

A study of the relationship between tag-signal characteristics and achievable performances in acoustic fish-tag studies

John E. Ehrenberg and Tracey W. Steig

Ehrenberg, J. E., and Steig, T. W. 2009. A study of the relationship between tag-signal characteristics and achievable performances in acoustic fish-tag studies. – ICES Journal of Marine Science, 66: 000–000.

Acoustic tags have been used in fish behaviour studies in a variety of marine and fresh-water environments. The intended objectives of these studies vary widely. In some cases, the studies require accurate three-dimensional tracking of the individual fish locations. In other cases, tags are used for estimating the fish survival along a migration route. There are varieties of acoustic-tag signal-encoding schemes that have been proposed and used for implementing tag systems. The purpose of this paper is to explain the relationship between the various characteristics of acoustic signals transmitted by the tags and the tag-system performance that can be achieved. In particular, the ranges at which the tags can be detected and uniquely identified, the positional accuracy, as well as the number of unique codes that can be assigned to individual fish are all functions of the signal type. This paper demonstrates that when the pulse-repetition period is used to encode the tag identification, the range performance for the tag is superior to that achieved by using a scheme that has binary-encoded bits as part of the transmitter signal. The parametric results presented in this paper will assist investigators in their selection of the type of acoustic tags or tag parameters needed to achieve the objectives of acoustic fish-tag studies.

© 2009 International Council for the Exploration of the Sea. Published by Oxford Journals. All rights reserved.

Keywords: acoustic tags, fish tracking, fish telemetry, acoustic-tag performance, fish behaviour

Running Heads: Acoustic fish tags; J. Ehrenberg and T. W. Steig.

Received 29 July 2008; accepted 23 December 2008.

J. E. Ehrenberg and T. W. Steig: Hydroacoustic Technology Inc., 715 NE Northlake Way, Seattle, WA 98105, USA. Correspondence to J. E. Ehrenberg: tel. +1 206 633 3383; fax +1 206 633 5912; e-mail: Consulting@HTISonar.com

Introduction

Acoustic tags have been used extensively for fresh-water (Steig, 1999; Steig *et al.*, 2000; Steig and Timko, 2000) and marine (Welch *et al.*, 2006) fish behaviour studies over the past several years. Advances in microelectronics have enhanced the capabilities that can be incorporated into both the acoustic tags and the associated receiving and processing systems. As a result, a number of types of signal have been proposed for tag systems. Many of the users of these systems are confused by the various options available.

The basic goal of all tag studies is to study fish behaviour by observing tagged fish as a function of time or location or both factors together. The easiest tag system to implement has identical signals transmitted by all units. This is sufficient as long as there is no desire to study the behaviour of a number of individual fish simultaneously. For this

type of tag, the measure of performance is simply the range at which the tag can be detected and, in some cases, tracked in three dimensions. However, in most cases, there is a desire to study the behaviour of multiple fish simultaneously. In this case, the signals transmitted by the tags must be encoded with a unique identifier that can be recovered by the receiving system. There are various signal-encoding methods that have been developed for providing unique tag identification (ID). The Methods section of this paper will develop the relationship between the tag-signal characteristics and detection range, three-dimensional tracking performance, and unique tag ID for two tag-encoding techniques representative of the two approaches that have been used. In one approach, all the identification information is encoded into the single transmission from the tag. In the other, the tag ID is extracted by processing multiple tag transmissions. A comparison of two commonly used tag systems is then presented in the results section.

Methods

The performance of an acoustic-tag system can be characterized by the range at which individual tags can be detected, the range that a tag can be accurately tracked, and the range at which a tag can be uniquely identified. Methods for determining the detections, tracking, and identification performance for tag systems are developed below.

The basic problem of detecting a signal in a noisy environment has been studied extensively in the radar, sonar, and signal-processing literature. An interesting result that has come out of these studies is that for conditions with no multipath and additive Gaussian noise, there is one optimal receiver structure for processing any transmitted radar/sonar signal, and a universal expression for characterizing the signal detection performance as a function of the signal-to-noise ratio (*SNR*). This optimal receiver is the incoherent matched filter. A block diagram of the receiver is illustrated Figure 1. A digital signal-processing method for implementing the incoherent matched filter has been described by Baggeroer (Oppenheim, 1978).

