Estimating detection probabilities for linear acoustic monitoring arrays

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Estimating Detection Probabilities for Linear Acoustic Monitoring Arrays

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Abstract.—Acoustic monitoring is a widely used low-cost technique for studying the movements of aquatic animals. One common deployment configuration is a linear array of receivers such that passage of a tagged animal across a line of receivers is detected. The typical goal is to estimate the fraction of a population that moves across the line. Receivers in an array can have nonoverlapping or overlapping detection probability envelopes. It has been assumed in the case of nonoverlapping arrays that the detection rate of tagged animals is proportional to the coverage of the line. Unfortunately, the estimation process is not as simple as previously believed. In fact the probability of detection is more Gaussian-shaped rather than uniform with distance from the receiver, and varies over time due to biotic and abiotic noise. Wind-generated noise in particular can have a major influence on the performance of receivers. Range testing, while important, will not solve the problem. In fact, the temporal complexity of this variable detection probability envelope renders a statistical solution improbable. Simulation modeling provides a potential alternative for estimating detection probability for nonoverlapping arrays, however, for most situations, the best solution is to design an overlapping array, with the detection range estimated for the worst environmental conditions.

Introduction

The study of animal movements in marine environments remains a core focus for marine scientists. For example, movement information is used in fisheries stock assessments to set stock boundaries (e.g., Hampton and Gunn 1998), and a recent need is in the design and location of fisheries management zones (Hobday and Hartmann 2006; Pecl et al. 2006) and marine protected areas (Louzao et al. 2006). For many species traditional mark–recapture studies have been used to obtain this information, but this approach is limited by the scale and the need for recapture of tagged animals. The real-time monitoring of animals in the ocean has been undertaken by a variety of labor intensive methods, including active acoustic tracking. An additional constraint in active tracking is that a few animals are only tracked for short periods of time immediately after tagging when behavior may

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also be modified (e.g., Gunn et al. 1999; Lutcavage et al. 2000; Davis and Stanley 2002), or there is discontinuity in tracking of species with more site fidelity.

One option for increasing the efficiency of acoustic telemetry is the use of passive acoustic receivers to detect tagged study animals. Relatively low-cost acoustic listening receivers are being used widely throughout the world (for review see Heupel et al. 2006). Animals tagged with acoustic tags emitting an acoustic pulse are detected when they pass close to these receivers, i.e. within the detection range. The technology is robust and simple, and is one of a suite of new tools being used for a number of new ocean monitoring studies (OTN, www.oceantrackingnetwork.org; CoML-POST www.coml.org/descrip/post, Welch et al. 2003; IMOS-AATAMS-Australia; http://www.imos.org.au/facilities/tagging-monitoring.html). Some of the study goals, as with other historical studies, are to discover the migration routes taken by the tagged animals, estimate the fraction of animals surviving, and determine site fidelity.

When receivers are arranged in groups or arrays, two patterns are common; clusters and lines (for review, see Domeier 2005; Heupel et al. 2006). A recent survey involving 20 large projects with a total of over 1300 receivers deployed showed an even split between these two patterns (Heupel et al. 2005). Lines of receivers are usually employed in migration studies, where the goal is to estimate the fraction of tagged animals that cross a line of receivers (e.g., Comeau et al. 2002; Stark et al. 2005, Pecl et al. 2006). A common configuration is a cross-shelf array (e.g., Welch et al. 2003; Hobday 2003). These linear configurations have been variously described as lines, gates, or curtains (Heupel et al. 2006). The arrangement of the receivers can be such that detection ranges are overlapping (receivers closely spaced), or nonoverlapping (receivers widely spaced).

In this paper, we discuss the issues associated with the technology incorporated in the VR1, VR2, VR2W, VR3 and VR4 family of receivers manufactured by Vemco/Amirix (www.vemco.com)—henceforth referred to simply as the receiver—but the findings can also be extended to other types of receivers such as the Vemco VR100 and products from suppliers such as Sonotronics (www.sonotronics.com) and Lotek (www.lotek.com). Most receivers detect a train of coded pulses which encode in the time intervals between pulses an 8, 12, or 16 bit ID Code (or 8 bits of sensor data plus an 8 bit ID code). If all the pings in a coded sequence are not received correctly, the tag will not be registered at the receiver. When receivers are recovered, the set of tag detections (tag ID, data from any sensors on the tags, date and time) can be downloaded, and the results used to address the study question.

In this paper, detection probability for a particular distance is the proportion of coded pulse trains that arrive at the acoustic receiver from that distance that are correctly decoded. This can only be correctly measured from data collected in detection range tests conducted under the full range of anticipated conditions. Our overall goal is to provide guidance to users designing arrays and/or attempting to interpret data from arrays by:

1. Demonstrating the underlying factors which lead to variations in a receivers' detection probability envelope size and shape (geometry) and how these will vary depending on environmental (usually weather) conditions. This is supported by the results from extensive field tests.

2. Illustrating the biases and errors that can be introduced in estimates of total number of fish passing a receiver or line of receivers based on actual number of detections by a nonoverlapping array.

3. Providing guidance on situations where these biases can be kept to a manageable level.

4. Providing guidance on the factors determining the detection performance of an array (both overlapping and non overlapping designs).

Estimating Animal Movements— Uniform versus Gaussian Detection Probability

The proportion of animals crossing a line of receivers may be simply reported as the number detected divided by the number of animals tagged, however, this assumes that all animals that crossed the line were detected. If this assumption is not valid, for example because the line is not completely covered as in a nonoverlapping line of acoustic receivers, or if the interval between pulses is too long given the swimming speed of the tagged animal (Welch et al. 2003), then the true number of animals crossing will be underestimated (Hobday et al. 2009). Thus, one can consider correcting the number of animals detected for the proportion of the line in which detections were actually possible.

For example Comeau et al. (2002) estimated Atlantic cod *Gadus morhua* crossing rates based on a uniform model of detection probability (Figure 1a). For that study, detection probability (RE) (different from our definition of detection probability) was calculated as:

$$RE_1 = \frac{\sum_1^N \frac{2D_r}{M_r}}{N} \quad (1)$$

where N is the number of receivers, D_r is the average detection range, and M_r is the distance between adjacent receivers. The probability of detection inside the 'detection range' is assumed to be 100%, although corrections could be made to this formula to account for

a detection rate of less than 100% at the receiver. A conclusion based on this calculation for receivers that do not have overlapping detection ranges, would be that if RE is 0.5 and 20% of animals were detected at the line, that 40% of animals must have crossed the line. That is, the total percentage of the study population that crossed the line (T%) is

$$T_\% = \frac{D_\%}{RE} \quad (2)$$

where D% is the percent of tagged animals detected at the line, and RE is the receiver efficiency as defined in equation (1).

The above method assumes that the detection range is constant, and animals are only detected at a single receiver and are moving in only one direction with distance from the receiver uniformly distributed. Any deviation from these assumptions biases the estimate. In most cases, large biases will also be introduced by the fact that, as this paper will demonstrate, the detection probability envelope differs greatly from the uniform rectangular shape (Figure 1). The decline in detection probability at longer ranges is caused by diminished receiver range during periods when acoustic conditions are less than ideal, most commonly due to environmental noise. We will refer to this type of nonuniform detection probability envelope as Gaussian as it can be approximated with a Gaussian distribution (see below).

