Note
This may vary slightly from the published version as it is taken from my final draft

Acoustic Telemetry Overview

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Introduction

Acoustic telemetry is the use of an acoustic transmitter (hereafter referred to as tag) attached to or implanted in an aquatic animal to locate and gather information about its presence, movements, and behavior in the underwater environment. Fish are the most commonly tagged animals in acoustic telemetry studies, but other aquatic animals have been studied (Sauer et al. 1997; Niezgoda et al. 2002; Cooke 2004). Early acoustic telemetry technology (Trefethen 1956) relied on relatively large tags that were only suited for use in larger fish such as adult salmon (Johnson 1960; Hallock et al.; 1970). As technology evolved, smaller tags became available (Figure 1) allowing smaller fish to be tagged (Voegeli et al. 1998; Steig 2000), often by gastric or surgical implantation (Moore et al. 1990; Adams et al. 1998). Tags and receivers evolved together to allow for greater range and reliability (Stasko and Pincock 1977; Ehrenberg and Steig 2003; Grothues 2009). Through the use of more sophisticated signal coding methods, it has become possible to simultaneously monitor much larger numbers of fish (Cole et al. 1998; Bach et al. 2003; Ransom et al. 2008; McMichael et al 2010) and to monitor the movements of fish over large geographic areas (Hubley et al. 2008; Evans 2010).

An acoustic monitoring system consists of the tags and the receivers. The fundamental components of an acoustic tag are the acoustic transducer, the battery, and the electronics, which is everything else that makes the tag function. The acoustic transducer (universally a lead zirconate titanate (PZT) cylinder as discussed in a later section) converts electrical energy to acoustic energy that in turn propagates through the water and is detected by the receiver. The electronics facilitates and controls the conversion of the electricity from the battery to acoustic energy. The end result is a tag that emits a signal consisting of short bursts of sound waves. As sound propagates relatively well in water, tags can often be detected at significant ranges (up to 1000s of m) with appropriate signal characteristics, receiver design, and environmental conditions. Receivers can be used on a mobile platform, such as a boat, to follow or track (often referred to as mobile tracking) a tagged fish or receivers can be placed at a fixed location to detect tagged fish that move near enough to the receiver to be detected (often referred to as passive tracking). Multiple receivers may be employed to cover larger areas, and/or to position tagged fish near or within the receiver array. This chapter will focus on the underlying principles, methodology, and application of acoustic telemetry.

Underwater Acoustics Basics

The Basic Signal

Because acoustic signals can be distorted as they travel through the water, acoustic telemetry systems use pulsed communication, where each tag transmission consists of a short burst of sound containing a number of pressure wave cycles (Figure 2). Depending on the application and the system design used, the transmission frequency generally falls in the range of 30 to 400kHz, and the duration of the transmission, often referred to as the pulse width or pulse length, falls in the range of less than 1 ms to 10 ms or more. The strength of the signal emitted by the tag is usually stated as a measure of acoustic pressure and is expressed in decibels (dB) with respect to 1 micro Pascal measured at a distance of 1 m from the tag (i.e., dB re 1 μPa @ 1m). In more familiar terms, 141 dB re 1 μPa @ 1m is equal to 1 milliwatt of acoustic power, 151 dB is equal to 10 milliwatts, 161 dB equals 100 milliwatts, and so on.

Frequency Considerations

In acoustic tags, the size of the tag is a function of the frequency because lower frequencies require larger diameter resonant elements (acoustic transducers) and higher frequencies require smaller resonant elements. For example, while they can to some extent be used at lower frequencies, at 30 mm diameter element is most efficient with a transmission frequency of 30 kHz and a 3 mm diameter element is most efficient at 300 kHz. Table 1 shows the diameter of a resonant element for some of the commonly used transmission frequencies. This dimension clearly places constraints on the achievable tag size at the lower frequencies. Since the frequency has a significant effect on the maximum range, the researcher must select a frequency that is suitable for the size of the species but will also yield the desired detection range. In other words, the frequency used for a study is influenced by the size of the tag that can be carried by the study animal without significantly affecting the health and behavior of the animal and the reception range requirements. For this reason, tags for smaller fish are usually restricted to higher frequencies with correspondingly shorter maximum ranges.

Detection Range under Ideal Conditions

Detection range is of primary interest in most acoustic telemetry studies, and range, for a given signal strength is dependent on three major factors, namely spreading loss as distance between transmitter and receiver increases, distortion suffered by the signal as it travels through the water and noise levels at the receiver. To understand how signal distortion effects and noise sources can impact detection range, it is first useful to have some knowledge of the predicted range under ideal conditions. This can be calculated using the Passive Sonar Equation (Urick 1983):

$$SNR = SL - 20\log(R) - \alpha R - NL \qquad (1)$$

SNR = Signal to Noise Ratio (dB) at Range R
SL = TagTag Signal Level (dB re 1 μPa @ 1m),
R = Range (m)
α = Absorption (dB/m)
NL = Noise Level (dB re 1 μPa).

In the equation, absorption (α) depends on water properties such as temperature, salinity, or conductivity as well as the frequency of the transmission (Tucker and Gazey 1966) and this is the factor that creates range variations with frequency and between salt and fresh water.

Note that, due to the form of the equation, one cannot calculate detection range directly; rather, one iterates values of R until the point is reached that the right hand side of equation (1) is equal to the minimum SNR at which the receiver will detect a signal (a specification the manufacturer should provide). Table 1 shows the results of typical maximum range calculations made this way (See Table caption for assumptions.). From this, one can see that, in general, range is greater in fresh water than salt water at any given frequency, and range is greater at lower frequencies and then decreases as the frequency increases. These results also assume that the propagation of the signal occurs in a normal spherical pattern.

Factors Causing Reduction in Detection Range from Ideal

Conditions in practice, however, are seldom ideal and, hence, the theoretical maximum range calculations shown in Table 1 are seldom observed. In particular, conditions in both fresh and salt water environments can degrade the signal to the point that detection range is so poor that acoustic telemetry is not feasible. Because environmental conditions vary greatly within and between study sites, the most reliable way to estimate the detection range of a particular system in a given environment is through *in situ* range testing. Additional information on conducting range tests can be found in Chapter 7.2 and in the section “Study and Application Considerations" below.

Fresh water is not pure, and among other chemical properties, includes some level of salinity. The effect of salinity in fresh water is often not accounted for when identifying factors that could affect detection range. The results shown in Table 1 assume a salinity of zero when, in fact, most fresh water has a salinity of at least a few parts per thousand. This discrepancy has little impact at lower frequencies but, as the frequency increases to around 300 kHz and above, absorption losses due to even low salinity levels can result in significant decreases in the detection range.

The characteristics and capabilities of the receiver used in an acoustic telemetry system can also significantly impact achievable detection ranges. The receiver characteristics used to calculate the results in Table 1 are representative of a reasonably sensitive receiver. While it is sometimes sufficient to simply detect the signal in active tracking applications, passive tracking often requires the receiver to detect information encoded in the transmission. Depending on the coding scheme employed, the range at which a tag signal can be decoded may be considerably less than the range at which its presence is merely detected (Ehrenberg and Steig 2009). This is exacerbated by the fact that, in order to keep the size of the receiver down and to extend the length of time the receiver can function using the internal battery, many passive tracking receivers are less sensitive than the one assumed in Table 1.

Acoustic Noise

Acoustic noise in the underwater environment is often the major limitation to achieving maximum tag detection range, especially when lower frequencies are used. Natural sources of underwater acoustic noise include wave action (Dahl 1994), flow noise, riverine bed-load movement (Belleudy et al. 2009), biological noise such as produced by snapping shrimp (Readhead 1997), rain (Bjorno 1994), and even snow (Crum et al. 1999). As an example of the significance of some of these noise sources, range in the ocean for an acoustic system operating at 70 kHz could be reduced from almost 1.5 km under ideal conditions to a few hundred meters in high winds accompanied by heavy rain (Hobday and Pincock, in press). With frequencies above 100 kHz, the dominant noise source is inherent thermal noise (i.e. that caused by the random vibration of water molecules) with, except in a few unusual cases, other environmental noise sources have a negligible effect.

Man-made noise from any device or machine that produces high frequency vibrations can also interfere with the ability to detect the signal. Examples of man-made noise sources include, sonars or fish finders, boat motors and shipping traffic, hydroelectric turbines, and pumps to name a few. With the exception of high frequency sonars operating at frequencies near that of the tags, man-made sources will cause some interference, but this can usually be mitigated and is generally not a significant factor when using frequency above 200 kHz.

Electrical Noise

Ambient acoustic noises can interfere with the detection of the signal, but electrical noise can also affect the performance of the acoustic system. Once the signal is detected and converted to an electrical signal by the receiving hydrophone, electrical noise can degrade the signal and affect the detection range. To minimize unwanted electrical noise in the receiving system, proper grounding and shielding procedures should be implemented. Most manufactures of acoustic telemetry systems have addressed this issue when they designed and built the equipment. However, the researcher needs to understand the basic principles of properly grounding and shielding electrical systems, or should consult the manufactures to ensure the system is properly installed. For example, a significant amount of electrical noise will be present in the system if it is plugged directly into the electrical system on a boat or directly into a gas powered generator. In these instances, a device (such as a power inverter or battery backup unit) that aids in removing the electrical noise should be used between the acoustic system and the main source of electricity.

Signal Distortion Effects

Physical structure in the environment can interfere with the propagation and/or integrity of the signal as it travels from the tag to the receiver, thereby affecting the detection range as well as the ability to decode information that might be embedded in it . High levels of entrained air may entirely block the acoustic tag signal because the sound is scattered by the air bubbles and the signal is degraded to a point that it never arrives at the hydrophone. Because woody debris and aquatic plants usually contain some gas bubbles, they can have a similar effect on the acoustic signal. High concentrations of large suspended particles, such as sand or silt, can have a similar effect, causing the signal to be scattered (Richards et al. 1998). Similarly, the interface between bodies of water that have different densities, like haloclines or thermoclines, can potentially reflect and/or refract the signal in such a way that it never reaches the receiver (Tucker and Gazey 1966). Further distortion of the signal can be caused by Doppler shift (Urick 1983), water currents, and temperature and salinity gradients.

