

FIELD SERVICE TECHNICAL PAPER 001 (FST-001)
BROADBAND ADCP ADVANCED PRINCIPLES OF OPERATION
01 OCTOBER 1996

1. INTRODUCTION

This Field Service Technical Paper defines some advanced principles of operation for the Broadband Acoustic Doppler Current Profilers (BBADCPs) manufactured by RD Instruments (RDI).

2. OVERVIEW

The ADCP transmits acoustic pulses from a transducer assembly along four beams (Figure 1). The transducers receive backscattered sound from zooplankton and small particles floating ambiently with the water currents. Using the Doppler principle, the ADCP converts the backscattered sound into components of water-current velocity. The ADCP measures the speed and direction of the water currents at multiple locations in the water column. The ADCP makes a profile of these measurements for up to 128 locations called depth cells. Depth cells can be from 5 to 3200 cm in length (depending on model frequency). The following paragraphs provide a general description of how our ADCPs operate. This description does not explain every detail of the mathematics involved in determining the water-current solution; it is an overview of ADCP water-current measurements.

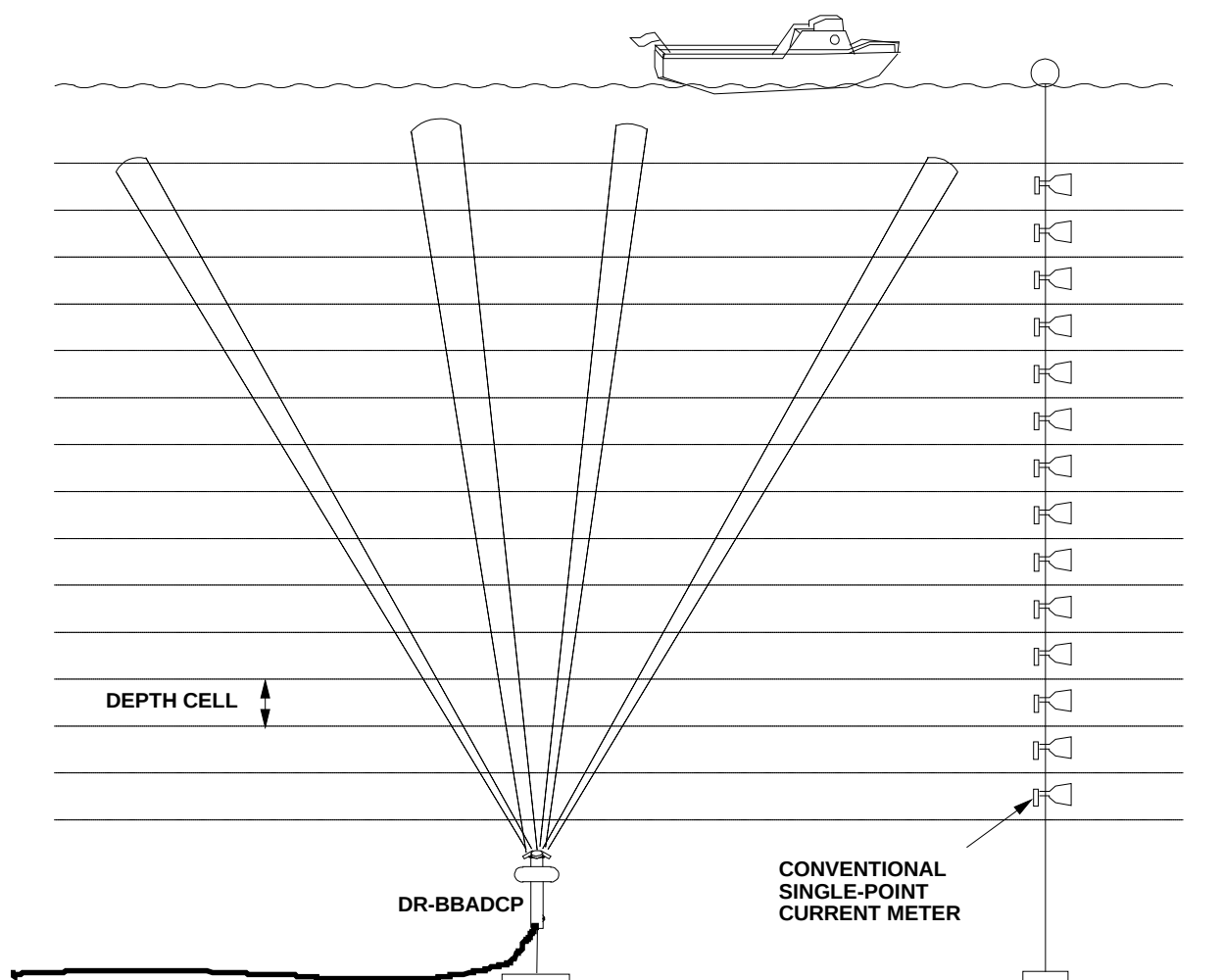


Figure 1. A Typical Direct-Reading BBADCP Profiling Technique

2.1. WHAT IS AN ADCP?

The name *Acoustic Doppler Current Profiler* (ADCP) is an accurate description of how the instrument determines water-currents throughout the water column.

A - Acoustic. The ADCP is a sonar. It uses sound to sense current velocities in the water. RDI manufactures six transmit frequencies: 75, 150, 300, 600, 1200, and 2400 kHz.

D - Doppler. The ADCP uses the Doppler effect to measure the motion of the water. The Doppler effect refers to the compression or expansion (i.e., a change in frequency) of the transmitted sonar signal caused by the relative motion between the ADCP and the scattering material in the water column (Figure 2). Because this material is moving with the water currents, and at the same speed, the magnitude of the Doppler effect is directly proportional to the velocity of the currents. By measuring the frequency of backscattered echoes (echoes returned from the scattering material) and comparing it to the transmitted frequency, the ADCP can determine the velocity of the water currents.

