

# A Comparison of Broadband and Narrowband Fisheries Sonar Systems

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## Abstract

Some of the differences between broadband and narrowband sonar systems applied in fisheries hydroacoustics are examined. Following a brief discussion of the advantages and disadvantages of broadband sonar, three different aspects of narrowband and broadband sonar systems are compared: detection, Doppler processing, and split-beam localization. Summaries are provided that compare representative broadband and narrowband sonar systems.

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## Table of Contents

<b>TABLE OF CONTENTS</b> .....	<b>I</b>
<b>LIST OF FIGURES</b> .....	<b>II</b>
<b>LIST OF TABLES</b> .....	<b>II</b>
<b>1 INTRODUCTION</b> .....	<b>3</b>
<b>2 ADVANTAGES AND DISADVANTAGES OF BROADBAND SONAR SYSTEMS</b> .....	<b>3</b>
2.1 ADVANTAGES OF BROADBAND SONAR .....	3
2.1.1 <i>Species Identification</i> .....	3
2.1.2 <i>Target Detection</i> .....	4
2.1.3 <i>Target Size Discrimination</i> .....	4
2.1.4 <i>Stable Signal Estimate</i> .....	4
2.2 DISADVANTAGES OF BROADBAND SONAR.....	5
2.2.1 <i>Lower PRF</i> .....	5
2.2.2 <i>Blanking Range</i> .....	5
2.2.3 <i>Increased Reverberation</i> .....	5
2.2.4 <i>More Complex Processing</i> .....	5
<b>3 DETECTION</b> .....	<b>5</b>
3.1 SONAR EQUATION .....	6
3.1.1 <i>Basic Active Sonar Equation</i> .....	6
3.1.2 <i>Broadband Active Sonar Equation with Reverberation</i> .....	6
3.2 PULSE COMPRESSION .....	6
3.2.1 <i>Linear Frequency Modulation (Chirp)</i> .....	6
3.2.1.1 <i>Basic Concept</i> .....	7
3.2.1.2 <i>Incremental-Frequency Explanation</i> .....	7
3.2.1.3 <i>How Range Resolution Is Improved</i> .....	8
3.2.1.4 <i>Relative Merits of Chirp</i> .....	8
3.2.2 <i>Binary Phase Modulation</i> .....	8
3.2.2.1 <i>Basic Concept</i> .....	9
3.2.2.2 <i>Sidelobes</i> .....	10
3.2.2.3 <i>Limitations of Phase Coding</i> .....	10
3.3 THE TIME-BANDWIDTH PRODUCT (TB).....	10
3.3.1 <i>Time-Bandwidth and Range Resolution</i> .....	11
3.3.2 <i>Comparing Narrowband and Broadband Range Resolution</i> .....	11
3.4 PROCESSING GAIN (PG) .....	12
3.4.1 <i>PG Equation</i> .....	12
3.4.2 <i>Comparing Narrowband and Broadband PG</i> .....	12
3.5 REVERBERATION LEVEL (RL) .....	12
3.5.1 <i>RL Equation</i> .....	12
3.5.2 <i>Comparing Narrowband and Broadband RL</i> .....	13
3.6 SUMMARY OF NARROWBAND/BROADBAND SONAR EQUATION COMPARISON .....	13
<b>4 DOPPLER PROCESSING</b> .....	<b>14</b>
4.1 NARROWBAND (INCOHERENT) AND BROADBAND (COHERENT) DOPPLER MEASUREMENTS, BASED UPON ZEDEL 14	
4.2 DOPPLER-BASED RIVERINE SONAR .....	16
4.3 COMPARING NARROWBAND AND BROADBAND DOPPLER RESOLUTION .....	17



**5 SPLIT-BEAM LOCALIZATION ..... 17**  
5.1 SPLIT-BEAM ANGULAR RESOLUTION ..... 17  
5.2 PHASE ANGLE RESOLUTION..... 18  
**6 SUMMARY..... 18**  
**7 REFERENCES..... 19**

**List of Figures**

Figure 1. Characterization of Stable Signal Estimation with Broadband Sonar.....4  
Figure 2. Characterization of Pulse Compression. From Stimson (1983).....7  
Figure 3. Characterization of Binary Phase Modulation. From Stimson (1983).....8  
Figure 4. Example of 3-Digit Binary Phase Modulation. From Stimson (1983).....9  
Figure 5. Example of 7-Digit Binary Phase Code. From Stimson (1983). ..... 10

**List of Tables**

Table 1. Summary of Narrowband and Broadband Sonar Performance..... 13



## 1 Introduction

Broadband sonar systems offer some advantages over the traditional narrowband fisheries sonar systems that are predominantly used today. In the first section that follows, some of these advantages and disadvantages are discussed. There are three specific aspects of sonar systems that then compared. First, in §3, is an examination of the differences in target detection between the two types of sonar systems. Then, in §4, is a review of incoherent and coherent Doppler measurements, based on the work of Zedel. Finally, in §5, is a comparison of split-beam localization using these different sonar systems. The final section of the paper summarizes our comparison and provides concluding comments.

## 2 Advantages and Disadvantages of Broadband Sonar Systems

How is broadband different from narrowband? What are the advantages? What are disadvantages? Each of these topics is discussed below.

### 2.1 Advantages of Broadband Sonar

There are four primary advantages of broadband sonar over the existing narrowband systems: (1) spectral information for species identification, (2) improved target detection, (3) more stable estimate of signal, and (4) improved target resolution. Each of these is addressed in the following three sections.

#### 2.1.1 Species Identification

Recently, the fisheries hydroacoustics community has began looking at broadband (and wideband) sonar as method for assessing fish stocks. In the plenary address at the 1995 *ICES International Symposium on Fisheries and Plankton Acoustics* held in Aberdeen Scotland, David MacLennan (1996), one of the most distinguished members of the fisheries hydroacoustics community, gave his impression of what might lie ahead (pg. 515, emphasis added by SciFish):

*In spite of the availability of an impressive suite of analytical tools such as neural net processing, expert systems, and new methods of discriminant analysis, we believe that these data processing aids cannot successfully resolve the problem of acoustically aided species identification without being fed clues with better discrimination capabilities than are available at present. In general, existing survey techniques do not measure many of the features that are necessary for accurate target classification. In the most, general case, it may well be impractical to extract good classification clues from an acoustics sensor that is optimized for biomass assessment. A well-established theorem in information theory holds that the information-carrying capacity of a communications channel depends on its bandwidth. Thus, **the trend toward the use of wideband systems is likely to be a fruitful approach.***

*Increasing the bandwidth in acoustical signal processing has the potential to achieve greater overall resolution with an acoustical sensor. In essence, one improves the ability to distinguish the individuals in a school or aggregation and perhaps even the component parts of individual animals. Information so derived provides detail for examining structure, shape, ping-to-ping motion, and **fine-scale distribution**. In addition to increasing range resolution, there are other dimensions to be explored, such as **spectral analysis** of echoes using the Doppler affect to reveal target motion and behavior.*

SciFish and their strategic partner, RD Instruments, have built nearly ten broadband sonar systems for fish identification and demonstrated repeatedly that it is capable of fish species identification using the data collected. SciFish is now making a commercial version of the system under a mutually exclusive arrangement with RD Instruments (SciFish 2000). The later section on Classification describes the preliminary classification results we have achieved in the Kenai River during Phase I, where we were able to discriminate sockeye from chinook salmon 90% of the time.