Echoes due to reflections from the water surface, bottom, or any other object can be a problem if they reach the receiver with sufficient strength to be detected. Such echoes, often referred to as multipath signals, can either distort the signal seen by the receiver by extending its apparent duration or produce what appear to be additional transmissions or in more extreme cases, a replica of the transmitted signal. These affects will depend heavily on the relative positions of tags to the hydrophones, and the presence of reflective surfaces such as the bottom of the river or lake, the surface of the water, and other underwater structure.

While distortion effects such as multipath and Doppler shifts do not usually impact the ability to detect the presence of a tag, they can have a significant impact on the range at which the information contained in the signal can be decoded. As well, because the speed of sound in water is many orders of magnitude less than the speed of radio waves, the impact of such distortion is much greater than with radio telemetry. Furthermore, these effects make it impossible to use many modulation schemes that work well with radio telemetry.

Velocity of Sound

The speed of an acoustic signal as it travels through the water is not particularly important from the standpoint of simple tag detection, but it is an important variable for systems that use triangulation to determine the position of tagged animals near or within a hydrophone array. Mackenzie (1981) provides a simple equation for finding the speed of sound in sea water of a given temperature, salinity, and depth. Del Grosso and Mader (1972) provide a similar calculation for fresh water. Both methods produce estimates that are generally acceptable for most acoustic telemetry applications. More precise, but more complex equations for the speed of sound in sea water may be found in http://www.comm-tec.com/Library/Technical_Papers/speedsw.pdf.

Acoustic Telemetry Principles

Coding Information into the Signal

In studies where the objectives are relatively simple and only require tracking the movements of a few individuals, the signal transmitted by the tag can be relatively simple. However, when objectives require using tags with sensors to collect additional information such as temperature and depth, the signal must be encoded to enable this information to be transmitted to the receiver. In the case of monitoring large numbers of fish, encoding the signal enable each tag to emit a unique signal that can be used to identify individual fish. This unique signal is called the tag identification code, or ID code. In the early days, the number of fish that were tagged and released as part of any study was small; so the number of ID codes required was small. In the past ten years, however, the amount of data encoded in the signal as well as the number of fish tagged and released has increased dramatically. Many experiments now tag hundreds or thousands of fish, and thus require comparable numbers of ID codes and systems able to detect and decode information from numerous tags simultaneously. Also, the amount of data transmitted by each tag is greater due to the increased use of sensors. The need for unique ID codes is also the result of the worldwide increase in the use of acoustic telemetry (O'Dor et al. 2009). With more researchers using the same monitor system, more unique ID codes are needed to eliminate the risk that redundant ID codes are detected within multiple study areas, which would result in the collection of erroneous data and could put scientific conclusions at risk. While encoding the signal seems like a simple way to increase the capability of the monitory system, it does not come without a cost. In particular, encoding the signal can, as mentioned above, reduce the maximum range at which tag signals can be decoded and may limit the number of tags that can be simultaneously detected by receivers, and reduce the precision of the estimates of the position of the tags.

Coding Method Taxonomy

Because of the distortion of amplitude, pulse length and phase described above, the only realistic building block of any coding scheme is a tone burst (Figure 2) which transmits on a single frequency. With a tone burst (which for simplicity, we will refer to as a pulse) as the fundamental building block, the methods of coding data can be grouped into one of four categories based on two criteria.

The first criterion is the number of pulses used to transmit the signal. In what we call a Pulse Interval Scheme (Figure 3), each transmission consists of a single pulse and the data is encoded in the period between successive pulses. In what we call a Coded Scheme, each transmission consists of a series of pulses with the intervals between successive pulses representing a binary number. Figure 4 shows a typical Coded Scheme transmission where the length of time needed to transmit the data is called the Code Length and the time between successive transmissions is called the Transmission Interval.

The second criterion deals with the nature of the pulses themselves. When all transmitted pulses are the same, we will refer the method as a Single Color Signaling (or simply Single Color) scheme. On the other hand, a Multiple Color Signaling (or simply Multiple Color) scheme is one in which there is more than one type of transmitted signal. Multiple color signaling systems can be achieved in a number of ways including using a different frequency for individual pulses or by changing the phase (Phase Shift Keying) or frequency (Frequency Shift Keying) of the signal within each pulse to represent a binary number. The motivation for any multiple color scheme is to increase the amount of data that can be transmitted. The tradeoffs to achieve this are discussed below.

Table 2 classifies the most common coding methods used today according to the above criteria and in the following section we summarize the features, advantages and disadvantages of each approach to coding.

Coded with Single Color Signaling

The advantages of using a coded approach are the ability to encode hundreds, thousand or even millions of uniquely identifiable codes, the ability to encode sensor value(s) and the ability to easily automate the detection algorithms. As well, only a single detection is necessary to identify individual fish when multiple fish are within the detection range of the system. On the other hand, as will be discussed in a separate section below, coded signals can collide with one another and prevent either signal from being decoded by the receiver. In summary, single color schemes are very effective when individual receivers are not required to simultaneously detect a large number of tagged fish in a short period of time. It also offers the advantage that relatively simple tag and receiver implementations are possible. As a consequence, receivers can be relatively small and be deployed without servicing for a year or longer. This feature has led to the emergence of a number of large collaborative projects used to monitor the movements of fish over vast geographic areas. (e.g., The Ocean Tracking Network, the Australian Acoustic Tracking and Monitoring System, the Atlantic Cooperative Tracking Network and the Pacific Ocean Tracking project)

Pulse Interval with Single Color Signaling

The advantages of pulse interval coding with single color signaling include near immunity from the potential of multiple signals colliding when many tagged fish are within the detection range of the receivers (Ehrenberg and Steig 2003), all the energy transmitted by the tag is used for both detection and decoding (i.e., the maximum detection range and maximum decoding range are the same as is the case with any single color scheme) and the ability to retrieve movement and behavior information from a single hydrophone and receiver. Because of the ability to predict the expected arrival of the next pulse with high precision it becomes possible to graphically display time ordered pulses such as those in Figure 5. Disadvantages include the requirement that multiple pulses must be detected to ensure positive identification of the tag signal, and that more sophisticated tag and receiver designs are required to precisely control transmission intervals in the tag and allow for precise time stamping of tag receptions.

Using a single pulse interval to distinguish individual tags limits the number of potential tag codes to only several thousand unique ID codes. When a second pulse is transmitted at the same overall period, but at a fixed time interval from the first transmission, then the total available number of unique ID codes increases to hundreds of thousands. The spacing of the second pulse can also be used to transmit sensor data. Regularly spaced pulses allow for automating the process of tracking the tag receptions from individual hydrophones (through time), or from multiple hydrophones in a positioning array. Short, regular pulse intervals also provide the best detection scenario for mobile tracking.

Coded with Multiple Color Signaling

This approach has the advantages of single color signaling with the added advantage of increasing the available data bandwidth. Higher bandwidth allows more tags to be simultaneously present at a receiver and still be reliably detected or, for a given number of tags, more frequent updates from each tag. More rapid updates can offer a number of advantages – for example, greater certainty if fish are moving rapidly past a receiver, more frequent updates from any tag sensors and, in fine positioning applications (See below.), more detail on movements.

Pulse Interval with Multiple Color Signaling

While other possibilities may exist, the only technique used to date involves the use of a number of Pulse Interval coded tags, each operating on a different frequency. Because the individual fish can be identified by their frequency, the interval between successive pulses can be used to encode sensor data. While the individual tags use single color signaling in such a scenario, the receiver must be able to identify the transmitted frequency for each detected signal. This is the simplest example of using multiple color signaling to increase bandwidth. For example, if each tag were to use a transmission interval of one second, data would be updated for all tags simultaneously at this rate, provided the receiver is able to detect pulses on any of the frequencies simultaneously. This approach can be very effective in a situation with a requirement to monitor detailed interactions between individual fish (Sauer et al 1997). However, its applicability is limited as it cannot be used with a large number of tagged fish since, because of the low frequencies used in acoustic telemetry and the need to maintain sufficient separation between the frequencies used, only a small number of frequencies can be used. Therefore, we will not consider this approach in subsequent discussion of coding system performance issues where the focus is on large numbers of tagged fish.

Data Rate in Coded Systems

Although this section deals with coded systems which are digital in nature, transmitted signals in Pulse Interval coded systems are also subject to distortion and hence one must consider the proportion of transmitted data that is successfully recorded by the receiver. However, since tag data (ID code or sensor data) is inherently analog (i.e., the time between pulses), the issues are different and are addressed separately below.

Received Data Rate

Central to any discussion of acoustic telemetry system performance are the related issues of data rate and communication errors of various types. In a telemetry application where one or more tags are transmitting data to be detected at a receiving site, we can define the Transmitted Data Rate as the total amount of data transmitted by all tags within range of a receiver (e.g., in the case of n tags, n times the amount of data transmitted by each tag). Except in the simplest of situations, not all the signals reaching the receiver will be successfully detected which leads to the definition of Received Data Rate as the amount that is correctly recovered at the receiver.

There are three factors to consider in determining the received data rate in a particular situation:

1. Distortion Errors: These arise from distortion of the signal between the time it leaves the tag and arrives at the receiver, and the distortion is sufficient enough that the receiver fails to correctly detect the signal.

2. Collision Losses: These occur when transmissions from two or more tags overlap at the receiver and the receiver fails to decode at least one of them.

3. False Positives: These occur when a decoding failure from one of the two mechanisms above is not detected by the receiver and appears to be valid data but is not. These errors have a far more serious implication than reduction of received data rate as they can introduce false data. For example, recording detections as true when they are not can lead to the false conclusion that a fish was present when it was not. See Chapter 7.2 for further discussion on this issue.

Taking these errors into account, the effective received data rate of a system is given by:

$$\text{Received Data Rate} = TR - DL - CL - FP \qquad (2)$$

TR = Transmitted Data Rate

DL = Distortion Error Rate

CL = Collision Loss Rate

FP = False Positive Rate

Error Detection in Coded Systems

Like any digital communication system, coded acoustic telemetry systems will exhibit transmission errors of one or more of the types described above. Furthermore, because transmission errors occur frequently in an underwater acoustic environment, acoustic telemetry systems are particularly vulnerable.

