has been implemented via radio-linking hydrophones to record simultaneous signals on a single recorder (Møhl et al. 2000; Hayes et al. 2000; Wahlberg et al. 2001). Another implementation is using a distributed horizontal array of GPS-synchronised receivers (Møhl et al. 2001, 2003; Miller and Dawson, 2009). Such an array has been used to calculate the source level and radiation patterns of clicks produced by sperm whales (Madsen et al. 2002; Møhl et al. 2003). However, the large spacing of elements needed to accurately estimate the range of distant animals makes beam directivity difficult to resolve with high accuracy, since it was rare for the narrow beam of sperm whales, for example, to simultaneously ensonify multiple channels that were up to 2000 m apart (as in Møhl et al. 2003). To increase the chances of a given click ensonifying multiple hydrophones on the array at once, Heerfordt et al. (2007) proposed an array with several closely spaced hydrophones. The number of hydrophones and the spacing between them is therefore a compromise between having hydrophones close enough for several channels to be consistently ensonified by a highly directional biosonar beam, and of having a large enough aperture to accurately measure the range to vocalising animals (Wahlberg et al. 2001). Deploying an array for a longer duration, increasing the number of hydrophones, and deploying elements at the foraging depths of the target species also increase the probability of recording on-axis clicks (Møhl et al. 2000; Heerfordt et al. 2007).

Recording sounds in the habitat in which they are produced presents a challenge when studying whales that echolocate at depth (Heerfordt et al. 2007). Deploying a tethered hydrophone array to the foraging depths of deep-diving animals has been rare, as it necessitates a long, multi-core cable connected to the research boat. This cable transmits the analogue signals received by the hydrophones to an on-board multi-channel high sample-rate data acquisition system. Such cables for deep sea applications are heavy, expensive, and difficult to deploy, especially from smaller vessels, largely restricting this approach to projects for which large oceanographic vessels are available. To simplify the cable requirements, Heerfordt et al. (2007) developed a 10-element, 950 m long vertical hydrophone array using fibre optic cables which was used to study the biosonar beam patterns of deep-diving odontocetes. Individual elements in this array digitised data at depth and transmitted these data on a time-division basis to a recording system on a boat. This approach enabled the use of a thin lightweight fibre optic cable which could be deployed from a 45 ft sailing vessel. While this array design overcomes some of the challenges of deep sea bioacoustics, including the requirements for a wide aperture and high bandwidth, the implementation required cabling to a vessel and faced the problem that failing opto-couplers affected data transmission from lower nodes of the array. The tough conditions encountered at sea dictate that a practical hydrophone array should be robust to the failure of individual receivers if it is to be used repeatedly.

The need for a cable tethered to a vessel is a major impediment to achieving a robust, easily deployed deep hydrophone array. A key improvement would therefore be to make the array record autonomously. Macaulay et al. (2015, 2017) developed such a system for a different but equally challenging recording environment: energetic tidal rapids that form in narrow channels between islands. The autonomous recorder in this case was housed in a drifting float with a surface-suspended rigid array of 4 hydrophones and a vertical array of 6–8 hydrophones. Movement sensors spaced regularly along the vertical axis of the array produced a time series of the precise 3D locations of the hydrophones, used to interpret the TDoA. This array was used to track the high frequency echolocation signals of porpoises as it drifted through the rapids. The array was not built for deep water applications (maximum depth 30 m) but it represents a step towards autonomy in multichannel recorders. Similarly, Barlow et al. (2018) simultaneously deployed a series of two-channel vertical drifting acoustic spar buoy recorders (DASBRs) to depths of ~100 m, and achieved localisation using the TDoAs between two hydrophones on the same drifter, or by using the TDoAs between the direct path and the surface-reflected echolocation click. Such a nested-array configuration, with smaller aperture arrays nested within a larger aperture array, has also been employed by Gassmann et al. (2015) to track beaked whales. Each small aperture array provided a bearing to the sound, and where these bearings crossed indicated the 3D location of the whale, thus eliminating the need for precise synchronisation between recorders on their widely spaced array. However, none of these implementations have enough receivers to properly quantify the source properties of biosonar clicks