Influences on Detection Range and Probability

The maximum distance at which a receiver can detect signals is influenced significantly by environmental noise conditions (authors' personal observations). A longer discussion of the environmental factors influencing detection range is provided in Heupel et al. (2006); here we focus on the factors with temporal variation that influence esti-
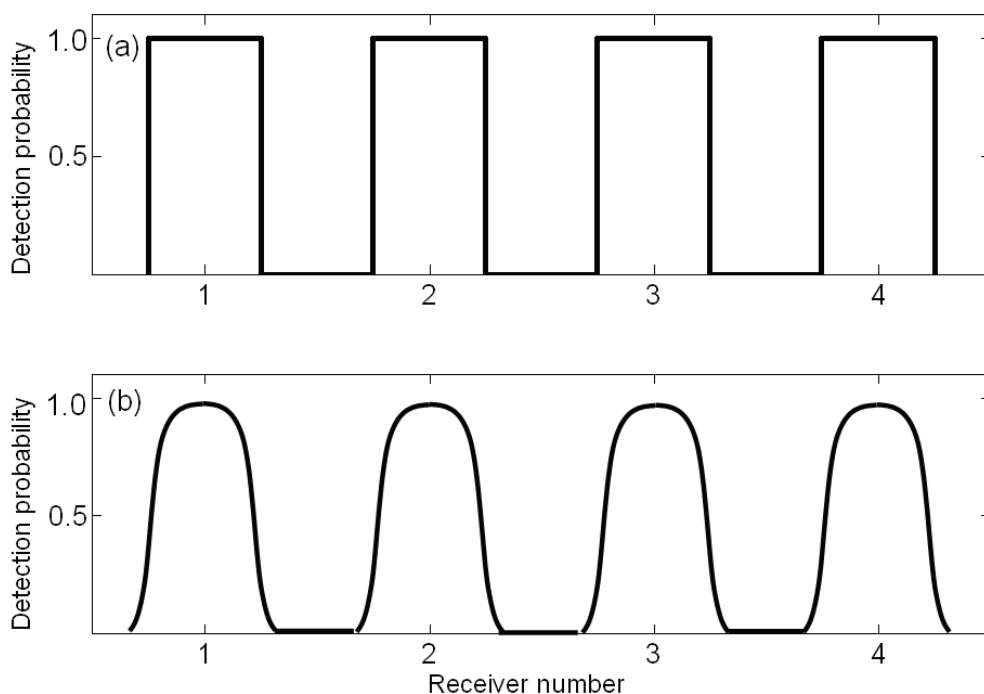
FIGURE 1. Schematic illustration of two detection probability models as a function of distance from four receiver locations. **A.** Uniform detection probability envelope. **B.** Gaussian-shaped detection probability envelope.

mates of detection probability envelope size and shape. Most attention is given to abiotic variables, which are more commonly the limiting factor for signal detection, although biological or manmade sources can be significant in some locations.

Biotic factors that lead to variation in the detection range, defined as the maximum detection distance, and detection probability (detection at any distance), over time include biological growth and biological noise. Biological growth can occur on the receivers and may lead to a gradual long-term decline in detection range (Heupel et al. 2008). Deep placement (>25 m) or regular cleaning/replacement of receivers minimizes this impact (authors' personal observations; Heupel et al. 2008). A daily cycle (short-term) in detection range can also occur due to nocturnal cycles in biological noise generated by

fishes (Families Batrachoididae, Gadididae, Holocentridae, Sciaenidae, Pomacentridae, and Gobiidae) (e.g., Fine 1997) or snapping shrimp (e.g., *Alpheus*) (Johnson et al. 1947; Knowlton and Moulton 1963).

Abiotic factors that influence detection include environmental changes such as wave action ("sea state" noise)—a major cause of variation in detection probability in open ocean arrays. Deterioration in detection range/probability also occurs with heavy rainfall, which may be the most important factor for some embayed settings (Simpfendorfer et al. 2008). The mooring design can also impact detection: detection range and probability can be impacted by noisy moorings, shadow areas due to floats or nearby structures, or daily/seasonal changes in boat traffic (Clements et al. 2005; Heupel et al. 2006; Simpfendorfer et al. 2008).

Receiver Characteristics and Shape of the Detection Probability Envelope

The VR2 detection range is approximately omni–directional. Thus, detection range for a bottom mounted receiver in water deeper than the receiver's range will form a semicircular detection probability envelope (Figure 2a), while the detection probability envelope in more typical deployments in shallower water are more constant with depth (Figures 2b and 2c). Therefore, in theory the envelope shape for a shallow deployment will be close to cylindrical in the water column, moving towards a half sphere as deployment depth increases. In practice, one is interested in the range at the same depth as the fish is swimming which, unless the receiver and the fish are at the same depth, will be less than the maximum detection range.

The maximum detection range of a receiver is strongly influenced by ambient noise, the most common influence being weather-related. We have thus restricted our analysis to this example, however, the analysis is no different if other noise sources are significant. Wind-generated noise leads to a decrease in maximum detection range (Figure 3) (Wenz 1962; Urick 1983). Wind data can be combined with the detection pattern of the receiver to determine the size and shape of the detection probability envelope. Because detection range varies with noise levels (e.g., Figure 3) receiver detection range is not constant, but will increase or decrease in all directions according to local conditions at the time. Therefore, in a long term test, varying acoustic conditions will cause detection rates to decline as distance increases and as the percentage of time that acoustic conditions are suitable for detection decreases. A number of other users have also noted this behavior in their field studies (personal communication to authors; Simpfendorfer et al. 2008), and their observations in part motivated this paper.

