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*Review*

# Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays

*M. R. Heupel*[A,F], *J. M. Semmens*[B,C] *and A. J. Hobday*[D,E]

[A]Center for Shark Research, Mote Marine Laboratory, 1600 Ken Thompson Parkway, Sarasota, Florida 34236, USA.
[B]Marine Research Laboratories, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania, Private Bag 49, Hobart, TAS 7001, Australia.
[C]Pacific Ocean Shelf Tracking Project, Vancouver Aquarium Marine Science Centre, PO Box 3232, Vancouver, British Columbia V6B 3X8, Canada.
[D]School of Zoology, University of Tasmania, Private Bag 5, Hobart, TAS 7001, Australia.
[E]CSIRO Marine Research, Hobart, TAS 7001, Australia.
[F]Corresponding author. Email: mheupel@mote.org

*Abstract.* The recent introduction of low-cost, moored data-logging acoustic receivers has provided opportunities for tracking marine organisms over small (hundreds of metres) and large scales (hundreds of kilometres). Acoustic receivers have been deployed in many different environments to examine specific hypotheses regarding the movement of aquatic species. This technology provides many advantages for studying aquatic animal movement patterns, but also has limitations and provides unique difficulties for users. Study design, applications, advantages and limitations are discussed with examples from past and current studies. Data management and analysis techniques are in their infancy and few standardised techniques exist. Complications with data management and potential data analysis techniques are discussed. Examples from the literature are utilised wherever possible to provide useful references.

*Extra keywords*: acoustic monitoring, movement patterns, telemetry, tracking.

## Introduction

Acoustic monitoring – the use of passive acoustic monitors capable of recording the presence of hundreds of animals tagged with acoustic transmitters – has become an increasingly popular research tool (e.g. Standora and Nelson 1977; Klimley *et al*. 1988, 1998; Lagardère *et al*. 1990; Nelson 1990; Tulevech and Recksiek 1994; Bégout and Lagardère 1995; Lacroix and McCurdy 1996; O'Dor *et al*. 1998; Voegeli *et al*. 1998, 2001; Lacroix and Voegeli 2000; Heupel and Hueter 2001; Starr *et al*. 2002; Cote *et al*. 2003; Welch *et al*. 2003; Heupel *et al*. 2004; Lacroix *et al*. 2004*a*). What was once considered a novel technology has rapidly evolved into a powerful tool for observing animals in coastal and continental shelf ecosystems. Researchers around the world are using acoustic telemetry to address a wide range of science and management questions in a variety of species, including teleosts, chondrichthyans, crustaceans and cephalopods. Any aquatic species to which a transmitter can be attached or implanted without modifying the behaviour of the animal is potentially suited to this technology.

Over time, the use of acoustic monitoring technology has evolved with changing technology and application to new environments. There are several types of system available with multiple applications. Each of these systems has its own set of benefits and constraints. Earliest acoustic monitoring studies typically involved a small number of submerged, omnidirectional, multi-channel, independent receivers spread distant from one another to determine animal presence or absence (e.g. Klimley *et al*. 1988; Nelson 1990; Voegeli *et al*. 2001; Lacroix *et al*. 2004*a*). These receivers evolved into smaller, single-channel, independent receivers that detect uniquely coded acoustic tags (Voegeli *et al*. 1998, 2001; Lacroix and Voegeli 2000). In addition to independent receivers, several linked systems have been developed. Cable- and radio-linked telemetry systems can be used to define the fine-scale movements of individuals based on signal detection time at multiple receivers (e.g. Cote *et al*. 1998, 2003; O'Dor *et al*. 1998; Klimley *et al*. 2001). Studies using cable-linked systems such as the MAP_500 (Lotek Wireless, Lotek Marine Technologies Inc., St John's, Canada), have reported location accuracy of ±1 m when an acoustic signal

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was detected by at least three hydrophones (Cote *et al*. 2003). The radio-linked equivalent of the MAP_500 is the VRAP system (Vemco Ltd, Shad Bay, Canada), which can provide 3D data for an individual to an accuracy of 1–2 m (Klimley *et al*. 1998; O'Dor *et al*. 1998).

In this text we will discuss the use of submerged, independent single-channel acoustic monitors to passively track animal movements. Two main approaches have been taken to utilise these receivers: (*1*) gate or curtain systems to monitor animal movement along a directed path or migration route (e.g. Lacroix and McCurdy 1996; Hobday 2003; Welch *et al*. 2003; Lacroix *et al*. 2004*a*, 2005; Thorstad *et al*. 2004; Finstad *et al*. 2005); and (*2*) regular or irregular grid systems where multiple receivers are deployed to examine movement patterns within a defined study region (e.g. Heupel and Hueter 2001; Starr *et al*. 2002; Heupel *et al*. 2004).

Despite the widespread use of this technology, few studies have described the methods involved (Lacroix and Voegeli 2000; Clements *et al*. 2005; Lacroix *et al*. 2005). Here we examine the benefits and constraints of using independent acoustic receivers along with practical considerations for deployment and use of this technology. Many new studies are being developed using this technology and this text is provided as a means of summarising some of the issues that arise when using this technology and defining its limitations. We will examine practical concerns as well as database and analytical issues that face users of this technology. Although published data using these systems are somewhat limited, examples from the literature will be identified to provide additional support and information.

There are several options in acoustic monitors, but we will discuss use of one common low-cost option, the Vemco VR2 receiver. The low-cost of the VR2 unit allows users to deploy large numbers of receivers as opposed to several strategically placed, more expensive units. Arrays of over 50 units have been reported in recent years (Comeau *et al*. 2002; Welch *et al*. 2003; Lacroix *et al*. 2005; Stark *et al*. 2005) compared with the 3–4 units typical of linked systems. Therefore, the use of this technology provides greater flexibility and often allows researchers to cover a larger geographic area than is possible with cable- or radio-linked systems, although it has lower location accuracy.

The VR2 is a fully submerged receiver that continuously monitors the environment for the presence of a unique, digitally coded transmitter signal (Lacroix and Voegeli 2000). VR2 receivers are single-channel, omnidirectional units that record the time, date and identity of animals fitted with acoustic transmitters that swim within range of the unit (Lacroix and Voegeli 2000; Voegeli *et al*. 2001). These receivers are also capable of recording telemetered data, such as temperature and depth, when appropriate transmitters are used. Receiver deployment times of up to 18 months are achievable for some current receiver battery options, with 5-year battery-life models currently being field tested, making long-term studies feasible (D. Webber, personal communication).

