USING TIME SYNCHRONIZED LOW POWER AUTONOMOUS RECORDERS FOR MARINE MAMMAL ACOUSTIC LOCALIZATION

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1 INTRODUCTION

The collection of underwater acoustic data at sea has traditionally been a large-equipment, large budget affair, if multi-element time-synchronized acoustic data are desired. This poses challenges to young researchers, particularly bioacoustics researchers, trying to create a flexible, independent research program. However, over the past decade two trends have combined to create new opportunities in underwater acoustics research: the development of compact, low-power data acquisition systems, and the realization that the background ambient noise in the ocean can be used to time-synchronize individual recorders, effectively creating a multi-element array. The ability to deploy autonomous instruments into arbitrary "insta-array" geometries with conventional fishing gear may permit non-intrusive array measurements in regions currently too isolated, expensive, or environmentally hostile for standard acoustic equipment. To illustrate these potentialities two recent studies are presented here.

The first research effort demonstrated how a set of autonomous recorders attached to a rope can be time-synchronized to form a four-element vertical array, or "insta-array"[1,2]. The acoustic data are initially time-synchronized by performing a matched-field global inversion using acoustic data from an humpback whale, and then by exploiting the spatial coherence of the ocean ambient noise background to measure and correct for the relative clock drift between the autonomous recorders. The technique is illustrated by using humpback whale song collected off the eastern Australian coast to synchronize the array, which is then used to track the dive profile of the whale using matched-field processing (MFP) methods.

The second research effort demonstrates a deep-water deployment of the autonomous recorders, as part of a study on how sperm whales (*Physeter macrocephalus*) remove fish off demersal longline gear deployments in the eastern Gulf of Alaska. By attaching these recorders to the "anchorlines" of commercial fishing gear, continuous monitoring of the ambient noise environment before and during gear haul is now possible[3]. The presence of acoustic multipath from sperm whale "clicks" effectively creates a large-aperture vertical array that yields three-dimensional tracks of the animals, in the vicinity of the gear[4], side-stepping the time-synchonization issue.

Both studies illustrate how multi-element arrays can be deployed using standard fishing gear with small field expense, creating new opportunities for bioacoustics, and all of underwater acoustics, to explore.

2 BACKGROUND

2.1 Motivation

The field of underwater ocean acoustics presents special entry challenges to a young academic researcher, as deploying multi-element acoustic deployments is an expensive, risky, and time-consuming affair, a situation not helped by deteriorating research budgets caused by the end of the Cold War. The situation is worse for bioacoustics, where the timing of interesting events cannot be predicted, and where the location of these events are often hostile to traditional deployment methods. In 1999, having just received my Ph.D. degree in acoustic oceanography, I almost left the field because of these barriers to open-ocean acoustic research. In this paper I discuss why I changed by mind.

An old proverb describes how small inconveniences can snowball into large consequences:

For want of a nail the horseshoe was lost,
for want of a shoe the horse was lost,
for want of a horse the knight was lost,
for want of a knight the battle was lost.
So it was a kingdom was lost - all for want of a nail.

Similarly, I concluded early in my research career that a primary reason ocean acoustics is so expensive comes down to humble wires—specifically, array cables. The need to use cable to transmit individual element data to a central recording station has been a basic feature of acoustic technology since the days of A.B. Wood, and when a real-time signal is needed there is indeed no other option. But I believe that hydrophone cables are the proverbial “nail” in ocean acoustics. Array cable is expensive and fragile, leading to expensive and fragile arrays. A cable with any degree of robustness also tends to be heavy, so when the signal has to be transmitted over any distance the weight of the array equipment becomes substantial. Heavy arrays, in turn, require large and bulky anchors and floatation for deployment, requiring expensive vessels with winches to deploy and retrieve them. Once deployed, the array system usually cannot be moved, limiting the effective operational range of the system and removing the flexibility of following interesting transient phenomena. The deployment and operation of the array is usually complex enough that specialists are required to be present. Finally, whenever the system is altered, such as changing the array element spacing, a new array must be built and a new deployment strategy designed, restarting the cycle. Thus the construction cost of an array is only a portion of the complete system cost of deployment, data collection, and recovery. The field collection of multi-element array data at sea has thus traditionally been a large-scale, large-ship, and large-budget affair, requiring substantial lead times and advanced scheduling to conduct a deployment of fragile equipment. As a result many interesting transient ocean phenomena, including bioacoustic signals, have remained difficult to study using the advantages of multi-element array systems. Thus for lack of an alternative to array cable, a kingdom of opportunity is lost.