When designing an array, observations of a decrease in detection probability need to be interpreted with care. In particular, long-term testing showing a detection probability of X percent at a particular range does not mean that X percent of the transmissions from a particular tagged fish passing will be detected. Rather, it means that virtually all transmissions from a fish will be detected for X percent of the time that fish is within that range; and conversely, few or no detections at $100 - X\%$ of times. As a consequence, at distances for which the long term detection probability is below 100%, the probability of a particular fish being detected by that receiver is unknown. This imposes the requirement that the detection envelopes of adjacent receivers need to overlap significantly to ensure detection of passing fish. The issue of the amount of overlap required will be addressed in a later section. The actual shape of the detection probability envelope depends on how wind (or other environmental factor) varies throughout the test. For example, wind speed
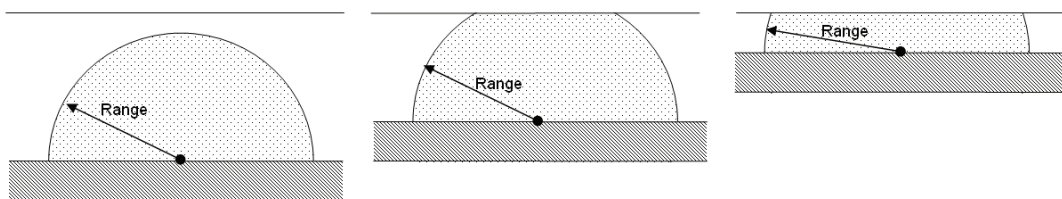
FIGURE 2. Detection range for a bottom-mounted receiver. A. Depth greater than detection range. B. Moderate depth. C. Shallow depth.
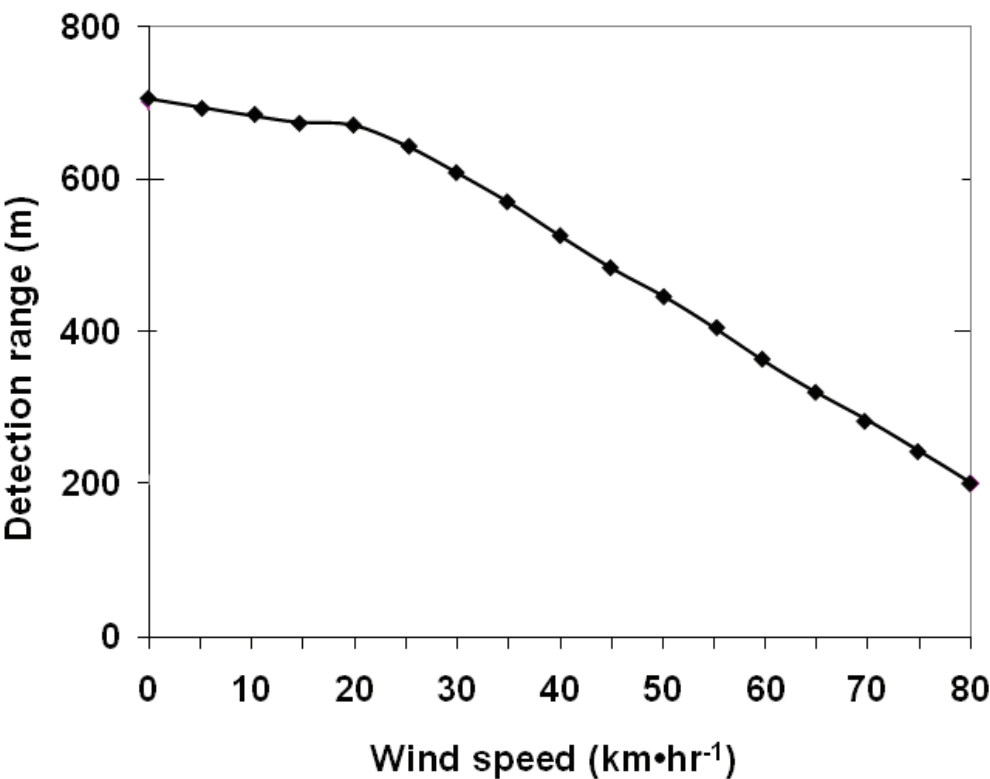
Figure 3. Theoretical VR2 detection range as a function of wind speed in normal ocean conditions (Transmitter Power: 153 dB re 1 uPa @ 1 m). Results are calculated by bringing together noise level for a particular wind speed from Wenz curves (Wenz 1962) and the signal level at various ranges from the sonar equation (Urick 1983). An online calculator (www.vemco.com) can be used to develop similar detection range relationships for other transmitter powers and receivers.

distributions can often be approximated by a Gaussian distribution, as used in this paper.

Detection Tests to Determine Detection Range

Clearly, knowledge of the effective range of the receivers and the shape of the detection probability envelope is essential for interpreting the results from an acoustic array. Most users now recognize that detection tests can define the envelope shape and range, however, detection tests results are only applicable to the whole experiment if the conditions for the test either match those encountered in the experiment or if allowance is made for differ-

ences in environmental conditions compared to when detection tests were performed. In stable and known ocean conditions (i.e., deep water), one can estimate performance reasonably well based on the manufacturer's receiver and tag specifications by bringing together noise level for a particular wind speed from Wenz curves (Wenz 1962) and the signal level at various ranges from the sonar equation (Urick 1983) so that and detailed range testing may be unnecessary (Pincock 2009). However, if conditions are suspected to be variable or unknown, especially in shallow, estuarine, or obstruction-rich waters, the number of factors that can influence range and their variability from one location to another dictate that in situ range testing be done.

The most rigorous—but unfortunately the most time consuming—procedure involves installing a receiver in an actual anticipated or representative deployment situation, placing a tag a fixed distance away, and determining from the receiver log the percent of transmissions that were detected (Heupel et al. 2006). These controlled detection tests would be repeated for a number of ranges with sufficient time at each range for all representative conditions to be encountered—this may require many days at each location to experience the full range of conditions (e.g., consider infrequent winter storms or seasonal tidal signals). If this procedure is considered to be too time consuming or unrealistic, a variety of other methods can be used to determine range, and the method depends on the isolation of the study area (the number of times the array can be visited to conduct experiments); further discussion is provided in Heupel et al. (2006).

1. Towed tag(s). Tags can be deployed behind a vessel and towed/drifted past the receiver. If the positions of the receiver and the vessel-tag are known, usually via GPS, then linking the timestamp of the detection at the receiver with the vessel location at the time of signal transmission can be used to determine the distance between the two objects, and hence the detection range. Issues with this approach include vessel noise interfering with the test—this should be ruled out in advance with testing designed for this purpose if the vessel is available—and variable depth of the towed tag. Using a depth tag for this test ensures that one knows the depth of the detected tag. The time interval between tag acoustic pulses must also be short to allow sufficient detections, particularly when vessel speed is relatively fast. This towing method is usually employed in remote locations, where the array is only visited a few times. Tests should be carried out in a range of environmental conditions; however, this is rarely possible, particularly for the worst conditions. Repeated experiments over a number of years may increase the sample size of detection tests in a range of conditions. An example of comprehensive testing of this type is presented in the next section.

2. Sentinel tag(s). This involves simply mooring one or more low repetition rate (e.g., 1 transmission per hour) tags at known distances from the receiver throughout the study time period and analyzing the detection rate of these tags over time. For example, if one places three sentinel tags at varying distances from the receiver (such that one tag is within a range at which 100% detection is anticipated, with the other two further out) examination of the receiver log will show the times when reception at the longer ranges is good and when it is not. It is possible that fouling on the sentinel tag(s) without change in the abiotic environment may also decrease the detection range over time, but this is also an issue for the receiver (Heupel et al. 2008). Ideally, receivers and sentinel tags would be raised and cleaned before this becomes a significant issue. Using sufficient tags to describe the envelope may also be prohibitive.

3. Direct noise and sound propagation measurements. The general approach involves collection of ambient noise data with subsequent off-line analysis, which takes into account the observed attenuation of the signals, noise levels present and the detection threshold and bandwidth of the receiver. This approach has the potential to provide direct insight into issues surrounding expected

[maximum] detection range as well as factors limiting it and may even point the way to improving the situation. However, the equipment and analysis tools required are not available to most users. Attempting this approach for all receivers in a large array in a remote location would be a challenging under taking and likely impractical.

Environmental Influences in a Controlled Detection Range Test

Results from comprehensive detection tests at a depth of 20 m in Shad Bay, Nova Scotia (a sheltered bay) illustrate receiver performance in variable conditions. Tests were conducted by mooring tags for one week at set distances on the same horizontal plane as the receiver. The detection characteristics observed (Figure 4a) are similar to those illustrated in Figure 1b (with the exception that no data were collected at longer ranges where the detection rate would have been less than 50%). The increase in performance at 550 m illustrates one of our concerns with variable weather: ocean conditions were calmer during the time the transmitter was at this distance, and so range was greater than at 475 m. Results from a distance of 275 m illustrate the influence of environmental variation (Figure 4b). Detection probability was commonly over 95%, but there were periods when performance was poorer. While in situ weather observations were not made, examination of regional online weather data showed that the two points of greatly diminished performance occurred during the two most extreme wind/rain conditions in the area during this test.

Data for this receiver at all distances over the two month test period showed that, with the exception of the results at 550 m discussed above, the general trend as distance increased was a decrease in the percentage of time in which detection probability was high (Table 1).

Environmental Influences in Experimental Array Detection Tests

Cross-shelf arrays have been deployed by the first author since 2002 in southern Western Australia to determine the migration speed and cross-shelf position of juvenile southern bluefin tuna *Thunnus maccoyii* (Figure 5) (Hobday 2003; Hobday et al. 2009). The study area is located where a fishery-independent survey for juvenile tuna is carried out, and estimates of migration speed and timing and time spent inside the survey area are required to correct the observed biomass levels.