The threshold, T , is set, based on the noise level, to achieve a desired false detection rate. For a higher threshold, there will be fewer false alarms. However, a higher threshold will also reduce the probability of detecting an actual tag signal. The trade-off between the probability of detection and the probability of false alarm for a given *SNR* is characterized by the receiver's operating-characteristics curve illustrated in Figure 2 (Van Trees, 1968; Nielsen, 1991; Urick 1967).

The *SNR* is

$$SNR = \frac{2E_s}{N_o} = \frac{2P_s\tau}{N_o}, \quad (1)$$

where E_s is the total energy in the received signal, N_o is the acoustic-noise, power-spectral density, P_s is the received acoustic power, and τ is the signal duration. In the special case where the transmitted signal is a CW pulse, the receiver has a bandwidth, $BW = 1/\tau$ and

$$SNR = \frac{2P_s}{N_o BW} = 2 \frac{P_s}{P_N}, \quad (2)$$

where P_N is the noise power in the band. There are two interesting things to note from this result. First, the performance of the received signal depends on the energy in the received signal. The energy in a signal is the power in the signal times the duration of the signal. Second, it is only possible to achieve both a high probability of detection and a

low probability of false alarm when the SNR is greater than 10 to 12 dB, as demonstrated in Figure 2. As an example, a 10 dB SNR will provide greater than 90% probability of detection with a 0.01 probability of false alarm. This applies for each hydrophone that may be used.

Acoustic-tag systems capable of three-dimensional tracking are based on the same algorithms that are used to determine position accurately with the Global Position System, GPS (Parkinson and Spilker, 1996). The acoustic-tag signal must be received by at least four hydrophones. By knowing the positions of the four hydrophones and measuring the relative signal arrival times at the hydrophones, the location of a tagged fish can be estimated. The performances of acoustic-tag tracking systems are affected by acoustic noise, uncertainties in the sound speed, and multipath. An analysis of the effect of noise and uncertainties in sound speed has been presented in an earlier paper (Ehrenberg and Steig, 2002). They demonstrated that the standard deviation (s.d.) of the arrival time measurement is

$$\sigma_{rms} = \frac{1}{\sqrt{SNR BW}}, \quad (3)$$

where BW is the baseband-signal bandwidth. In the case of the standard CW-pulse signal, the baseband bandwidth, BW , is the reciprocal of τ . For example, a one ms long CW pulse signal has a baseband bandwidth of $1/.001 = 1000$ Hz. If the received signal level is ten times greater than the noise s.d. out of the matched filter ($SNR = 100$ or 20 dB), then, using this equation, the s.d. of the arrival-time measurement is 0.1 ms. If one attempts to increase the SNR for a CW signal by transmitting a longer pulse, the required bandwidth is decreased as the inverse of the pulse length, and the denominator in the equation for the s.d. remains constant. Similarly, if a shorter pulse is used with a wider bandwidth, the increase in the bandwidth is cancelled by a decrease in the SNR (Ehrenberg and Torkelson, 2000). The way to get around this limitation is to use a wideband signal waveform such as a Barker-encoded signal, rather than a CW pulse. Barker-encoded signals are implemented using phase-reversal encoding to achieve higher time-resolution measurement (Ehrenberg and Steig, 2003). The implementation of an incoherent, matched-filter receiver for phase-encoded signals, such as the Barker-encoded signal, has been described by Baggeroer (ibid). The effects of multipath on tracking performance can vary greatly depending on the acoustic environment. In general, multipath effects decrease as the temporal resolution of the signal increases. Therefore, another advantage of a wideband signal, such as the Barker-encoded signal, is that it minimizes the adverse effects of multipath.