If acoustic data do not need to be analyzed in real-time, then the only reason cables are needed is to ensure adequate time-synchronization of the data. Since 1999 a theme of my research efforts has been a search for alternate time-synchronization methods, eliminating the need for array cable. I have now demonstrated how sets of lightweight, low-power, autonomous acoustic recorders can be attached to fishing gear, forming a lightweight array deployment that in turn requires relatively small anchors and thus relatively small vessels and modest field costs. This in turn has created a flexibility that has permitted fieldwork to be conducted in areas that are otherwise too expensive for this type of research. Without anchor the entire system weighs only a couple of kg, and is compact enough to transport via carry-on luggage on a commercial airliner.

In the following sections I discuss how the development of low-power recording devices has made modular array concepts technically feasible, and review two studies where the combination of these recorders with fishing gear has permitted bioacoustic data to be collected under circumstances that would otherwise be impractical.

2.2 Equipment

The hardware that has made my research possible originated with marine mammal acoustic monitoring tags, originally developed to study the effects of anthropogenic noise on individual marine mammal behavior. The acoustic elements used in the present design are slight modifications of a marine mammal tag[5,6] developed by Bill Burgess of Greeneridge Sciences, Inc., and are illustrated in Figure 1 with AA batteries inserted. This so-called "Bioacoustic Probe" was designed to sample acoustic data at sampling rates of 100 Hz to 20 kHz using an HTI-96-MIN/3V hydrophone (typical sensitivity of -172 dB re 1 V/μPa) and storing the data to 1 GB of flash memory with 16-bit precision. In addition, auxiliary measurements of pressure, temperature, and acceleration on two axes are sampled once a second and also stored to memory. Four AAA batteries were found to provide sufficient energy to fill the memory. All components except for the hydrophone have been inserted into a transparent acrylic pressure case with a Delrin end-plug, manufactured by Cetacean Research Technology in Seattle, WA. The resulting length and diameter of each recorder is 25 cm and 5 cm. The hydrophone is connected to the internal electronics via a Subconn underwater connector, and the pressure sensor is embedded in an external port of the pressure case. External power can be provided to the electronics via the same connector. The device is programmed via infrared transmissions from either a handheld PDA or a laptop. The accelerometer chip (MXA2500GL, Memsic Inc., North Andover, MA 01845) is mounted perpendicular to the main circuit board to allow the tilt of the recorder from the vertical to be measured along two axes.

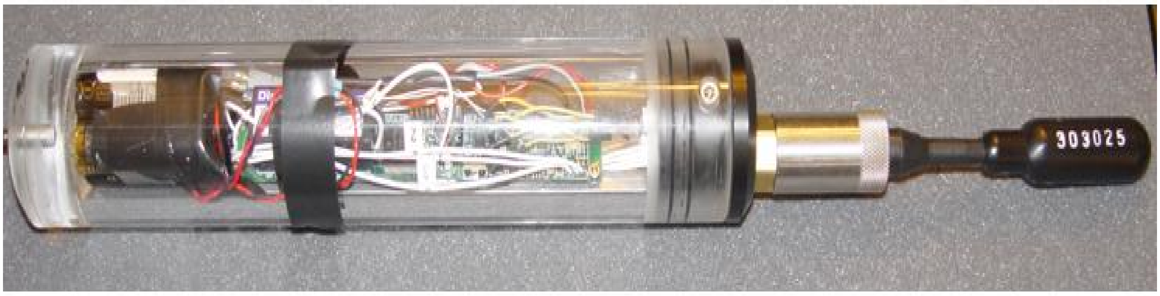

Figure 1. Autonomous recorder, adapted from bioacoustic tag design by Bill Burgess of Greeneridge Sciences, Inc.