Most coded tag schemes use the standard approach of an Error Detection Code (EDC) as a basis for the rejection of erroneous transmissions. This involves adding extra bits to the transmission (the EDC). At the receiver, the EDC is recalculated from the decoded data and compared to the received EDC. Transmissions in which the calculated and received EDCs differ are rejected as this could only occur as a result of a transmission error in either the EDC bits or the data bits in the received signal or both.

The use of EDCs to detect errors can never be perfect. Regardless of the scheme used, there is a non-zero probability that a transmission error will slip through the comparison test and result in creating a false positive. The best one can do is increase the "robustness" of the EDC to the point that the probability of such false positives becomes as small as possible. Of course, the cost of more robust error detection is that the portion of transmitted bits used for error detection rather than the actual data is higher, hence reducing the decoded data rate. This tradeoff is severe in acoustic systems because the limited bandwidth only permits a small number of total bits to be transmitted.

The actual statistics on the probability of a false positive depends on the coding method, nature of the EDC, number of tags present, and the characteristics of the transmission path. A rigorous discussion of false positive probability is beyond the scope of this paper. However, as an example, Pincock (2008) addresses false positive probability and identified methods to identify them in a typical single color signaling coding method. The author also showed that without the use of EDCs, the false positive rate would be unacceptably high in all but the least demanding situations.

Performance Considerations for Coded, Single Color Systems

Estimating Received Data Rate

The major factor that reduces received data rate (Equation (2)) when a number of single color signaling tags are present in the monitoring array is the loss of data due to collisions. How the system performs when multiple tags are present depends on the coding method used and, to some extent, the algorithm used in the software of the receiver. Most vendors will provide some level of detail about how the system is designed to deal with potential collisions of the signals from multiple tags. If they do not, the researcher should ask for this information because it can have a significant effect on the performance of the system. At a minimum, the vendor needs to provide a general idea about the number of tags that can be monitored simultaneously by the receiver (often referred to as the number of resident tags). With this information, the researcher can use the following equation to estimate the performance of the system (Pincock et al., 2010).

$$TD = (RT \times CL)/TI \qquad (3)$$

TD = Tag Density

RT = Resident Tags

CL = Average Code Length (Figure 4)

TI = Transmission Interval (Figure 4)

Using this formula, and assuming the option exists for the researcher to specify the rate at which the tag emits the signal (often referred to as the transmission interval), the transmission interval can be chosen to be sufficiently long enough to decrease tag density to an acceptable level. Table 3 shows the estimated numbers of detections that will be recorded for various tag density values. For example, a tag density of 0.05 will yield a detection efficiency of about 91% and a tag density of 2.0 will yield a detection efficiency of about 1%. Clearly, longer transmission rates are good for system performance and can reduce the tag density values (Table 4; Pincock 2008). However, reducing the transmission rate decreases the frequency at which information is obtained about the study animal. Therefore, a balance must be reached between increasing the transmission interval to minimize the potential for collisions and having a transmission rate that is so long that the frequency data is collected does not meet the objectives of the study.

Effect of Coding Parameters on Performance

Code length also determines the overall performance of the system when multiple tags are simultaneously present in the monitoring array. Equation (3) shows that for a given number of Resident Tags and Transmission Interval, the percentage of transmissions detected by the receiver increases as the length of the code (Code Length) is decreased. For a particular scheme with a given number of bits, Code Length is determined by the two parameters as defined below:

1. Minimum Interval: The smallest interval between successive pulses used in the coding scheme. This essentially determines how immune the scheme is to multipath. Multipath echoes which die out in less than this time interval will not interfere with the decoding process.
2. Timing Sensitivity. This is the accuracy to which the difference between successive pulses must be measured at the receiver for the code to be interpreted.

Traditionally, single color coded systems have used conservative coding parameters to ensure satisfactory operation over a wide range of conditions and, in particular, for large scale applications in the ocean. For example, a minimum interval of 300 ms and timing sensitivity of 10 ms have been shown to be reliable in virtually all ocean environments to a range of 1 km or more. However, schemes that have shorter intervals and increased time sensitivity requirements can be used to increase the rate at which data is transmitted and decoded to allow for a larger number of resident tags. Table 4 illustrates the points discussed through a presentation of received data rate calculations with a representative scheme encoding 16 bits per transmission (including a 30% allowance for an error detection code). The results illustrate the performance improvement that can be obtained in high residency situations through the use of a longer transmission interval as well as the performance improvement that can be achieved through the use of more aggressive coding parameters. To illustrate the point, the table shows two extremes of coding parameter choices and, of course, less extreme values are possible.

<u>Performance Considerations for Coded, Multiple Color Systems</u>

With multiple color systems, it is not realistic to present a similar section to the above because the wide variety of potential approaches makes it impossible to generalize. However, it would be useful if users with experience, or the vendors, were to publish such information for the currently available systems. In the absence of this, we present some general comments with respect to the approach taken by the two existing commercial systems.

The two existing commercial schemes are very aggressive in that they use a large number of signal colors to create the potential for very high data rates at the cost of significant reduction in the maximum range (compared to that of a single color system) at which signals can be reliably detected. It should be noted that this range reduction is the result of the aggressive coding (i.e., the use of a very large number of signal colors). It is certainly possible to take a more conservative approach which uses a small number of signal colors to provide a modest increase in bandwidth over that of a single color scheme with little or no reduction in range; however, to date, there are no such products on the market.

Although the details are different, the two currently available commercial products using Multiple color schemes (Table 2) are similar in that they use thousands of signaling colors with each color representing the identification code for a particular tag. These transmissions are short and repeated at regular intervals, typically every few seconds. As a result of the short percentage of time that each transmission occupies, loss of data due to collision with transmissions from other is tags significantly less, two or more orders of magnitude less than those with a single color signaling system. This, along with the relatively rapid rate at which data is transmitted by each tag provides the potential for very high data bandwidth. However, the potential for collecting data at relatively high rates and the dramatic reduction in lost data due to signal collisions will, as range increases, be accompanied by increases in Distortion Error rate and false Positive Rate (Equation 2). The reason for this is that the receiver is required to accurately determine which one of the thousands of possible colors corresponds to the actual transmission and, as range increases, so does distortion making this task more and more difficult.

To date, there is little or no published information on the magnitude of these potential errors. However, the results reported by Weiland et al (2011) for one of the systems currently using multiple color signals (JSATS system) has provided some insight into the performance of this type of system. The authors showed received data rate (for which they use the term Decoding Efficiency) for a study conducted at John Day Dam on the Columbia River, Oregon. About half of the data was lost at a range of 120 m from the hydrophones, and nearly all the data was lost at a distance of 140 m. While the inherently noisy environment upstream of a hydroelectric dam may contribute to this relatively low performance, the major issue is the small amount of distortion (due to multipath effects and Doppler in particular) that can be tolerated before signals, while detectable, will be incorrectly decoded. On the other hand, with single color coding, as discussed above, detected signals are highly likely to be correctly decoding with resulting greater useful range for equivalent conditions.

Decoding Data in Pulse Interval, Single Color Systems

Pulse interval tags use the interval between tag transmissions to code a unique tag ID. To work properly, pulse interval systems using a large number of tags require very high precision in the timing of both the tag transmissions and the reception of tag signals at the receiver. This level of precision is relatively easy to accomplish with modern digital electronics and processors.

Pulse interval systems differ from coded systems in that they only require that tag signals arrive repeatedly within a known time window to be included as tag receptions. Multipath or noise signals arriving outside that window can be rejected. However, reception of a single tag transmission does not allow for recovery of tag ID. Multiple transmissions from each transmitting tag are required for positive ID. For this reason, it is useful that all potential tag transmissions received at the hydrophone be collected. This allows for review of all potential tag transmissions (either graphically as described in Ehrenberg and Steig 2003, or using automated processing methods described in Steig and Johnston 2010) to sort out any possible false positive tag IDs, and to assess general data quality with respect to changing environmental conditions.

Single color pulse interval systems (as currently implemented in commercially available systems) do not suffer from lost detections due to overlapping transmission intervals. For instance, if a tag is transmitting at 5 second intervals, with a 1 ms pulse length, then there are 4.999 s out of 5.000 s of time over which a pulse from a second tag may arrive without interfering with the first tag. As more tags are detected by a single receiver, the probability increases that two tag signals will arrive simultaneously. In the rare case that tag signals from two tags do arrive at the hydrophone at the same time, then the combined received signal level from both tags would be anywhere between the sum of both signals, and no signal at all. The percentage of time that a combined signal would be detected is very high, but would depend on the signal strength of both arriving pulses, the relative phase of the arriving signals, the signal level threshold of the receiver, and the pulse width acceptance criteria. However, most simultaneously arriving pulses would be detected. Because the arrival time history of detections for each tag is known, the combined detection signal can be assigned to both transmitting tags. For pulse interval systems, each tag is transmitting with a different interval between pulses, so if a combined detection does occur, it will be guaranteed not to occur on the next transmission of each tag.

The structure of the signal and the rate it is transmitted makes single color pulse interval systems particularly useful in high residency situations. Because there is only a single (or in some cases two) short tag transmission(s), the interval between transmissions can be very short relative to the interval between groups of pulses in a coded scheme. For this reason, single color pulse interval systems are also useful in situations where tags are within range of the receiver for a limited time. Without tag detection lost due to collisions, and with short transmission intervals, high numbers of tags transmitting simultaneously can be detected in short periods of time.

Acoustic Telemetry Equipment

Tag Components

Acoustic Transducer

Because it is the smallest shape that produces roughly omnidirectional radiation at resonance, cylinders are universally used for this purpose. As well the material universally used in transducer manufacture is lead zirconate titanate (PZT) as this provides the highest electric to acoustic efficiency (Herman, 1975).