C - Current. The Doppler effect is directional. Any shift in frequency corresponds to a velocity *component* along the transmitter's direction of send/receive. Velocities perpendicular to the direction of send/receive produce no Doppler shift. Figure 3 shows the geometry of two ADCP beams. These two beams measure two different components of the water-current vector. Because these components are not in the same direction, they can be transformed into two orthogonal vectors — one horizontal, one vertical. A second pair of beams, rotated 90° in azimuth from the first pair, generate another set of horizontal and vertical vectors. This gives a total of three orthogonal vectors (x, y, z), which are the three vector components of water current (u, v, w). NOTE: The ADCP only needs three beams to determine the three velocity vectors. The four-beam configuration provides two vertical vectors that the ADCP uses to check data integrity.

P - Profiler. The difference between the ADCP and conventional water-current meters is the ADCP's ability to measure a *profile* of the water currents throughout the water column. This is done by “range-gating” the backscattered signal in time. This process assigns discrete sections of the echo record to distinct sections of the water column (known as depth cells or bins). Therefore, the ADCP assigns separate measurements of the three components of water currents to different depth cells and generates a water-current profile.

3. NATURE OF ECHOES

To function properly, the ADCP must determine the Doppler shift of the echo returns. There are several ways to process a signal to determine this shift in frequency — phase lock loops, fast Fourier transforms, autocovariance. RDI uses the latter method in its narrowband and broadband ADCPs. We will start with a description of the echo record, and then describe how the narrowband and broadband ADCPs process this record to determine the frequency spectra of both the water and bottom echoes.

Simple pulse-Doppler sonar transmits a short burst of fixed frequency sound (F_t) into the water along a narrow acoustic beam. The sonar receives backscattered echoes first from the water mass and later from the bottom (ocean, river, lake, etc.). These returns have a Doppler-shifted frequency (F_D) caused by the relative motion between the transmitter/receiver (ADCP) and the scattering material. The backscattered echoes have a spectrum of nonzero bandwidth centered at F_D .

The main reason for the spectrum bandwidth is the length of the transmit pulse. A short pulse length generates a wide bandwidth. However, in most applications bandwidth has little effect on the Doppler frequency estimate. The precision of the frequency estimate is most affected by the cloud-like nature of the scattering material in the water.