For three-dimensional positioning, it must be emphasized that there must be sufficient SNR at the receiving hydrophones to assure that there is a high probability of detecting the tag signal simultaneously at four hydrophones. For the single-hydrophone-detection criteria of a 90% probability of detection and 0.01 probability of false alarm, there is a 65% probability of simultaneous detections on four hydrophones. Most biological-behaviour studies using acoustic tags require that the individually tagged fish can be uniquely identified. This can be achieved by a variety of signalling schemes. Two techniques that are being used will be considered here. The first uses a signalling scheme where the signal from each tag is encoded with a unique digital ID.

This approach is being used by the Juvenile Salmon Acoustic Telemetry System (JSATS; US Army Corps of Engineers, 2006) and its signal design is displayed in Figure 3. The tag signal is encoded using differential phase-shift keying, DPSK. The advantage of DPSK is that it does not require an exact knowledge of the carrier phase at the receiver

(Haykin, 1973). The '1's and '0's are encoded by differentially changing the phase of an individual bit relative to the phase of the previous bit. The first bit is used as a phase reference. If the next bit is a '0', the phase is not changed, and if it is a '1', the phase is shifted by 180°. For the JSATS signal, the first bit provides the phase reference, and the next seven bits are a Barker-encoded sequence used for tag detection. The next 16 bits have the unique tag ID (65 535 possible codes), and the last 8 bits are used for error detection and correction. The advantage of the approach is that each transmitted tag signal contains the unique ID. The disadvantage is that range, tag ID, and tracking performance is adversely affected by including all of this information into a single pulse. Note that only 7/32 or 22% of the energy is used for tag detection and 1/32 or 3% of the energy is used for each bit of the unique ID code. The eight parity bits can correct any single bit error that occurs in the 32 bit sequence. For the binary-phase encoded signal with single bit error correction, the *SNR* per bit must be sufficient to result in 23 of the 24 information plus parity bits being correct. A 5 dB *SNR* per bit will provide a 0.1 probability of incorrectly decoding the tag ID. However, because only 1/32 of the energy is in each bit, the *SNR* for the total encoded signal required to achieve this identification performance is $10 \log(32) + 5 = 20$ dB.

The second approach uses multiple transmissions from the tag to provide the unique ID. This approach has been adopted by Hydroacoustic Technology Incorporated (HTI). The HTI signal is illustrated in Figure 4. Rather than encoding the unique code in the transmitted signal, the ID is encoded in the period between pulses.

The advantage of this period-encoding scheme is that all the energy in each transmitted signal is used in both the detection and tag ID. The disadvantage is that at least two sequential tag transmissions must be used for period measurements and the period timing must be tightly controlled. The jitter in the period of the signal is minimized by using a crystal-controlled oscillator in the tag. In this case, the performance is limited by the *SNR* for the received pulse. For typical *SNRs*, period differences of less than 1.0 ms can be accurately measured. Ehrenberg and Steig (2002) demonstrated that the s.d. in the arrival time for a 20 dB *SNR* is 0.1 ms. Other potential issues with the period-encoding scheme are the effect of multiple tags within a given area and the number of possible unique codes. Various methods have been developed for distinguishing the signal from individual tags. One visual method for identifying the tag period utilizes an echogram for displaying the signals, with the vertical scale equal to the tag period and the horizontal axis corresponding to the scan number (Ehrenberg and Steig, 2003). They also established that by utilizing this method, large numbers of tags (greater than 50) could be tracked simultaneously by the tag receiver without confusion between individual tags. The number of possible codes is determined by the selection of the encoding periods. For example, by varying the periods over a ten-second interval, 10 000 unique codes can be achieved. By using two pulses at 15 unique time slots, 150 000 unique codes can be achieved.