We have previously discussed in connection with Table 1 the tradeoff between the desire to use a low transmission frequency to achieve good transmission range and the fact that small transducers are only efficient at higher frequencies. This trade off is particularly important in salt water applications. For example, if a 3 mm diameter transducer were chosen in an effort to produce a small tag, the optimum electric to acoustic efficiency is obtained at mechanical resonance (approximately 300 kHz). However, at this frequency in salt water (20 degrees C, 35 ppt salinity), acoustic absorption losses are much higher (10.2 dB per100 m) than would be the case if a lower frequency could be used (e.g., Absorption loss is 3.8 dB per 100 m at 100 kHz). The effect is less in fresh water but can be significant at very high frequencies. While it is possible to use a small transducer and drive it at a frequency below its resonance frequency to achieve the benefits of a lower transmission frequency, the resulting loss in electric to acoustic efficiency will lead to shorter and shorter range the further one moves away from the optimal resonance for the transducer.

Batteries

The most important battery requirement for acoustic tags is high energy per unit of weight or volume which would suggest the use of lithium batteries. Lithium batteries are used in some cases but, because their explosion risk, inadequate peak current capacity for high power tags and unavailability of small versions suitable for use in miniature tags, other formulations are more prevalent. In particular, silver oxide batteries are often used for miniature tags and alkaline batteries in larger tags requiring higher power output. A more detailed description of the battery types used in tags (including types in addition to those discussed above) and the associated tradeoffs can be found in chapter 5.1 of this book.

<u>Electronics</u>

The electronics of the tag, which is essentially everything besides the transducer and the battery, perform the functions of creating the acoustic signal, transmission sequence encoding

ID, and delivery of power to the acoustic transducer. If an environmental sensor is included in the tag, then the electronics must also determine the sensor readings and encode these into the tag transmissions.

Over the past decade, advances in low power electronics have made it feasible to use a single microcontroller chip with firmware running in self contained flash memory to realize the above functions. In addition, microcontroller firmware can also support functions such as turning the tags off for periods of time to save battery life (often call "sleep" periods). Similarly, if study objectives require getting different information during different times over the duration the tag is in the fish, the microcontroller can be used to alter the coding of the data to meet these needs. In addition to the microprocessor, other components are usually needed to control the tuning of the tag to the proper frequency (usually with a separate crystal), to provide a time reference, and to provide a way to activate the tag before (or potentially after) it is implanted in the fish. As an alternative to the microprocessor option, tags with simple functionality (e.g., single color pulse interval tags) can be constructed with circuitry which is potentially smaller than a microcontroller chip.

Activation of the tag can be accomplished in several ways. It can be as simple as two wires that the user solders together and then protects in some way. As this process is potentially time consuming and subject to failure (particularly with miniature tags using very fine wire), internal magnetic switches are commonly used with various forms of activation, the simplest being the removal of a magnet attached to the tag. At least one manufacturer provides the ability to activate the tag without using a magnet as well as program the operational parameters of the tag in the field.

Some tags, particularly larger ones, will have additional components such as a power amplifier (possibly including inductive components to help maximize efficiency), signal condition components, and circuitry required to integrate some sensors. Table 5 summarizes sensors that are commonly used in commercially available acoustic tags. Various other sensors including dissolved oxygen, pH, electromyography (EMG), and electrocardiogram (ECG) have been used but are not generally available in commercial products.

Assembly and Encapsulation

Electronic assembly routinely uses small surface mount parts in preference to bulkier through-hole parts that were used in the past. For the smallest tags these are often un-encapsulated chips (Figure 6a) which are connected directly to the printed circuit board. After the transducer, battery, and electronics are assembled they must be encapsulated in some way to protect them from damage. Tags are normally encapsulated in one of two ways. The first encloses the components in an epoxy-filled cylindrical tube (Figure 6b) which has the advantages of being rugged and protecting the electronics from damage due to increased pressures at depth. The second widely used way to encapsulate the components of the tag is called conformal encapsulation. This process uses a thin layer of protective coating to encapsulate and protect the components (Figures 1a, 1c and 6c). Depending on the mechanical configuration of the components, this approach can lead to significant size and weight reduction over using the cylindrical tube encapsulation process. However, conformal coating is inherently less robust, thereby creating a higher risk of tag failure due to physical damage to the components.

Tag Miniaturization

One of the challenges in using any type of active tracking technology to study small animals (for example fish that are less than 100 mm in fork length) is the need for extremely small tags that can be carried by the study animal with minimal affect on its behavior. In recent years, there has been considerable interest in making tags smaller than those currently available (Figure 1). While this is feasible, there are some constraints that factor into how small a tag can be, and miniaturization often results in an increase in the cost of the tag, reduction in the battery life, and can decrease the detection range of the tag. Currently, the size and shape of the battery is a major factor limiting the miniaturization of the tag. The flat arrangement of currently available batteries shown in Figure 7 provides one example of a configuration that facilitates miniaturization of tags. The configuration shown is based on a single 4.8 mm diameter battery (the smallest silver oxide cells available at the time of writing) and an electronics board sufficient to contain a single integrated circuit (in the form of a bare chip) and tuning elements. The acoustic transducer shown is less than 3 mm in diameter, indicating a transmission frequency in the vicinity of 300 kHz. Using a single cell (unlike most current miniature products which typically use two) in such a design limits the demands that can be put on the battery. Furthermore, a single cell provides relatively low battery voltage and reduces the potential power output by a factor of four from what would be expected if two cells were used. This configuration also uses a 300 kHz transducer which can reduce detection range compared to tags that use lower frequencies.

To achieve further miniaturization of the tag, significant reductions must be made to the size of the battery or transducer. While it is unlikely that the size of the transducer can be reduced, a breakthrough in battery technology could have a significant impact on tag size and available voltage, however, little has changed in the last few decades in battery technologies. The focus area for the battery industry has been elsewhere and smaller batteries for miniature tags is a relatively small part of the market with the result that battery companies are reluctant to invest research and development costs that would likely not be recuperated.

Life, Size and Range tradeoffs for Larger Tags

While the objectives and parameters of each individual acoustic telemetry study will dictate the acceptable tag to body mass ratio (Jepsen et al. 2005), in general, larger fish can accept larger tags with larger batteries so the available energy allows for greater latitude in what can be achieved with respect to range, sensors, and programming. For example, Table 6 demonstrates tradeoffs between size and life for a typical tag operating at 80 kHz (i.e., using a 12 mm transducer). Assumptions behind the specifications shown are outlined in the table caption. Fresh water range at 80 kHz is not shown in the table because the best configuration for a larger transmitter at this frequency would be relatively large with a range capability far beyond what would normally be required in fresh water.

Tag life is of course impacted by the addition of sensors. However, since sensors are typically activated briefly before each transmission, the effect is usually minimal. For example, a sampled sensor consuming 0.5 ma would reduce battery life from those shown in Table 6 by about 10%; but this would rise about 95% without sampling (e.g., 11 days instead of 145 days for a tag that does not have a sensor, as shown in the first row of the table).

Finally, for some tags that are activated using a magnetic switch, battery energy is consumed at a low level even when they are stored in the deactivated state. This is often referred to as quiescent drain. Therefore, it is important for users to be aware of the potential for the tag to use battery power even when the tag is turned off. If this is the case, the vendor should provide data to determine the length of time between manufacture and activation which can be tolerated without significant battery life deterioration.

Hydrophones

Hydrophones are the acoustic equivalent of radio antennas in that they convert acoustic signals to electrical signals. Usually, a transducer similar to the type used in the tags is used to accomplish this function in the hydrophone. In some submerged passive telemetry receivers, the hydrophone is integral to the unit while, in other cases, where separation between the hydrophone and receiver components is required, cabled connections are used. Mobile tracking receivers would normally use a cabled connection.

Hydrophones are generally categorized as omidirectional or directional. Most passive tracking applications use omnidirectional hydrophones to increase the probability of detecting tags regardless of the direction the fish approaches the monitoring area. While size considerations don't preclude the use of spherical transducers in such hydrophones, a single PZT cylinder is usually used for cost and ease of manufacturing considerations. While, as would be expected, these transducers are most sensitive at their resonant frequency, satisfactory performance can be achieved below the resonant frequency and they are often used this way.

In the simplest implementation of mobile tracking, the researcher follows a fish by continuously steering towards the strongest signal. This requires that the hydrophone be directional – i.e., producing a stronger signal when pointed in the direction of the tag, thereby giving an indication of the direction the signal is coming from. There are different ways to make a hydrophone directional. If the length of the hydrophone in any direction exceeds a few wavelengths, it becomes directional on that plane. The Vemco VH110 (Figure 9a) is an example of this approach using a number of interconnected cylinders in a line with sound absorbent material at the back of the hydrophone so there is not a 180 degree ambiguity as to where the signals is coming from Since the cylindrical shape is maintained vertically, looking forward, the unit is directional horizontally but omnidirectional vertically. An alternative to this approach is the use of a parabolic reflector (e.g., Sonotronics DH-4 shown in Figure 8b). However, a hydrophone like this cannot be used when the tracking vessel is moving at higher speeds. A parabolic reflector directional hydrophone is directional vertically as well as horizontally so that one would need to search vertically as well as horizontally to find a tag signal while operating on deep water.

Another approach that can be used in a mobile tracking application is described by Vickery (1998). They define this approach as a Short Baseline Assembly and can be an attractive option since it does not require large separation between the hydrophones and does not create much drag when on a moving boat. The basic setup for this system involves having multiple hydrophones (3- 4) that are slightly offset from one another. This approach allows the researcher to monitor a number of tags simultaneously in a number of different directions from the boat without the need to steer the boat towards each tag. Unfortunately, the complexity of this approach (installation issues, requirement for a multichannel receiver, and specialized training for the users) has limited its use. The only commercial available product that we are aware of that was capable of achieving this was the now-discontinued Vemco VH4 series.