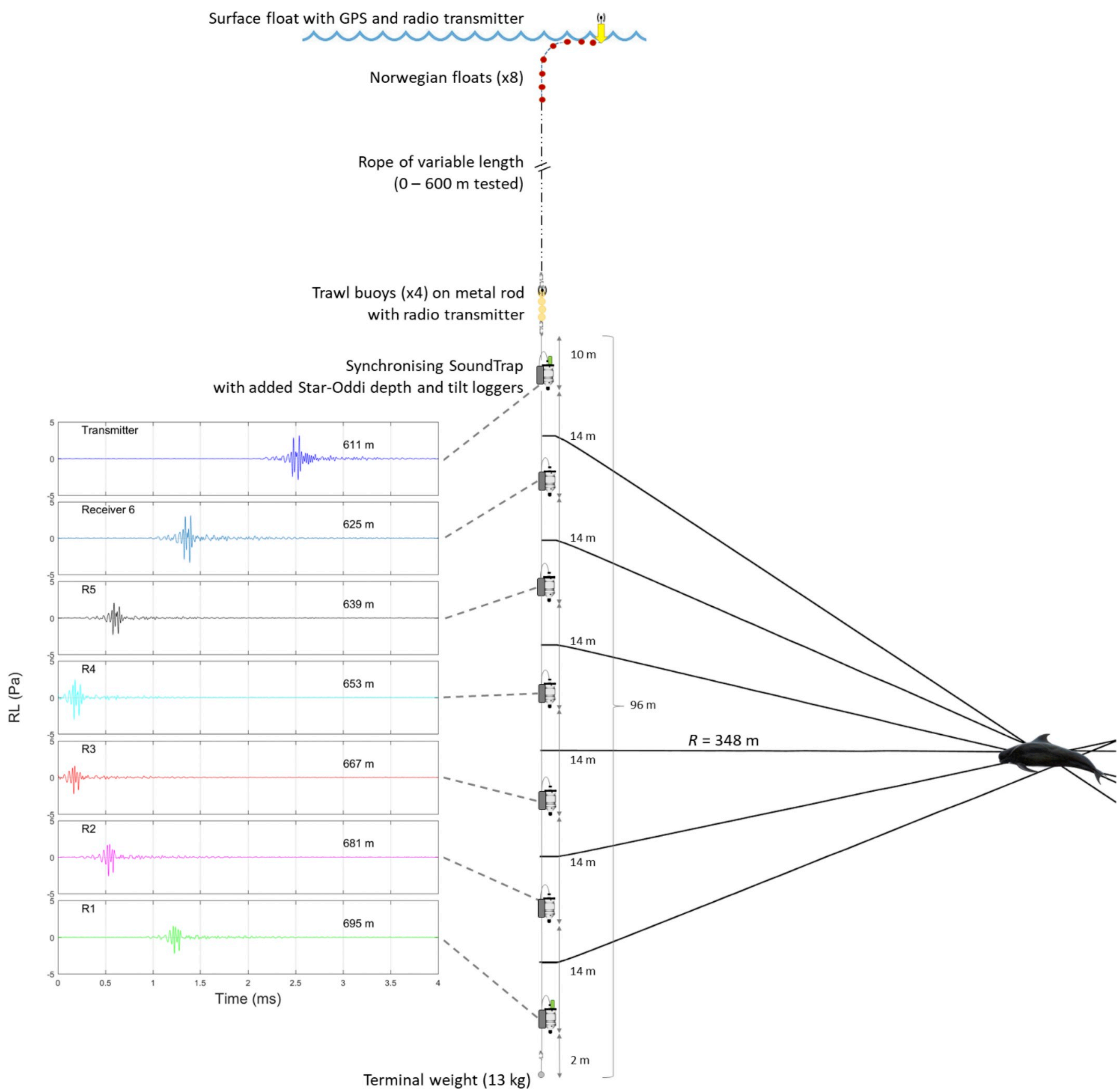

Fig. 1. Diagram (not to scale) of the 7-channel vertical hydrophone array. Star-Oddi depth and tilt loggers are attached to upper and lower recorders. Waveforms of a single pilot whale click, as received on all time-aligned channels, are shown on the left. Hyperbolae, which appear here as straight lines due to the relatively long range to the whale, indicate the loci of source locations that give the measured TDoAs between pairs of consecutive recorders. These loci intersect at a range of 348 m from the 4th recorder. The estimated whale depth for this click was 661 m.

from deep-diving toothed whales. Thus, there exists an equipment gap requiring the creation of a multi-hydrophone, deep-water vertical array which can be deployed for longer periods of time, autonomously, from a small boat.

Here we report on the development and performance of such an autonomous, drifting, large-aperture, deep-water vertical hydrophone array, designed to quantify the acoustic parameters of echolocation clicks from odontocetes in the deep sea. The array uses off-the-shelf high performance autonomous recorders to eliminate the need for expensive and cumbersome cables. The approach combines the benefits of multi-channel, high sample rate recordings that usually require cabled attachment to a boat for digitisation, with the autonomous ability and longer recording durations (up to about 1 week, battery-limited) more typical of deep-water single-channel recorders. This paper describes the array design, how it can be deployed from a small vessel, and demonstrates array recordings from short-finned pilot whales. An accompanying set of software tools enable the creation of multi-channel time aligned audio files from independent but synchronised recordings, effectively turning a set of autonomous recorders into an ad hoc array.

2. Materials and methods

2.1. Array design

The vertical linear array comprises 7 SoundTraps (ST300-HF, Ocean Instruments, Auckland, New Zealand, www.oceaninstruments.co.nz). The ST300-HF are self-contained digital sound recorders with a sampling rate of up to 576 kHz with 16-bit resolution and a low self-noise level (~30 dB re 1 μPa/Hz). The broadband (160 kHz) dynamic range is 90 dB and clipping occurs at a received level (RL) of either ~172 dB re 1 μPa (high gain) or ~186 dB re 1 μPa (low gain). The high dynamic range of the low-gain setting accommodates for the large variations in received levels that are expected from odontocetes with a narrow beamwidth, and the high gain setting, with its low clipping level, enables ambient noise measurement. The ST300-HF are single-channel recorders and so require external equipment to enable synchronisation of multiple units. The seven recorders are accordingly linked together by a cable which extends for the length of the array. The array is then deployed at the desired depth by suspending it with a rope from a drifting buoy (Fig. 1).

2.1.1. Synchronisation

A firmware modification for the recorders allows synchronisation of multiple devices connected to a common cable, to sample-level accuracy. This firmware employs one SoundTrap (set to be the 'transmitter') to generate an RS-485 timing message every second, which is received on the other SoundTraps (configured as 'receivers'). Upon receiving a message, all receivers record their respective current audio sample numbers, and save the timing message along with sample number to a log file. After data collection, single-channel wave files are time-aligned using information stored in this log file.

The synchronising protocol corrects for the variable and inevitable clock drifts of the individual instruments. The maximal clock drift of an individual SoundTrap is ~2 s per day (~2 × 10ˆ-5). At a sampling rate of 576 kHz, this corresponds to a potential timing error of ~13 samples/s. To maintain localisation accuracy it is advisable that the synchronisation pulses occur frequently (here we used 1 Hz). Custom software in MATLAB (The Mathworks Inc., Natick, MA) was developed to synchronise the recordings from the SoundTrap array (provided in Supplementary Material A). This software is applicable to any array of sound recorders that log an external synchronisation pulse.

2.1.2. Cable and breakouts

All array components are commercially available and can be readily assembled using low-cost laboratory equipment. Step-by-step directions for building the array are provided in Supplementary Material B. The cable used to distribute the time-synchronisation signals (Cortland Cable Co., diameter = 0.7 cm) contains 4 insulated wires reinforced with braided liquid-crystal polymer (Vectran®) to give an overall breaking strength of ~900 kg. Of the four wires, only two are used to transmit the differential (RS-485) synchronisation message; the other two wires are unneeded (in our implementation one is wired as a common ground) and so a two-wire cable would suffice. The mass of the 96 m cable is 11.5 kg, including the seven SoundTraps, and it is slightly negatively buoyant in seawater.

Each SoundTrap connects to the cable via a SubConn connector pigtail (MacArtney Underwater Technology, MCIL8M) which is tied electrically to the two active wires of the cable. These attachments are secured in waterproof breakouts made of Scotchcast™ epoxy resin (3M-2131). This flexible resin was chosen to allow bending of the cable near the join and prevent salt water ingress without compromising adhesion of the breakout. The resin was poured into custom 3D prints which were designed to provide a consistent mounting point for the SoundTraps, so that the hydrophone element position remained constant between deployments and field seasons (see Supplementary Material B). Cable ties, aligned over the flanges of the breakouts and the SoundTraps, secure the recorders, preventing their detachment from the cable at sea.

The hydrophone elements on each SoundTrap are protected with custom-built cages of 2.5 mm stainless steel wire. The wires do not interfere with the received waveforms for tested frequencies up to 150 kHz; This would only problematically impact sound propagation at very high frequencies where λ approaches the wire diameter. Small LED lights, built into the SoundTrap to confirm operation, are taped over, in order to not intentionally attract any animals to the array at depth.