## Matching study objectives to array design

Clearly defining the study objective is an important step in designing an acoustic system. For example, will the array be used to provide 'acoustic recaptures' similar to a mark–recapture tagging study, or will it be used to define home-range size/activity space or migration routes? The answer to this question will dictate the layout of the acoustic array (see below). The temporal and spatial scale of the desired information should also be considered. For example, will the data be required to define fine-scale habitat use on a scale of metres or hundreds of metres? Is it necessary to know exactly where an animal is within a region or simply whether it has remained within the region (e.g. inside a marine reserve)? Will the study duration be long or short term? Long-term deployment may require that the data be periodically recovered from the receivers, whereas with short-term experiments, the receivers may need to be recovered only once. Recovery frequency will require development of a receiver recovery system that is compatible with the objectives and the environment (e.g. depth, flow rate). These and a variety of other relevant questions need to be considered to ensure the right type of system is selected to address the study objectives.

Human use/activity within the study region is also a consideration for deployment of receivers. If heavy fishing effort occurs in the area and the region is trawled or heavily travelled, it may affect the type of receiver deployment used. For example, Clements *et al*. (2005) noted that boat traffic was a concern in their study and that it was the primary cause of receiver loss. The ease of maintaining and moving receivers is also a consideration. Lacroix and Voegeli (2000) modified their original mooring system to allow equipment to be set quickly and allow rapid access to the receiver. The mooring system consisted of suspending the receiver 10–15 m below the surface via a weighted float-and-anchor system designed to reduce drag and maintain the receiver in a vertical orientation relative to the current. The rope was attached to 5 m of chain and a 20–25-kg trawl anchor allowing easy retrieval. This method was a vast improvement over heavy concrete anchors that required a hydraulic boom to move. Clements *et al*. (2005) also commented on receiver deployment and loss in a high-current area. In their study, they deployed a ketch anchor along with a weighted mooring line similar to that of Lacroix and Voegeli (2000). Ketch anchors were used because they are more resistant to dragging. Other studies in shallower depths have utilised tie-down/screw anchors that can be screwed into the sediment and provide a secure anchor system that can easily be attached to a mooring system via chain or mooring line (Heupel and Hueter 2001). As these studies indicated, designing an appropriate anchor system is a key factor in the success of acoustic monitoring studies.

Definition of the type of data required will dictate the type of acoustic telemetry the project requires and how best to deploy the selected technology. For example, studies to define habitat use on a scale of metres may be better served using active tracking or cable- or radio-linked monitoring systems. These approaches are designed to provide fine-scale movement data (on a scale of metres) with high accuracy. However, these systems can be expensive or may not be suited to long-term studies owing to high labour or maintenance requirements. In addition, cable- or radio-linked systems are geographically limiting and can only cover a relatively small area (e.g. 40 $m^2$ (O'Dor *et al*. 1998), 0.05 $km^2$ (Cote *et al*. 2003), 1 $km^2$ (Klimley *et al*. 2001)). In comparison, acoustic monitoring with independent, submersible units can only report whether an animal is within the detection range of a receiver and thus will provide position information on a scale of tens to hundreds of metres. These units can, however, be used to monitor large areas using grids (e.g. 184 $km^2$, M. R. Heupel, unpublished data) or continental margins using curtains (e.g. hundreds of kilometres, Comeau *et al*. 2002; Welch *et al*. 2003; Hobday and Kawabe 2004; Lacroix *et al*. 2005). Although data are not provided at the scale of metres, establishing independent receivers in a pattern so that their detection ranges overlap can provide long-term movement and habitat use patterns within the study region (Fig. 1). The objective of an acoustic grid with overlapping detection ranges is to ensure that the study animal maintains continuous communication with the acoustic receivers to monitor movement patterns and use of the study site (e.g. Heupel and Hueter 2001; Heupel *et al*. 2004; Lacroix *et al*. 2005). These data can also provide some indication of direction of movement based on the sequence of detections when multiple arrays are used (Lacroix *et al*. 2005). Simpfendorfer *et al*. (2002) also demonstrated centre of activity locations with an accuracy greater than receiver location by using a weighted means approach (see data analysis section).

Answering fishery-relevant questions, such as defining the long-term survivorship of individuals, may only require an occasional acoustic recapture of an individual. In this instance, the user may not need to record habitat use or movement patterns, but simply know whether the individual is still moving (i.e. still alive) and being detected. In this scenario, a gridded array may be the most appropriate approach, but the user would not need to maintain continuous contact with the study subject, and thus the receivers need not have overlapping detection ranges (Fig. 2).

If data are required to determine if an animal remains within a set region (e.g. marine reserve), it may not be necessary to define how the individual is using the reserve, but only to monitor when individuals exit or return to the region (e.g. Comeau *et al*. 2002; Lacroix *et al*. 2005). Alternatively, information may be required to determine species movement along a directed path or migration route. In both of these cases, the user could set up a linear array or acoustic curtain/gate system to monitor when individuals pass a reserve boundary or pass through each of a series of acoustic curtains (Fig. 3) (Comeau *et al*. 2002; Welch *et al*. 2003; Lacroix *et al*. 2004*a*, 2005;

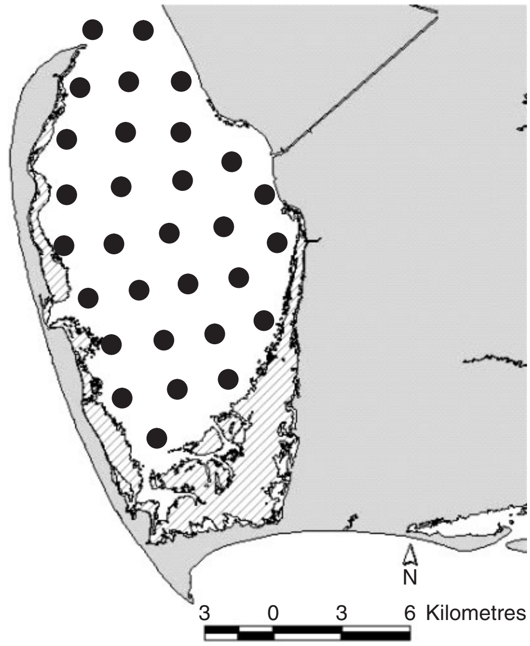


**Fig. 1.** Example of a study site with an acoustic array deployed in a grid format where individual points indicate acoustic receiver placement.