3 MATCHED-FIELD PROCESSING OF HUMPBACK WHALE SONG USING TIME-SYNCHRONIZED RECORDERS

3.1 Matched-field processing concept (MFP)

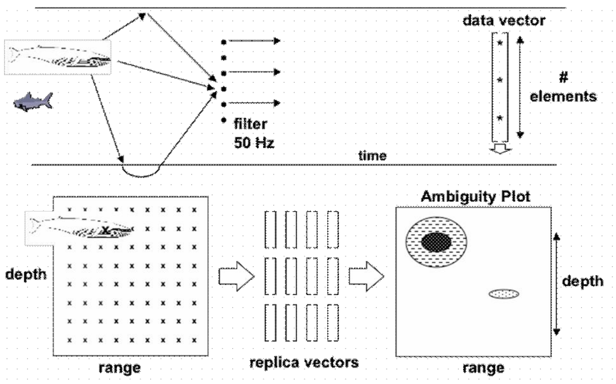

Figure 2. Concept of MFP on a vertical array.

One of the main motivations of developing a modular wireless array system was to permit matched-field processing (MFP) methods to be applied to marine mammals. The term MFP is a general description of any tracking technique that involves a comparison between a measured acoustic field and a set of modeled fields computed with a propagation model[4 ,5]. While MFP can take place with any array geometry, a vertical array provides a convenient and compact deployment for performing the technique[6]. Figure 2 illustrates how sound from a low-frequency marine mammal call would be received on several hydrophones of a vertical array. Due to the effect of multipath from the ocean surface and bottom, the relative amplitude and phase of a given frequency component will vary between each hydrophone. To determine the range and depth of the source, a numerical model is run that simulates the acoustic field produced by a hypothetical source over a grid of ranges and depths. For each location the relative amplitude and phase of the chosen frequency component across the array is computed. The modeled fields are then correlated with the measured data, and the location that yields the highest correlation is selected as the true source range and depth. Thus dive profiles and the profile ranges can be extracted from measurements at a single geographic point.

In practice the ocean environment, including the sound speed profile and sediment properties, is not sufficiently characterized to enable an accurate numerical simulation. Thus a “focalization” technique can be used that treats the ocean bottom properties, array geometry, and water column sound speed profile as additional parameters to solve[7,8]. As searching over this wide parameter space yields many local suboptimal matches, a global inversion technique such as a genetic algorithm[9] or simulated annealing[10] is typically used. The MFP technique was successfully tested on blue whales in 1996 off the California coast, over frequency ranges between 17 and 112 Hz[11]. However, testing the method on other species has been difficult, given the traditional difficulties in deploying a vertical array.

3.2 Experimental Setup in Australia

An opportunity to test the modular array concept arose in 2003. The annual spring migration of humpback whales off eastern Australia has been monitored visually and acoustically off Peregian Beach, Sunshine Coast in Queensland, for several years[1-3]. The 2003 field season was the first year of an expanded two-year research program called the Humpback Acoustic Research Collaboration (HARC), lead by Mike Noad of the University of Queensland and Doug Cato of the Defense Science and Technology Organization (DSTO) of Australia. Songs from singing whales were acoustically tracked by cross-correlating sounds from an animal across 3-5 hydrophones distributed over a 3 km aperture. The derived differences in a sound’s arrival times are then used to generate a set of hyperbolas whose intersection yields an animal’s range and azimuth from the array center. In addition, the close vicinity of the animals to shore permitted visual fixes on the animals to be measured from nearby Mt. Emu. The combination of an independent acoustic and visual tracking system in this area has provided a good opportunity for testing the modular system.

A modular vertical array was deployed over a period of two weeks in late October 2003 in 23 to 25 m deep water off Peregian Beach, about half a kilometer beyond the deepest hydrophone of the distributed array. The array consisted of six autonomous recorders taped to a rope. The system was anchored to the bottom with a plow anchor, and two subsurface floats kept the assembly straight. The entire system was light enough to be deployed and retrieved by hand from a small vessel (Figure 3).