**2.1.2 Target Detection**

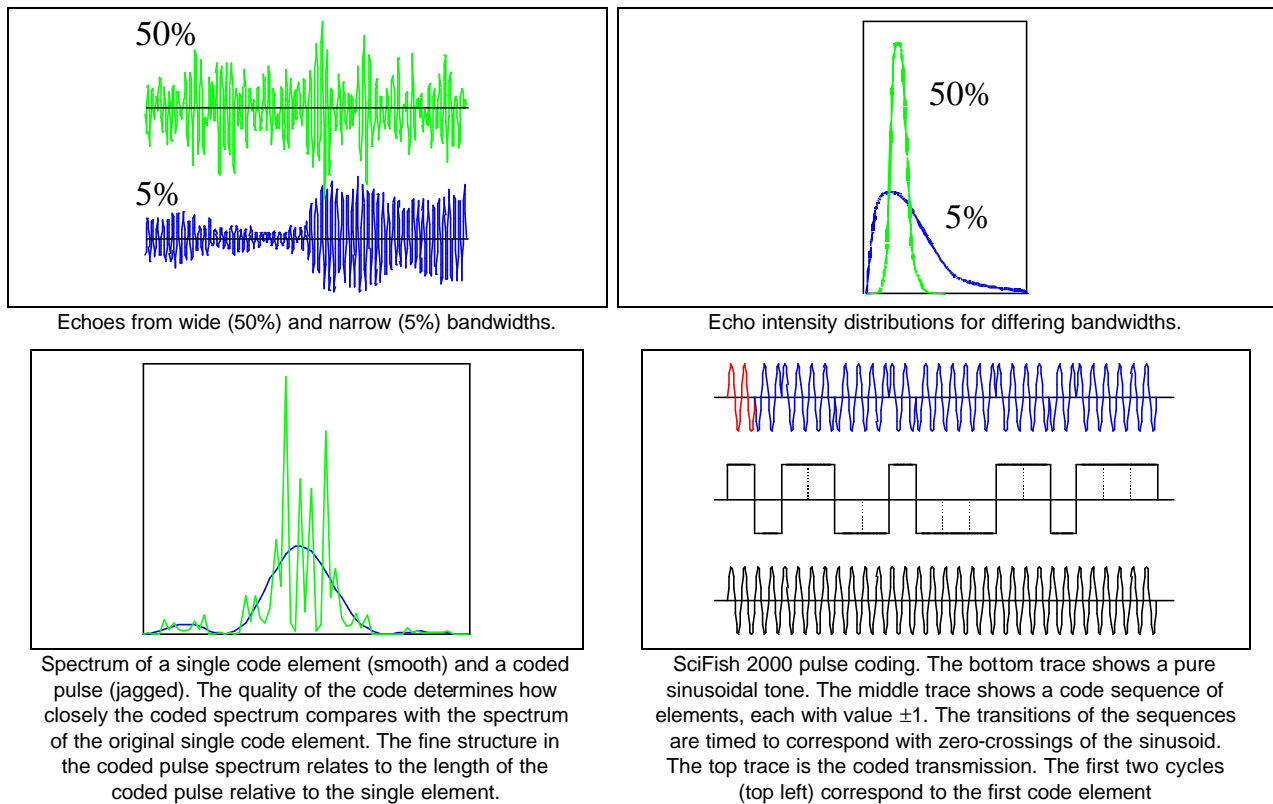
Ideally, if we wanted both long detection range and fine range resolution, we would transmit extremely narrow pulses of exceptionally high peak power. But there are practical limits on the level of peak power one can use. We have learned from airborne radar signal processing that we can obtain long detection ranges at reasonable ping rates by using fairly wide pulses.

One solution to this dilemma is pulse compression. That is, transmit internally modulated pulses of sufficient width to provide the necessary average power at a reasonable level of peak power; then “compress” the received echoes by decoding their modulation.

The two most common methods of coding are line frequency modulation and binary phase modulation. Each of these is described in the later section on Pulse Compression where we illustrate how broadband sonar can improve the target detection by nearly 19 dB over the current narrowband systems in use today.

**2.1.3 Target Size Discrimination**

One of the more powerful attributes of broadband sonar systems is the ability to exploit the time-bandwidth product to realize improved target size discrimination. The wider the bandwidth and the longer the pulse duration, the better the range resolution, and hence the target discrimination. As we show in the later section on Time-Bandwidth Product, the SciFish broadband sonar provides 1 cm range resolution, more than a 10-fold improvement over the current narrowband sonar systems in use today.



**Figure 1. Characterization of Stable Signal Estimation with Broadband Sonar**

**2.1.4 Stable Signal Estimate**

Broadband echoes enable more stable estimates of echo intensity. **Figure 1** illustrates narrow and broad bandwidth echoes. The assumption is that the background scatterers are uniformly distributed and the same for both echoes. The narrow bandwidth echo was chosen to illustrate the effects of “Rayleigh fading”—this is the



substantial difference in the echo intensity between the first and second halves of the echo. In contrast, the intensity of the broad bandwidth echo is more constant. **Figure 1** shows the associated probability distributions of echo intensity. The narrow bandwidth has a chi-squared distribution with 2 DOF while the broad bandwidth distribution is the same but with more degrees of freedom (DOF). More DOF means less variation in intensity plus less chance of echo intensity being near zero (the Raleigh fading).

The key point of the **Figure 1** is that the broadband backscatter gives a more stable representation of the scatterers actually present in the water. To understand how this broadband approach works, consider first that a short pulse separates targets better than a long pulse. Then consider the different approaches narrowband and broadband systems use to obtain longer pulses to profile greater distances. Narrowband systems transmit longer pulses by simply lengthening their monochromatic pulse. The consequence is that they obtain coarser spatial resolution. In contrast, broadband systems transmit coded pulses—the code element length is the same as the original short pulse (see figures below). The objective is to retain the bandwidth of the single code element even though coding lengthens the pulse. With the use of the signal autocorrelation, one can recover an effective pulse length that is the same as the original short pulse.