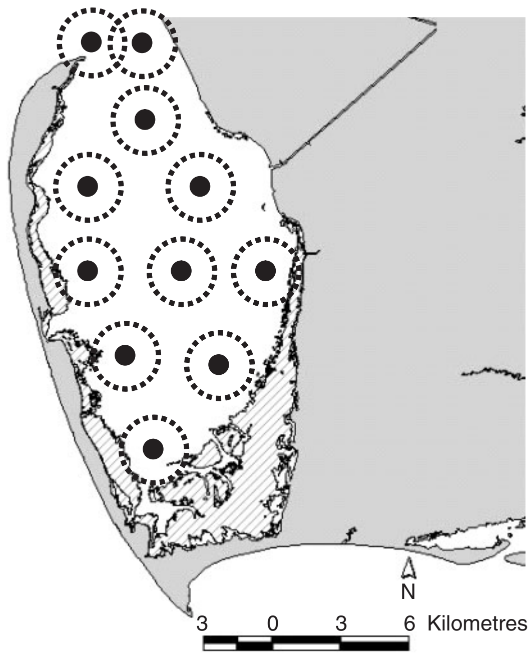


**Fig. 2.** Example of a study site with an acoustic array deployed in a 'fisheries' format. This system uses a grid layout, but does not require detection range overlap and allows receivers to be widely spaced. Individual points indicate acoustic receiver placement with dashed circles representing the detection range of each receiver.

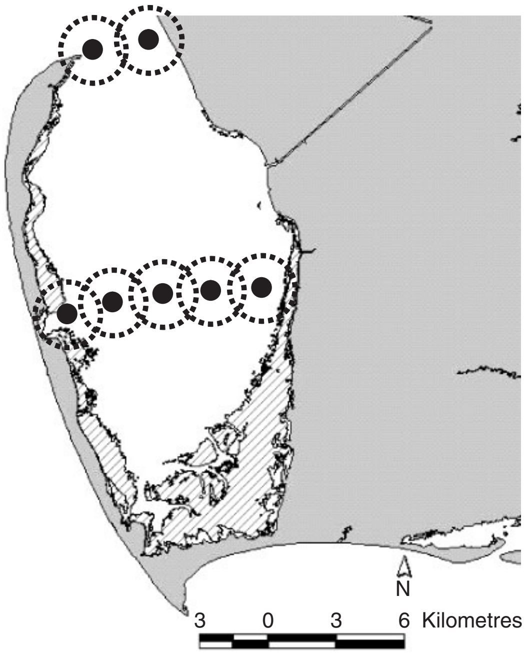


**Fig. 3.** Example of a study site with an acoustic array deployed in gate (upper) and curtain (lower) formats where individual points indicate acoustic receiver placement. Dashed circles represent the detection range of each receiver.

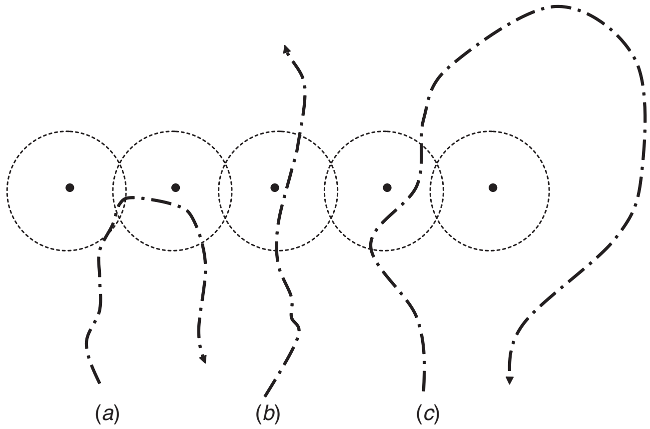


**Fig. 4.** Examples of potential tracks of an animal approaching an array designed to examine movement out of or into an area. (*a*) An animal approaches the stations, enters the detection range, and then returns in the original direction. (*b*) An animal approaches and passes across the line. In both cases, the same number of detections may be recorded, but the directionality cannot be distinguished, thus the fraction leaving or entering the area is unknown for such a design. (*c*) An animal crosses the line, and then returns at the end of the array, or through a hole in the array.

Thorstad *et al*. 2004; Finstad *et al*. 2005; Stark *et al*. 2005). This approach would require fewer receivers than a grid array, but provides a different type of data by only providing information as individuals pass near or through the gate/curtain. In most cases, the receivers comprising these curtains will have overlapping detection ranges (Comeau *et al*. 2002; Welch *et al*. 2003, 2004; Lacroix *et al*. 2004*a*, 2005; Stark *et al*. 2005). In cases where large areas need to be covered, this may not be possible and the distance between receivers can be based on a trade-off between the numbers of tagged individuals detected, the cost of additional receivers and the area covered.

Single curtain lines suffer from the complication that detections could be the result of an individual crossing the line or, alternatively, moving close enough to the line to be detected, but not crossing through (Fig. 4). Detection of individuals that do not cross through the line could cause misleading results if it is assumed the animals were detected as they moved out of the region. Some researchers have thus used multiple curtains (Lacroix *et al*. 2004*a*, 2005), whereas others have used a series of cross-shelf acoustic curtains separated by some distance (Welch *et al*. 2003; Hobday and Kawabe 2004). Parallel curtain arrays (Fig. 5) can help address questions about swimming direction but require a greater number of receivers and an increased cost. In some cases, a combination of grid and linear arrays may be required, such as when the movement and habitat use of a species at a particular site is needed as well as the direction and timing of movement away from this site. These examples illustrate how study objectives can greatly influence the type of data collected from a study site and the acoustic array design required to collect those data.

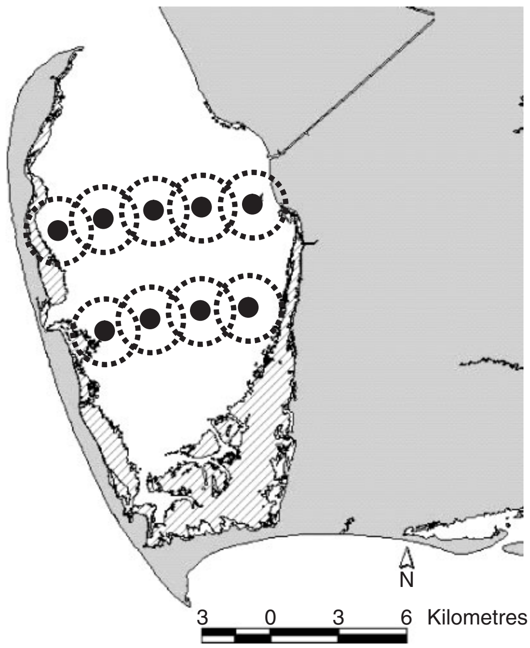


**Fig. 5.** Example of a study site with an acoustic array deployed in parallel curatin format where individual points indicate acoustic receiver placement. This configuration helps define whether fish have passed through one receiver line and provides information on directionality of movement. Dashed circles represent the detection range of each receiver.