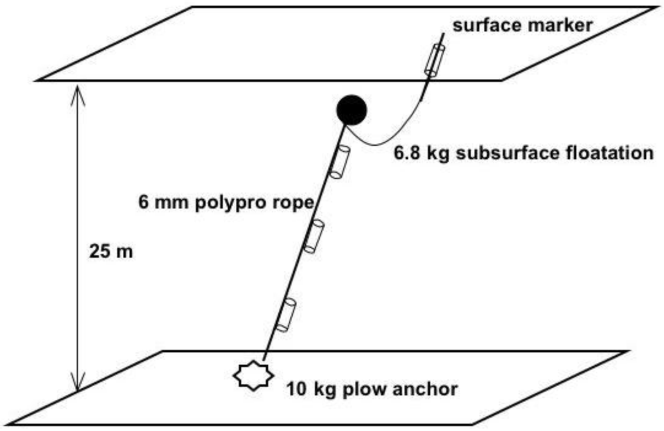

Figure 3. Deployment geometry of modular array system in Australia.

During the observation period in question up to 40 pods a day passed by both array systems, of which at least five animals were singing close enough to the distributed array so that the range and azimuth of the singer could be estimated. Near noon-time on October 23, 2003, one animal was estimated to pass within 300 m of the vertical array, so this track was selected as a promising data set to apply the MFP technique, even though only four recorders were working at the time.

3.3 Time-synchronization: the challenge of clock drift.

In this study time-synchronization without wires took place in three stages: First, cross-correlations between hydrophones of the humpback whale signal were used to coarsely align the time series to within a few milliseconds. Then the inversion software package SAGA[7] was used to invert for the remaining clock offset, the position of the whale, and orientation of the vertical array, using standard “focalization” methods discussed in Section 3.1. These are standard inversion procedures that will not be discussed further here.

The key challenge remaining was how to account for the clock drift that can desynchronize the time records quite quickly for low-power systems. In principle one can simply perform a series of inversions to estimate how the clock offsets evolve over time, but this is computationally expensive. A more convenient approach is to exploit the spatial coherence of the ambient noise background[8-16] to estimate the relative clock drifts between instruments. The “background” ambient noise recorded on two hydrophones is spatially correlated, with the strength of the correlation decreasing with increasing instrument separation. This correlation arises because the background noise signal is the cumulative sum of a large number of individual source events, each of which propagates through the same waveguide environment. Sometimes the propagation path from a particular acoustic event passes through both hydrophones, and if enough of these events occur over a given time interval, the ambient noise between both phones will become correlated. Several analytical expressions for the ocean ambient noise correlation have been derived, including one for an infinitely deep ocean[8] and for a range-independent waveguide[9]. Recent work on these expressions indicates that an estimate of the Green’s function connecting the hydrophones can be extracted from samples of ambient noise[11,14-18].

Here three properties about the ambient noise field are assumed. First, the noise between hydrophones is assumed to be spatially-correlated, so that a non-zero normalized mutual coherence function can be measured in the frequency domain via

$$\gamma_{ij}^{T_0}(f) = \left\langle \frac{X_i^{*T_0}(f) X_j^{T_0}(f)}{\left|X_i^{T_0}(f)\right|\left|X_j^{T_0}(f)\right|} \right\rangle \quad (1)$$

where $X_j^{T_0}(f)$ is the discrete Fourier transform of a segment of data recorded on hydrophone *j* at a given time T_0, evaluated at frequency *f*. The asterisk designates complex conjugation, and the brackets < > represent the expectation operator, or ensemble average. The inverse Fourier transform of Eq. (1) will be defined as the normalized coherence time function, or "coherence function" for brevity[19]. The second assumption is that the ambient noise statistics are ergodic, so that the expectation operation in (1) can be interpreted as a time average over a short time interval. Finally, in the absence of clock drift, strict-sense stationarity is assumed in that a measurement of the normalized coherence function (1) at time T_1 would be equal to the value measured during T_0. That is, both the statistical properties of the ambient noise sources and the characteristics of the propagation environment are assumed to remain relatively constant between T_0 and T_1.