Detection tests using towed tags have been undertaken for these cross-shelf arrays over a number of years in a range of sea states [Beaufort 0–7, 0–35 knots]. Receivers are typically moored at a depth of 25 m below the sea surface at a depth of 40 m (coast) to 140 m (shelf break). When receivers are recovered, the time of detection is matched with the position of the vessel to determine the maximum detection distance (Figure 6).
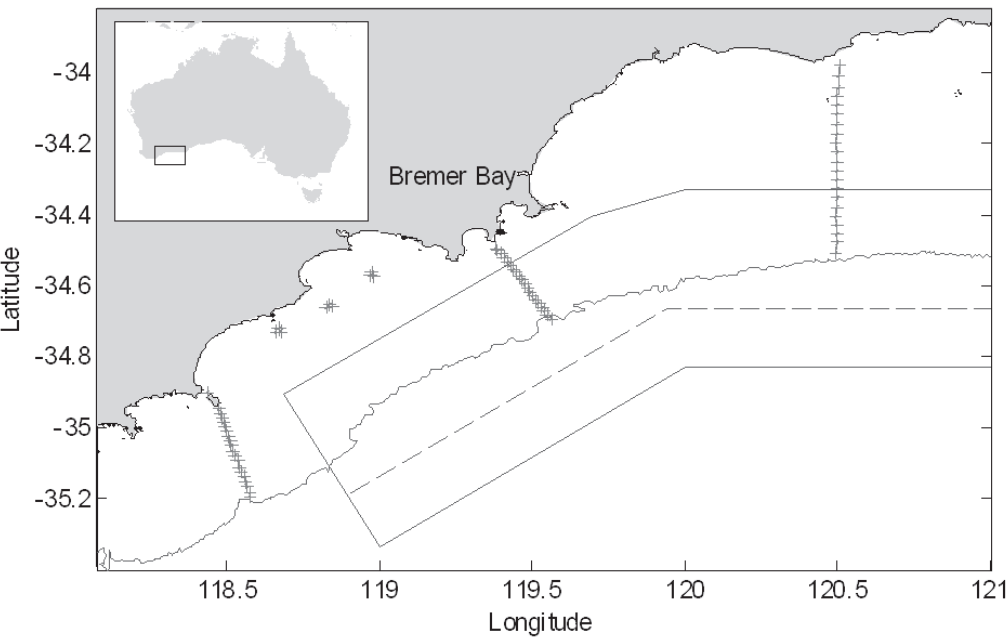
Data from these detection tests shows a decline in detection frequency with distance (e.g., Heupel et al. 2006, Figure 7) that is consistent with a Gaussian-shaped, rather than uniform detection probability envelope. The decline in frequency very close to the receiver is due to limited detection tests where the vessel drifted within 50 m of the receiver. Thus, for the conditions under which these tests were conducted, the equation provided by Comeau et al. (2002) would underestimate the proportion of detected animals, as coverage is in fact less than assumed using a uniform detection probability envelope. The observed detection probability envelope shape (Figure 7) is consistent with both the theoretical shape (Figure 1b) and the results from controlled field measurements (Figure 4 and Table 1).

(a)

(b)
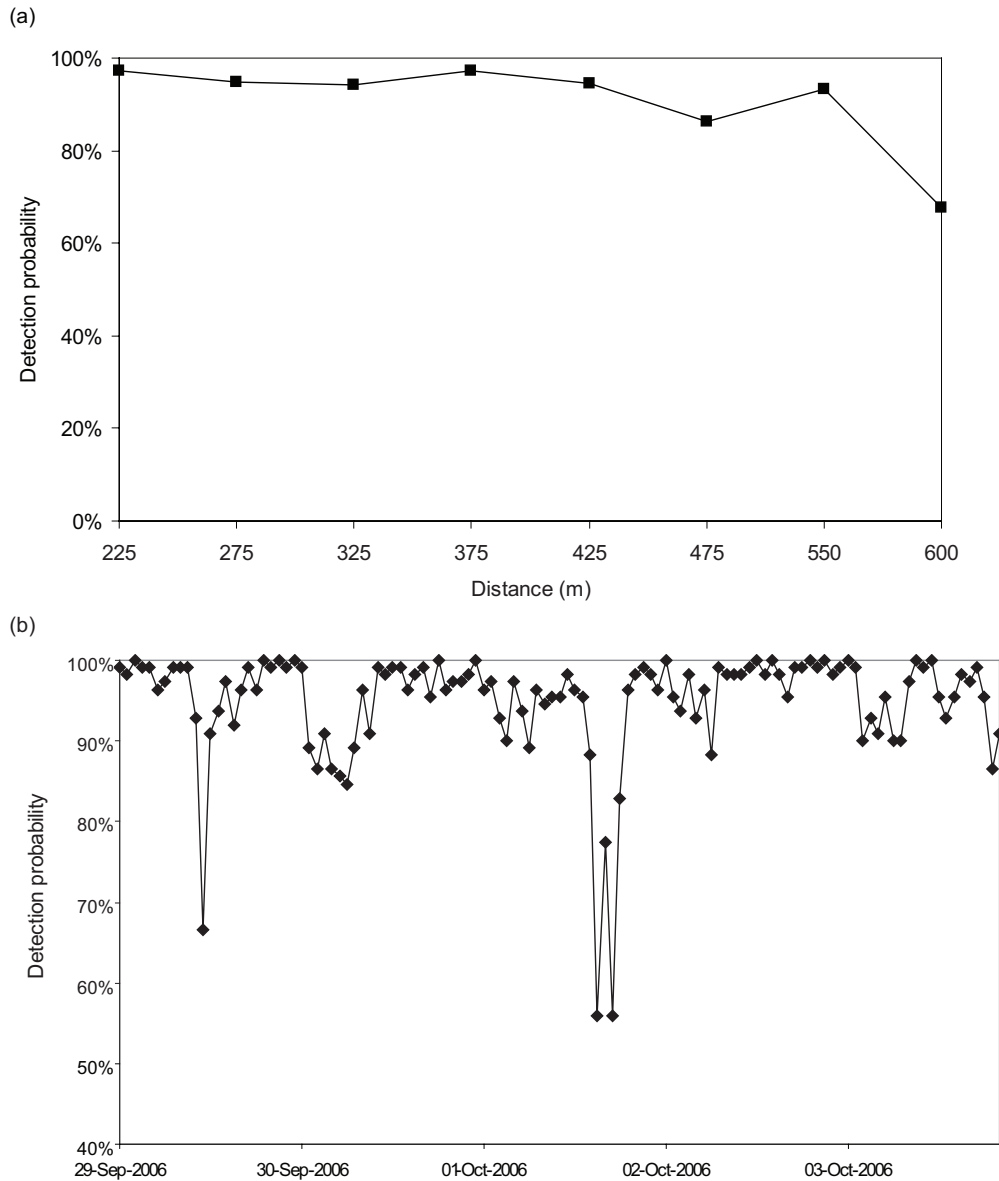
FIGURE 4. A. Controlled detection test results from Shad Bay, Nova Scotia, September–November 2006. Test tags were moored at increasing distances from the receiver for 1 week at each distance. B. Detection probabilities at a distance of 275 m from the receiver with each data point representing one hour during which 110 tag transmissions took place.

TABLE 1. Detection probability summary for a range of distances in the Shad Bay detection test (25 September to 25 November, 2006).