Noise Considerations and Preamplifiers

Ideally, the hydrophone converts the acoustic signal to an electrical one with no degradation of the tag signal. However, the quality and specification of the hydrophone can degrade the signal, so it is important for the researcher to know what they are getting when they acquire hydrophones. One of the important specifications is referred to as the Noise Floor of the hydrophone/preamplifier combination. The Noise Floor is the acoustic pressure which corresponds to the electrical noise at the hydrophones output when there is no signal. In short, it is a measure of how much background noise is generated by the hydrophone itself when there is nothing the hydrophone is listening to. Ideally, this should be less than approximately 26, 30, 36 and 40 dB re 1 uPa/√Hz at 75, 150, 300 and 400 kHz respectively (Wentz 1962). If the Noise Floor is less than these values, it is safe to say that the hydrophone will not cause further degradation of the signal. The manufacturer should have accounted for this when they designed the hydrophone and well designed hydrophones operating up to about 100 kHz usually meet these specifications. However, above 100 kHz where acoustic noise approaches the thermal limit as discussed above, added noise contributed by the preamplifier electronics will cause the noise floor to increase above the acoustic level seen by the hydrophone.

Receiving Systems

Receivers typically perform two basic functions. The first is the detection of the actual transmission as distinct from other acoustic sources and noise. The second involves decoding information within the transmission, i.e., the individual ID of the tag and sensor data if any is present in the signal. With the exception of some basic mobile tracking receivers, receivers today store detection data for subsequent retrieval, transmission, and/or analysis. In some systems, this information includes all potential tag signals, whether or not the signal can be decoded. Some receiving systems will also record specific aspects of potential tag signals such as amplitude, pulse length or shape, and signal to noise ratio. These additional measurements may assist in distinguishing true tag signals from multipath or noise. Most systems also time stamp the incoming tag signals with various degrees of accuracy. The accuracy of the time stamp depends on the objectives of the study. If simple presences/absence data is all that is required, time stamping to the nearest second would be quite adequate. However, if the data is being used to triangulate the position of the signal in 3 dimensions based on differences in the time the signal arrives at four or more hydrophones in the detection array, the accuracy of the time stamp is much more critical.

Broadband Receivers

Broadband receivers are basic systems consisting of minimal filtering and simple circuitry to detect the presence of a transmitted pulse. The motivation for this simplicity is to minimize size and/or power consumption to facilitate easy deployment and autonomous operation for long periods. These are important requirements in many passive tracking applications. The disadvantage of such receivers is that because of their greater bandwidth, sensitivity of the receiver is sacrificed.

Narrowband Analog Receivers

As the name implies, the heart of such a receiver is a narrow band filter matched to the bandwidth of the transmitted pulses (taking into account frequency distortion created by the underwater medium). Usually, such receivers shift the incoming signal to a higher frequency (often a standard intermediate frequency such as 455 kHz) before filtering.

Not surprisingly a narrow band receiver will outperform a broadband receiver in most situations. For example, the range of 950 m shown in the first row of Table 6 would rise to almost 1500 m if a good quality narrow band receiver were used. Of course, with the additional circuitry, power consumption will be significantly higher. Mobile tracking has traditionally used narrowband analog receivers (e.g., Vemco VR60, Sonotronics USR-08 and Lotek SRX 400). Some passive tracking receivers (e.g., Sonotronics SUR-1 and Vemco VRAP) are also narrowband receivers.

Digital Receivers

The major motivation for digital receivers is to overcome limitations of analog receivers; these limitations include:

- The dynamic range of analog receivers is limited (i.e., if the gain is not properly set, the signal may either be too low to be detected, or so high that the receiver is saturated with the strength of the tag signal so no detections are recorded)
- It is not realistic to construct very complex filters for analog receivers and the accuracy of their coefficients is limited by the accuracy of components used. Therefore, potential detection range is lower than theoretically possible.
- Detection range can be increased by using multiple filtering strategies depending on acoustic conditions. The potential to do this with an analog receiver is very limited.

The underlying concept of a digital receiver is straightforward: conversion of the amplified hydrophone output to a digital data stream followed by digital processing to implement the detection algorithm. With ongoing improvements in the amount of processing that can be achieved by the receiver at a given power consumption rate makes the use of digital receivers more and more practical. Of course, power consumption is still significantly higher than for an analog receiver with similar performance (typically on the order of ten times as high at the time of writing). Examples of systems that use digital receivers are Vemco VR100, Lotek MAP 600, and HTI 290, 291 and 295.

Fine Positioning Systems

The Basic Principle

Where there is an array of receivers and tags are simultaneously identified by at least three of them, it is possible to determine two dimensional fish position to (depending on factors discussed below) a resolution of a meter or even better (Ehrenberg and Steig 2002). Positioning is accomplished by measuring the difference in arrival time of the same transmitted signal at different hydrophones/receivers. When detection is by four or more hydrophones, with hydrophones separated vertically as well as horizontally, three-dimensional positioning is possible (Evans, 2010). However, in shallow-water studies where tag transmission range is several times that of water depth, wide spacing of receivers vertically isn't possible. One approach to three dimensional positioning in shallow water is to position tags horizontally using 3 (or more) hydrophones deployed in a horizontal plane, and then use tags that have depth sensors to provide the third dimension (Sauer et al. 1997).

Error Sources

The accuracy of any fine-scale positioning system is limited by three factors: array geometry, the accuracy to which hydrophone positions are known, and timing synchronization between detections at the various hydrophones. These are discussed briefly below.

Ideally, the tag should be within the volume defined by the hydrophones in question. The position of tags can be determined outside of this volume, but the position accuracy degrades rapidly as the distance from the array increases. The hydrophones should be reasonably uniformly spaced as well; otherwise, variability in the shorter dimension(s) will be greater.

Uncertainty or variability in hydrophone positions will directly impact the calculated tag positions. The locations of hydrophones can be determined at the time of installation using a GPS receiver, and/or can be adjusted or fine tuned with 'time of flight' measurements of signals transmitted by the hydrophones themselves. For this analysis, sound velocity measurements are important to convert the 'time of flight' measurements to distances. If positioning accuracy requirements are demanding, significant effort is required to ensure that hydrophones are positioned or moored in such a way that they will not move with wind or current. If hydrophones move, then some method of recording their movement and applying the changes in position to the received tag data is required.

Positioning algorithms are based on differences between times of arrival of the signal at each hydrophone and, therefore, any discrepancies between the time references for detections at various hydrophones will increase positioning error. For systems with cabled hydrophones and a single receiving site (e.g., HTI Model 290), this issue doesn't arise. An alternate approach used by the Vemco VRAP System transmits detection information by radio in real time to a central receiving site. A disadvantage of the two approaches above is that the infrastructure (cables, radio links, etc.) required limits the geographic scope over which fish can be monitored to approximately 1 km^2 or less. These systems also tend to be costly.

The Vemco VPS system (Espinosa et al. 2011) takes a different approach by using an extendable array of autonomous receivers and synchronization or reference tags in known positions. Post processing algorithms are then used to correct for drift between the time references of the individual receivers. If array geometry is such that each group of three receivers reliably detects at least one reference tag, this approach can be as accurate as the traditional approaches described above (Vemco 2010). On the other hand, if less accuracy is required, one can use fewer receivers to cover a given area. In addition, because of the simplicity of the autonomous receivers, these systems can be deployed unattended for long periods of time.

Study and Application Considerations

Mobile versus Passive Tracking

Early acoustic telemetry studies almost always involved mobile tracking – typically a single tagged fish (with or without a sensor) was followed from a boat. While this provided some previously unknown knowledge of fish behavior, studies were limited by the restriction to only tracking one fish at a time, and the relatively short duration of tracking activities due to the need to keep in continual contact with the fish. As a result of these limitations, the vast majority of today’s activities involve passive tracking in which fish presence (and possibly sensor data) is logged by stationary receivers.

Passive tracking studies can be broadly divided into two classes: *Habitat Usage* and *Migration*. Migration studies most commonly use lines of receivers to monitor passage of fish down a river (Perry et al, 2010) or along a coast (Chittenden et al. 2009). Habitat usage studies, on the other hand, are concerned with the behavior of a group of fish in a relatively restricted area – for example, in a lake or bay (Semmens 2008, Bacheler et al. 2009, Suski and Ridgway 2009), near a dam (Steig 2000, Ransom et al. 2008), near a coral reef (Chapman et al. 2005), near a fish aggregation device (Bach et al. 2003), or in a river (Bowen et al. 2009). In such studies fish position may be very rough (i.e., presence or absence of a tagged fish at a particular receiver) or may involve fine positioning.

Recently, the availability of the marine gliders (e.g., Webb Research's Slocum Glider and Liquid Robotics' Wave Glider) has led a number of researchers to investigate the potential for mobile tracking mission which would survey large expanses of the ocean for the presence of tagged fish.

Hydrophone Placement for Passive Tracking Applications

In most cases, researchers have choices as to where to place hydrophones. This is particularly true for migration studies where there is seldom a precise requirement of where lines should be placed. With the above in mind, one should try to adhere to the following guidelines as much as possible:

- Avoid hydrophone placements where underwater sound sources (e.g., fish finders, acoustic water level measurement devices, Acoustic Doppler Current Profilers) might be present
- Keep hydrophones/receivers and cables (if receivers are wired) away from electrical equipment, pumps, motors, power lines, etc.
- Avoid hydrophone placements in areas where air bubbles might be present.

- Be aware that woody debris, aquatic plants and the like in the path between the tag and receiver will seriously degrade performance.
- Be aware that noise from boat engines and propellers can cause temporary degradation of the ability to detect signals.

Range Testing

While it is possible to calculate the detection range of a given receiver and tag combination for assumed ocean or fresh water conditions, the noise and propagation characteristics of the local environment for a particular study are often unpredictable, particularly in fresh water environments. For this reason, *in situ* range tests are recommended to verify that tags are detected throughout the range of interest (Celedonia et al. 2008, Webber 2009, Loher et al. 2010).

While the details of range testing will vary somewhat depending on the nature of the study and the equipment being used, the following guidelines should be kept in mind:

- Tags used in the range tests should have a similar power level to those planned for use in the study.
- In situations where seasonal (e.g., in many riverine environments) or weather-related (e.g., in the ocean) conditions vary significantly during the study period, one should try to take range measurements in the worst case situation. If this is not realistic, then the results should be derated to compensate for this.
- If a boat is used as part of the test procedure (e.g., to position tags), ensure that engine noise, boat electronics, bubbles from the wake of the boat, or the boat hull

itself, do not obscure or interfere with tag signals. Often this possibility can be eliminated by suspending the tag on an independent drifting float.