Suppose that (1) is computed at a time T_0 where the data have been synchronized, and then re-computed at a later time T_1 when the data have become mis-aligned in time by an amount τ. We assume that the clock drift rate is small enough that a short data sample subjected to a Fourier transform experiences no effective drift within that sample. From the Fourier shift theorem one obtains

$$\gamma_{ij}^{T_1}(f) = \left\langle \frac{X_i^{*T_1}(f) X_j^{T_1}(f)}{\left|X_i^{T_1}(f)\right|\left|X_j^{T_1}(f)\right|} \right\rangle \approx e^{i2\pi f\tau} \left\langle \frac{X_i^{*T_0}(f) X_j^{T_0}(f)}{\left|X_i^{T_0}(f)\right|\left|X_j^{T_0}(f)\right|} \right\rangle = e^{i2\pi f\tau} \gamma_{ij}^{T_0}(f) \quad (2)$$

where the third assumption has been employed in the third expression. The resulting normalized coherence function $\gamma_{ij}^{T_1}(t)$ simply becomes a time-shifted version of the original coherence function measured at T_0:

$$\gamma_{ij}^{T_1}(t) = \gamma_{ij}^{T_0}(t-\tau) \quad (3)$$

The implication of (3) is that the clock drift τ can be measured simply by tracking how a stable peak of the coherence function shifts with time, even if the drift is non-linear in time. Equations (1)-(3) also assume that the time segments collected from the two hydrophones have at least some time overlap, and that the relative separation between the hydrophone pair remains constant between T_0 and T_1. The auxiliary pressure, inclination, and temperature measurements on the autonomous recorders can be used to confirm or adjust this last assumption.

After extracting a clock drift estimate from the normalized coherence time function, the acoustic data can be time-aligned without performing a computationally intensive inversion for every event of interest. While the clock drift estimates used here were manually extracted from a plot of the coherence function vs. time, automating this measurement should be possible.

3.4 Results

Figure 4 shows a MFP ambiguity surface conducted on one call at 11:53, using 12 frequency components incoherently averaged using a Bartlett processor, which is simply the normalized correlation between the measured and modeled fields. A value of 0 indicates no match between data and model, while a value of 1 indicates a perfect match. The animal seems to be located at 20 m depth at 633 m range. Contemporary hyperbolic fixing placed the animal at 510 m range from the array. The animal seems to be only a few meters above the ocean bottom when making this call. Note that caution must be exercised when using relatively few hydrophones because one can obtain false locations with relatively high correlations, as seen in the figure.

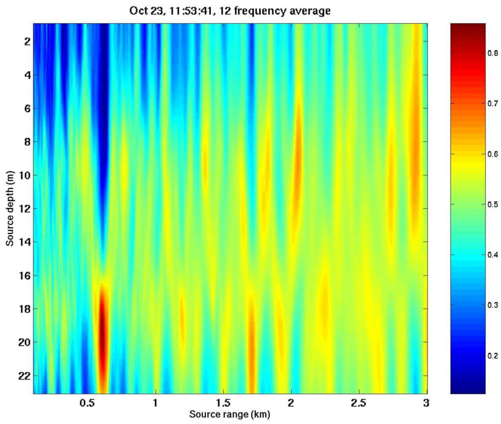

Figure 4. Ambiguity surface of correlation between measured data and modeled acoustic field, as a function of range and depth, using 12 frequencies spaced between 100 and 1000 Hz.