The ranges at which a tag can be detected, uniquely identified, and accurately tracked, provide a useful measure of the performance of a tag system. In all cases, the range performance depends on the received *SNR*, as defined in (1) and can be written in dB as

$$SNR = 10 \log(2) + P_s + 10 \log(\tau) - N_o, \quad (4)$$

where P_s and N_o are in dB. The received power is a function of the tag's acoustic source level, SL , the range from the tag to the hydrophone, R , and the acoustic absorption α (dB m^{-1}). Therefore, *SNR* in dB is

$$SNR = 10\log(2) + SL - 20\text{Log}(R) - \alpha R + 10\log(\tau) - N_o, \quad (5)$$

where N_o is in dB. Note that τ depends on how the signal is being used. In particular, for the binary-phase-encoded signal illustrated in Figure 3, the signal duration for detection and tracking is the length of the seven Barker-encoded bits. However, the single bit duration must be used to determine the SNR and to calculate bit-error probability for tag ID. For the period-encoded signal illustrated in Figure 4, the entire signal is used for determining whether there is detection, and for identification and tracking.

Results

This section presents a comparison of the detection, tracking and identification performance of two common applications of acoustic-tag systems. One very common application for tags is to study the behaviour of fish near hydropower dams. The second application is for an open-river environment. The acoustic noise near a hydropower dam can be very high and is typically at least 20 dB higher than it would be in an open river.

Figure 2 reveals that the received SNR must be at least 5 dB to get acceptable detection performance; a 5 dB SNR will provide a probability of detection of 0.65 with a probability of false alarm of 0.1. For three-dimensional tracking, which requires simultaneous tag detections on four hydrophones, a 5 dB SNR would provide a probability of detection of only 0.18 with a probability of false alarm of 0.1. As stated earlier, a 10 dB SNR will provide a 0.65 probability of four detections with a 0.01 probability of false alarm at each hydrophone.

For the period-encoded signal, a 5 dB SNR will result in sufficient tag detections to allow the period to be measured and the tag uniquely identified. The encoded signal requires a 5 dB SNR per bit for tag ID. However, as pointed out earlier, a 5 dB SNR per bit is equivalent to a 20 dB SNR for the total signal, because there is only 1/32 of the energy in each bit.

The relative performance of a period-encoded tag and a binary-phase-encoded tag in a hydropower-dam and in an open-river environment illustrated in Figures 5 and 6 respectively. The tag and environmental parameters used for this comparison are typical of values for these applications. The acoustic frequency of the tag is 300 kHz. The fresh-water acoustic absorption is 28 dB km⁻¹. The source level produced by the tag is 150 dB|| μPa , and the total pulse length is 1 ms. The noise spectral density at the dam is assumed 70 dB|| μPa in a one Hz bandwidth and is 50 dB|| μPa in a one Hz bandwidth in the open river. These noise spectral-density values are typical of what has been measured at actual tag-deployment sites. The plots clearly display the binary-phase-encoded-pulse, signal-performance penalty that results from partitioning the signal into a seven-bit sequence used for detection and tracking and a twenty-four-bit segment used for ID and error correction. For the dam environment (Figure 5), the binary-phase-encoded signal had a detection range of approximately 75 m, a tracking range of approximately 50 m, and an identification range of less than 25 m. The period-encoded pulse has a detection and identification range of approximately 140 m and a tracking range of about 90 m. Figure 6 demonstrates the same relative performance for an open-river environment. The ranges achieved for the river environment are greater because of the lower noise present.

For three-dimensional tracking studies, the individual fish must be detectable over the entire area of interest. Therefore, the number of receiving hydrophone systems that the encoded-pulse technique will require to provide equivalent detection-tracking performance will be between 5.7 and 14.4 times the number that the period-encoded

technique will need. This is because the number of hydrophone systems required to cover a given area is proportional to the square of the distance between hydrophones. For line-array studies designed to determine the number of migrating fish passing a point in the river, the number of hydrophone systems required for the encoded-pulse technique is between 2.4 and 3.8 times that required for the period-encoded approach.