**Study design I – receivers**

Detection range of the receiver is highly dependent on study site conditions and the type of transmitter used (Voegeli *et al*. 1998; Lacroix and Voegeli 2000). Detection range across studies and locations is probably the most variable factor researchers will have to deal with. For example, Clements *et al*. (2005) showed that the position of the receiver in the water and the presence of the mounting bar caused variability in transmitter detections. They point out that the mooring system used can cause signal blockage decreasing the probability of detecting transmitters. Clements *et al*. (2005) also point out that the position of the receiver within the water column may be critical for good signal reception. The water column position of the animal being tracked can have an influence on the detection range (e.g. 60 m for a benthic octopus (J. M. Semmens, unpublished data) compared with up to 800 m for pelagic tuna (Hobday 2002) using identical transmitters) and the behaviour of the study animal can also dictate the positioning of the receiver in the water column. Some studies have moored the receiver near the surface and pointed it in a downward direction to detect fish below (Clements *et al*. 2005; Ohta and Kakuma 2005), some moor them in the middle of the water column to monitor the movement of pelagic species that prefer this depth (Heupel and Hueter 2001) and others moor receivers near the bottom pointing up to record animals near the benthos or above the receiver (Lacroix *et al*. 2004*a*, 2005; J. M. Semmens, unpublished data).

In addition to mooring configuration, the amount of noise and physical disturbance within the study site can decrease detection range. Finstad *et al*. (2005) reported variable detection ranges within a Norwegian fjord system. Receiver detection ranged from 45 to 620 m depending on sea conditions, including wave action, salinity and depth. For example, a receiver placed close to the benthos may be exposed to greater benthic noise sources (shrimps, oysters, barnacles, etc.) than a receiver moored in the middle of the water column. Conversely, a receiver placed near the surface may be exposed to greater noise from wave action and air bubbles within the water column that can affect the detection range (Voegeli and Pincock 1996; Klimley *et al*. 1998; Voegeli *et al*. 1998). Working in areas of high noise, high current flow or high turbidity can be problematic. Areas of high flow may have a high density of air bubbles within the water column that directly affects how well a receiver can detect an acoustic signal (Thorstad *et al*. 2000), as can a high level of suspended matter in the water (Voegeli and Pincock 1996; J. M. Semmens, unpublished data). Testing equipment within each study site is important and has been recommended in previous publications using this technology (Voegeli and Pincock 1996; Lacroix and Voegeli 2000). Heavy boat traffic can also cause noise pollution. Positioning receivers near navigation channels may cause detection difficulties when boat traffic is present. Finally, users can talk to manufacturers about producing custom monitoring systems that can incorporate gain (signal strength) in the data record. This information can help define how well a receiver is performing.

Aside from noise in the water column, Clements *et al*. (2005) reported difficulties detecting transmitters owing to noise from the mooring line. Noise-producing organisms can settle on the mooring lines and receiver causing increased noise (M. R. Heupel, personal observation). Bottom substrate can cause changes in detection range too. Rocky or reef regions may provide barriers to sound, causing a reduction in detection. Soft sediments may absorb sound, causing acoustic signals to travel a shorter distance than they would in a region with hard substrate.

The reported variability in signal detection is due to signal loss as the transmission travels through the aquatic environment. Two types of losses occur: (*1*) loss due to spreading of the radiating wave with distance; and (*2*) absorption of acoustic energy by the water (or other objects in the environment) (Voegeli and Pincock 1996). In addition, signal transmission travels differently in salt and fresh water. In salt water, a 69 kHz signal would attenuate at a rate of 2 dB $km^{-1}$ compared with 30 dB $km^{-1}$ for fresh water (Voegeli and Pincock 1996). For example, use of VR2 receivers in adjacent study sites, one estuarine and the other fresh, revealed that detection range in fresh water declined to ~600 m in fresh water compared with 800 m in estuarine conditions using the same transmitters (M. R. Heupel, unpublished data). Based on this information, conditions within the study site should be considered before choosing to use acoustic telemetry. Radio telemetry might be more effective when working in freshwater systems and should be considered as an alternative to acoustic monitoring.

In addition to variability in fully marine and freshwater systems, users can expect to experience changes in detection range based on gradients within the water column, such as picnoclines or thermoclines. Refraction occurs when acoustic signals hit a boundary layer (Voegeli and Pincock 1996). In addition to refraction, sound velocity in water increases with temperature, causing a sound wave to bend as it passes through a temperature gradient (Voegeli and Pincock 1996). This variation within the environment may dictate where in the water-column receivers are deployed to provide the best opportunity to detect fish movements. Based on these considerations, users should have a good understanding of conditions within their study site and take them into account when establishing a study, placing receivers and defining signal detection range.

*Deployment constraints*

An adequate anchoring system needs to be designed to ensure the units do not move within the study site, potentially confounding results, and causing difficulty in relocating the equipment for downloading, maintenance or removal from the study site (Clements *et al*. 2005). It may also be important to note if the receivers will change physical location or position in the water column with changing tides or currents. Movement of the receiver may affect detection range and recorded location of animal presence. For example, a receiver close to the surface with a long mooring line and poor surface floatation may move with the current. Movement of the surface float may cause the receiver to be positioned at an angle in the water column, directly affecting the listening area of the receiver by potentially skewing reception to one direction (Clements *et al*. 2005). Other considerations that may reduce detection range over the period of a study include settlement of fouling organisms, such as barnacles, hydroids and algae. Receivers tethered with floatation should be separated from the floats by at least a few metres to minimise the acoustic shadow (Welch *et al*. 2004), which may be a considerable fraction of the detection range in, for example, receivers in deep water with a large air-filled float above them. The interference effect of floats and fouling organisms on reception of pulses is largely unknown, but avoiding the potential interference is sound practice (Lacroix *et al*. 2004*a*, 2005; Clements *et al*. 2005). Human interference with equipment is also a consideration in most study sites owing to vessel presence and fishing effort in the area (Clements *et al*. 2005; M. R. Heupel, personal observation). As a result, sub-surface deployment may be favoured (e.g. Heupel and Hueter 2001). Finally, ease of recovering the equipment may need to be a factor in anchor design if the equipment needs to be accessed regularly or is placed in deep water (Lacroix and Voegeli 2000; Lacroix *et al*. 2005). In the case of receivers deployed in non-diveable depths without subsurface floats, acoustic or mechanical releases (Welch *et al*. 2003, 2004; Stark *et al*. 2005; A. J. Hobday, unpublished data) and/or snag-lines (Welch *et al*. 2004; Stark *et al*. 2005) will need to be incorporated into the mooring system in order to allow recovery of the equipment. Recovery of equipment is not always assured, and the design of suitable mooring and recovery systems for the array environment is critical (Welch *et al*. 2004; Clements *et al*. 2005).