## 2.2 Disadvantages of Broadband Sonar

### 2.2.1 Lower PRF

Longer pulses mean lower pulse repetition frequency (PRF). The difference between the pulse widths between narrowband and broadband pulses defines the amount of time difference. But, when taking into account the need to wait for a complete round trip for each acoustic ping to the desired range, this limitation is not significant.

### 2.2.2 Blanking Range

When the pulse is being transmitted, it is not possible to simultaneously listen. This limits the close range of the transducer. The far field for the 4 degree SciFish 2000 is approximately 3 m, so the blanking range, which is exactly as long as the pulse, would still place targets in the near field. Having said this, it is still well known that sockeye salmon do tend to travel closer to the shore, so this would require that the transducer be aimed downstream to provide the greatest probability of detection.

### 2.2.3 Increased Reverberation

Longer pulses could mean more reverberation, but with matched filter (pulse compression) detections being used, the reverberation level is measured at the compressed time interval. A comparison of narrowband and broadband reverberation estimates is found later in this document.

### 2.2.4 More Complex Processing

It is undeniable that broadband sonar signal processing is more complex than its narrowband counterpart. But, the signal processing that is being used is well understood and has been applied and used in a wide range of applications. In addition, the speed of processing has grown dramatically, placing the processing requirements well within the range of current technology. This subject is specifically addressed near the end of this document.

## 3 Detection

The ability to detect an echo from a target decreases with range. Loss of echoes with increasing range results from lower signal-to-noise ratios (SNR's) for long-range acoustic signals in the riverine environment. While it is difficult to characterize the acoustic condition with a simple model, the primary acoustic mechanisms for the low SNR include the following (Xie, 2000):

- Increase of volume reverberation with range;
- Amplification of ambient noise level by the time-varying gain;



- Scattering and absorption of acoustic energy by fish targets, especially at heavy densities;
- Acoustic shadowing by irregular topography and surface bubbles; and
- Dissipation of acoustic energy with range, especially at high frequencies.

In the following sections, various aspects of this detection loss will be examined by building the sonar equation for the riverine environment and providing comparative values for two existing narrowband and broadband sonar systems.

### 3.1 Sonar Equation

All the characteristics of the sonar system, the sound transmission, and the scattering characteristics of the objects are combined in the sonar equation. The sonar equation is usually expressed in decibels after all quantities have been made dimensionless by the use of reference distances and reference sound pressures.

#### 3.1.1 Basic Active Sonar Equation

The active-sonar equation for the monostatic case in which the source and the receiver are coincident and in which the acoustic return of the target is back toward the source is:

$$SL - 2TL + TS - (NL - DI) = DT$$

where:

SL = Projector Source Level

TL = Transmission Loss

TS = Target Strength

NL = Noise Level

DI = Directivity Index

DT = Detection Threshold

#### 3.1.2 Broadband Active Sonar Equation with Reverberation

The basic sonar equation must be modified to include two additional terms that are significant to the development of a broadband riverine sonar. These are:

PG = Processing Gain from exploiting the time-bandwidth product for detection

RL = Reverberation Level, both from volume reverberation and surface reverberation

Which results in the modified sonar equation

$$SL - 2TL + TS + PG - (RL + NL - DI) = DT$$

### 3.2 Pulse Compression

#### 3.2.1 Linear Frequency Modulation (Chirp)

Because it is similar in sound to the chirping of a bird, this method of coding was called “chirp” by its inventors. Since it was the first pulse compression technique, some people still use the terms chirp and pulse compression synonymously.

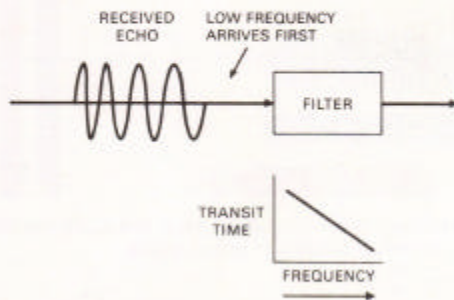


3.2.1.1 Basic Concept

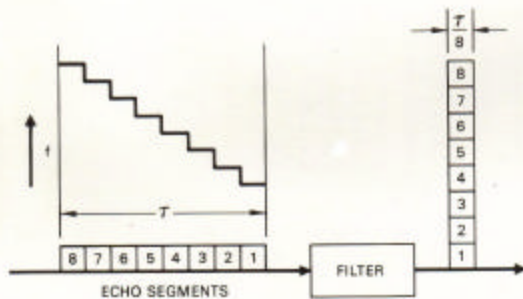
With chirp, the sonar frequency of each transmitted ping is increased at a constant rate throughout its length. Every echo, naturally, has the same linear increase in frequency.

The received echoes are passed through a filter. It introduces a time lag that decreases linearly with frequency at exactly the same as the frequency of the echoes increases. Being of progressively higher frequency, the trailing portions of an echo take less time to pass through the leading portion. Successive portions thus tend to bunch up. Consequently, when the pulse emerges from the filter its amplitude is much greater and its width much less than when it entered. The pulse has been compressed.

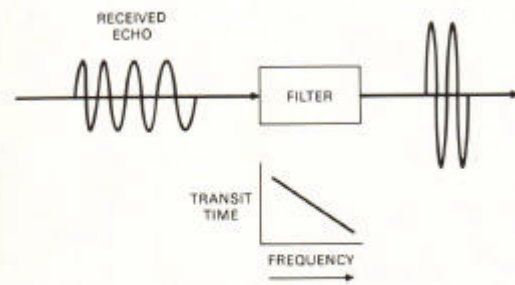
All methods of pulse compression are essentially matched filtering schemes in which the transmitted pulses are coded and the received pulses are passed through a filter whose time-frequency characteristic is the conjugate (opposite) of the coding.



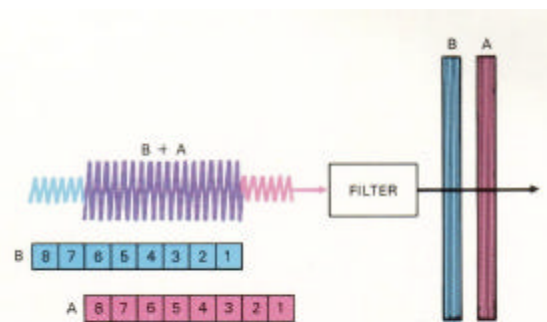
With chirp, transmitter frequency is increased linearly throughout pulse. Echo is passed through filter that introduces time lag inversely proportional to frequency.



Linear frequency modulated pulse can be thought of as being made up of segments of progressively higher frequency. In going through filter, second segment catches up with first; third, with second; etc.



Since trailing portions of echo take less time to pass through filter, successive portions tend to bunch up; amplitude of pulse is increased and width is decreased.