2.1.3. Array dimensions

2D localisation (*i.e.* depth and range) of a clicking animal is possible with a vertical array if at least 3 elements detect a click, but the accuracy of localisation depends on the hydrophone spacing. In the chosen configuration, the array comprises 7 evenly-spaced hydrophones, ~14 m apart, resulting in an overall aperture of ~84 m (distance between the top and bottom recorders). This spacing accommodates a directional narrow-band high frequency click, ensuring that an animal with a half-power beamwidth of 10° will ensonify at least 3 sequential hydrophones. Specifically, the dimensions of the array are designed to provide sufficient spatial resolution to be able to measure the biosonar beam of a deep water, high frequency echolocator, such as dwarf/pygmy sperm whales (*Kogia* spp*)*. A range of estimated source levels projected from a range of distances from the centre of the array assuming a half power beamwidth of 10° and appropriate absorption at 130 kHz were simulated, and the maximum range at which the simulated received level exceeded a signal-to-noise ratio (SNR) of at least 10 dB above estimated background noise levels was considered. For the chosen configuration, this meant that for the lowest considered source level of 175 dB re 1 μPa (Madsen et al. 2005), a minimum of 3 hydrophones were ensonified with sufficient SNR at a range approximately 10x the array aperture. The relatively large time delays between these widely-spaced hydrophones enable more accurate localisations of distant sound sources while reducing the sensitivity to timing errors. Applying the rule-of-thumb that localisation accuracy becomes poor at a range of ~5-10x the aperture of the array (*e.g.* Kyhn et al. 2009; Macaulay et al. 2017), this means that animals could be localised with moderate accuracy at a range of up to ~840 m from the array, if both the top and bottom recorders receive the signal.

2.1.4. Buoyancy, weight, depth and tilt

To deploy the array to different depths, a single cross-braided polyester rope (6 mm diameter, with 650 kg breaking strength) connects the top of the hydrophone array cable to a surface float (Fig. 1). A series of 8 Norwegian floats (15 cm diameter) at 2 m intervals below the surface float provide distributed buoyancy to decouple surface wave movement from the array. The highly visible surface float contains both a radio transmitter (MM150, Advanced Telemetry Systems) and a GPS device (Tractive GPS pet tracker, www.tractive.com) to provide real-time positioning of the array, viewable on a mobile phone app. This GPS can operate for a maximum of 5 days, but a range of similar devices are commercially available to accommodate longer deployments.

Between the array and the rope are four U70 trawler buoys (18 cm diameter, Daconet), depth rated to 2000 m, mounted on a stainless steel rod. These buoys are tightly spaced with rubber padding between them to avoid any movement noise. Similarly, all metal-to-metal contacts (*i.e.* between the stainless steel thimbles and shackles that connect the cable array, trawl buoy rod, rope, and surface float) are wrapped with clear PVC tubing (Tygon®, Saint-Gobain Performance Plastics) to prevent clinking noises that could contaminate acoustic recordings. As a precaution, a radio transmitter (MM150, Advanced Telemetry Systems, depth rated to 2000 m) is attached to the rod of trawler buoys. The purpose of buoyancy in this location (between the cable array below and the rope extension above) is two-fold: to allow for the array to come to the surface should the rope be cut, and to increase tension, and therefore straightness, on the cable section of the array below.

Weights (sand in biodegradable cotton bags) are attached at the bottom of the array to keep the array vertical and linear. The amount of weight added is adjusted slightly according to deployment location (as varying temperature and salinity affect water density) as well as the amount of rope added to the top of the array (*e.g.* 13 kg of weight was used for an array with 600 m of rope). Of this weight, 10 kg are attached via a galvanic magnesium timed release (Neptune Marine Products), so that, should the extension rope become cut/entangled, or the weight become stuck on the seafloor, the array would float to the surface once the release corrodes. The release time (determined by the circumference of the magnesium coupling) is chosen to be significantly longer than the intended deployment duration.

Two autonomous inclinometer, depth, and temperature data loggers (Star-Oddi DST tilt, Reykjavik, Iceland) are attached to SoundTraps at the top and bottom of the array, and sampled at 1 Hz. These are roughly synchronised with the SoundTraps by tapping them against one of the SoundTraps at the beginning and end of each deployment. Having the array close to vertical facilitates quantifying the depth of localised animals, but the array only needs to be straight (and not necessarily vertical) in order to resolve acoustic parameters such as source level, peak frequency, beam pattern, *etc.* (Heerfordt et al. 2007). Known deviations from verticality, recorded with the Star-Oddi loggers, can be used in calculations of the localisation errors. For example, if localisations are calculated assuming that the array is vertical, but it in fact is θ degrees off vertical, the depth of a localisation point will be subject to a error of $sin(\theta)*range$. Thus greater tilt angles introduce larger errors in depth.

2.2. Calibrations and performance assessment

2.2.1. Instrument calibrations

All SoundTraps were individually calibrated against a Reson 4034 hydrophone (Teledyne, Slangerup, Denmark) in a 3 m deep cedar tank. A series of pure tones (in 10 kHz steps, from 10 to 200 kHz) were projected to each device at a range of 2 m. In addition, artificial clicks were projected at different angles to a SoundTrap attached to the cable in an open water environment to investigate the degree of acoustic shading introduced by the cable. This resulted in a maximal nominal loss of 1.5 dB, which would only be problematic at very high frequencies (where λ approaches the cable diameter). Star-Oddis were individually calibrated for depth (in a pressure tank, from 20 to 300 m in steps of 10 m, and from 300 to 1000 m in steps of 100 m) and tilt (at 0, 20, 45, 70 and 90°) using a protractor.

2.2.2. Performance assessment of time synchronisation

Time synchronisation performance was tested in air for a duration similar to that of a field deployment (2 h 44 m). As an independent timing check, an acoustic tone burst (10 kHz sine wave, 100 μs duration, 1 V_{pp}), generated by a signal generator (Agilent), was projected every 10 s to a string of parallel-connected custom-made pingers, with each pinger taped to the hydrophone of a SoundTrap in the array. Thus each recorder received an external synchronising ping with no transmission delay, as well as the cable-borne electrical timing message pulse. The electrical timing signals were used to align the sound data recorded on the different devices (see section 2.1.1), and the relative timing of the external pings across the recorders was used to assess the accuracy of this alignment procedure as a function of time.