## Study design II – transmitters

The second component of signal reception in a study site relates to the type and size of acoustic transmitter used. Larger transmitters have greater battery power and signal output, making them easier to detect at greater distances than smaller transmitters. However, as in all tagging studies, the size of the transmitter is dictated by the species under investigation (e.g. Lacroix *et al*. 2004*b*). Transmitter selection is not considered in detail in this contribution, but is a major consideration in all telemetry studies and should be thoroughly researched. When considering transmitter size and detection, the behaviour of the study species (e.g. swimming speed, schooling behaviour, etc.) should be considered in conjunction with environmental parameters such as current speed.

Another consideration in transmitter configuration is code repeat rate. Repeat rate, similar to size, comes with trade-offs. Faster repeat rates provide more data and, in some cases, allow individuals to also be manually tracked, but equate to shorter tag duration because the batteries are depleted more quickly. Fast ping rates might be important if working with a curtain system where animals may move through quickly. A long repeat rate might allow an individual to pass through the curtain undetected. Repeat rate is also a consideration when working with individuals that do not move far or quickly. In this case, a small number of individuals may fill up receiver memory quickly by remaining near the receiver. In addition, if multiple individuals are present near a receiver, code collisions can occur (Lacroix and Voegeli 2000). Code collisions occur when two acoustic signals are received simultaneously. The result of this collision is that the receiver may not record either individual because it cannot decode the signal, or a false signal may be recorded based on the overlap of the two competing transmissions. RCODE transmitters are designed with a pseudo-random signal repeat function to avoid repeated code collisions (Voegeli *et al*. 1998; Lacroix and Voegeli 2000). Based on concerns due to code collision when numerous individuals are present, Lacroix and Voegeli (2000) recommended acquiring accurate knowledge of the detection range of the receiver based on conditions within the study site. Discussions with manufacturer staff will help users to define an appropriate ping rate based on receiver detection range, array design and study objectives. Vemco has a 'coded pinger detection simulator' program that was developed to predict the time needed to detect RCODE transmitters and the detection success as a function of the number of transmitters present within the receiver detection range (Lacroix and Voegeli 2000). This program can help define the optimum ping rate for a given study.

Even with optimal repeat rates for a given study signal collisions will occur (M. R. Heupel, personal observation). When examining data from receivers, it is important to consider code collision as an opportunity for false data to be recorded. False codes may be relatively easy to identify if a code number that is not included in the range used in the study or a code that has not been deployed yet is detected (Clements *et al*. 2005; M. R. Heupel, personal observation). However, this could be the result of a false code, or the presence of an individual from another study that has moved into your study site. In these instances, it is best to look at how many detections of that code were recorded and if it was recorded on more than one receiver. If multiple detections were recorded, then it is possible that an unknown individual has moved into the study site. If there is only one detection, then it is likely to be a false code and should be regarded as dubious unless it can be confirmed by another receiver (Clements *et al*. 2005).

## Study design III – system testing

The development and deployment of an acoustic monitoring array (either grid or linear) requires considerable preparation and field-testing to be effective (Lacroix and Voegeli 2000; Clements *et al*. 2005). Placement of receivers is critical to the design of successful acoustic array systems. In order to define appropriate receiver locations, it is necessary to understand the environment in which the receiver will be deployed and to test the detection range of receivers in that environment (Lacroix and Voegeli 2000; Clements *et al*. 2005). The detection range of the equipment in a specific study site will determine how far apart receivers can be deployed (and maintain overlapping detection ranges if needed). This can be achieved by conducting *in situ* range tests and noise surveys. Using a broad-spectrum hydrophone, the study site can be surveyed to define any areas of high noise (Fig. 6). Noise sources can be biological (e.g. oyster bars, alphaeid shrimps), physical (e.g. water flow, wave action, tidal currents, type of coastline) or anthropogenic (e.g. vessel noise, noise devices to scare marine mammals from vessels, fish farms, underwater construction, etc.). Temporal variation at short-term (storms), daily (diurnal, wind) and seasonal scales (average wave height) can further complicate the interpretation of study results and should be considered as explicitly as possible. Locating regions of the study site that contain high noise contamination can provide valuable information on how well the acoustic equipment will perform. However, preliminary surveys may not be possible for remote or large-scale acoustic arrays, such as linear arrays to examine migration routes. In situations where comprehensive surveys cannot be carried out, it would be advisable to survey a sub-sample of locations where habitat features or water flow change. Without noise survey data, there is a higher degree of uncertainty about factors that could affect the equipment that researchers must take into consideration when examining study results.

The next step in defining equipment performance in a given location is to conduct range tests. In situations where deployment is remote, repeated recovery is impractical, or temporal variation in detection range is expected, range testing may occur following deployment and the results interpreted in light of the detection range (A. J. Hobday, unpublished data). Pre-deployment testing requires the user to have at least one receiver and one or more acoustic transmitters identical in power output to those to be used with the study species. To test detection range, the receiver should be deployed within the study site in the same configuration that will be used for the study (Lacroix and Voegeli 2000; Clements *et al*. 2005).

Once the test receiver or array is deployed, range testing can be done in several ways. The user can hang a transmitter off the side of a boat at a given distance from the receiver at a set time and continue to move further from the receiver through time (which should be synchronised with the clock of the receiver) (e.g. Klimley *et al*. 1998; Lacroix and Voegeli 2000; Arendt *et al*. 2001*b*; Clements *et al*. 2005). The timing of detections can then be matched with the distance the transmitter was from the unit to generate a detection profile (Lacroix and Voegeli 2000). During range testing it is advisable to use more than one transmitter and turn off the boat engine to decrease potential noise sources. Signal strength of individual transmitters may vary so testing more than one tag may prove to be very useful in more accurately defining detection range (M. R. Heupel, personal observation, E. Thorstad, personal communication). Test transmitters should be deployed in a manner that is representative of the study species (Lacroix and Voegeli 2000; Clements *et al*. 2005). For example, testing transmitters mid-water may not be representative of transmitter performance if it is to be attached to a benthic species. A second, and potentially more useful, way of testing detection range is to moor transmitters in the study site at set distances from the receiver (Simpfendorfer *et al*. 2002). Test transmitters can be left in place in the study site for several days to define the number of transmissions the tag emitted (based on tag setup variables) and the number detected by the receiver (Fig. 7). Moored transmitters will give the user a better understanding of the probability of transmitter detection and will allow temporal variation in detection range to be examined. The probability of detection decreases with increasing distance from the receiver and so the detection range is, in reality, the distance from the receiver where a set proportion of transmissions will be logged (Lacroix and Voegeli 2000; Simpfendorfer *et al*. 2002; Clements *et al*. 2005). Range testing will provide important data on how the receiver performs in different