Alternatively, if the same number of detection-hydrophone systems were used in a line array to detect period-encoded-signal tagged fish and the binary-encoded-signal tagged fish, there would be lower detectability of the latter. As an example, to achieve similar precision in paired-release detection studies comparing acoustic tags and passive, integrated-transponder (PIT) tags, approximately 100 times more PIT tags are required (Steig *et al.*, 2005). This is because they have limited detection ranges (0.3–0.6 m) and the detectors are primarily installed in relatively small bypass channels, pipes, and fish ladders. As a comparison, acoustic tags have relatively large detection ranges (100+ m) and are primarily installed in front of dams and in open rivers. For acoustic tags, this greater detection range translates into higher detection rates compared with PIT tags. The higher detection rates for acoustic tags translate into smaller sample sizes to achieve comparable precision estimates. For the same reason, the binary-encoded tags have shorter detection ranges than the period-encoded tags and require a significant increase in sample size of the tagged fish to achieve comparable precision as the period-encoded tags. This translates into increased costs that stem from the additional number of tags and hydrophones required. This in turn results in increased deployment and analysis efforts.

Conclusion

This paper describes the detection, tracking, and identification performance as a function of range for two commonly used acoustic-tag signals. Directly compared are the binary-phase-encoded and period-encoded signalling schemes for the same set of operating parameters (e.g. pulse length and source level), therefore both tags should have similar size and tag life. Because the period-encoded technique uses all the energy in the pulse for detection, tracking, and identification, its range performance is significantly better. Thus, the number of hydrophone receivers required to cover a specific area will be less. The price paid for this increased performance is additional complexity in the processing required to extract the unique tag ID.

References

- Ehrenberg, J. E., and Steig, T. W. 2002. A method for estimating the “position accuracy” of acoustic fish tags. *ICES Journal of Marine Science*, 59: 140–149
- Ehrenberg, J. E., and Steig, T. W. 2003. Improved techniques for studying the temporal and spatial behaviour of a fish in a fixed location. *ICES Journal of Marine Science*, 60: 700–706
- Ehrenberg, J. E., and Torkelson, T. C. 2000. FM slide (chirp) signals: a technique for significantly improving the signal to noise performance in hydroacoustic assessment systems. *Fisheries Research*, 47: 193–199.
- Nielsen, R. O. 1991. *Sonar Signal Processing*, Artech House, Boston 367 pp.
- Parkinson, B. W., and Spilker, J. J. 1996. *Global Positioning System: theory and practice*, Volume I. American Institute of Aeronautics and Astronautics, Inc. Washington DC. 834 pp.

- Oppenheim, A. O. Editor 1978, Applications of Digital Signal Processing. Prentice-Hall, New Jersey. 499 pp.
- Steig, T. W. 1999. The use of acoustic tags to monitor the movement of juvenile salmonids approaching a dam on the Columbia River. Proceeding of the 15th International Symposium on Biotelemetry, Juneau, Alaska, 9–14 May 1999.
- Steig, T. W., and Timko, M. A. 2000. Using acoustic tags for monitoring juvenile chinook and steelhead migration routes in the forebay of Rocky Reach Dam during the spring and summer of 1999. Report to Chelan County PUD No. 1, Wenatchee, Washington, by Hydroacoustic Technology, Inc., Seattle, Washington.
- Steig, T. W., Skalski, J. R., and Ransom, B. H. 2005. Comparison of acoustic and PIT tagged juvenile Chinook, Steelhead and Sockeye Salmon (*Oncorhynchus* spp.) passing dams on the Columbia River, USA. Aquatic telemetry: advances and applications. Proceedings of the Fifth Conference on Fish Telemetry held in Europe. Ustica, Italy, 9–13 June 2003. Rome, FAO/COISPA. 2005. 295 pp.
- Urick, R. J. 1967. Principles of Underwater Sound for Engineers, pp 309–310, McGraw Hill, New York. 342 pp.
- US Army Corps of Engineers, Portland District, 2006, Request for proposal W9127N-06-R-0031, Juvenile Salmonid Acoustic Telemetry Systems (JSATS).
- Van Trees, H. L. 1968. Detection, Estimation and Modulation Theory, Part 1. John Wiley, New York. 697 pp.
- Welch, D. E., Gaboury, I., Melnychuk, and O’Dor, I., R 2006. Application of the Pacific Ocean shelf tracking system (POST): a permanent continental-scale acoustic tracking array for fisheries research and Ocean Observation. Oceans 2006: 1–5.

Figure captions

Figure 1. Optimum receiver for detecting a transmitted tag signal.