Time synchronisation performance was also tested in deep water using a modified version of the array with built-in piezo ceramic discs (SMD10T2R111WL, STEMiNC, FL, USA) sealed in epoxy resin, positioned 5 cm from each hydrophone element. These elements emitted synchronous acoustic tone bursts (215 kHz sine wave, 23 μs duration) every 110 ms. The tone bursts were generated by a custom-made pinger board molded into the top of the array and transmitted via one of the unused wires in the array cable. The high frequency of these synchronisation signals was chosen so as to be inaudible to toothed whales and also to ensure that the signals are only weakly detected by neighbouring recorders on the array, making the time of arrival of each signal unambiguous. The arrival time of each acoustic synchronisation ping relative to the preceding electrical timing message was calculated for each recorder. This produced a record of time synchronisation errors for each receiver with which to assess the time alignment of all devices on the array.

2.2.3. Localisation error due to time synchronisation errors

Despite the use of a common timing signal to synchronise recorders, some time alignment jitter is inevitable. This jitter is due to processor latency, as transmission and reception of the common timing signal requires processor time which must be interleaved with other tasks. A simulation was constructed in MATLAB to investigate how much extra error this jitter adds to localisation errors. Simulated toothed whale signals were generated on a grid of ranges and depths around a simulated array at ~600–700 m depth. Points on the grid were spaced at 10 m intervals in range and depth and extended up to a maximum of 420 m (5x the total array aperture of 84 m) above and below the array, and 840 m (10 x the aperture) in horizontal range from the array. For each point (in the 94 × 84 m grid), the received time delays on the array elements were calculated assuming a homogenous sound speed.

Two types of time delay error were considered: (1) errors generated by the small observed time alignment jitter of the SoundTraps, and (2) cross correlation errors which typically occur when calculating TDoAs of narrow band high frequency (NBHF) clicks, such as those produced by *Kogia*. To simulate the synchronisation errors, time errors were randomly drawn from the empirical distribution of time synchronisation errors observed during the timing validation trial and added to the simulated time delay measurements at each receiver. To examine cross correlation errors, *Kogia* clicks were used as an example as they are narrow band with a slowly varying waveform envelope. For this type of signal, there are multiple peaks in the cross-correlation function used to measure TDoAs, and even small amounts of noise can lead to the selection of a peak on either side of the true peak (Weinstein and Weiss, 1984; Gillespie and Macaulay, 2019). It was therefore assumed that a TDoA error corresponding to one cycle of a typical *Kogia* click was equally likely, so that each TDoA between channel pairs was accordingly modified by adding, with equal probability, +/- 9 μsec (the duration of one wavelength of a *Kogia* click (Madsen et al. 2005)).

Two scenarios were then considered: (1) perfectly time-synchronised SoundTraps for which the only error in TDoA was due to cross correlation errors, and (2) SoundTraps with time delay errors arising from both cross correlation errors and time synchronisation errors. Localisations were then run on the resulting simulated time delays using a Simplex optimisation method for localisation (Nelder and Mead, 1965; Press et al. 1988) and the errors in depth and range were recorded. The complete simulation was run 100 times through every possible grid position (7896 grid points) and median absolute values of depth and range errors, were plotted. The median absolute errors for each range bin, across all depths, was also plotted to visualise the impact that the time synchronisation errors had on localisation accuracy, and contextualise these errors by comparing them with errors that would be observed when cross correlating NBHF signals.

2.3. Field deployments

The vertical array was deployed and recovered from several small vessels to test its feasibility. These included a 4 m rigid-hull inflatable boat (RHIB) and a sport fishing boat (10.4 m), both in a maximum of sea state 5. The array was deployed by hand which took as little as 2 min when deployed without additional rope, and 14 min with 600 m of rope. Although recovery by hand-hauling was initially done, an electrical winch (North Lift line hauler LH200, running on 12 V and lifting up to 90 kg) greatly improved recovery time and effort, and made it comfortable to recover the array in sea states beyond 3. Retrieval time ranged from 4 min with no rope, to 18–27 min with 600 m of rope. The final ~96 m of cable array was always hand-hauled to avoid the recorders hitting the gunwale. The array was re-located for recovery using either positions sent by the GPS on the float, or by radio-tracking the VHF signal using a 3-element Yagi antenna and an R-1000 radio (Communication Specialists Inc.).

An example of a field recording demonstrating the array performance is taken from fieldwork in March 2019, in the waters southwest of Tenerife, in the Canary Islands of Spain (~28°N/16°W). Our configuration used high gain settings to improve the probability of getting on-axis clicks from deep diving whales with often unpredictable movements. An example from this fieldwork is shown to demonstrate the efficacy of the array. Bioacoustic descriptions emerging from this dataset will form publications of their own. Visual sightings of odontocetes at the surface prompted this deep-water deployment (with 600 m of rope, so that the deepest channel was ~696 m deep) and recorded signals from short-finned pilot whales (*Globicephala macrorhynchus*).

2.4. Analysis

2.4.1. Acoustic localisation and parameter quantification

Acoustic localisation of individual clicks was carried out on the synchronised multi-channel acoustic recordings based on the TDoAs of the click on each hydrophone. A simplified estimator can be used if it can be assumed that the array is vertical and the sound speed is constant, yielding an estimate of the range and depth of the sound source (Zimmer, 2011). A more complex iterative analysis is needed if the sound speed varies significantly over the sound propagation paths from the animal to each array element (Spiesberger and Fristrup, 1990). A vertical array is only able to resolve range and depth, *i.e.*, a 2D localisation points. If the array is straight but not vertical, the sound source is localised to a circle perpendicular to the array axis, leading to errors in the depth estimate. However, neither the tilt of the array nor the exact depths of the hydrophones impact measurements of acoustic parameters and beam directivity (Heerfordt et al. 2007), provided that the array is straight.

To determine the acoustic parameters of clicks, the following steps must be performed on the synchronised audio recordings for each detected click: i) identification of the same click in each hydrophone recording, ii) measurement of arrival times of the click, iii) measurement of received sound pressures on each device, iv) measurement of the sound velocity, and v) localisation of the whale (Wahlberg et al. 2001). Click examples shown here were detected, classified, and localised in PAMGuard (www.pamguard.org; Gillespie et al. 2008) using the Large Aperture 3D Localiser module, which used the hybrid time-delay based algorithm described in Macaulay et al. (2017). Sequences of clicks with slowly-varying inter-click interval and consistent localisations were presumed to come from single individuals. The most intense clicks in these sequences were identified as potential exemplars of on-axis clicks (Møhl et al. 2000). These potential on-axis clicks were only selected if they were recorded by the middle elements in the array, *i.e.* if the strongest version of the click was not recorded on either of the top or bottom channel (*sensu* Au and Benoit Bird, 2003; Ladegaard et al. 2017). The received levels of the presumed on-axis clicks were combined with the distance between the localised whale and the strongest receiving hydrophone to back-calculate apparent source levels (*e.g.* Møhl et al. 2003). Assuming that the whale was pointing directly at the strongest receiving hydrophone, the off-axis angle to each other receiver was inferred from the localised range and depth in order to estimate the biosonar beam radiation pattern (*e.g.* Zimmer et al. 2005; Nosal and Frazer, 2007; Shaffer et al. 2013).