Range (meters)	Percent of test period with detection probability > 0.95	Minimum detection probability observed in a one hour segment
225	84%	0.85
275	71%	0.65
325	67%	0.5
375	88%	0.85
425	62%	0.65
475	59%	0.1
550	70%	0.3
600	16%	0.05

FIGURE 5. Acoustic monitoring study area in southern Western Australia. Three lines of receivers run from the coast (depth ~40 m) to the 200 m contour, a distance of 30 km (middle line) to 50 km (eastern line). The box centered on the 200 m contour is the fishery-independent survey region; the dashed line divides a subsection of the survey region.
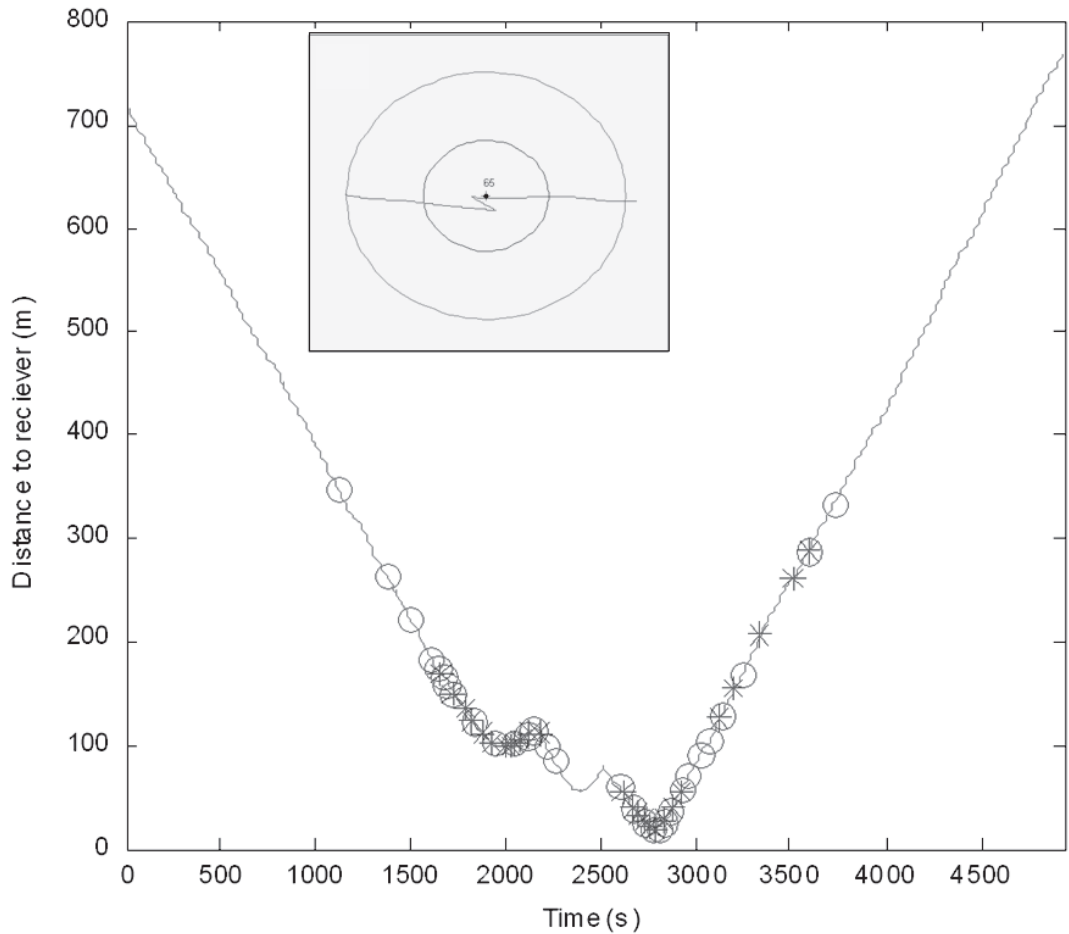
FIGURE 6. Detection range test example (southern Western Australia 2006–07). **Inset.** Drift track of two towed tags (V16, Output Level 153dB re 1 uPa @ 1 m) past one receiver in a linear array. The inner circle around the receiver represents the maximum observed detection distance in the test (360 m) and the outer circle is a radius of 800 m. **Main figure:** Pulse time (circles and stars) for each tag as a function of tag distance from the receiver. Initially vessel and tags drift toward the receiver and distance decreases, then distance increases again as the tags drift away. The discontinuity close to the receiver was when the engines were started to reposition the vessel.

(a)

(b)

(c)
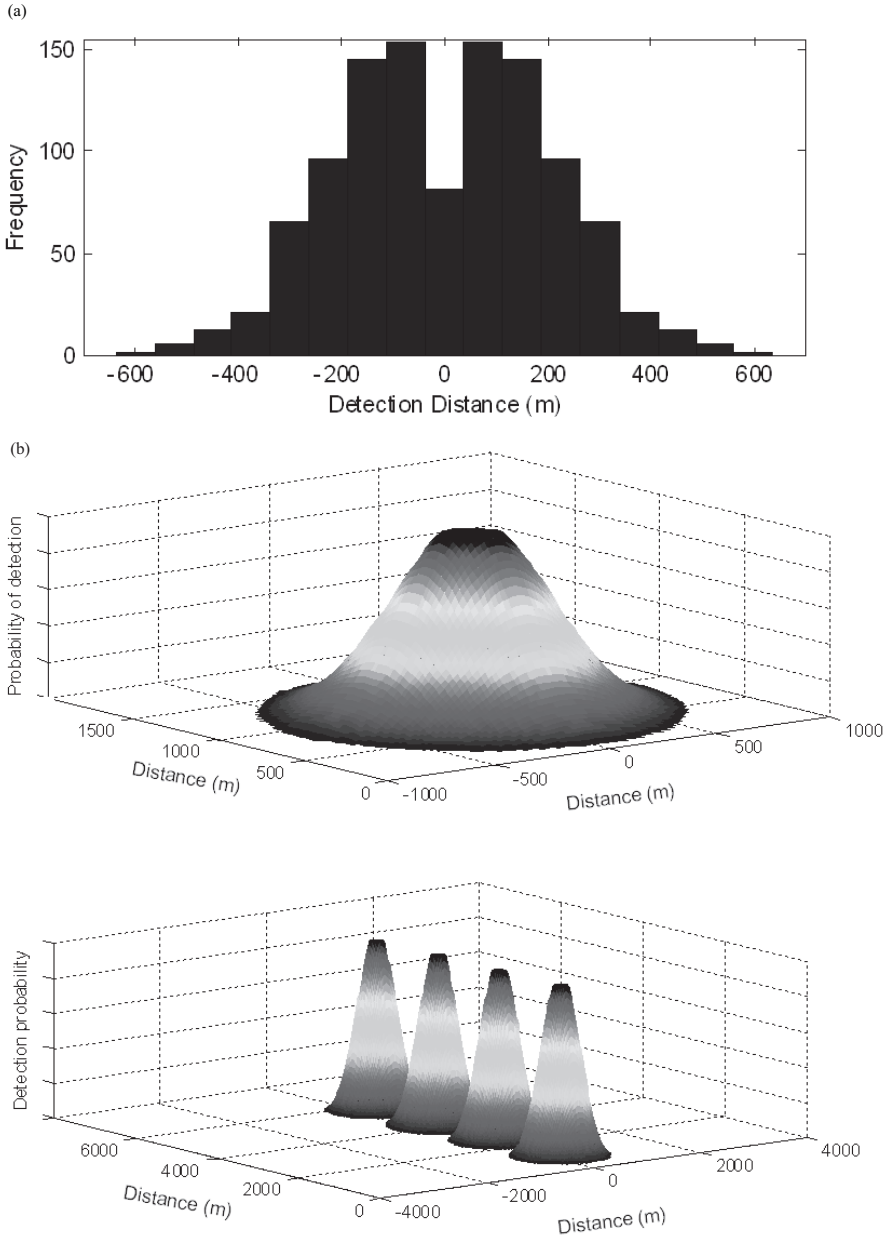
FIGURE 7. (a). Number of times that a towed acoustic tag was detected as a function of distance from the acoustic receiver combined from a large set of range test experiments in southern West Australia. The tag was towed at the same depth as the receiver (25 m). The histogram data are mirrored around the zero-distance point to form a detection probability envelope. The decrease in detection frequency close to the receiver is due to the difficulty of judging the drift of the vessel during the detection test from 600 m away, thus it does not drift the tag right over the receiver, and so the count of detections very close to the receiver is somewhat lower. **(b).** The detection probability envelope in two dimensions approximates a cone, with the maximum probability at the center and then decreasing in all directions from the receiver. **(c).** When arranged in lines, the cones form a leaky curtain, which will detect only a portion of the passing tagged animals. The top of the cones may be "flattened" in good conditions, indicating near-uniform detection to some range before a decline occurs.