As a pulse is sent through the water, the received echo at any instant in time is the sum of the individual echoes from the many scatterers ensonified (illuminated) by the pulse. In Figure 4, consider the sound pulse striking the two scatterers traveling with velocity, V , toward the ADCP. In comparing the transmitted and returned-echo pulses, we see (1) the amplitudes (intensities) have decreased (i.e., not all the energy was returned), (2) the return pulses are compressed due to the Doppler effect, and (3) that at any point in time the phases of the two return pulses are different. In the case of many scattering points, each will have a different backscatter amplitude and phase. As shown in Figure 5, these different amplitudes and phases produce a plot of amplitude and phase modulation versus time. As the pulse makes its way through the water column, this modulation continually changes because it “sees” new scatterers. The new scatterers return new phase information, different from that of the scatterers leaving the ensonified volume. This causes the *correlation* of the signal to decrease. Correlation is the comparison of the return signal of a pulse to itself (at a later time, t) that allows us to infer the frequency of the return pulse.

Why does this change in the group of scatterers cause the correlation to decrease? We can view correlation as two snapshots of the pulse separated by a time, t . At $t = 0$, the two snapshots are the same (the pulse is at one position) and the correlation is perfect as the return signal is coming from one (and the same) set of scatterers. As t increases, the two snapshots are of the pulse at different positions (the pulse has moved through the water). The phase information is now different for two reasons: (1) the whole group of scatterers has moved because of the velocity of the currents and (2) new scatterers have entered the volume of the pulse while others have left it. The correlation between the two snapshots is now less than perfect.

The first cause of this phase change is the information we want. The change in phase caused by the group movement, divided by the time between the snapshots, gives us the frequency of the Doppler shift. The second cause of phase change (scatterers entering/leaving the volume) is the cause of uncertainty in the frequency estimate. It produces a noise term in the estimation of the frequency. This is a random error that is associated with each velocity measurement. A longer pulse reduces this random error because the volume of new scattering material is a smaller percentage of the total pulse volume. That is, a longer pulse must travel farther to get an appreciable amount of completely new scattering material, thus the noise term is relatively smaller.

Bottom echoes are somewhat different for narrow beam sonars. If the transmitted pulse is long enough to completely ensonify the bottom (which is normally the case), the same scatterers with the same amplitudes and phases will dominate the received echo. The signals from these scatterers are combined at the receiver to produce an approximately-constant echo amplitude and phase-versus-time plot. This generates an echo similar to the backscattered signal of one scatterer; the echo record is sinusoidal. This means that bottom-velocity estimates are more precise than those for water.

The noise associated with either water or bottom measurements can be reduced by averaging multiple measurements. This is the strategy behind averaging several single-pulse measurements (known as *pings*) into *ensembles* (a group of averaged pings). The reduction in random error is proportional to the square root of the number of these independent measurements.

4. WATER ECHOES

Although this Technical Paper applies to our broadband system, an understanding of how our narrowband system processes water echoes will help you understand broadband processing.

4.1. Narrowband Processing

The primary function of an ADCP is to determine the frequency shift caused by the backscattered echoes. Because frequency is a change in phase with time, we can determine the frequency by looking at the change in phase of backscattered echoes as a function of time. A narrowband ADCP does this by using a signal processing technique known as autocovariance.

A narrowband ADCP transmits a single tone burst of duration T_P . As shown in Figure 6A, the returned signal is compared to itself at a specified time lag, T_L . At this time lag, the phase angle of the return signal should be the same value as the transmitted signal if there is no relative motion between the scattering material and the ADCP. The phase change of the signal at this time lag is zero. If there is relative motion (Figure 6B), the pulse expands or compresses (motion away or toward the ADCP), and a phase change occurs. Frequency equals phase divided by the quantity 2π times time, or:

$$f = \phi / (2\pi T_L) \quad (\text{Eq. 1})$$

where: f = frequency in Hz
 ϕ = phase in radians
 T_L = time in seconds

Therefore, the phase change divided by 2π times the time lag represents the change in frequency, or Doppler shift. Since velocity is proportional to the Doppler shift we can use the equation:

$$V \propto \phi / T_L \quad (\text{Eq. 2})$$

where: V = velocity
 ϕ = measured phase difference
 T_L = time lag

In fact, we can determine velocity, $\mathbf{V}$, by the relation:

$$V = \frac{\phi C}{4\pi F_0 T_L} \quad (\text{Eq. 3})$$

where: F_0 = transmit frequency in Hz
 C = speed of sound in m/s

Figure 7 shows the single pulse of length T_P , the time lag, T_L , and a plot of the change in phase versus time. This plot assumes the scattering material is moving with constant velocity, $\mathbf{V} \neq 0$. As the time increases (increasing lag), the change in phase measured for this material moving with velocity, $\mathbf{V}$, increases linearly, which follows from Equation 3. Figure 7 also shows the autocorrelation function of a pulse as a function of time. The autocorrelation function is constructed by correlating (comparing) the pulse with itself, as explained in Section 3 (Nature of Echoes). If the pulse moves through the water a distance of one pulse width, there is zero correlation because the scatterers are from a new volume of water. The level of correlation is important — the lower the correlation, the noisier the data, and the less precise the velocity measurement.

Note that the time lag cannot be greater than the pulse width. In fact, it must be much shorter than the pulse width to have a high correlation value (i.e., valid data). The point that the lag and pulse width are interrelated is very important. In Section 4.2, we will show that a large lag is actually *preferable*. A longer lag means a lower standard deviation (better precision) of the velocity measurement. However, if the lag and pulse width are inseparable, there is a limit to the precision of a narrowband velocity measurement for a given pulse size. The standard deviation for the horizontal velocity component of a narrowband system for a single ping is known to be:

$$\sigma_{NB} = \frac{1.6 \times 10^5}{F_0 D} \quad (\text{Eq. 4})$$

where: σ_{NB} = standard deviation in m/s for a narrowband system
 D = depth cell length in meters

Note that since the narrowband uses a fixed lag the equation for standard deviation depends only on depth cell length and transmit frequency. For an ensemble of N pings, Equation 4 would be divided by $N^{1/2}$.

4.2. Broadband Processing

Instead of one long pulse, a broadband ADCP transmits a series of short pulses. This allows the separation of pulse width and lag. Therefore, we can choose longer lags that give a better measurement independent of the size of the pulse. But, why is a long lag better? Let us look at what happens in a 2-pulse system.

A broadband ADCP transmits two pulses of duration T_P , separated by a lag, T_L . Figure 8A shows this pulse pair striking a scatterer that has zero velocity relative to the ADCP. When the pulse returns, the ADCP examines the phase at the lag, T_L , just like in the narrowband. In this case, the phase change is zero. In Figure 8B, the scatterer has a small velocity toward the ADCP, and the pulse pair is compressed due to the Doppler effect. The phase of the return pulse at the lag is nonzero, and as the velocity of the scatterer increases, so does the phase difference. In Figure 8C, the velocity is much greater and the phase difference is large — greater than 2π (one cycle). In fact, every time the phase change goes through a total of 2π , it wraps around and begins again. This causes periodicity of the phase-versus-time plot.

Figure 9 shows phase change as a function of time (again for scattering material moving with constant velocity, $\mathbf{V} \neq 0$), and the autocorrelation function of a 2-pulse system. It is quite different from Figure 7 for the narrowband ADCP. Two major differences are: (1) The width of the correlation peaks and their separation are independent of each other, that is, pulse width and lag are now independent, (2) The plot of phase with time repeats itself, linearly increasing from $-\pi$ to $+\pi$ at regular intervals.

The autocorrelation function of two pulses is created the same as for one pulse. However, by using a pulse-pair the result is a major peak centered on zero and two side peaks centered on $\pm T_L$. The width of each depends on the width of an individual pulse. Because of the two pulses, the function has nonzero correlation at lags greater than one pulse width. Valid data are now available at long lags, which lowers the standard deviation (increases the precision) of the velocity measurement.