In determining the range requirement (or receiver placement) in studies involving the detection of fish passing a given area, one needs to take into account the interval between tag transmissions and the potential migration rate of passing fish. If the swimming speed of the fish, and/or the water currents in the study area are extremely fast and the transmission rate of the tag is relatively slow it may be possible for the fish to pass through the study area in less time than the transmission interval. See Hobday and Pincock (in press) for a discussion of this issue.

Fine Scale Positioning

Studies incorporating two or three dimensional positioning can address objectives such as determining where within a body of water fish spend the most or least amount of time (Semmens, 2008), or whether or not environmental variables are correlated with fish behavior. While such behavioral studies can be and have been is used in a wide variety of situations, they are particularly important for determining the effects of man-made structures on fish populations (Steig 2000, Brown et al. 2009). Summarizing data can sometimes be challenging, as modern positioning systems can produce two or three-dimensional positions for large numbers of fish at intervals sometimes down to a few seconds. One approach to summarizing such data is to divide the study area into cells, count the number of individuals that enter the cell, and develop a density plot to describe areas utilized by more or less individuals (Steig and Johnston, 2010). Steig et al. (2009) used this method to summarize the density of sockeye salmon smolts

(Oncorhynchus nerka) by color, as they passed through the forebay of Rocky Reach Dam on the Columbia River, near Wenatchee Washington, USA (Figure 9).

Visualization tools can be a useful alternative to the analytic methods referred to above. For example, the VPS system described above produces KML files which produce a two dimensional animation in Google Earth (See, for example Vemco, 2011). When fine scale positioning data is overlaid on geo-referenced aerial images (See Figure 10, for example.), behavior of fish around specific features of a water body can be studied (Bowen et al. 2009).

Application Environments

While no two studies are exactly alike, broad categories can be defined based on the environment where the tags and receivers are deployed. Most environments can be represented in one of four categories: marine; riverine; lakes and reservoirs; and dams, power plant intakes and other man-made underwater structures. Some considerations with respect to each of these are discussed below.

Marine Environments

Most marine environments allow unrestricted movement of the tagged fish, so whether the study involves habitat usage or migration, receivers need to be installed with prior knowledge of the behavior patterns of the tagged fish. This can be particularly challenging in the case of studies involving fish which might move large distances. For example, although migrations close to coastlines involving paths of thousands of kilometers are often monitored today (Welch et al. 2003), detections away from the coast are unlikely due to the sheer area involved. However, various approaches to address this are now being investigated. Exploratory missions using marine gliders have already been mentioned. Others include using ocean observation buoys as receiving platforms of opportunity (e.g., NOAA, 2011) and using so called Business Card Tags (e.g., Vemco Mobile Transceivers) which add an acoustic receiver and data storage to acoustic tags carried by large mobile animals (e.g., sharks and seals) which might interact with fish of interest and hence record detections. The business card tag approach is described in more detail with some early results by Holland et al (2009).

Tag size is also an issue in the ocean. As discussed above, high frequency transmissions suffer from significant absorption loss in the ocean, and the majority of studies require tags to function for long time (months or years). As a result, very small tags which must operate at high frequency and use very small batteries are only suitable in a small subset of applications in the marine environment. For example, they could be used in studies designed to characterize the habitat usage of fish in relatively small, shallow areas along the coast or in estuaries.

Riverine Environments

Hydrophone deployment in rivers can be difficult, since the environment is often very dynamic, with changing water velocities, high debris loads, boat traffic, and even changing bottom profiles. Many areas (e.g., near rapids or waterfalls) are simply not suitable for acoustic tag studies because of large amounts of entrained air. Other areas may appear ideal at some times of the year but rapidly change to unsuitable locations with changes in flow and debris load.

Basic information such as migration rates or survival is often estimated using fixed hydrophones or hydrophone arrays placed at intervals along the river (Ransom et al. 2008, Evans et al. 2010). However, as more and more natural watercourses are impounded or altered for irrigation, hydroelectric generation, and\or flood control man-made structures are becoming increasingly important as subjects of fisheries research in rivers. Often, such studies require fine positioning capability to provide detailed information about movements such as preferred paths and responses to the structures in question. Typically, a significant amount of planning and testing is required for this type of study as the structures often create artificial aquatic environments which present challenges due to unusual electrical and/or acoustic noise as well as multipath signals created by confined spaces, often with good reflecting surfaces.

Lakes and Reservoirs

Freshwater lakes and reservoirs usually represent the most trouble free environments for acoustic tag studies. Noise levels are often low and the absorption of the acoustic signal is low so maximum detection ranges tend to be high. This environmental condition can simplify implementation of acoustic studies. For example, in smaller lakes, it is often possible to position receivers to allow complete coverage of the entire lake (Hanson et al. 2007). On the other hand, in cases where there are good reflective surfaces (e.g., rocky cliffs or bottom), echoes can arrive at the receiver long after the direct transmission arrives causing a great deal of lost data for systems using coding tags. Where this might be an issue, extensive range testing designed to determine suitable receiver locations is required to optimize data collection. These types of test could indicate that a tag with a weaker signal may be better than a tag with a very strong signal that bounces off of structures and generates a significant amount of multipath.

Summary

While acoustic telemetry may not be the desired technology for all research applications, the flexibility of this technology allows the researcher to meet many common study objectives.

The ability to collect relatively coarse information about the movement of fish over large geographic areas and simultaneously obtain 2 dimensional and 3-dimentional behavior information with an accuracy of less than 1 m makes this a very versatile technology. With this versatility comes system complexity and advanced knowledge and familiarity with the technology is critical to designing and implementing a successful study that delivers robust results. It is our hope that the material presented in this chapter, together with the information in other chapters of this book, will provide the research ample knowledge to successfully apply acoustic telemetry technology to address research and management questions.

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Tables

TABLE 1. Maximum Detection Ranges for tags of various frequencies in salt and fresh water where tag transmission level = 150 dB re 1 μPa @ 1 m, minimum signal to noise ratio for detection = 6 db, receiver bandwidth = 1 kHz, depth = 10 m, temperature = 20° C, wind speed = 0. Spreading is assumed to be spherical and the receiver is assumed to have characteristics representative of a reasonably sensitive active tracking receiver (i.e., bandwidth = 1 kHz; Minimum SNR for Detection = 6 dB).

Frequency (kHz)	Diameter of Resonant Transducer (mm)	Range in Fresh Water (m)	Range in Salt Water (m)
24	37	27,421	5,997
30	30	25,813	4,654

70	13	10,515	1,432
200	6	1,966	417
300	3	983	298
400	2.5	616	242

TABLE 2. – Categorization of commonly used coding schemes

Coded	Pulse Position
Single Color Signaling	**Single Color Signaling**
Vemco Coded	HTI
Lotek SA	Vemco Continuous
Multiple Color Signaling	**Multiple Color Signaling**
JSATS	Vemco VRAP with
Lotek MAP	Continuous Tags[1]

[1] Although each tag uses only a single color, each uses a different frequency; so the receiver has to deal with multiple colors.

Table 3. – Percentage of transmissions that will be detected as a function of tag density

Tag Density	Percent Detected
0.05	91%
0.1	83%
0.25	63%
0.37	50%
0.5	39%
0.75	23%
1.0	13%
1.25[1]	8%
1.5	4%
2.0	1%

[1] Some Tags are detected even if Tag Density is greater than 1 as the randomness of the process will create some empty space

Table 4. – Average time in minutes (unless otherwise stated) between detections of each resident tag in a representative 16 bit Coded single color signaling system with Transmission

Intervals (TI) of 60 and 120 seconds and two examples of Coding parameters (Conservative: Minimum Interval = 300 ms and Timing Sensitivity = 10 ms; Aggressive: Minimum Interval = 100 ms and Timing Sensitivity = 2 ms)

Resident Tags	Conservative		Aggressive	
	TI = 60 sec.	TI = 120 sec.	TI = 60 sec.	TI = 120 sec.
5	1.5	2.4	1.1	2.1
10	2.4	3.1	1.3	2.2
15	3.9	3.9	1.4	2.4
25	10	6.2	1.8	2.7
50	118	20	3.4	3.7
75	> 20 hours	67	6.4	5.0
100		220	12	6.8

Table 5. – Sensors commonly used in acoustic telemetry Tag

Sensor	Type	Comments
Pressure	Strain gauge(s) mounted on back of diaphragm exposed to water	Use to determine swimming depth. Major source of errors is temperature dependence of stain gauge resistance; errors can be reduced by arranging strain gauges in a bridge.
Temperature	Thermistor	Low cost, small and reliable; accuracies up to 0.1 ^{0}C are readily available
Activity and Motion	MEMS (Micro Electrical Mechanical System) integrated circuits, motion sensitive mercury switch and various custom mechanical devices	Usually three axis sensors are used. Normally acceleration changes are at too high a rate to be coded into transmissions. The normal practice is for on board processing to calculate desired information (e.g., average acceleration) and transmit that. Non MEMs implementations are often bulky

Table 6. – Representative specifications for larger tag operating at 80 kHz. Specification shown are based on the following assumptions: (1) electric to acoustic efficiency is 75%, (2) electronics consume 1 uA when not transmitting (conservative with today's technology and (3)

pulses being transmitted 1% of the time (battery life would adjust proportionally if percentage is different). Range calculations are based on the use of a broadband receiver

Battery	Typical Tag Dimensions (mm)	Maximum Theoretical Range in Ocean (Broadband Receiver)	Useful Life
Silver Oxide (3 V, 150 ma-hrs)	60 x 15	950 m	145 days
Silver Oxide (9 V, 150 ma-hrs)	80 x 15	1,175 m	145 days
Lithium (3.6 V, 2,100 ma-hrs)	100 x 15	950 m	5.6 years