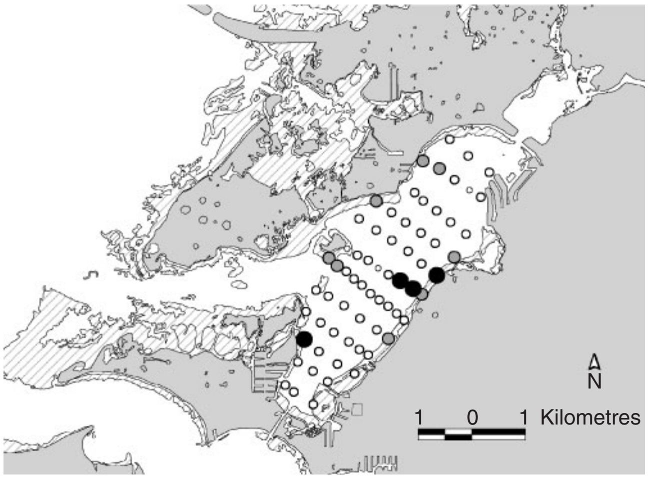


**Fig. 6.** Map of the Terra Ceia Bay (Florida, USA) study site showing the results of noise surveys at 69 kHz. Noise level was rated from 1 to 4 based on signal strength of background noise heard on the receiver where 1 = small open circle, 2 = larger open circle, 3 = small grey filled circle and 4 = large solid black circle. The two noisiest regions were due to an oyster reef and jetty pilings covered with barnacles and oysters (M. R. Heupel, unpublished data).

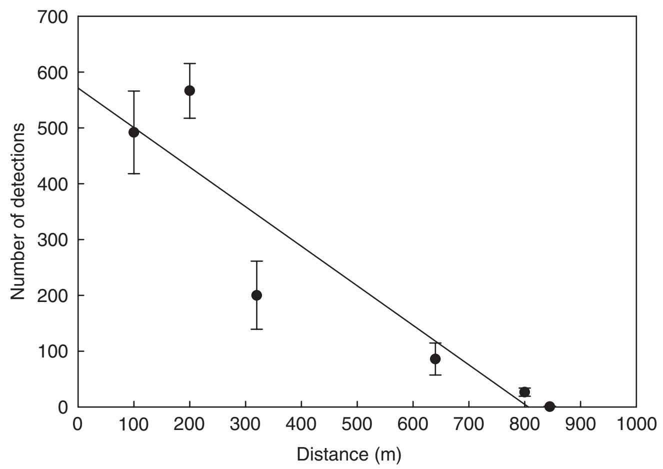


**Fig. 7.** Detection data from deployment of six acoustic transmitters for range testing in a Florida estuary. Transmitters were moored variable distances from each target receiver and the mean number of detections over one week for each transmitter is shown here. Bars indicate standard error and the line represents a linear regression ($r^2 = 0.8589$) (M. R. Heupel, unpublished data from Charlotte Harbor, Florida).

conditions (e.g. stages of tide or day *v.* night) and conditions during testing should be noted (Lacroix and Voegeli 2000).

Conducting range tests provides a direct measure of receiver performance in the study site. It should be noted that range testing should not be limited to the pre-deployment phase of establishing an array, but should be carried out as often as possible once the array is established to gain information on the performance of the entire array over a range of conditions. For large arrays, this can be achieved by towing the transmitter through or along the array and noting the time and position of the tag relative to the position of each receiver. Researchers should take care with this approach because, depending on the locations of the transmitter, towing vessel and receiver during range testing, calculating the distance of the transmitter from the receiver for each detection is not a trivial task (A. J. Hobday, unpublished data). Transmitters used for defining detection range might also be used in the study site as reference transmitters. The known locations of these receivers would help define system performance over time based on detection rates and could help interpret data collected from the system if detection through time varies.

Once the receiver detection range is determined, the user can decide on the most suitable location of receivers to achieve the study objectives. The distance between receivers can be defined by the amount of overlap at some percentage of expected detections, if the user wishes to have overlap among receivers. Welch *et al.* (2003) described a mathematical formula to determine the maximum separation distance between receivers to achieve a desired level of overlap. Consideration of habitat types and geographic constraints are also important in defining receiver deployment since certain habitats may make it difficult or impossible to moor a receiver at a desired location (e.g. rocky substrate, presence of a marked navigation channel).

## Applications for acoustic arrays

Acoustic arrays can provide vast amounts of data to address many scientific questions or lines of inquiry. Data inquiries can range from simple questions of animal presence/absence, to complex examination of animal interactions. Presence/absence data from an array can be used to examine the residence time of individuals and timing of movement events such as migration (e.g. Lacroix and McCurdy 1996; Arendt *et al.* 2001*a*; Lacroix *et al.* 2004*a*; Thorstad *et al.* 2004; Welch *et al.* 2004; Finstad *et al.* 2005; Heupel in press). Position or animal location data can be used to define home range, core areas and any repeated movement patterns (e.g. Heupel and Hueter 2001; Lowe *et al.* 2003; Heupel *et al.* 2004). In addition, movement data can be examined in relation to environmental variables collected concurrently via co-instrumentation or retrospectively from other sources (e.g. Klimley and Butler 1988). Commonly used variables examined include tidal state, water depth, day length, water temperature, and salinity (e.g. Bégout and Lagardère 1995; Bégout Anras *et al.* 1997; Klimley *et al.* 1998; Arendt *et al.* 2001*a*; Cote *et al.* 2003; Hobday 2002; Hobday and Kawabe 2004; Heupel in press). Additional sensors can be attached to the VR2 to gather environmental information, such as temperature, at all times during the study (Arendt *et al.* 2001*b*; Hobday *et al.* 2001; Hobday 2003; Hobday and Kawabe 2004). This alternative should be considered when working in dynamic environments, since telemetered transmitter data is only received when the tag is within the detection range of the receiver. Continuous information about the environment allows the visitation pattern of the animals to be placed in a wider context. Based on long-term deployment of receivers, annual or seasonal patterns of movement can be examined and factors that affect changes in habitat use or distribution can be elucidated (e.g. Arendt *et al.* 2001*a*; Heupel and Hueter 2001; Egli and Babcock 2004; Heupel *et al.* 2004). Location data can also be examined in relation to other biological components of the system including cohorts, predators and prey (e.g. Klimley and Butler 1988; Heupel and Hueter 2002; Heupel and Simpfendorfer 2005*b*).