Determining standard deviation for a broadband differs from that of a narrowband. We know from Equation 2 that velocity is proportional to the phase divided by the time lag; therefore, the standard deviation of velocity can be represented by the equation:

$$\sigma(V) \propto \sigma(\phi) / T_L \quad (\text{Eq. 5})$$

or

$$\sigma(V) = \frac{\sigma(\phi)C}{4\pi F_0 T_L} \quad (\text{Eq. 6})$$

where: $\sigma(\phi)$ = standard deviation of phase measurement

It is known that the lower bound for phase variance is:

$$\sigma^2(\phi) = \frac{R^2 - 1}{2} \quad (\text{Eq. 7})$$

where: R = correlation at lag T_L

Therefore, the standard deviation of velocity is:

$$\sigma(V) = \frac{(R^2 - 1)^{1/2} C}{\sqrt{2} 4\pi F_0 T_L} \quad (\text{Eq. 8})$$

where: $R = 0.5$ ideally for a 2-pulse system (Figure 9)

We can see from Equation 8 that a longer lag reduces velocity standard deviation. We can also see this graphically. It follows from Equation 3 and Figure 8 that phase differences increase as a function of velocity or lag. A phase change will be greater if the lag is longer *or* if the velocity of the material is greater. Figure 10 is a plot of phase as a function of the *velocity* of the scattering material for a given lag between the pulses.

Figure 10A is for two pulses with a short lag between them. The phase changes slowly as the velocity of the scattering material increases. Because the broadband is a phase-measuring device, there will be some error in its phase measurement of ϕ_m . These errors correspond to an uncertainty in the velocity, V_m . For a short lag, the velocity calculation can have a large error.

In Figure 10B, we have two pulses with a longer lag. Phase, as a function of velocity, changes rapidly. Although we have the same error in the measurement of phase ϕ_m , it corresponds to a much smaller error in velocity, V_m . A longer lag gives a better estimate of velocity. Therefore, a 2-pulse system can measure velocity with a lower standard deviation than a 1-pulse system.

You may have noticed one problem. How do we know on which interval from $-\pi$ to $+\pi$ the ADCP is making the phase measurement? Depending on which interval you are on, you get a different answer for velocity. Each of the intervals from $-\pi$ to $+\pi$ is known as an *ambiguity interval*, and the velocity at which the phase difference is exactly π is the *ambiguity velocity*. The ambiguity velocity, V_a , can be calculated from Equation 3 by setting $\phi = \pi$, or:

$$V_a = \frac{C}{4 F_0 T_L} \quad (\text{Eq. 9})$$

and the standard deviation is now:

$$\sigma(V) = \frac{(R^2 - 1)^{1/2}}{\sqrt{2} \pi} V_a \quad (\text{Eq. 10})$$

However, we must resolve the ambiguity in the phase measurement to get an accurate velocity measurement. The broadband uses several methods for resolving this ambiguity. We discuss these methods in Section 5 (Water-Profiling Modes).

The separation of pulse width and lag also means that any pulse width can be used. Extremely small pulses (only a few carrier cycles long) can be used to increase vertical resolution. Many of these small pulses can be averaged together into larger depth cells to further reduce the velocity standard deviation as shown in Figure 11. In narrowband systems, we had six measurements of the phase in every depth cell, but since the long pulse covered much the same volume of water for successive measurements, there were effectively two independent measurements per depth cell. The broadband uses pulses of four carrier cycles in length, which means we have several independent measurements averaged together within a depth cell. This reduces the velocity standard deviation by the square root of the number of pulses that fit into a depth cell. If D = depth cell length and P = length of the pulse, then the number of independent measurements within a depth cell is:

$$m = D / P \quad (\text{Eq. 11})$$

and the standard deviation is now:

$$\sigma(V) = \frac{(R^2 - 1)^{1/2}}{\sqrt{2} \pi m^{1/2}} V_a \quad (\text{Eq. 12})$$

Equations 1 through 12 are derived assuming we are using a one-beam system and all calculations are computed radially (i.e., along the beam path). For an actual ADCP using two beams inclined at an angle of θ from the vertical, the standard deviation of *horizontal* velocity is:

$$\sigma_H(V) = \frac{1.5 V_a (R^2 - 1)^{1/2}}{2\pi \sin \theta m^{1/2}} \quad (\text{Eq. 13})$$

The square root of 2 that was in the denominator has disappeared because of the geometry of a 2-beam system and because we are looking at the standard deviation of horizontal velocities. The factor of 1.5 arises from limitations of the signal processing and the fact that each code element measurement is not truly independent. This factor has been determined empirically.