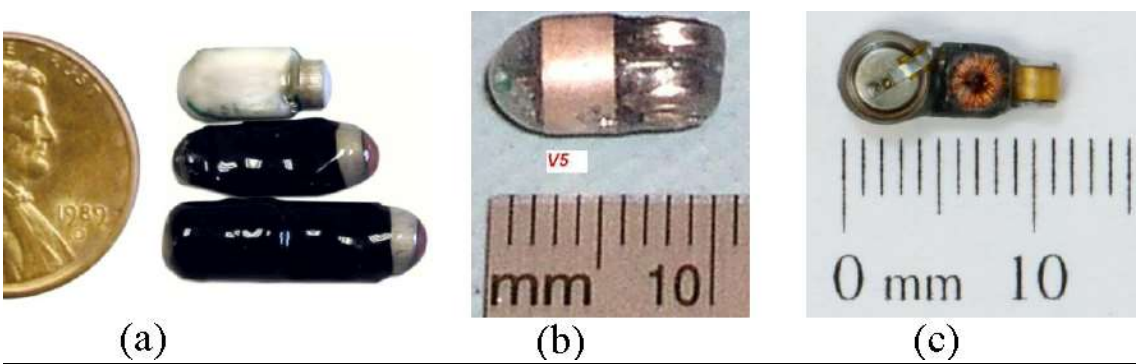


Figure 1

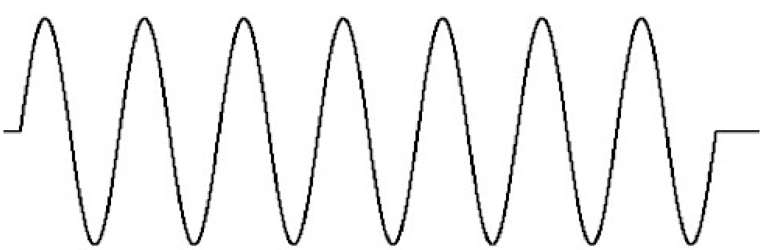


Figure 2

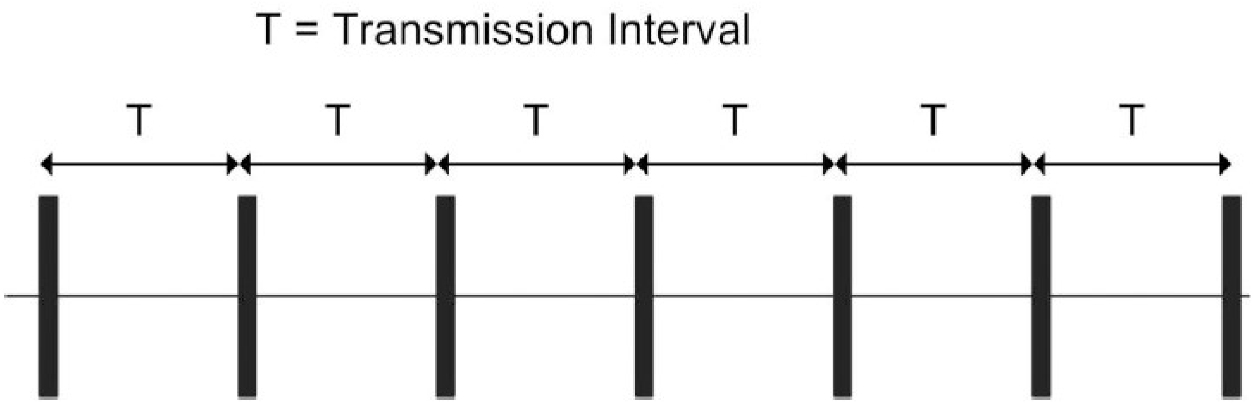


Figure 3

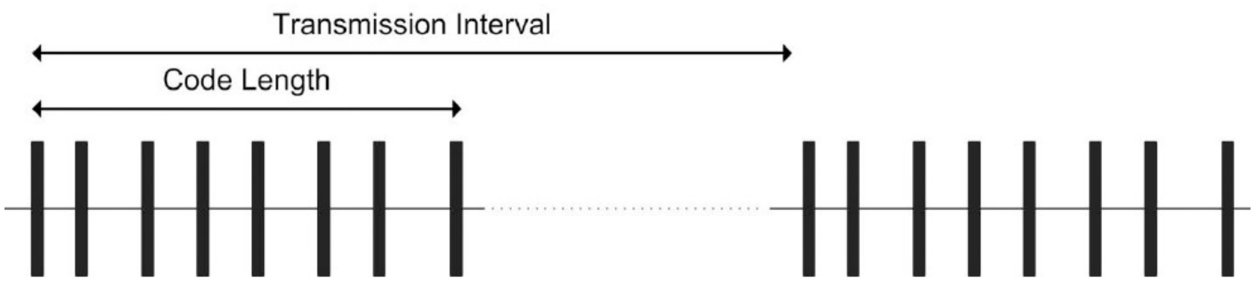


Figure 4

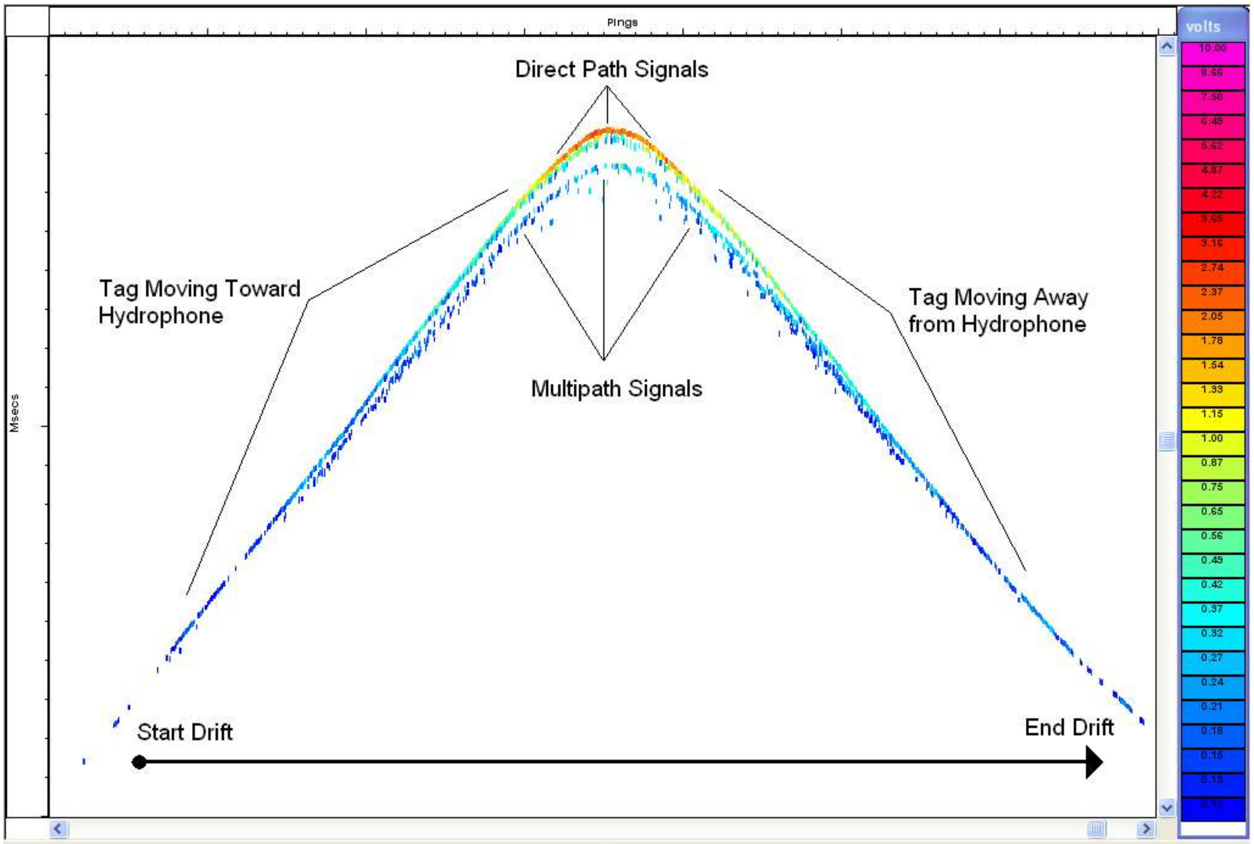
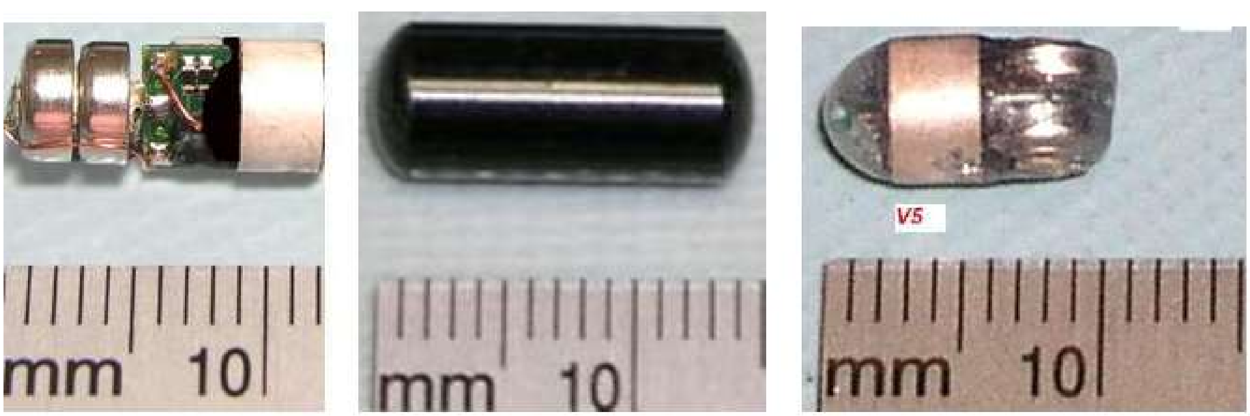


Figure 5



(a) (b) (c)