# Detection Probability Estimation Using a Simulation Model

In order to illustrate the difference in detection probability that can result from assumptions about the shape of the detection probability envelope we developed an individual based model (IBM). The IBM simulates tagged individuals migrating under a range of specified conditions (swimming speed, pulse rate, number of other transmitters present and weather related noise conditions) past a linear acoustic array. In the discussion below, we will focus on wind as being the dominant factor determining the noise at the receiver and hence the dominant influence on detection range at any given time. The approach is exactly the same if another noise source is significant.

The first step for the model is forming the detection probability envelope. This can be determined for particular wind statistics (mean wind speed and standard deviation) by first determining the relationship between range and wind speed for the transmitter being used (see Figure 3). Then, using the assumed wind statistics, one can determine detection range for different wind speeds, and hence plot the detection probability at different distances (Figure 8). The greater the wind variability, the more the envelope deviates from the uniform assumption (Figure 1a). The Gaussian approximation for the detection probability envelope (Figure 8) is obtained from

$$P_D(R) = 1 - \Phi(M, \sigma) \ (3)$$

where P_D is the detection probability and $\Phi(M, \sigma)$ the cumulative Gaussian probability density function with mean, M, and standard deviation, σ. M and σ are chosen to fit the calculated envelope with M moving towards the maximum detection range and
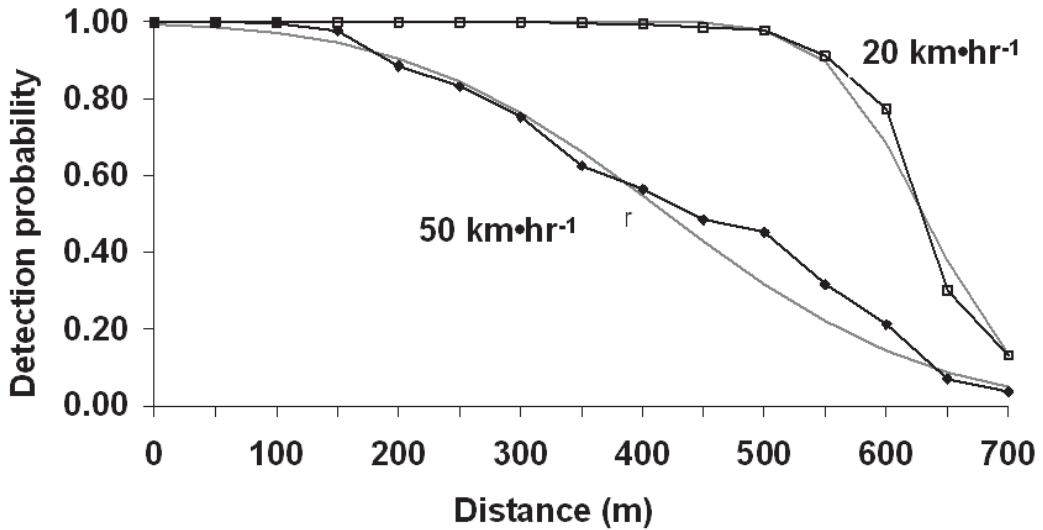
FIGURE 8. Calculated detection probability envelopes for two different mean wind speeds (standard deviation = 0.5 × mean wind speed). Black lines are the calculated results obtained using the on-line range calculator at www.vemco.com and are for a transmit level of 153 db re 1 μPa @ 1 m (the same as used for the tests in south-western Australia as in Figure 3). Gray continuous lines are Gaussian approximations of the type used in the model. The values of mean detection range (M) and SD to fit the data for (i) 20 km × hr^{-1} were M = 630 m and SD = 10% of M and (ii) 50 km × hr^{-1} were M = 420 m and SD = 40% of M.
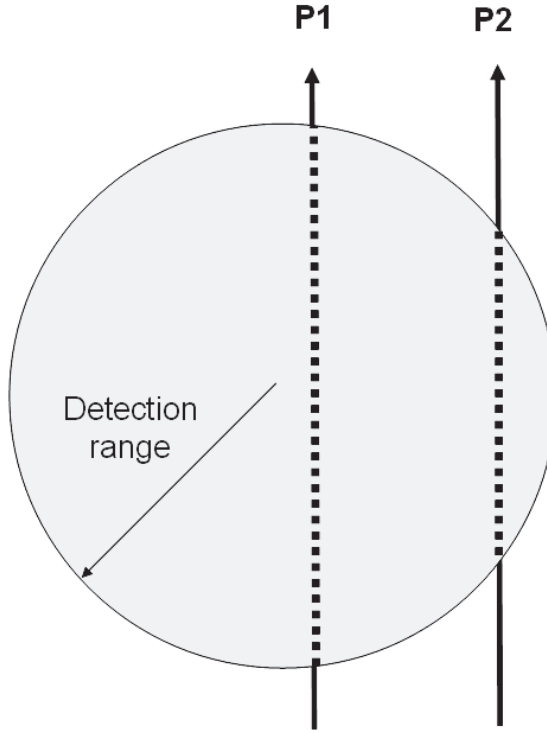
FIGURE 9. Two tagged fish passages (P1 and P2) perpendicular to an array. Path length (dashed line segment) for a particular fish passage increases as distance from receiver decreases and as detection range increases.

σ decreasing for less severe conditions (Figure 8). P_D is also a function of the difference in depth between the fish and receiver but, in the following, we assume that receiver and fish are at the same depth to simplify the discussion.

The second step is to determine the probability of detection of each tagged fish coming within range of a receiver. The model assumes that fish swim perpendicular to the array (Figure 9). More meandering paths would lead to a longer time within the detection probability envelope and to periods where the fish is closer to a receiver and hence more likely to be detected. The probability of a fish being detected crossing the line was the probability of at least one of n tag transmissions being detected, which is

$$P(D_{1 \text{ or more pulses}}) = 1 - P(U_{all}), \text{ where } P(U_{all}) = P(U_1) \times P(U_2) \times \dots P(U_n) \text{ (4)}$$

where $P(U_i)$ is the probability of transmission i being undetected. This depends on the distance of the fish from the receiver, the probability of detection at that range as determined by the detection envelope and the number of transmissions potentially detectable by the receiver. The number of possible transmissions (n) is determined by the path length (Figure 9), fish swimming speed and tag transmission rate.