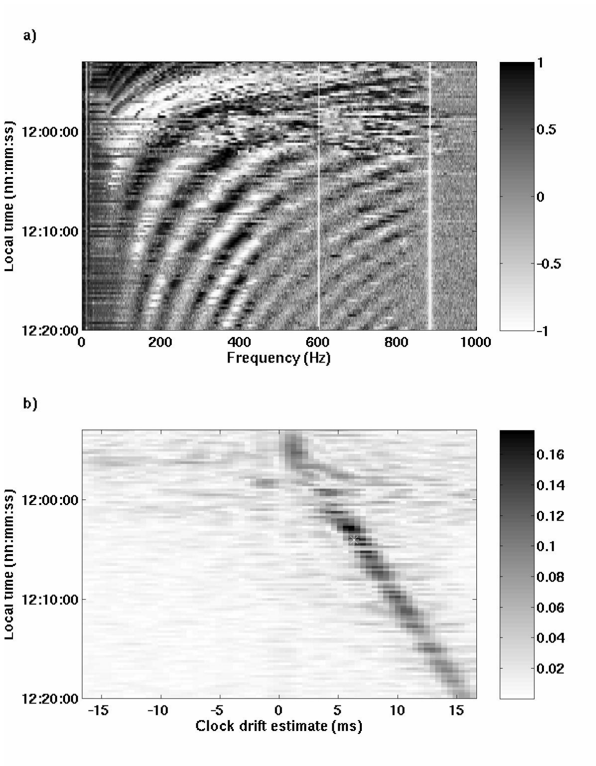

Figure 5. (a) Evolution of spatial coherence (real part) between two hydrophones over time vs. frequency. The ripple in the pattern provides the time offset between the two phones. (b) Inverse Fourier transform of plot, providing coherence function vs. time.

Figure 5 shows how the clock drift between two hydrophones was extracted using the ambient noise field, thus permitting the phones to be re-synchronized without another computationally intensive inverson. Figure 6 shows the final track thus derived from the animal, showing a good match between the hyperbolic fixes and a visual of an animal surfacing near the array. It seems that the singing animal spends most of its time a few meters above the ocean floors, but continues to sing as it rises to the surface, and keeps signing without nary a pause as it heads back down to the ocean floor.

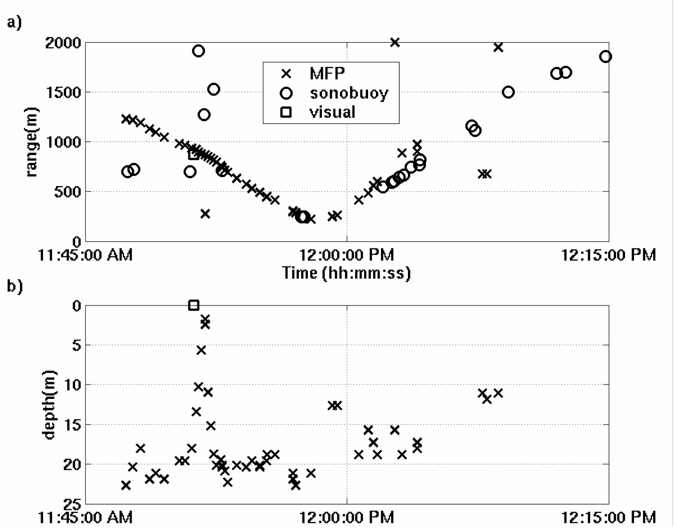

Figure 6. Subplot (a) shows range of humpback whale from vertical array as estimated by MFP(cross), acoustic hyperbolic methods (circle) and one visual sighting (square). (b) Depth profile of animal vs. time.