Analysis of interactions among aquatic individuals has traditionally been hampered by a lack of data. Acoustic monitoring can provide movement and location data on multiple individuals simultaneously to allow analysis of school fidelity (Klimley and Holloway 1999; Hobday 2003), group movement patterns and individual interactions (Klimley and Butler 1988; Heupel and Simpfendorfer 2005*b*). Acoustic arrays can also be used to collect fishery-relevant information by providing the data required to calculate direct estimates of mortality within a population (Heupel and Simpfendorfer 2002; Welch *et al*. 2004; Lacroix *et al*. 2005), estimate emigration or dispersal rates (Lacroix and McCurdy 1996; Welch *et al*. 2003, 2004; Lacroix *et al*. 2004*a*; Thorstad *et al*. 2004; Finstad *et al*. 2005), etc. These data can be utilised as mark–recapture-style data and applied to current assessment models and analysis techniques. Similarly, acoustic data can also be used to determine the validity of traditional mark–recapture techniques in instances where recapture rates are low (J. M. Semmens, unpublished data). Animals fitted with transmitters are also typically tagged with conventional tags that would allow survival to be estimated if exploitation is high. This may be important to demonstrate that animals that were not detected acoustically did not die (Heupel and Simpfendorfer 2002; A. J. Hobday, unpublished data).

Acoustic monitoring arrays can also be used to examine the design and utility of marine reserve systems (Starr *et al*. 2002; Lowe *et al*. 2003; Egli and Babcock 2004; Heupel and Simpfendorfer 2005*a*) or spatial fishery closures to protect spawning stock. Information concerning the amount of space a study species utilises, how long individuals remain within that space and how often they leave and return to that space are critical to implementing effective marine reserves and protecting spawning stock, which would otherwise be targeted by fishers. Finally, monitoring data can be applied to the development of individual-based movement models through the provision of movement data. Long-term movement data from acoustic monitoring rather than data extrapolated from short-term tracking should provide more robust results. Undoubtedly future research will continue to find new avenues for using this technology as more users continue to apply it to new questions.

## Advantages of acoustic arrays

In comparison to actively tracking an individual animal, acoustic monitoring is much less labour intensive. Acoustic monitoring removes the need to physically remain with a study animal and provides the opportunity to monitor animal movements during times when it is unsafe for researchers to be present (e.g. severe weather events). Removal of the necessity of remaining with a study animal also removes any bias inherent in running a vessel in close proximity to the animal and potentially influencing behaviour as a result of tracking, or observing unusual behaviour in the first few days as a result of tagging (e.g. Lutcavage *et al*. 2000; Walker *et al*. 2000). In addition, active tracking typically uses one focal animal, where acoustic monitoring allows multiple individuals to be monitored simultaneously. This allows the researcher to define behaviour for a larger subset of the population rather than for a small number of individuals tracked over different temporal scales or periods. An advantage of acoustic transmitters over alternative conventional or electronic tags (e.g. implantable archival tags) is that animals do not need to be physically recaptured to obtain the data. Instead, data is gathered by the receiver, which provides an acoustic recapture and logs the relevant information for future use.

Both linear and gridded acoustic array systems can provide data on long-term movement and biotic and abiotic association patterns. Long-term data make it possible to define seasonal or annual trends in population movement or behaviour patterns and interactions between species. Linear arrays make it possible to examine large-scale migration routes of aquatic animals and the rate of these migrations both through gates across coastal embayments (Lacroix *et al*. 2004*a*, 2005; Thorstad *et al*. 2004; Welch *et al*. 2004; Finstad *et al*. 2005; Stark *et al*. 2005) and/or stretching curtains of receivers from the coast out to the edge of the continental shelf (Welch *et al*. 2003; A. J. Hobday, unpublished data), such that animals are tracked as they move between each line of receivers in the array. If transmitters with sufficient battery life are used, it is also possible to collect multi-year data from individuals (Hueter *et al*. 2004; M. R. Heupel, unpublished data). This allows examination of interannual variation or ontogenetic changes in habitat use via grid arrays or movement pattern for both types of arrays. These arrays can be used to examine the migration of animals through portions of their life cycle and thus the survivorship of the various life stages can be determined (e.g. salmon smolt leaving the rivers for the ocean, see Moore *et al*. 2000; Welch *et al*. 2003). However, the size of animals and transmitters restrict the ability to monitor individuals throughout their life cycle. Large individuals can be fitted with large, long-life transmitters (lasting several years), but studies utilising young or small animals are temporally limited by the size of transmitter the individual can carry.

## Limitations of acoustic arrays

If the research question requires detailed information on the location of an individual at a scale of metres, then independent acoustic monitors may not be suitable. To acquire more accurate position locations for individuals requires active tracking of an individual or use of a more sophisticated linked monitoring system as described earlier. Additionally, both grid and linear arrays are limited to providing information on the movement of the animals while they are within range of the receivers. For linear arrays, this can mean that individuals are only detected for a very small proportion of the transmitter life. At larger geographic scales, alternative electronic tag options such as archival or satellite tags may be more suitable depending on the recapture likelihood or size of the animals (see Gunn and Block 2001).

Although acoustic monitoring alleviates the need and costs involved with actively tracking and following an individual, these systems still require a labour investment. Data needs to be retrieved from the units and the current technology requires the user to bring the unit to the surface to collect the data. This may prove to be logistically challenging in some study sites and impractical in others. The need to retrieve data directly from the receiver should be a consideration in all study plans. However, Vemco is currently producing a VR3 unit that contains an underwater modem that can communicate with a surface unit for *in situ* downloading, as well as a VR3 version that deploys a surface buoy to communicate with either ARGOS satellites or cellular phone networks, allowing researchers to retrieve data from the comfort of their office. Regardless of the receiver type, the costs involved in maintaining and downloading the receivers should be considered in study planning and budgeting. This is particularly the case in large linear arrays that often cover a large stretch of coastline and are generally deployed in relatively deep water.

### Data management

In many cases, researchers using VR2 technology collect large amounts of data that pose challenges beyond the capabilities of simple spreadsheet applications. A variety of options for data handling are available including databases and custom-written software utilising programming languages such as Matlab, Fortran and C (e.g. Simpfendorfer *et al*. 2002). Due to the large amounts of data provided by acoustic receivers it is advisable to establish a means of parsing and integrating data files from individual receivers into a database early in the study. Database programs will facilitate management of the large datasets and allow the data to be organised, refined and queried. Parsing of data files and integration into a database system is particularly important when working with large numbers of receivers. Without these systems in place, users can spend large amounts of time manipulating data files and sorting data.

Consideration of the desired outputs can suggest the best approach to data manipulation and interrogation. For example, is it necessary to have minute-by-minute data for an animal or can data be summarised into temporal or spatial bins? Summarising large amounts of data into temporal periods or units (e.g. 30 min, 60 min, 3 h, 12 h, etc.) may clarify data management and interpretation.