2.4.2. Ambient noise quantification

The array can be used to quantify ambient noise provided that this is more than 6 dB above the noise floor of the recorders. Self noise spectra were measured from recordings made in air in an anechoic room at Aarhus University, Aarhus, Denmark. During deployments, third octave levels (TOLs) of ambient noise from the lowest channel of the array in its deep-water configuration were measured to quantify the deep noise level in the study location. Measurements were computed over 30 s analysis windows, in third octave bands centred from 24.8 Hz to 161 kHz. Percentiles (5, 50, 95) of these 30 s measurements within each third octave band were calculated over a 5 h interval in which the array was drifting free of the vessel. Note that TOL measurements (in dB re 1 μPa) differ in unit from the reported spectral level of self noise, in power per Hertz. To obtain the noise level within a given TOL band (in dB re 1 μPa), add the nominal spectral level of self noise (here, 30 dB re 1 μPa/Hz) to $10*\log_{10}$(bandwidth of any third octave band, in Hertz).

3. Results

3.1. Field deployments

The array was deployed 23 times in the deep configuration, in a variety of sea-states. In the half-hour deployment in Tenerife shown here, the sea-state was low and the depth and tilt sensors on the upper and lower recorders confirmed that the array was oriented nearly vertically (mean tilt of 5.5–8.8° off vertical), and was close to straight, with a small difference in the tilt at the top and bottom of the array (STD 1.7–2.4°) which was within the ±3° accuracy of the tilt sensors. In less optimal deployment conditions with strong surface currents, the deep-water array was shallower by ~100 m than expected with the 600 m rope extension, indicating that the rope had a catenary, however the cabled part of the array still appeared to remain straight (mean array tilt of 7.4° off vertical, STD 2.8°) due to sufficient buoyancy and weights at the ends of the tensioned cable.

3.1.1. Globicephala example

An example recording of a short-finned pilot whale click received on all hydrophones of the 7-channel array is shown in Fig. 1. The pilot whale was localised to a depth of 661 m that overlapped with the depth of the array in its deep-water configuration (spanning 611–695 m). The whale's biosonar beam was first received on receiver 4 (highest RL at 137 dB re 1 μPa_{pp}), at a calculated range of 348 m from this channel. This click is suspected to be off-axis due to the low variation in RLs across the recorders and the double-pulse waveforms recorded by all elements. Localisations of preceding and following clicks ($n = 42$) are comparable in range (STD 12 m) and depth (STD 6 m), and therefore likely come from the same animal.

3.1.2. Other applications

Localisations of multiple successive clicks from the same animal can be used to reconstruct diving tracks of animals at depth (Freitag and Tyack, 1993). Localisations of 20 clicks spanning 12 s from a short-finned pilot whale, shown in Fig. 2, indicate that this animal was approaching the array in approximately horizontal swimming with a closing speed of about 1.6 m/s. This is most probably an underestimation of the actual speed of the animal because circumferential movements around the array axis cannot be resolved with a vertical array.

To demonstrate the use of the array to record deep sea ambient noise, a third octave level (TOL) analysis was conducted for the deepest channel (depth of ~695 m) from a longer duration (5 h) field deployment (Fig. 3). During this deployment, several odontocete species were visually observed at the surface: short-finned pilot whales, sperm whales (*Physeter macrocephalus*), and bottlenose dolphins (*Tursiops truncatus*). Peaks in the 95th percentile of ambient noise correspond to the frequencies of bioacoustic signals from these odontocetes, while variations at lower frequencies are likely due to traffic from a ferry and recreational boats. Note that this application does not use the features of the array, but is an added bonus of recording at depth.

3.2. Array calibrations

3.2.1. Time synchronisation calibration

Laboratory testing in air and a deep-water field test confirmed that alignment of multiple channels into a time-synchronised multi-channel WAV file was accurate over the duration of the deployments (maximum duration of 10 h). Raw data from the laboratory test and graphs demonstrating time alignment at the beginning and end of the deployment can be found in Supplementary Material A and in the Research Data.

The distribution of time synchronisation errors between the transmitter and all six receivers during the field test is shown in Fig. 4 (mean error = 0.5 samples, STD = 16.1 samples). Each node has similar distributions and are stable with time. The 90th percentile of this distribution is 27 samples, corresponding to an error in TDoA of 47 μs and a ranging error of ~7 cm. These are close to the expected per second drifts if the receivers have a clock drift of 2 s/day.

3.2.2. Localisation error from time synchronisation errors

Simulated localisation errors due to time synchronisation errors (Fig. 4) and potential errors in cross correlation increase with increasing range from the array (Fig. 5). This is a consequence of the increasingly small differences in TDoAs at long ranges which are therefore more susceptible to errors. Similarly, as a whale moves closer to the axis of the array, large change in range produce smaller changes in time delays, generating larger errors; when the whale is exactly above or below the array, TDoAs are the same regardless of range, thus error is infinite. Localisation errors arising from cross-correlation of NBHF clicks are comparable to the additional range and depth errors that arise due to SoundTrap time synchronisation, with range errors of <2% at ranges 10x the aperture of the array (Fig. 5). This simulation does not account for array bending, ignores off-axis click distortions by not considering how waveforms change with aspect to the array, assumes that sound speed is constant, and assumes that there is a good signal to noise ratio of clicks on all receivers on the array, so actual localisations will likely be less accurate.

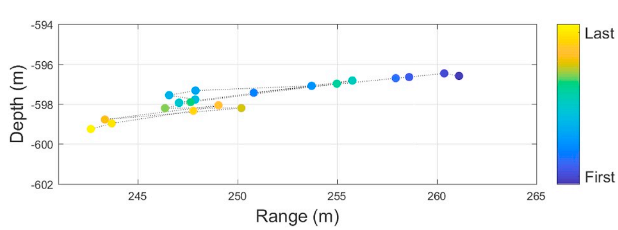

Fig. 2. Range-depth track constructed from localised clicks (n = 20) in a pilot whale click train over a 12 s period, demonstrating that the array can be used to track the diving behaviour of deep-diving toothed whales. Range shown is relative to the central channel on the array.