Figure 2. Probability of detection and false alarm as a function of the received signal-to-noise ratio output from the incoherent matched filter.

Figure 3. Structure for the differential phase-encoded signal used for the JSAT tag.

Figure 4. Structure for the HTI tag signal with identification encoded in the period.

Figure 5. Received *SNR* as a function of range for 1 msec binary phase-encoded and period-encoded pulses for a typical noise environment at a dam.

Figure 6. Received *SNR* as a function of range for 1 msec binary phase-encoded and period-encoded pulses for a typical noise environment in an open river.

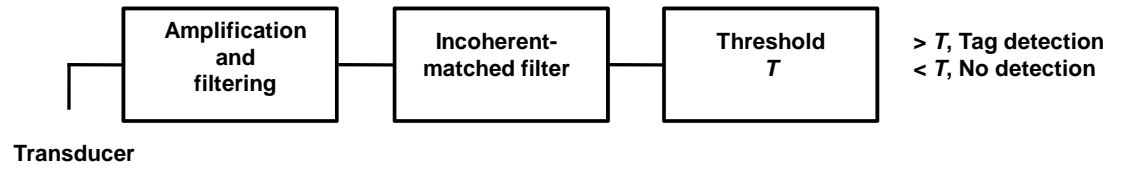


Figure 1

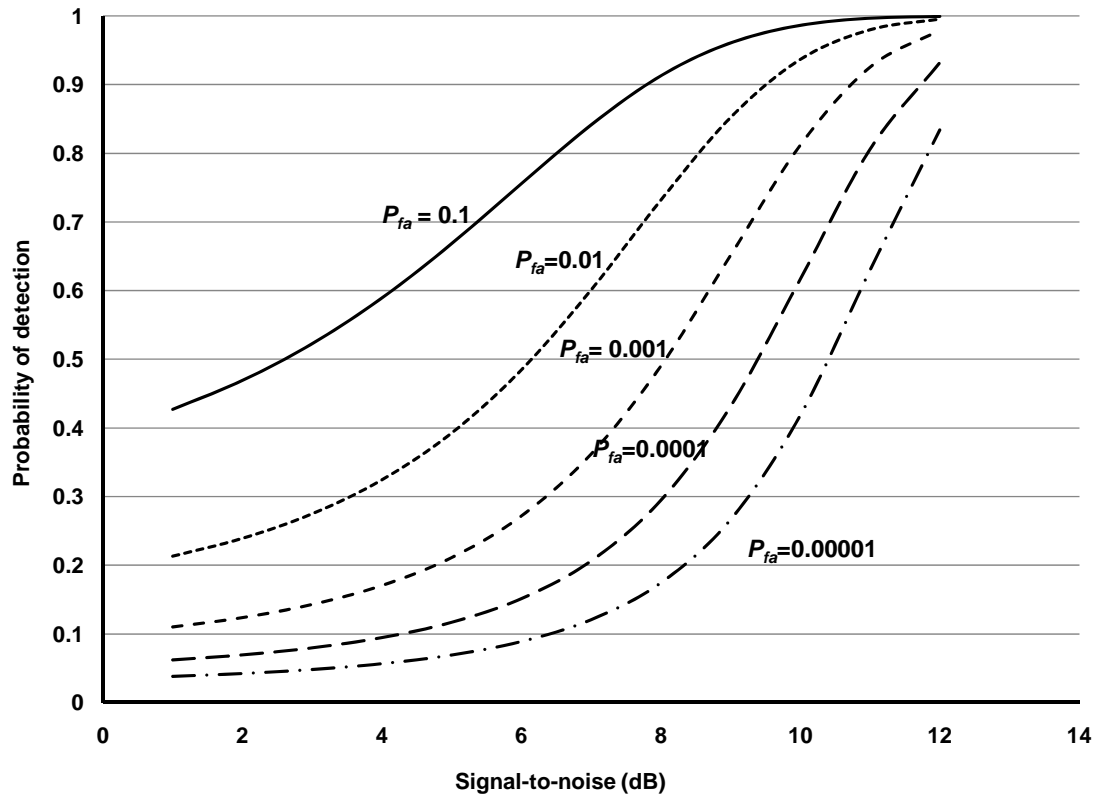


Figure 2

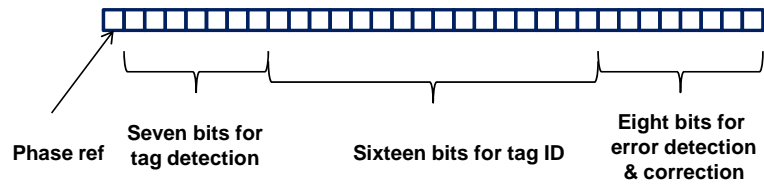


Figure 3

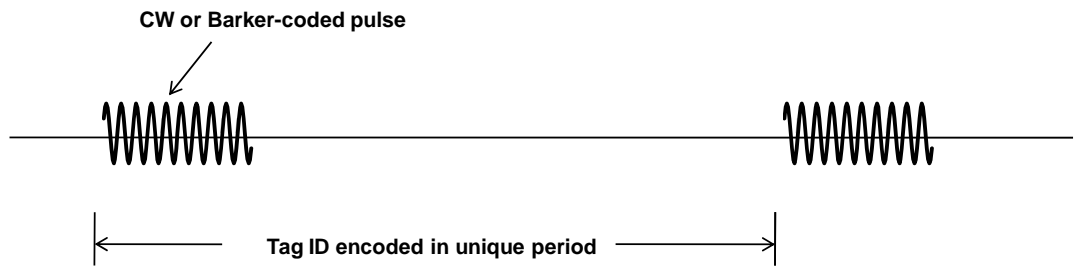


Figure 4

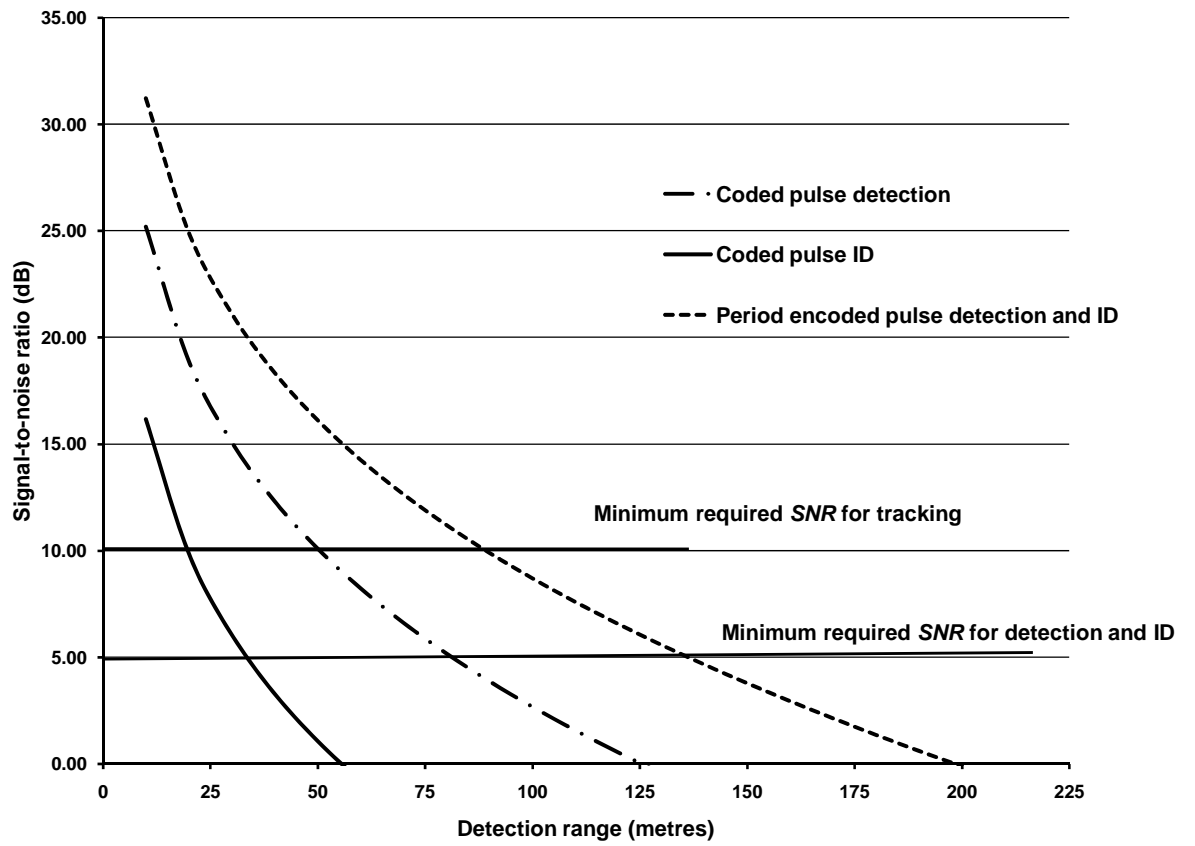


Figure 5

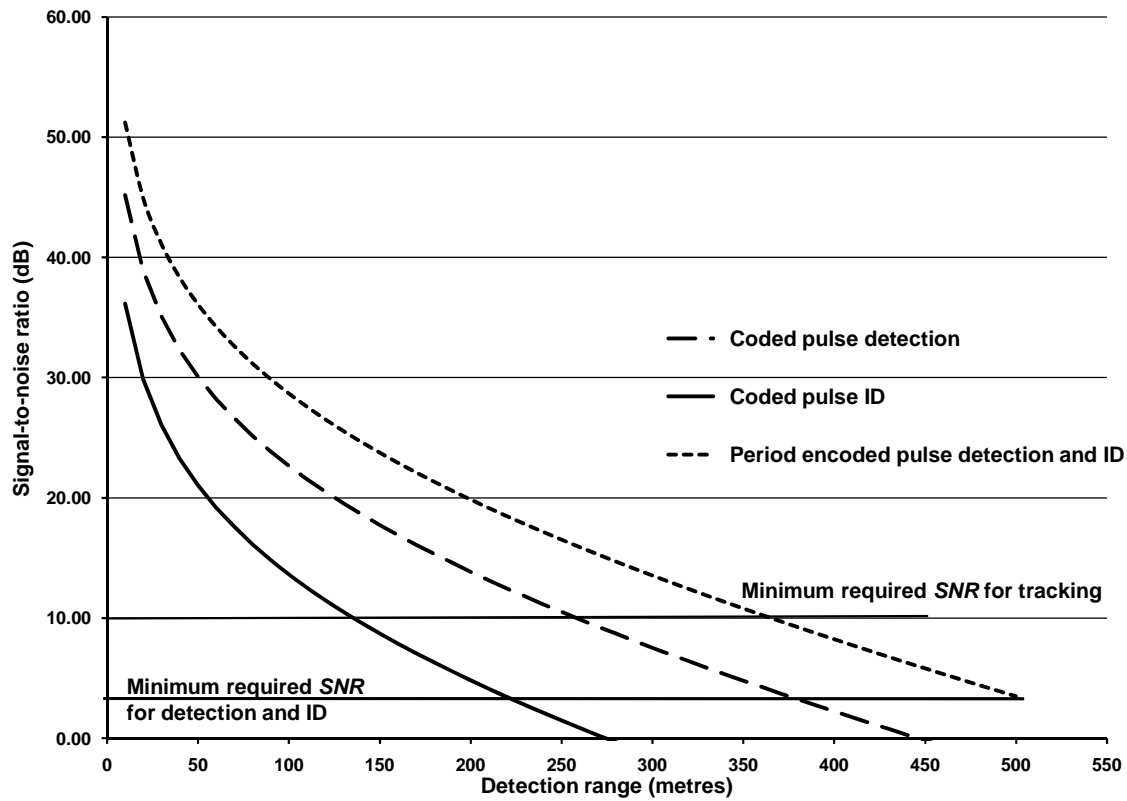


Figure 6