Echoes from closely spaced targets, A and B, are merged but, because of coding, separate in output of filter.

Figure 2. Characterization of Pulse Compression. From Stimson (1983).

3.2.1.2 Incremental-Frequency Explanation

What actually happens when an echo passes through the filter can be visualized most easily if we think of the echo as consisting of a number of segments of equal length and progressively higher frequency. In fact, in one form of pulse coding—incremental frequency modulation—the transmitted wave is modulated in exactly this way. The first segment, having the lowest frequency, takes longest to get through the filter. The second segment takes less time than the first; the third less time than the second, etc.



The increments of frequency are such that the difference in transmit time for successive segments just equals their width. If the segments are 0.1 microseconds wide, the first segment takes 0.1 microseconds longer to go through than the second; it, in turn, takes 0.1 microseconds longer to get through than the third, etc. As a result of passing through the filter, the second segment catches up with the first; the third segment catches up with the second; the fourth segment catches up with the third, and so on. All segments thus combine and emerge from the filter at one time. The output pulse is only a fraction of the width of the received echo; yet, it has many times its peak power.

### 3.2.1.3 How Range Resolution Is Improved

**Figure 2** shows what happens when the echoes from two closely spaced targets pass through the filter. Since the range separation is small compared to the pulse length, the incoming echoes are merged indistinguishably. In the filter output, however, they appear separately—staggered by the targets' range separation.

It seems like magic... until you consider the coding. Because of it, each segment of the echo from the near target emerges from the filter at the same time as the first segment of this echo. And each segment of the echo from the far target emerges as the same time as the first segment of that echo. The difference between these times, of course, is the length of time the leading edge of the transmitted pulse took to travel from the first target to the second and back.

The range resolution is thus improved by the ratio of the width of the individual segments to the total width of the pulse.

### 3.2.1.4 Relative Merits of Chirp

Linear frequency modulation has the advantage of enabling very large compression ratios to be achieved. In addition, it is comparatively simple. No matter when a pulse is received or what its exact frequency is, it will pass through the filter equally well and with the same amount of compression.

The principal disadvantage is a slight ambiguity between range and Doppler frequency. If the frequency of a pulse has been, say, increased by a positive Doppler shift, the pulse will emerge from the chirp filter a little sooner than if there were no such shift. The sonar will have no way of telling whether this difference is due to a Doppler shift or to the echo being reflected from a slightly greater range.

## 3.2.2 Binary Phase Modulation

As the name implies, in this type of coding the frequency phase of the transmitted ping is modulated, and the modulation is done—as in incremental frequency modulation—in finite increments. Here, though, only two increments are used:  $0^\circ$  and  $180^\circ$ .

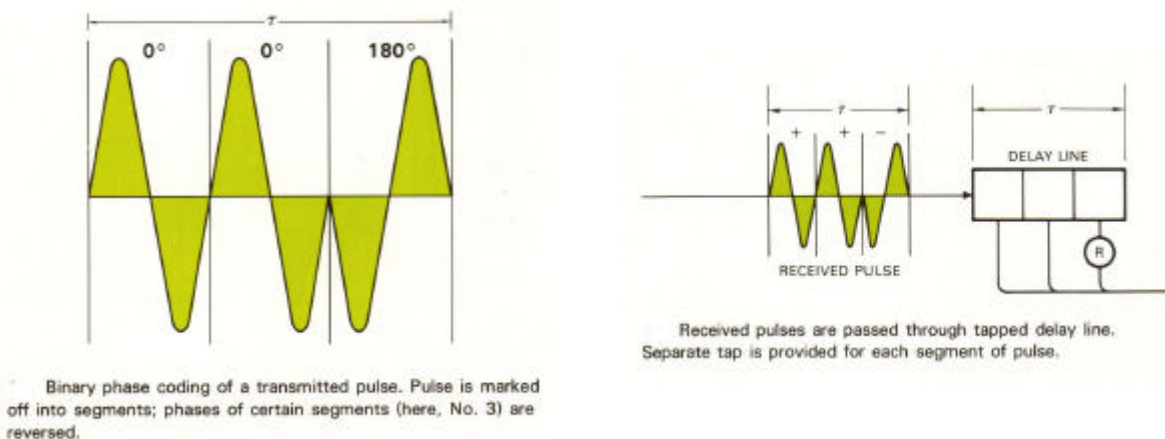


Figure 3. Characterization of Binary Phase Modulation. From Stimson (1983).



### 3.2.2.1 Basic Concept

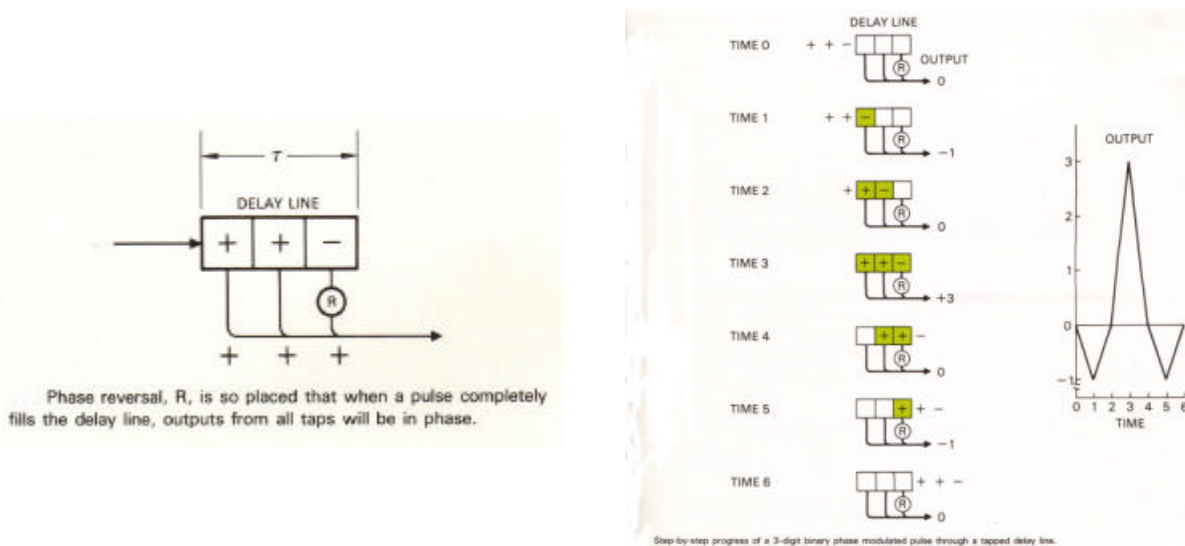
Each transmitted pulse is, in effect, marked off into narrow segments of equal length. The frequency phase of certain segments is shifted by  $180^\circ$ , according to a predetermined binary code. This is illustrated for a three-segment code in the figure below (**Figure 3**). A common shorthand method of indicating the coding on paper is to represent the segments with + and - signs. An unshifted segment is represented by a +; a shifted segment by a -. The signs making up the code are referred to as digits.