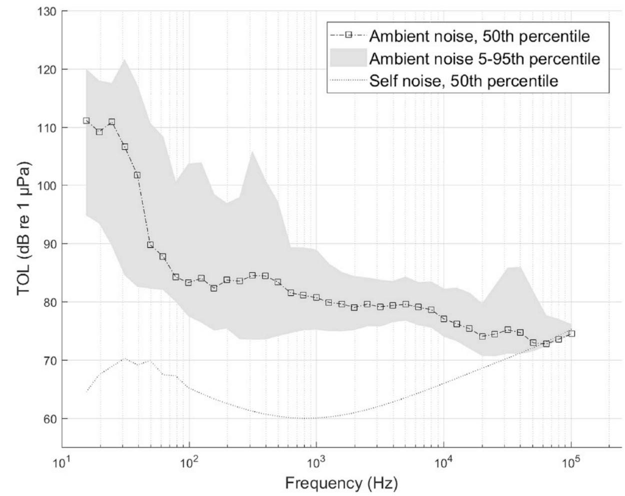

Fig. 3. Third octave levels of deep-water ambient noise from the deepest channel (~695 m) of one deep water deployment lasting 5 h. TOLs were calculated over 30 s intervals. The self noise of the SoundTrap is also shown, illustrating that ambient noise measurements were limited by self noise above about 30 kHz in this location.

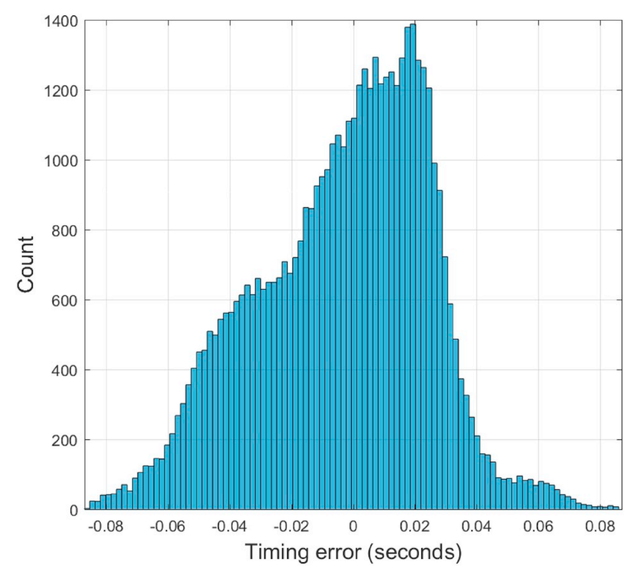

Fig. 4. Time synchronisation errors for six SoundTraps on the array with respect to the seventh recorder which acted as the timing master. This distribution was taken from one field deployment (n = ~43,800 acoustic timing pings) recording at a sample rate of 576 kHz.

4. Discussion

Studying the sounds of deep-diving, echolocating toothed whales is challenging in the marine environment. Specifically, collecting multi-channel, high sample rate data of sufficient quality for acoustic parameter quantification has typically required expensive specialised equipment deployed from a large vessel making such studies inaccessible to many researchers. Here, an autonomous deep-water vertical hydrophone array was designed to obtain high quality deep water array recordings from a small boat with a relatively small budget of ~$31K USD (see Supplementary Materials, Table B1), compared to the cost of deploying a deep water array from an oceanographic research vessel.