When the probability of more than one transmitter being within range of the receiver becomes significant, determination of $P(U_i)$ needs to take "collisions" into account—a collision being the occurrence of transmissions from different transmitters overlapping

in time which leads to failure to detect one or both tags (Pincock 2009).

This model was first parameterized to reflect the tuna migration study in southern Western Australia which used tags transmitting at random intervals between 20 and 69 s at an output level of 153 dB re 1 μPa @ 1 m, giving a range in calm ocean conditions of from 700 m to just over 200 m in very severe conditions (Figure 3). Wind speed for this study can be reasonably approximated as Gaussian with a mean of 20 km·hr^{-1} and standard deviation of 10 km·hr^{-1} (Figure 10).

Applying the model to some representative scenarios (for wind conditions similar to those of the study area as well as more severe conditions) for situations in which there are no collisions (i.e., no more than one transmitter is within the detection range of the receiver at any time) shows that detection decreases with swimming speed and increased time between tag transmissions (Table 2). As these results summarize detection performance for tags that come within the maximum detection range of a single receiver, it is no surprise that there is never a situation in which 100% of transmitters are detected. For this model, this would only occur if the wind were constant and known for the entire period. The significant fall off in detection probability for stronger wind conditions (50 km·hr^{-1}) is due to the fact that many of the fish swimming within the maximum range of the receiver are out of the effective detection range in these conditions (Table 2).

These results also illustrate the biases that will be introduced if one attempts to estimate the total number of fish passing a receiver based on a uniform detection probability envelope assumption (equation (1) and (2) using a range determined under a fixed set of conditions (Table 2). The exact value of these errors depends on the wind statistics, which will likely differ from the Gaussian assumption, but the trend is clear. Depending on conditions, predictions can range from serious over-estimation to serious under-estimation.

Results for two different uniform envelopes (Table 2) demonstrate that, while in certain situations, it might be feasible to choose the right distance, great care is required. This is discussed further in the next section.

When multiple transmitters are present, a number of each tag's transmissions will not be detected and this detection probability decreases as the tag density (number of tags present within the receiver detection range) increases. This effect is the same as increasing the mean time between transmissions (Table 2). For example, the decline in detection probability for fish swimming at 4 m·s^{-1} with an average tag transmission interval of 120 s at a wind speed of 20 km·hr^{-1} when tag density increases to 3 tags, is from 84% to 67%. Note that it is not realistic to predict detection rates over a study period since this would require a meaningful estimate of the statistics of tag density and its correlation with detection range – an unlikely possibility. These calculations simply illustrate how performance degrades with tag density (Table 2). Since collisions are random, the resulting detection rates for a single trial are also variable and, therefore, the detection rates shown for a tag density of 3 tags are the minimum that will be observed 95 times out of 100. Average detection rates would be higher than these minimums, but design to achieve a minimum detection rate is recommended. While the preceding analysis concentrates on a single receiver, the biases will be the same for a nonoverlapping array if one tries to make a determination of the total number of tagged animals crossing the whole array.

Discussion—Implications for Detection Probability

Given the results and various confounding variables, is there a solution for estimating detection probability, and thus the number of animals that actually cross a line of non-

(a)

(b)
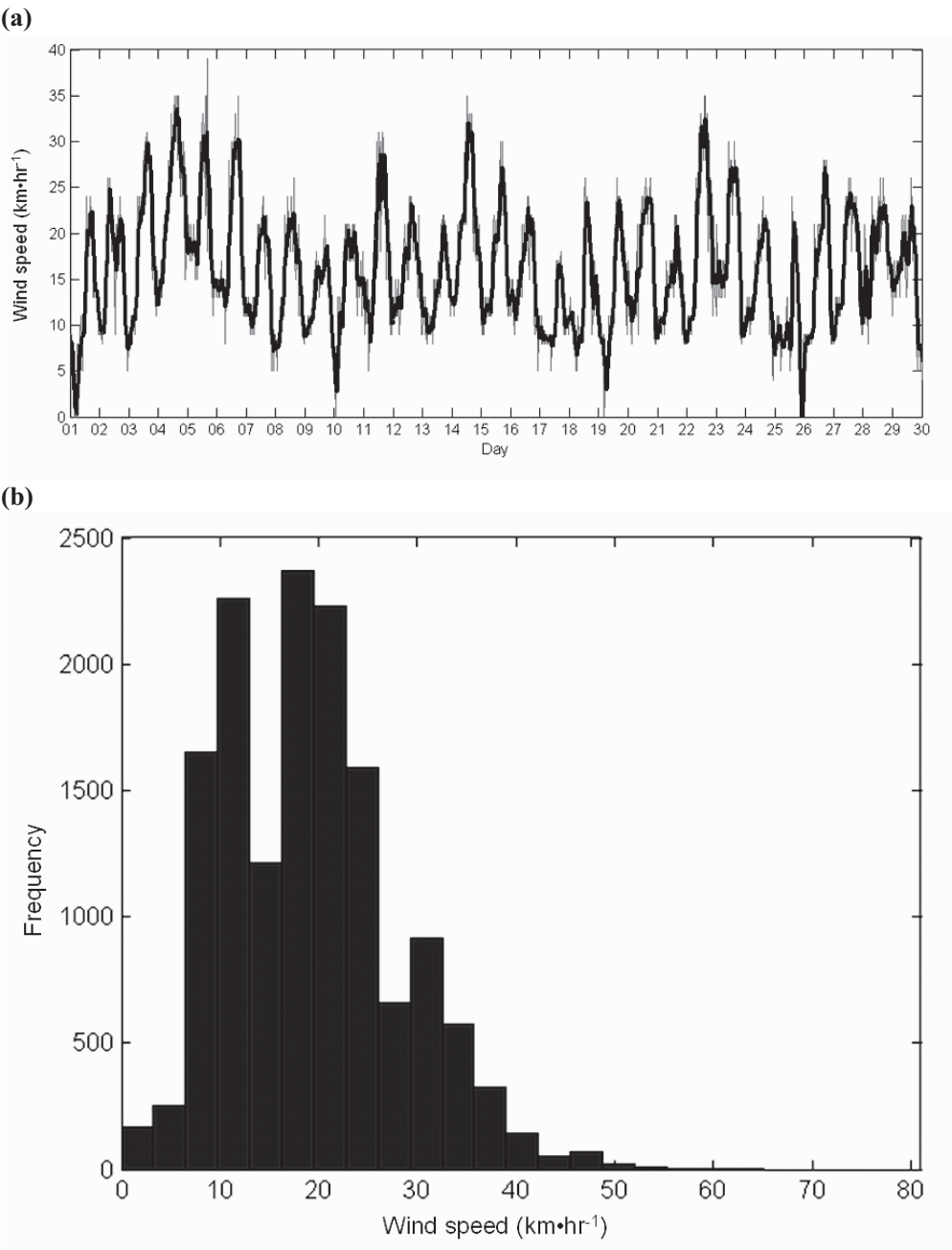
FIGURE 10. (a). Example time series of winds in January 2006 close to the array of receivers in southern Western Australia. Note the diurnal signal, as well as lower frequency cycles. The 30 min record has been smoothed with a 5-point centered running mean. **(b).** Frequency distribution of wind speed at Hopetown, Western Australia (close to the acoustic array) measured every 20 min for the months January to May for the years 2003 to 2006.