The received echoes are passed through a delay line, which provides a time delay exactly equal to the duration of the uncompressed pulses,  $\tau$ . Thus, as the trailing edge of an echo enters the line, the leading edge emerges from the other end. The delay line may be implemented either with an analog device or digitally.

Like the transmitted pulses, the delay line is divided into segments. An output tap is provided for each segment. The taps are all tied to a single output terminal. At any one instant, the signal at this terminal corresponds to the sum of whatever segments of a received pulse currently occupy the individual segments of the line.

Now, in certain of the taps,  $180^\circ$  phase reversals are inserted. Their positions correspond to the positions of the phase-shifted segments in the transmitted pulse. Thus, when a received echo has progressed to the point where it completely fills the line, the outputs from all the taps will be in phase. Their sum will then equal the amplitude of the pulse times the number of segments it contains.

To see step-by-step how the pulse is compressed, consider a simple three-segment delay line and the three-digit code, illustrated in **Figure 4**. Suppose an echo from a single point target is received (see Figure below). Initially, the output from the delay line is zero. When segment no. 1 of the echo has entered the line, the signal at the output terminal corresponds to the amplitude of this segment. Since its phase is  $180^\circ$ , the output is negative: -1.



**Figure 4. Example of 3-Digit Binary Phase Modulation. From Stimson (1983).**

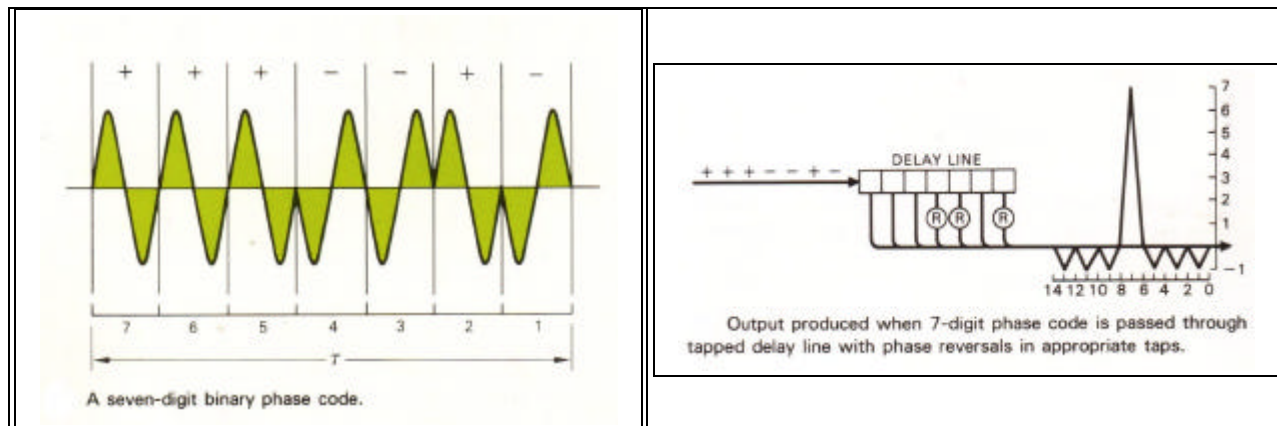
An instant later, segment no. 2 has entered the line. Now the output signal equals the sum of segments no. 1 and no. 2. Since the segments are  $180^\circ$  out of phase, however, they cancel: the output is 0.

When segment no. 3 has entered the line, the output signal is the sum of all three segments. Segment no. 1, you will notice, has reached a point in the line where the tap contains a phase reversal. The output from this tap, therefore is in phase with the unshifted segment no. 2. The phase of segment no. 3 also being unshifted, the combined output of the three taps is three times the amplitude of the individual segments: +3.

As segments no. 2 and no. 3 pass through the line, this same process continues. The output drops to zero, then increases to minus one, and finally returns to zero again.



A somewhat more practical example is shown in the figure below (**Figure 5**). This code has seven digits. Assuming no losses, the peak amplitude of the compressed pulse is seven times that of the uncompressed pulse, and the compressed pulse is only one-seventh as wide.



**Figure 5. Example of 7-Digit Binary Phase Code. From Stimson (1983).**

### 3.2.2.2 Sidelobes

Ideally, for all positions of the echo in the lines—except the central one—the outputs from the same number of taps would have phases of  $0^\circ$  and  $180^\circ$ . The range outputs would then cancel, and there would be no range sidelobes.

One set of codes, called the Barker codes, comes very close to meeting this goal. Two of these have been used in the examples above. As you have seen, they produce sidelobes whose amplitudes are no greater than the amplitude of the individual segments. Consequently, the ration of mainlobe amplitude to sidelobe amplitude as well as the pulse compression ratio, increases with the number of segments into which the pulses are divided—i.e., the number of digits in the binary code.

Unfortunately, the longest Barker code contains only 13 digits. Other binary codes can be made practically any length, but their sidelobe characteristics, though reasonably good, are not quite so desirable.

### 3.2.2.3 Limitations of Phase Coding

The principal limitation of phase coding is its sensitivity to Doppler frequencies. If the energy contained in all segments of a phase-coded pulse is to add up completely when the pulse is centered in the delay line, while canceling when it is not, very little shift in phase over the length of the pulse can be tolerated, other than the  $180^\circ$  phase reversals due to the coding.

## 3.3 The Time-Bandwidth Product (TB)

One of the most important features of the time series analysis is that for a broadband signal, a higher time-domain resolution,  $1/B$ , where  $B$  is the bandwidth of the signal, can be obtained through various forms of signal processing. For a sufficiently broad bandwidth of the signal (or equivalently, a sufficient short pulse length), the different parts of an individual animal can be resolved acoustically. Ideally, in a noise-free environment, i.e., the signal-to-noise ratio (SNR) approaches infinity, the acoustic impulse response of the target can be obtained via either direct deconvolution (in the time domain) or the Fourier transform/Inverse Fourier transform process (in the frequency domain).

A combination of electrical noise of the data acquisition system and ambient noise in the water detected by the receiver degrades the quality of the data. Increasing the transmit power can help offset these effects but that improvement is restricted by the limitations of the power amplifier and transmit transducers. For a constant transmit power, the wider the bandwidth of the transmitter, the weaker the transmitted power spectral density, and hence the lower the SNR in the spectral domain at the receiver.