The major advantages of this array are that it is autonomous, thereby

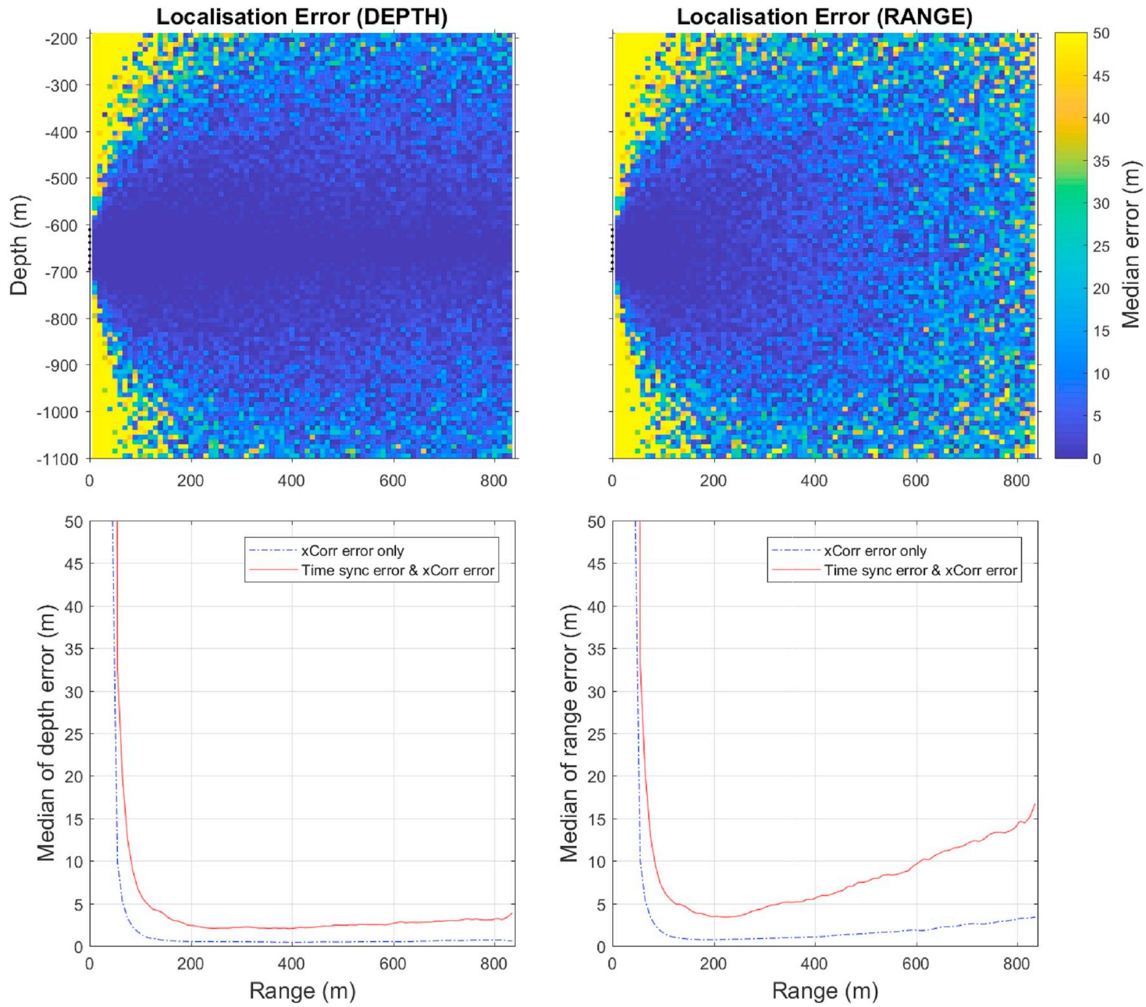

Fig. 5. Simulated source localisation errors for a 7-hydrophone array, showing errors in depth (left) and range (right). (Top): Simulated localisation error surfaces. Small black points at range of 0 m and depth between ~600-700 m represent the locations of each of the recorders on the array. Each 10 m grid point shows the median error value from 100 simulations. For each run, the localised position calculated from manipulated time errors are compared to the known source location. (Bottom): The median depth (left) and range (right) errors across 100 simulations and across all depths as a function of horizontal range to the array.

eliminating an expensive multi-conductor cable to a ship-based recorder, and that it is capable of recording at depth (up to ~700 m tested here). While some toothed whales dive deeper than the maximum depth at which this array was deployed (~700 m), tagging studies have demonstrated important echolocation behaviours, such as the foraging buzzes of sperm and beaked whales, to occur at these depths (Watwood et al. 2006; Johnson et al. 2006). If deep-water SoundTraps are used (depth rated to 1000 m), the array can be deployed even deeper. It can be deployed and retrieved rapidly from a small boat using a low-cost battery-powered winch. It is also resistant: a total of 34 deployments to maximum depths ranging from 100 to 700 m were carried out without mechanical failure of the cable or failure of the electrical connections. The SoundTraps that comprise the array have low self-noise and a large dynamic range, and can sample at high rates (up to 576 kHz) making them well-suited for the target application but, in principal, any compact autonomous recorder could be used provided that it has the capability of being synchronised with an external signal. The large aperture (~84 m presented here) allows for accurate localisations at distances of several hundred metres. The array requires an electrical-mechanical cable to distribute a timing signal to the recorders but this can be a small diameter, inexpensive cable and need be no longer than the aperture of the array itself easing the practicalities of array transport, deployment, and recovery. As a result, the array is highly portable (total shipping weight of ~14 kg, excluding sand for the weights, which is locally-sourced), enabling its deployment from small boats (*e.g.* a RHIB). This portability and autonomy permit flexibility in fieldwork scheduling, because the array can be deployed and recovered relatively opportunistically alongside other at-sea data collection or when animals are sighted in the vicinity of the vessel. An additional advantage of using autonomous recorders is that these can be separated from the array and used for other projects when the array is not needed, making the most of a limited equipment inventory, indeed some of the recorders used here were borrowed from other researchers. While our maximum field deployment duration was 10 h, the battery endurance of the ST-300HF SoundTraps sampling at 576 kHz is about a week, enabling longer deployments if the challenges of tracking and recovering a drifting array over longer intervals can be resolved.

A fundamental limitation of any acoustic array is that animals can only be tracked accurately up to ranges of about 10x the length of the array. Although the array design presented here could be readily extended to track animals at greater ranges, there are some limitations associated with a longer array. The longer the array, the heavier and less portable it becomes, thereby making it less practical for deployment from small boats. Moreover, additional electronics (*e.g.*, a line driver) may be required to transmit timing messages over a longer cable. Longer arrays are also more difficult to keep straight and vertical. The straightness and verticality of the array also depend on deployment conditions: although the typically low water currents at depths of hundreds of metres make it possible to achieve a straight and vertical array with relatively little weight and buoyancy, high surface currents and sea-state can pull the array up to shallower depths and away from verticality. Array straightness, but not verticality, is critical when quantifying acoustic parameters such as source level, peak frequency or beam pattern (Heerfordt et al. 2007). Array verticality matters when it is important to minimising errors in estimating the depths of localised animals, *i.e.* when describing their depth distributions and diving patterns. To achieve a more vertical array, greater buoyancy and weight are required at the terminal ends of the array, and these increase the difficulty of deploying and recovering the array.

Localisation errors introduced by the SoundTrap time synchronisation method developed here are of the order of 10–20 μs and so are comparable in magnitude with timing errors that arise in the cross correlation of multi-cycle NBHF clicks (Fig. 5). This means that localisation errors for species producing these high frequency clicks are not greatly increased due to inaccuracies in the synchronisation. In other words, the effect of the timing errors observed between channels on the array (Fig. 4) is comparable to the effect of errors in time delays calculated for multi-cycle clicks on a perfectly time-synchronised array (Fig. 5). This effect would be slightly smaller for other deep-diving echolocators, such as beaked whales and sperm whales; Even though these whales have fewer cycles in their clicks and thus the magnitude of timing errors arising from cross correlation errors are expected to be smaller, the reduced error would make very little practical difference in terms of localisation errors. Increasing the array aperture will tend to decrease the impact of synchronisation errors as the time differences of arrival of clicks impinging on the array increase for an animal in a given location. Additionally, localisation accuracy is a function not only of range to the source, but also of the aspect of the source to the array (Madsen and Wahlberg, 2007).

Conversely, time synchronisation errors become increasingly dominant as the array aperture is reduced setting a practical lower limit on the size of the array. In the array described here, the 90th percentile of timing errors was less than 27 samples at 576 kHz, or 47 μs, which effectively means an uncertainty in the relative location of recorders of <7 cm. In a small aperture array this distance is a larger proportion of the inter-hydrophone spacing, increasing the impact of timing errors on localisation accuracy. The timing synchronisation method presented here is therefore not suitable for a small aperture array, such as an autonomous star-array configuration. In this case, a single multi-channel recorder is a better solution (e.g. a 4-channel SoundTrap). Note that 4-channel SoundTraps were not used on our array because their sample rate is limited to 374 kHz, greater latency problems in time synchronisation are expected due to the higher loading of its processor, and with each hydrophone requiring its own cable, the array would be thicker and more delicate. Additionally, with hydrophones spliced at each node, this would preclude their use in other applications.