Table 2. Summary of results from analysis of model simulation using acoustic transmitters with output 153 dB re 1 μPa @ 1 m for two wind conditions (20 km·hr⁻¹ and 50 km·hr⁻¹), a range of swimming speeds and mean transmission times. The percent of tags detected when 1 or 3 acoustic tags are present are shown. The predicted percent of tags detected is based on a tag density of 1 using an assumption of a uniform envelope of 500 m and 300 m.

Wind conditions mean ± SD (km·hr-1)	Swimming speed (m·s⁻¹)	Mean time between tag transmissions (s)	Percent of tags detected from simulation using Gaussian model (tag density)		Predicted percentage of fish using uniform envelope assumption (compared to number predicted from Gaussian model)	
			1 tag	3 tags	500 m envelope	300 m envelope
20 ± 10	0.5	45	90%	90%	126%	210%
	4.0	45	89%	88%	125%	208%
	0.5	120	90%	90%	126%	210%
	4.0	120	84%	67%	118%	196%
	0.5	240	90%	89%	126%	210%
	2.0	240	84%	77%	118%	196%
	4.0	240	59%	11%	83%	138%
50 ± 25	0.5	45	58%	59%	81%	135%
	4.0	45	57%	42%	80%	133%
	0.5	120	57%	59%	80%	133%
	4.0	120	47%	25%	66%	110%
	0.5	240	59%	57%	83%	138%
	2.0	240	47%	37%	66%	110%
	4.0	240	19%	2%	27%	44%

overlapping acoustic receivers? Clearly, as the results indicate, a deterministic solution as proposed for a simple uniform detection probability envelope by Comeau et al. (2002) is usually impractical given the complexities of the marine environment that impact the shape of the Gaussian envelope.

Is it possible to use a Gaussian envelope (i.e., time varying uniform envelope whose size is determined by wind or other range limiting factor) to predict fish passage? Theoretically it is possible, but this requires that the actual conditions for the study be identical to the assumed noise conditions. An example of variation in number of fish predicted when the mean wind deviates just 5 km·hr^{-1} from the assumed value illustrates the problem (Table 3). While the results might be acceptable in some cases, these are optimistic as other factors such as standard deviation of winds differing from the assumed value and deviations from standard Gaussian shape could introduce significant additional errors.

To this point, we have focused entirely on wind or other noise sources as the cause of errors in predictions of fish passing a nonoverlapping array. Large as these might be, even larger errors could arise from the fact that predictions of this type are based on an assumption that the actual passage of fish is uniformly distributed both in space and time. In summary, then, all the uncertainty of such predictions leads to the conclusion that acceptable results with regard to estimating total fish passage are usually only possible with an overlapping array, such that detection is as close as possible to 100%.

Finally, with regard to nonoverlapping arrays, and assuming that fish passage is uniform in space and time (or alternately that the statistics are known), a nonoverlapping array could still be feasible if measures are taken to determine the detection probability envelope characteristics throughout the study. Possibilities include:

1. The use of a set of "sentinel" tags at known and increasing ranges from the receiver. At any given time, the envelope applied to the detection data would be based on which of the sentinel tags were being detected. Even two or three such tags would significantly improve predictions.

2. The use of a receiver which can detect the ambient noise level and log it with detections. One can use knowledge of the noise level to obtain reasonably accurate estimates of the detection probability envelope over time. The underlying technology of the VR2 cannot support this capability but future, likely more expensive products, could.

TABLE 3. Example of errors in the predicted number of fish passing a linear array due to differences in mean wind speed from the assumed value using a Gaussian envelope. For this example swimming speed is 2 m·s^{-1} and mean time between transmissions is 60 seconds.

Mean wind speed (km·hr-1)	Percent of tags detected	Predicted number of tags per 100 passing with actual mean wind speed varying by ± 5 km·hr-1
10	93%	98 to 103
20	85%	94 to 104
30	75%	93 to 105
40	64%	92 to 108
50	53%	91 to 110

3. Artificially shortening the receiver's detection range so that there is little or no variability of detection probability envelope. Successful implementation of this approach would require a high level of confidence on the distribution of fish passage in space and time as it has the effect of ignoring many detectable transmissions.

Thus, we suggest that overlapping arrays are best for estimating total fish passage because of variation in the detection range with environmental variability, and hence the shape of the detection probability envelope over time. Criteria and formulae for the design of overlapping arrays as well as the performance as receiver separation and sample size (i.e., the number of tagged fish actually crossing the space between the receivers) are presented elsewhere (e.g., Welch et al. 2003; Pincock 2009). For example, the formulae provided by Welch et al. (2003) could be adapted for the expected minimum distance based on expected environmental conditions. In designing overlapping arrays, we provide a few overall comments.

The general objective is to place receivers so that in the entire space between them, one or both receivers have a detection probability close to 100%. For example, a separation of 1000 m (2 times reliable detection range) would be appropriate if moderate wind conditions shown will be experienced during the experiment (20 km·hr⁻¹), but less than 400 m between receivers is needed for the more severe conditions (50 km·hr⁻¹) (Figure 8). Pincock (2009) suggests the separation be twice the distance at which the receiver detection probability falls to 50% under the worst anticipated conditions and shows that few if any fish will be missed with such a strategy.

Since the amount of overlap is chosen to ensure detection in the worst conditions anticipated, many tags passing the linear array will be detected by more than one receiver.

This helps improve the quality of the data. It is tempting to shorten the time between tag transmissions so that fast-moving fish are more likely to be detected; however, the potential for collisions when multiple tags are passing complicates this potential solution. As the number of tags within the detection range increases, higher transmission rates will actually lead to a reduction in detection rate (Table 4). Therefore, if a large number of tags within the detection range are likely, the time between transmissions needs to be relatively long. Of course, there are limits to this and it may not be realistic to set parameters appropriately to deal with the simultaneous arrival of a large number of fast moving fish. Such scenarios, if anticipated, require more complex tag coding schemes, or multiple overlapping lines of receivers (e.g., Pecl et al. 2006).

In conclusion, the often observed (and theoretically predicted) trend of declining detection rate with distance is not a simple single variable issue, but rather results from a combination of receiver characteristics and the surrounding noise and propagation conditions. Users need to carefully consider whether the conditions for their receiver locations permit array design based on stable and known ocean conditions or if they need to conduct in situ testing. In most cases they will not be able to spend the time and effort to produce results comparable to the two examples described here. Therefore, it is important to take into account the extent to which environmental conditions for the study might be worse than those for the measurements and place the receivers accordingly.

A simulation and modeling approach as outlined above to estimate the detection probability can be very useful. While the analysis presented here used a combination of tools and software developed by CSIRO and Vemco, we are investigating the possibility of making an integrated capability available to other researchers. This would support vari-

TABLE 4. Example of the time taken to detect all tags present within a detection array for a range of numbers of tags present and two mean transmission intervals (30 s and 120 s).

Number of tags	Time (minutes) to detect all tags	
	30 seconds	120 seconds
2	1.1	2.5
4	2.9	4.5
6	5.5	6.5
8	9.5	8.5
10	15.7	10.7
20	151	25.5

ables such as tag characteristics, fish swimming speed, fish residency, receiver separation, (environmental) noise, and propagation conditions (either for stable and known ocean conditions or modified according to the result of site specific range or other testing).

The methods described here can be modified for most applications including acoustic receiver clusters. In the case of acoustic clusters, animal movements and habitat use may also be underestimated if the detection range/probability is subject to variation. Armed with a more realistic understanding of the behavior of these widely-used low cost receivers, the quality of information from this technology will only improve. The major programs that plan on using this technology will no doubt further improve the quantitative and statistical treatment of the data collected.

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