### 3.3.1 Time-Bandwidth and Range Resolution

Range resolution, as defined by several texts, is a complex function of pulse envelope shapes, bandwidth and duration, and specific definitions of ambiguity and resolution. In the classical sense, the minimum achievable range resolution is  $\frac{1}{2}$  of a wavelength. Since transmission of  $\frac{1}{2}$ - or 1-wavelength pulses is impractical, the more common definition centers around the transmitted pulse length, as:

$$\Delta r = \frac{t}{2}$$

where:

t = pulse length in meters

$\Delta r$  = Range resolution in meters, with subscripts NB for narrowband, and BB for broadband.

This definition makes idealistic assumptions regarding the pulse shape, bandwidth, sidelobe content, and time and spatial sampling. This method is classically employed with narrowband systems where the pulse width (PW) and envelope energy detection determine the minimum range resolution. The pulse length is determined by the product of the transmit time and the speed of sound in water (1500 m/sec). For the HTI Model 241, the range resolution ( $\Delta r_{NB}$ ) using this approach is:

$$\Delta r_{NB} = \frac{(0.0002) \cdot (1500)}{2} = 0.15 \text{ meters}$$

For broadband systems, or processing that acknowledges the bandwidth potential, the range resolution of such a system is enhanced by inverse proportionality to the Time-Bandwidth (TB) product, a dimensionless number, which accounts for some additional factors of pulse width and frequency content. Extra processing is required to achieve this enhancement that recognizes the characteristics of the transmitted pulse. Here, the minimum range resolution ( $\Delta r_{BB}$ ) can now be expressed as:

$$\Delta r_{BB} = \frac{t}{2TB}$$

where we add:

T = Transmit Time, in seconds

B = Bandwidth, in Hz

Obviously, range resolution is enhanced (reduced) by a factor of the TB product if the signal processing is built to accommodate this factor. This is often referred to as signal compression, or matched filtering.

### 3.3.2 Comparing Narrowband and Broadband Range Resolution

For the 150 kHz SciFish sonar, the transmit time (T) for the typical 2 meter pulse is 0.0013 seconds with 50% bandwidth (75 kHz) and a TB = 97.5, resulting in a range resolution of

$$\Delta r_{BB} = \frac{2}{2 \cdot (0.0013) \cdot (75,000)} = 0.01 \text{ meters}$$

As a comparison, the HTI Model 241 sonar, if processed in this fashion, has a transmit time of 0.0002 for each pulse and has a 5% bandwidth (6 kHz), with a TB = 1.2, resulting in a range resolution of

$$\Delta r_{BB} = \frac{.3}{2 \cdot (0.0002) \cdot (6,000)} = 0.125 \text{ meters}$$

which shows an enhancement compared to the classical resolution (from above) of:



$$\Delta r_{NB} = \frac{(0.0002) \cdot (1500)}{2} = 0.15 \text{ meters}$$

From these numbers, there is a clear advantage (over 1 order of magnitude) in resolution in extending the bandwidth and/or pulse length. The penalty required is in complexity of the processing, a factor that has been minimized in recent years by the prodigious advances in high speed processors readily available in off-the-shelf desktop and portable computers.

### 3.4 Processing Gain (PG)

#### 3.4.1 PG Equation

The processing gain (PG) achieved by exploiting the time – bandwidth product of a broadband sonar is expressed as

$$PG = 10 \log_{10}(TB)$$

where

T = Transmit Time, in seconds

B = Bandwidth, in Hz

#### 3.4.2 Comparing Narrowband and Broadband PG

For the 150 kHz SciFish sonar, the transmit time (T) for the typical 2 meter pulse is 0.0013 seconds with 50% bandwidth (75 kHz), resulting in a processing gain of

$$PG_{BB} = 10 \log_{10}((75000)(0.0013)) = 20 \text{ dB}$$

As a comparison, the HTI Model 241 sonar has a transmit time of 0.0002 for each pulse and has a 5% bandwidth (6 kHz), resulting in a processing gain of

$$PG_{NB} = 10 \log_{10}((6000)(0.0002)) = 1.2 \text{ dB}$$

### 3.5 Reverberation Level (RL)

The backscattering of sound off the river bottom is known as bottom reverberation, and it is the primary source of signal interfering with fish echoes. The level of bottom reverberation is determined by bottom composition and roughness, e.g. the combination of sand, gravel and rocks. For some geometries there can also be reverberation coming from an imaging sonar, i.e. sound that has been forward-scattered from the water surface before reaching the river bottom and backscattering via the same path. Added to this bottom reverberation, is a volume reverberation caused by the highly efficient scattering of entrained bubbles, which are themselves produced by episodic wind and rain events. Perhaps contrary to some views, backscattering from the water surface itself contributes substantially less to the overall reverberation level in comparison to the above-mentioned sources.

#### 3.5.1 RL Equation

For the purpose of this exposition, assume the sonar is equipped with a time-varied-gain (TVG) function that exactly matches spherical spreading loss,  $40 \log R$ , where R is range from sonar. Then, the Reverberation Level, RL, is approximated by

$$RL = RL_{Volume} + RL_{Bottom}$$

where



$$RL_{Bottom} = 10\log\left(\frac{ct}{2}f\frac{R}{\cos\theta}\right)$$

$$RL_{Volume} = 10\log\left(\frac{ct}{2}fR^2\right)$$

and

$c$  = Speed of Sound in Water

$\tau$  = compressed time

$\phi$  = beam width

$\theta$  = grazing angle with bottom

$R$  = range to target

Computing the RL for a narrowband and a broadband sonar will illustrate the affect of reverberation on each. Let's begin by assuming that the grazing angle is 0 degrees, resulting in

$$RL = 10\log\left(\frac{ct}{2}fR^2\right) + 10\log\left(\frac{ct}{2}fR\right)$$

### 3.5.2 Comparing Narrowband and Broadband RL

For the narrowband sonar, lets use the HTI 243 with a 4 degree beam at a range of 20 m and with a speed of sound of 1500 m/sec. The HTI 243 has 5% bandwidth at 120 kHz, resulting in a pulse-compressed time of  $\tau = 0.075/1500$  seconds. With these parameters,

$$RL_{NB} = 10\log\left(\frac{1500 \times 0.075}{1500} \times \frac{1}{2} \times \frac{4p}{180} \times 20^2\right) + 10\log\left(\frac{1500 \times 0.075}{1500} \times \frac{1}{2} \times \frac{4p}{180} \times 20\right) = -12.6 \text{ dB}$$

For a similar broadband sonar, lets use the assume a 4 degree beam at a range of 20 m and with a speed of sound of 1500 m/sec. The SciFish 2000 has a 50% bandwidth at 150 kHz, resulting in a pulse-compressed time of  $\tau = 0.02/1500$  seconds. With these parameters,

$$RL_{BB} = 10\log\left(\frac{1500 \times 0.02}{1500} \times \frac{1}{2} \times \frac{4p}{180} \times 20^2\right) + 10\log\left(\frac{1500 \times 0.02}{1500} \times \frac{1}{2} \times \frac{4p}{180} \times 20\right) = -24.1 \text{ dB}$$

### 3.6 Summary of Narrowband/Broadband Sonar Equation Comparison

**Table 1** summarizes of the differences between the Narrowband and Broadband sonar found throughout this section. In addition, this table takes into account the difference in SL between the two sonar systems.