Within the constraints on array size discussed above, an important advantage of building the array, as opposed to buying a complete commercial solution, is that it can be readily adapted to the intended application and research question. The number of hydrophones and their spacing can be adjusted as desired (see section 2.1.3 and Supplementary Material B), depending, for example, on the intended localisation range, in concert with the desired beam pattern resolution for directional clicks. To modify the distances between hydrophones, additional cable would be required for larger node spacing, and alternatively, coiling up the cable between nodes would allow for smaller node spacing. For example, the array could be built to be 500 m long, extending the localisation range to several km, if interested in more distant loud sound sources of lower frequency, whose propagation is less subject to frequency-dependent absorption losses. However, it is important to consider the accuracy required by the research question, prior to considering array geometry. For example, localisation range errors resulting in <2 dBs of error in apparent source level are rarely critical (Madsen et al. 2007). However, the same errors in range of some 20% on a linear scale can result in larger errors in biosonar beam pattern estimation (up to ±3°), as the aspect angles measured between receivers to the localised whale are impacted on a linear scale, not a logarithmic scale. Thus there are a number of practical design trade-offs that must be considered when adapting the array to different applications.

It is possible, in principle, to have no surface expression (*i.e.*, no float), so that the array is not only autonomous, but independent of the surface. To do this, additional weight would be added so that the array is slightly negatively buoyant and so slowly descends upon deployment, collecting a vertical acoustical profile of the water column. With sufficient tension on the array, the array will sit vertically on the seafloor. Weights may be attached with magnesium releases as used here or with acoustic releases. When the ballast is dropped, the array would become positively buoyant and rise to the surface. This approach has the benefits of complete decoupling from wave movement and avoids the risk of boats colliding or tampering with the surface floats. However, there is an increased risk that the array would drift far or become snagged and not return to the surface. On steep terrain, such as that found at the edge of the continental shelf, the array may also travel down the slope and into water depths that exceed the ratings of the recorders, radio-transmitters, trawl buoys, and depth/tilt sensors.

The example shown here demonstrate the use of the array for characterising the signals from deep-diving toothed whales. The array could also be used with no rope extension, in a shallow-water configuration. Additional information collected by the array can also be exploited to improve tracking and to assess the acoustic context in which animal sounds are produced. Echoes following echolocation clicks, for example, are likely generated by surface reflections, offering the opportunity for an additional virtual hydrophone for each surface reflection for each recorder, positioned above the water surface at a height equivalent to the depth of the receiver (Urick, 1983; Møhl et al. 1990). Usage of these surface bounces can improve the vertical resolution of localisations (*e.g.* Barlow et al. 2018) and effectively increase the aperture of the array (Wahlberg et al. 2001; Madsen and Wahlberg, 2007).

The array has the potential to study sounds beyond biosonar. For example, the array can be used to study sound production in the many deep sea fishes and invertebrates whose bioacoustics remain largely unquantified (Hawkins and Popper, 2017). Additionally, ambient noise (Fig. 4) can be quantified along the drift trajectory of the array potentially enabling studies of how deep sea animals adjust vocal output to accommodate changing noise levels (*e.g.* Parks et al. 2007) or react to vessel passes (*e.g.* Wisniewska et al. 2018). Knowledge of ambient noise is also relevant when defining baseline levels in acoustic impact studies, estimating the zone of acoustic influence of an anthropogenic sound, and monitoring levels of rising anthropogenic noise (Richardson et al. 1995; Hildebrand, 2009). To obtain reliable recordings of low frequency ambient noise it is critical to decouple recorders from wave motion and avoid vessel noise, both of which are achieved by the drifting array described here. Recently, eco-acoustic monitoring applications (*e.g.* acoustic complexity indices) have been used to provide insight into the presence and abundance of marine life (*e.g.* Bolgan et al. 2018; Kaplan et al. 2018), and have been suggested to assist with the detection of cryptic, soniferous species (Staaterman et al. 2017). Using the array to localise such sound sources can establish whether one or several animals are vocalising. As such, the array could be used to remotely monitor the largely unquantified soundscapes of deep marine habitats that are otherwise difficult to sample, and estimate the biodiversity therein.

5. Conclusions

We have reported on the design and performance of a large multi-element, vertical array that addresses a number of challenges facing studies of deep sea bioacoustics. Critically, the array overcomes the high cost and difficulty of deployment of conventional cabled arrays by using commercially-available single channel autonomous recorders. A robust synchronisation method is described that effectively turns these independent recorders into a multi-channel synchronised acoustic array capable of recording with a wide dynamic range at a high sample rate. The lightweight array is portable and can be deployed from small platforms of opportunity. Data collected with the array can be used to quantify the source parameters of toothed whale clicks, which is valuable both for understanding the acoustic ecology of these species and for informing the design of passive acoustic monitoring systems. The array design presented here can be used as is, or modified, to record the largely undescribed sounds of other marine taxa, and/or to quantify deep sea ambient noise levels and estimate biodiversity at different depths of the water column.

Ethics statement

Fieldwork in Tenerife was under the authorisation of the Spanish Ministry for Ecological Transition MITECO, permit SGPM/BDM/AUTSPP, and with an animal experimentation ethics authorisation from CEIBA of the University of La Laguna (CEIBA2017-0276).

Author contributions

- CEM and PTM designed the array.
- CEM built the array, with help from PHT.
- CEM, PHT, CAD, DEC, MJ, NAS, and PTM collected the data.
- CEM analysed the acoustic data.
- PHT and CEM analysed the depth and tilt sensor data.
- JA provided the SoundTrap firmware modification for synchronisation.
- JA and MJ provided analysis support.
- CEM and PTM wrote the manuscript.
- All authors revised the manuscript, and approved of the final version.

Declaration of competing interest

None.

Acknowledgements

Array development and PhD funding for CEM were supported by the Danish Council for Independent Research (FNU) to PTM (grant 27125). Fieldwork for CEM was funded by the Oticon Foundation (grant 18-0340), the William Demant foundation (grant 19-0386), and the Danish Acoustical Society. NAS was funded by a Ramón y Cajal fellowship from the Spanish Government. Many thanks to the researchers who generously lent us their SoundTraps: Jonas Teilmann, Magnus Wahlberg, and Jakob Tougaard. Thanks to the Zoophysiology workshop at Aarhus University (Niels Kristiansen, John Svane Jensen, Mehran Jahanara, and Lasse Vestergaard Sørensen) for preparing trawl floats, and designing both the 3D-printed moulds for the breakouts and the ping-board in the vertical array. Thanks to the collaborating students and researchers of the University of La Laguna for their help in the field, and to the crew and owners of the vessel Punta Umbría, where we navigated to find pilot whales off Tenerife. Jamie Macaulay (University of St Andrews), Magnus Wahlberg (University of Southern Denmark), Michael Ladegaard and Kristian Beedholm (both Aarhus University) are kindly acknowledged for helpful feedback and discussions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dsr.2020.103233.

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