4 DEEP-WATER TRACKING: SPERM WHALE DEPREDATION AROUND LONGLINES

4.1 Background

In the eastern Gulf of Alaska (GOA) an active longline fishery for sablefish *Anoplopoma fimbria* (also called black cod and butterfish) occurs throughout the year. Sablefish occur on the continental slope, and most commercial longliners fish for sablefish in water depths between 400 m and 1000 m. The continental shelf off Sitka, AK, is very narrow; consequently, the sablefish grounds are relatively close to shore, within 12 miles. Sperm whales (*Physeter macrocephalus)* have been noted interacting with fishing operations with increasing frequency[20]. For example, in the GOA depredation of longline gear set for sablefish by sperm whales has been occurring since at least 1978 in the domestic U.S. fishery and observers on Japanese longline vessels in the Gulf of Alaska reported depredation occurring in the mid 1970s. The fishery occurred throughout the year until the early 1980s, when fleet expansion resulted in a shortened season. By 1994, the entire quota was caught in two weeks. In 1995 individual fishing quotas were implemented, reducing overall effort while maintaining an 8 month open season, March to November. This extended season apparently provided more opportunities for sperm whales to depredate longline gear, and by 1997 reports of depredation had increased substantially, although a large-scale statistical analysis of data over the past seven years could not find a statistically-significant effect of depredation on total catch rate[21].

In 2002 the Southeast Alaska Sperm Whale Avoidance Project (SEASWAP) began as a collaboration between the fishing community and local scientists to document the extant of the population involved in this behavior. In 2004 an acoustic component was added, which involved the deployment of the autonomous recorders discussed in Section 2.2. Section 4.2 discusses how these recorders could be attached to fishing gear to permit 3-D tracking of sperm whales around the vessel.

4.2 3-D tracking using anchorline deployments

A schematic diagram of a demersal longline deployment is shown in Figure 7. The longline is anywhere from 4 to 6 km long and when deployed rests on the ocean floor. At either end of the longline sits a 30 kg anchor, from which an "anchorline" rises the 300-1000 m depth to a surface spar buoy. These anchorlines make ideal locations for attaching recorders into a vertical array configuration. Furthermore, local fishermen are often willing to deploy an additional instrumented anchorline before their actual deployment, to permit the entire sequence to be acoustically monitored.

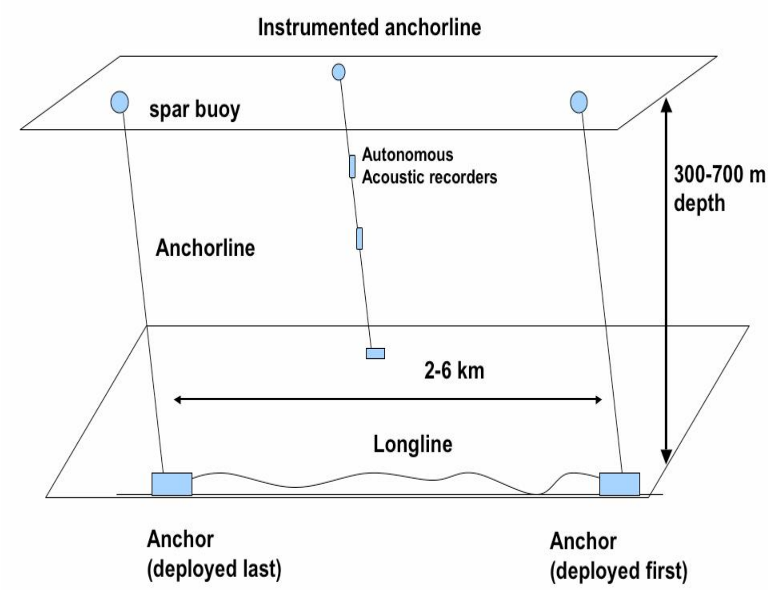

Figure 7. How longline gear can be converted into a vertical array for 3-D tracking.

When sperm whales approach within a few water depths of the longline deployment, their impulsive 'clicks' are often associated with multi-path reflections from the ocean surface and bottom that can be separated in time from the direct arrivals (Figure 8). These arrivals effectively create a large-aperture "virtual vertical array" that can be used to estimate the range and depth of the animals (Figure 9)[4]. If the bathymetry profile extending from the anchorline changes sufficiently with azimuth, then the bearing of the animal can also be determined[4].

To date the existence of multipath has not required time-synchronization between multiple recorders; however, a deep-water multi-element deployment from this gear to test ambient-noise time synchronization is planned in 2007.