**Table 1. Summary of Narrowband and Broadband Sonar Performance**

HTI 241 (NB)		SciFish 2000 (BB)
+4.0 dB (2000 W)	SL Difference	0.0 dB (800 W)
+0.8 dB	Processing Gain (Time-Bandwidth)	+20.0 dB
-0.2 dB	Volume Reverberation	+5.5 dB
+4.6 dB	TOTAL	+25.5 dB



## 4 Doppler Processing

### 4.1 Narrowband (Incoherent) and Broadband (Coherent) Doppler Measurements, Based Upon Zedel<sup>1</sup>

Under ideal conditions, Doppler current profilers receive acoustic backscatter from a near continuous distribution of acoustic scatterers. The backscattered signal represents a convolution between the transmitted pulse and some scattering function. In the simplest Doppler sonar system (the incoherent or narrowband system), the target speed is estimated from the frequency shift observed in backscatter from a single acoustic pulse. The phase and amplitude of the speed estimate is related to the bandwidth of the backscattered sound. Speed uncertainty for a narrowband system is given by (Theriault, 1986)

$$s_v = \frac{c}{4ptf}$$

where

$c$  = speed of sound in water

$\tau$  = pulse length in seconds

$f$  = acoustic frequency

The bandwidth of the backscattered signal is given by  $1/\tau$ . To increase speed accuracy, it is necessary to increase  $\tau$  or  $f$ , but this cannot be done arbitrarily: acoustic attenuation increases rapidly with increasing frequency thus limiting the maximum range, and range resolution is determined by  $c\tau/2$  so that increasing  $\tau$  increases the minimum length scale that can be resolved (Zedel, 1996).

Improved estimates in both speed and range resolution can be achieved with fully coherent Doppler systems such as described by Lhermitte & Serafin (1984). Such systems analyze the phase change between successive transmissions rather than the phase evolution (or frequency shift) on a single transmission. If the spatial distribution of scatterers has not changed significantly in the time between transmissions, then the change in phase is due only to the 'coherent' motion of the scatterers (Zedel et al, 1996). In effect, the change in range to acoustic scatterers is determined by the change in phase between successive transmissions and this allows an estimate of the speed of those scatterers

$$v = \frac{(\Delta f \pm n\pi)c}{4pft}$$

where

$c$  = speed of sound in water

$\Delta\phi$  = change in phase

$t$  = time between pulses

$f$  = acoustic frequency

$n = 0, 1, 2, \dots$

The movement of scatterers over a distance greater than a quarter wavelength cannot be unambiguously resolved with coherent systems: this characteristic is represented by the  $\pm n\pi/4$  term above. The ambiguity velocity

<sup>1</sup> This section is largely based on the papers by Len Zedel (Zedel, et al, 1996; 1999). His work in this area remains the most cogent and complete in the field.



$$\Delta V = \frac{c}{4ft}$$

is the maximum speed that can be measured unambiguously and it usually constrains the choice of  $t$  to meet the speed measurement requirements of any application. Range determination also becomes ambiguous when backscatter from more than one acoustic pulse is received at any time. To eliminate the range ambiguity problem, coherent Dopplers are normally operated in a manner such that the first pulse transmitted has reached the systems maximum range before the next pulse is transmitted. This restricts the operating range of these systems to  $ct/2$ : that range to which a pulse travels before the next pulse is transmitted.

For systems operating in a fully coherent mode, the system accuracy is bounded by (Zrnich, 1977)

$$S_v = \frac{cw^{1/2} e^{4p^2} w^2 t^2}{4p^{1/4} (t)^{1/2} t}$$

where

$c$  = speed of sound in water

$w$  = bandwidth of the coherent acoustic scatterer (the exponential term represents the signal decorrelation and is normally close to unity)

$t$  = time between pulses

Comparing this equation with the earlier narrowband (incoherent) system accuracy it can be seen that for the coherent system, the code lag  $t$  provide an independent parameter that can be used to control accuracy and the pulse transmission length  $\tau$  no longer affects accuracy. The sample bandwidth  $w \neq 1/\tau$ ,  $w$  is determined by the time over which backscatter from a given location will remain coherent; the decorrelation time is  $1/w$ . For these systems, the sample bandwidth contributes to the error in two ways: (1) the bandwidth of sampled speeds appears as a random component in speed estimates, and (2) the phase becomes less accurately defined so that eventually, meaningful phase change estimates are no longer possible. The decorrelation time defines an upper limit on the time lag between acoustic pulses and depends on the operating frequency and the environment. This is an important constraint because with coherent Dopplers, accuracy can be improved by increasing the time lag between pulses, but only up to the limit imposed by the decorrelation time. For most oceanographic applications, the coherent sampling scheme is not practical; as noted by Brumley et al. (1991), the decorrelation time for a 307 kHz system is about 20 msec which would only allow a maximum unambiguous range of 15 m.

Broadband Doppler systems represent a compromise between the coherent and incoherent processing techniques. These systems transmit a single pair of acoustic pulses in time as dictated by the speed ambiguity and decorrelation time. Acoustic backscatter is then recorded for this pulse pair to the range limit of the sonar before another pulse pair is transmitted. The received data is correlated with itself at a lag corresponding to the time between transmitted pulses; the phase of the correlation allows an estimate of the scatterer speed just as for the coherent system. There is one significant complication in this scheme and that is that the backscatter is received from more than one range at a time causing self interference which substantially degrades the signal to noise ratio. This interference is quantified by the correlation coefficient of the received signal: in fully coherent systems, the correlation coefficient is often close to 1 while in the broadband system the correlation coefficient is typically 0.5. High correlations can be seen in broadband systems when a single dominant scatterer is encountered and there is consequently no interference due to backscatter at other ranges. Despite this signal degradation, the speed accuracy of a broadband system is superior to that of a narrowband system (Pinkel et al, 1992). Coded pulses are used to retain range resolution while transmitting sufficient energy to allow the necessary correlation computations. Accuracy is recovered because with a large bandwidth receiver, it is possible to realize many independent samples of the signal phase shift.