Figure 6

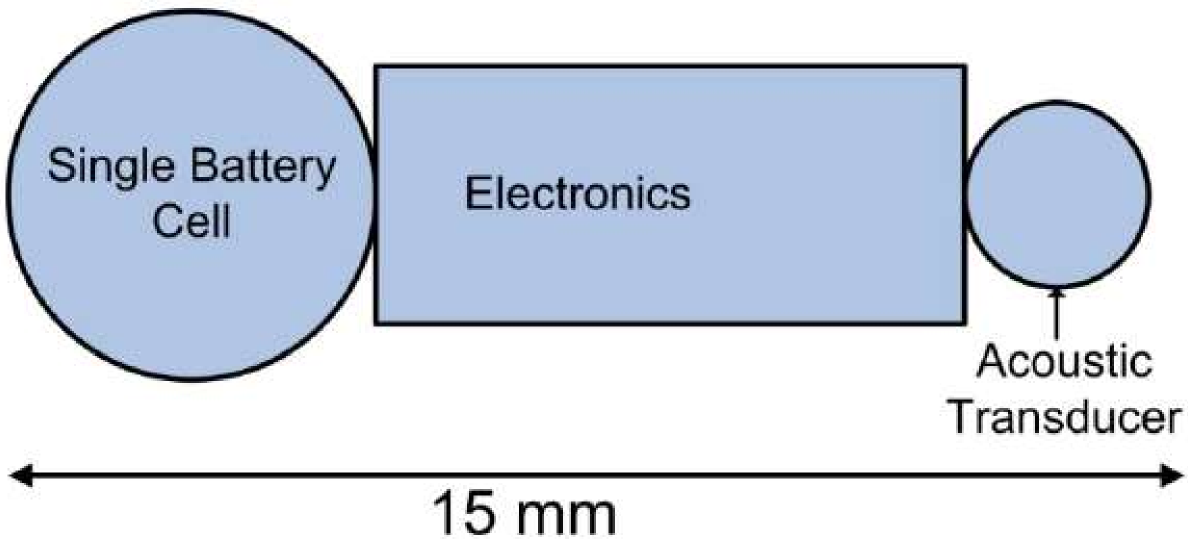


Figure 7

(a)

(b)

Figure 8

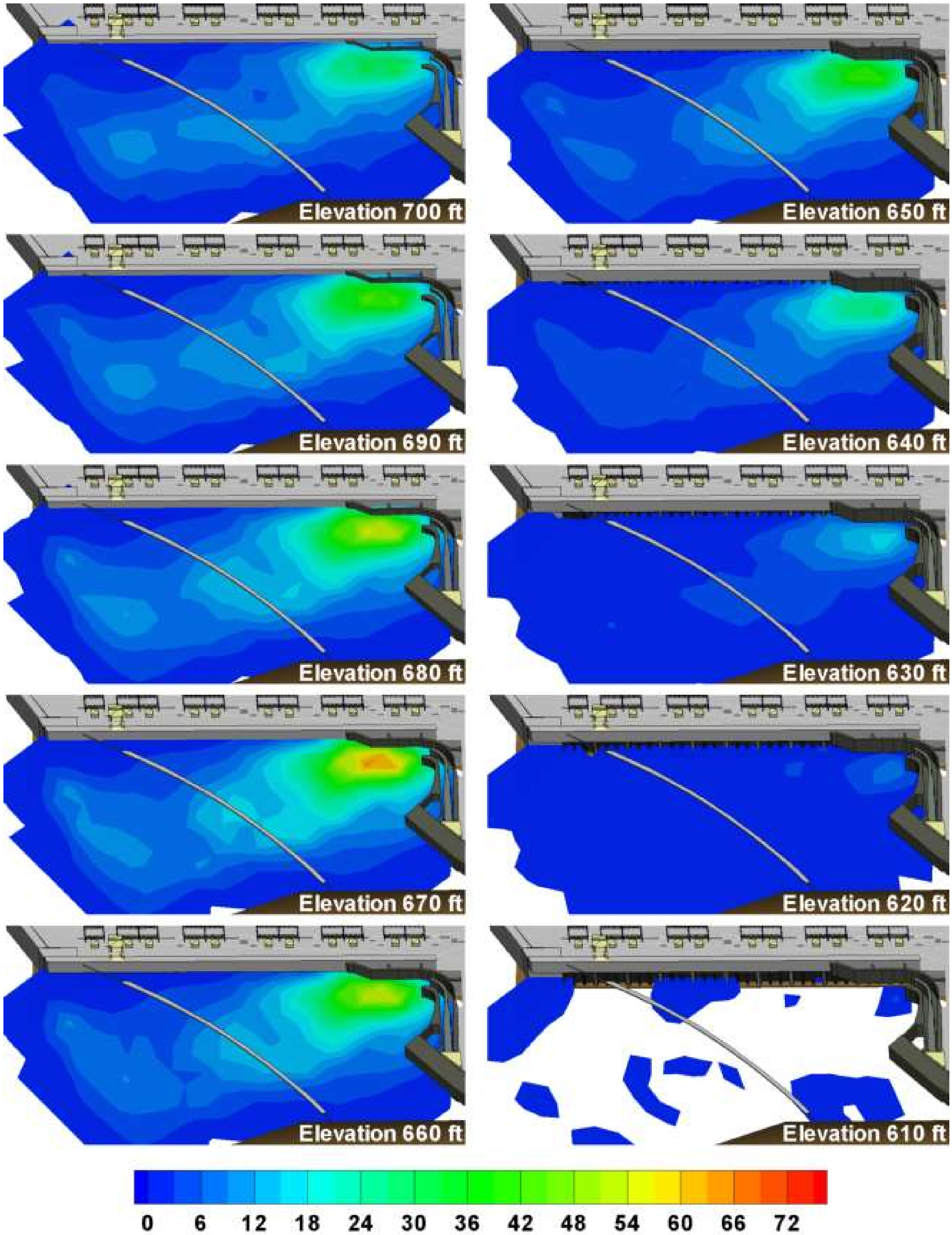

Elevation 700 ft
Elevation 650 ft
Elevation 690 ft
Elevation 640 ft
Elevation 680 ft
Elevation 630 ft
Elevation 670 ft
Elevation 620 ft
Elevation 660 ft
Elevation 610 ft
0 6 12 18 24 30 36 42 48 54 60 66 72

Figure 9

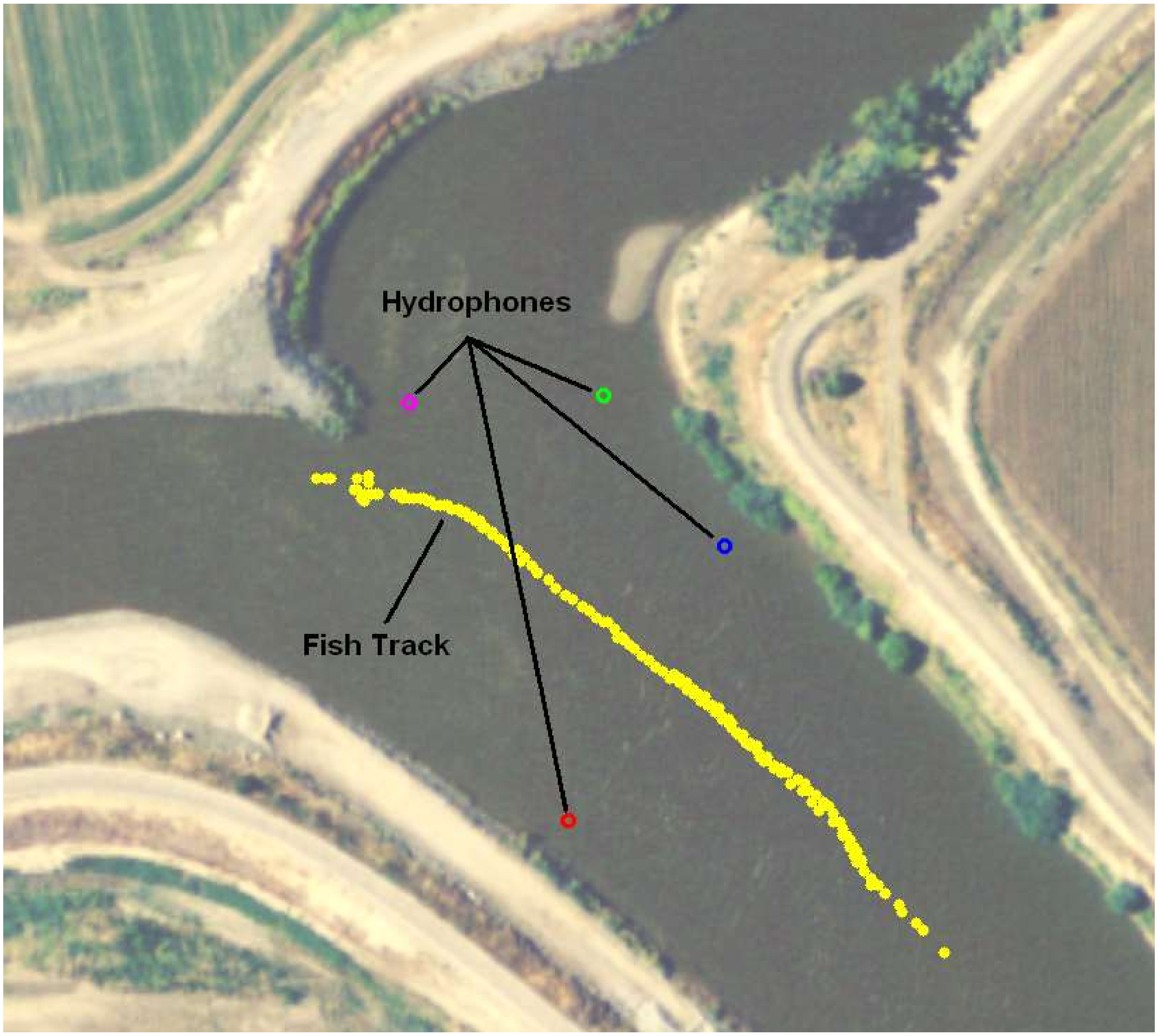


Figure 10