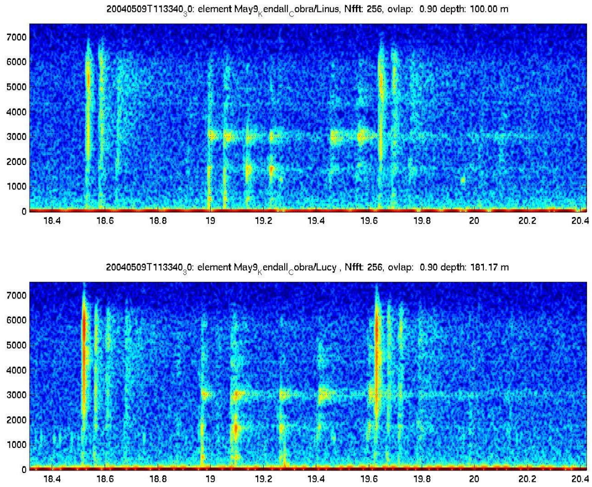

Figure 8. Top and bottom subplots are spectrograms of sperm whale clicks received on two instruments on the same anchorline at depths of (a) 100 m and (b) 180 m respectively. The many multipath reflections visible for each click allows precise localization and tracking. The x-axis shows time in units of seconds, and the y-axis shows frequency in Hz.

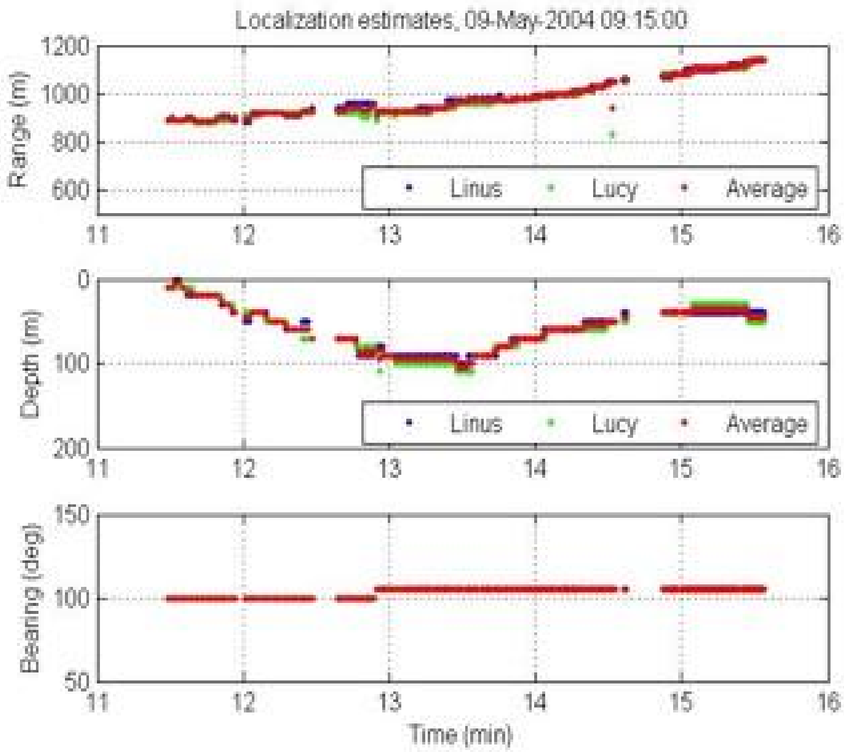

Figure 9. An example of (a) range, (b) depth, and (c) bearing of a sperm whale independently determined from two recorders on an anchorline.

5 CONCLUSION

The existence of small low-power autonomous acoustic recorders has opened up the opportunity of making bioacoustic measurements in locations that would have been impractical a decade ago. Examples presented here include the deployment of hydrophones a few hundred meters deep off the Alaskan coast during opportunistic encounters with sperm whales, and the convenient deployment of a vertical array off the Australian coast, situations that normally would have required an oceanographic vessel. The further development of techniques for time-synchronizing these instruments, even those demonstrating large amounts of clock-drift, opens up the possibility for sophisticated yet portable and flexible array deployments that may provide new opportunities for observing underwater acoustic activities from biology and many other sources of interest in the ocean.

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