For the broadband systems, speed accuracy is given by



$$s_v = \frac{c\alpha(1/r^2 - 1)^{1/2}}{4ft\rho^2 M_a^{1/2}}$$

where

$c$  = speed of sound in water

$\alpha \cong 1.5$  = scaling component to accommodate system limitations

$\rho$  = correlation coefficient, typically about 0.5

$t$  = time between pulses

$f$  = acoustic frequency

$M_a$  = the number of samples realized per averaging interval

No matter what data processing mode is used, Doppler profiling systems can only measure speeds radial to the acoustic transducer. In a practical sense, what this means is that a particular transducer will measure the component of velocity resolved along the beam: well defined beams are needed to get well defined velocity components. However, if three dimensional velocity is of interest, it is necessary to use multiple beams with different orientations to measure multiple components of velocity. Sonar systems employing multiple intersecting beams can achieve three dimensional velocity measurements at a point (Lhermittee & Lemmin, 1990).

## 4.2 Doppler-Based Riverine Sonar

Dahl and Mathison (1984) described the use of Doppler information as a target classification method that could be used in rivers of the Pacific Northwest. The relative motion between fish and sound source can be realized as a shift in frequency. The Doppler shift in the echo from a fish swimming at velocity  $V_f$  is approximated by

$$\Delta f = \frac{f_0 V_f \cos \mathbf{f}}{c}$$

where

$c$  = speed of sound in water,

$Df$  = magnitude of frequency shift in Hz

$V_f$  = fish swimming velocity in m/sec

$f_0$  = carrier frequency in Hz

$\mathbf{f}$  = angle formed by fish trajectory and transducer's MRA

The Doppler shift magnitude, either up or down from the carrier frequency, therefore depend on the component of the fish velocity along the MRA and provides some valuable information for classifying the fish relative to debris and other acoustic targets such as entrained bubbles.

A crude estimate of the Doppler resolution,  $Ds$ , is (Altes, 1981)

$$\Delta f = \frac{1}{TB}$$

where

$Df$  = magnitude of frequency shift in Hz

$B$  = Bandwidth of sonar system in Hz



$T$  = transmission time or pulse duration in seconds

### 4.3 Comparing Narrowband and Broadband Doppler Resolution

For the 150 kHz SciFish sonar, the transmit time ( $T$ ) for the typical 2 meter pulse is 0.0013 seconds with 50% bandwidth (75 kHz), resulting in a Doppler resolution of

$$\Delta f_{BB} = \frac{1}{0.0013 \times 75000} = 0.0103 \text{ Hz}$$

As a comparison, the HTI Model 241 sonar has a transmit time of 0.0002 for each pulse and has a 5% bandwidth (6 kHz), resulting in a Doppler resolution of

$$\Delta f_{NB} = \frac{1}{0.0002 \times 6000} = 0.833 \text{ Hz}$$

## 5 Split-Beam Localization

Split beam localization utilizes the phase difference between two beams to localize a target in the far field. The equation used for measuring the angle off MRA is:

$$a = \frac{2pD}{\lambda} \sin \theta$$

where

$\alpha$  = phase difference between the two beams, in radians

$D$  = distance between the two receiving elements, in meters

$\lambda$  = wavelength of the carrier signal being transmitted, in meters

$\theta$  = Angle off MRA to the target, in radians

### 5.1 Split-Beam Angular Resolution

To determine the angular resolution of the 150 kHz broadband SciFish sonar, we need to express the split-beam equation shown above in terms of  $\alpha_{\min}$ ,  $D$ , and  $\lambda$ . To do this, we first solve for  $\theta$ , which results in the equation

$$\theta = \sin^{-1} \left[ \frac{a\lambda}{2pD} \right]$$

For a split-beam broadband transducer with a 6" ceramic that is quartered for each of the four beams, we have a distance between receiving elements ( $D$ ) of 3" = 0.075 meters.

The wavelength ( $\lambda$ ) for the 150 kHz SciFish sonar is  $c/\mu$ , where  $c$  = speed of sound in water (1500 m/sec) and  $\mu$  is the carrier frequency (150,000 Hz), resulting

$$\lambda = \frac{c}{\mu} = \frac{1500}{150000} = 0.01 \text{ meters}$$

To determine the minimum split-beam angular resolution, we need to determine the minimum measurable phase ( $\alpha_{\min}$ ) between the two received signals. The discussion of this is found in the next section. The resulting equation is:



$$\mathbf{a}_{\min} = \frac{1}{N^2 T p} \text{ radians}$$

where

$N$  = number of samples used to compute phase difference

$T$  = time between samples

For the 150 kHz SciFish sonar, we typically use a 1024 point sample interval and we sample at 500,000 samples / second, resulting in a minimum measurable phase difference of 0.152 radians.

Using these values, we can now solve for the angular resolution of the 150 kHz SciFish sonar.

$$\mathbf{q} = \sin^{-1} \left[ \frac{\mathbf{a}l}{2pD} \right] = \sin^{-1} \left[ \frac{(0.0152)(0.01)}{2p(0.075)} \right] = 0.0032 \text{ radians}$$

or 0.185 degrees of angular resolution. If we have a transducer that produces a beam that is 8 degrees wide by 4 degrees high, then we have an effective tracking grid of approximately 40 by 20.

## 5.2 Phase Angle Resolution

In Burdic (1991), it is discussed "intuitively" that the accuracy of determination of  $(t_1 - t_2)$  is inversely related to the width of the autocorrelation function and the resolution of two signals is enhanced if the width of the correlation function is small compared with the separation in time between targets - trivial case. In another thought process: if

$N$  = number of samples in our sample interval

$T$  = time between samples

$t$  = sample interval =  $NT$

then,  $f_0 = 1/t$  is the lowest frequency (1st bin) and  $t = 2f_0/n$  should be the minimum time difference, with the equivalent phase angle being  $t/2\pi$  radians ( the 2 comes from putting 1/2 the samples in sine, 1/2 in cosine for the FFT).

Given,

$$f_0 = \frac{1}{t} = \frac{1}{NT} = \text{lowest frequency}$$

$$t = \frac{2f_0}{N} = \frac{2}{N^2 T}$$

we can express  $\alpha_{\min}$  as

$$\mathbf{a}_{\min} = \frac{t}{2p} = \frac{1}{N^2 T p}$$

which emphasizes the advantage of using a larger number of samples  $N$  to improve our phase measurement.

## 6 Summary

We have analyzed several aspects of the broadband sonar system's performance relative to its narrowband counterpart, including detection, the Doppler contributions to counting and classification, and split-beam localization performance. When comparing the detection performance between two sonar systems, the HTI Model 241 and the SciFish 2000, we realize more than 20 dB improvement in detection capability with the broadband



sonar. When comparing the ability to measure Doppler shifts with the same two sonar systems, we find that the SciFish 2000 is able to measure frequency differences as small as 0.01 Hz, while the HTI Model 241 offers frequency resolution of 0.8 Hz – an 80-fold improvement. Finally, we show that a split-beam realization of a broadband sonar system provides angular measurement resolution of 0.003 radians.

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