### Data analysis

Once the target dataset is identified, analysis of the data can be completed. There are currently no standardised methods for analysing acoustic monitoring data. This is probably the result of the broad applicability of this technology. Acoustic receivers can be used to address a wide array of study questions as discussed earlier. Unfortunately, statistical approaches to analysing these data have lagged behind technological advances within the field. This is one of the biggest limitations of utilising and publishing acoustic monitoring data and users should be aware of the potential data complications, consider the possibility of having to implement or develop unique tests and consider data analysis early in the project design.

Most acoustic monitoring studies are undertaken to test a specific or directed hypothesis. This means datasets from this technology can range from simple presence/absence data to continuous location data. Presence/absence data can be analysed similar to tag–recapture data, with each detection from a transmitter treated independently as a sighting or recapture event. This is probably the simplest way of examining an acoustic monitoring dataset. Examination of continuous location data causes greater complications owing to the large amounts of data gathered and the need to sort and interpret datasets from multiple individuals within the same time frame.

In either of these data scenarios, it is important to consider how much data is needed. Examining minute-by-minute data over a period of months may be tedious and unnecessary in many cases. It may be more reasonable to consider the available data over a larger time step (e.g. 30, 60 min, 1, 6, 12 h). This will help reduce the amount of data gathered and potentially simplify analyses. Techniques such as position averaging (Simpfendorfer *et al*. 2002) may become more common as users need to package data in more reasonable temporal units. Filtering of high-frequency data is one way to undertake such temporal analysis, another is Fourier or spectral analysis (e.g. Arendt *et al*. 2001*b*; Hartill *et al*. 2003; Ohta and Kakuma 2005; Heupel and Simpfendorfer 2005*b*).

The presence of individuals within a given site can be looked at in several ways. Klimley *et al*. (1998) suggested using circular clock diagrams to display short-term residency data and charts for long-term data. Ohta and Kakuma (2005), Klimley *et al*. (2003) and others have used charts to display individual presence and this approach appears to be an effective means of displaying large amounts of temporal data. Spatial data are more complex than simple tag–recapture-style data and are typically described via home-range calculations (e.g. Hartill *et al*. 2003; Lowe *et al*. 2003; Heupel *et al*. 2004), or examination of habitat use (e.g. Arendt *et al*. 2001*a*; Lowe *et al*. 2003). Minimum convex polygons and kernal utilisation distributions have been commonly used to analyse home-range sizes in both aquatic and terrestrial studies. These methods continue to be applied and have been used in acoustic monitoring research (e.g. Lowe *et al*. 2003; Heupel *et al*. 2004). Data used for home-range calculations can also be used to examine site fidelity using linearity indexes (Lowe *et al*. 2003). The 'animal movement extension' for ArcView (Hooge and Eichenlaub 2000) is often used to do these calculations and produce maps of the data.

Some applications of acoustic data have examined migration patterns of released individuals (Lacroix and McCurdy 1996; Hobday *et al*. 2001; Comeau *et al*. 2002; Lacroix *et al*. 2004*a*; Thorstad *et al*. 2004; Welch *et al*. 2004; Finstad *et al*. 2005). These studies typically look for individuals to pass a specific point or through a line of receivers to define migration. These data are used to calculate the rate of progression through the area. Similar data have been used to examine swimming speed based on movement past known points. Most of these analyses have not incorporated statistical analyses except in instances where rate of movement is compared across groups or related to physical parameters such as water temperature (Comeau *et al*. 2002; Lacroix *et al*. 2004*a*; Thorstad *et al*. 2004; Finstad *et al*. 2005). In other studies, site fidelity has been compared with physical parameters to determine if parameters influence distribution (Humston *et al*. 2005). In most of these studies, standard correlation type approaches were applied.

Acoustic monitoring data have also been gathered to examine more complex life history and movement patterns. For example, Heupel and Simpfendorfer (2002) used life history tables, Kaplan–Meyer and Program SURVIV estimates to define mortality rates of a population based on acoustic monitoring data. Examination of individual location and movement data can be as simple as the application of a generalised linear model or analysis of variance to examine the amount of time spent within a specific location (e.g. Heupel and Simpfendorfer 2005*a*) to complicated population modelling (e.g. Naughton *et al*. 2005). Previous studies have examined subjects as diverse as diel activity patterns (e.g. Bégout and Lagardère 1995; Bégout Anras *et al*. 1997; Klimley *et al*. 1998; Arendt *et al*. 2001*b*; Cote *et al*. 2003), behaviour (e.g. Cote *et al*. 2003; Ohta and Kakuma 2005) and use of marine protected areas (e.g. Starr *et al*. 2002; Lowe *et al*. 2003; Egli and Babcock 2004; Heupel and Simpfendorfer 2005*a*). Interactions between monitored individuals have also been conducted. Klimley and Holloway (1999) examined school fidelity of yellowfin tuna using log-survivorship analysis to determine if the probability of an event occurring at a given time was random. Heupel and Simpfendorfer (2005*b*) also used a time series analysis to examine aggregation patterns of monitored individuals. In this paper, temporal data were analysed via spectral analysis to identify regular periodicity in the timing of behaviours. This text also employed the use of nearest neighbour analysis, which was first used by ecologists and foresters (Clark and Evans 1954) and has been since applied to birds (Boettcher *et al*. 1994) and copepod swarms (Leising and Yen 1997).

Although publications on quantitative methods for handling acoustic monitoring data are currently limited, there are many precedents for handling this type of data in other telemetry studies, such as those on birds and mammals (e.g. Boettcher *et al*. 1994; Leising and Yen 1997). These methodological and statistical approaches can be applied directly, or after slight modification. Researchers have been (and will continue to be) required to develop customised analytical techniques to take full advantage of their data, but it is important to consider literature from outside the field of marine or aquatic science for direction in handling long-term telemetry data. Until standardised methods are established, users may struggle with data analysis and publication, but many of the problems faced in this field have already been addressed in avian and terrestrial literature. As this field advances, a set of accepted methods will arise to ensure that data are examined in a statistically rigorous fashion and new methods of data analysis will likely be developed.

## Summary

The use of acoustic monitoring systems is expanding and the utility of this technology is likely to continue to increase in the field of aquatic science as this tool is incorporated into ocean observing platforms. Understanding the applicability, benefits and limitations of this technology is becoming increasingly important as more research groups choose to use this technology. In this text, we outlined some of the common issues in using independent, submerged receivers to aid new and current users in their research. Continued and expanded use of this technology will reveal solutions to some of the current difficulties as well as outline further drawbacks. Advanced use of the technology will require advanced data analysis techniques that will have to be designed to suit the technology and the study questions. Acoustic monitoring has evolved into a powerful research tool and has the potential to provide insights into aquatic ecology not previously possible.

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