As stated earlier, the pulse length, T_P , is only four carrier cycles in length. By taking into account the two-way travel of sound in the water column, and that the transducer beams are inclined at an angle θ to the vertical, we can represent T_P as:

$$T_P = \frac{2C \cos \theta}{F_0} \quad (\text{Eq. 14})$$

and Equation 13 becomes:

$$\sigma_H(V) = \frac{1.5 V_a}{\pi} \left[\frac{(R^2 - 1) 2C \cos \theta}{F_0 D} \right]^{1/2} \quad (\text{Eq. 15})$$

For a 1200-kHz system using 1-m depth cells, $V_a=80$ cm/s and $R=0.8$ (Water Mode 4, described below), 30° beams, and $C=1490$ m/s, the single-ping horizontal standard deviation is 1.3 cm/s. Compare this to 13 cm/s for a narrowband system. The broadband's performance is a factor of ten better in this case.

You may note that if we transmit extremely small pulse widths, the range of the ADCP will be greatly affected. A small pulse simply does not get much energy into the water. To avoid this problem, the broadband emits a coded sequence of pulses. Each *code element*, four carrier cycles in length, is followed by another, which is pseudo-randomly assigned a phase shift of 0° or 180° . By constructing a large pulse in this way, we retain the measurement independence of the small pulses, but get enough energy into the water to ensure ample profiling range. Figure 12 shows a sample code and its corresponding autocorrelation function (“+” is normal or 0° phase change, “-” is a 180° phase change). Note there is again high correlation at lag T_L , just like a simple 2-pulse system.

5. WATER-PROFILING MODES

A profiling mode describes the set of transmitted sonar pulses whereby the broadband ADCP measures the velocity of the water and resolves any ambiguity in the phase measurement. The broadband ADCP has several profiling

modes. Each mode is described in terms of the above explanation of broadband operation. The system default is Water-Track Profiling Mode 4 (WM4) for firmware versions 3.xx and later.

5.1. Mode 1

Use Mode 1 in dynamic environments where sudden changes in velocity are possible (e.g., heavy shear conditions, rigorous vessel motion). Mode 1 uses a set of pulses with a short lag. The default horizontal ambiguity velocity is very high, about ± 10 m/s, so ambiguity-resolving errors are avoided. The high ambiguity velocity results in a velocity standard deviation per ping at least twice as high as Mode 4. This means four times as many pings must be averaged for a similar ensemble standard deviation. The Mode 1 ambiguity velocity is, however, selectable with the WV command. A lower ambiguity velocity will lower the velocity standard deviation, but will increase the chance of an ambiguity-resolving error. The WV-command can be set to its optimum standard deviation by using the following formula.

$$WV = (\text{Max Water Velocity}) \times (\sin H) \times 2 \quad (\text{Eq. 16})$$

where: *Max Water Velocity* = the maximum ADCP velocity motion plus the maximum actual water velocity
H = the beam angle of the transducer.

Recommendation: Use Mode 1 in dynamic environments where sudden changes in velocity are possible (e.g., heavy shear conditions, rigorous vessel motion).

5.2. Mode 4

Mode 4 (Default mode) uses a single set of pulses with a long lag. The lag is dependent on depth cell length. The lag will either be one-half the depth cell length, or will have a horizontal ambiguity velocity of 160 cm/s, whichever is greater. For most depth cell sizes, the value of 160 cm/s is used. Using a minimum depth cell size will decrease the lag and raise the ambiguity velocity, and the velocity standard deviation, slightly. The ambiguity is resolved on this single set of pings by an RDI proprietary signal-processing algorithm.

If the water becomes too shallow or if the signal return is too weak, then the ADCP will automatically switch to Mode 1 (WM1). This mode, in its default setup, will have a higher standard deviation, but it can be adjusted by the use of the WV-command (ambiguity velocity) to reduce the standard deviation.

The ADCP uses bottom-tracking to detect if the water is too shallow for Mode 4. This works well when the ADCP faces down. However, when the ADCP is faces up, bottom-track is usually not enabled. Even if bottom-track is enabled in an upward facing ADCP, there is no guarantee it will collect valid data. Therefore, when the ADCP is used in the upward direction, you should use Mode 1 if the water is shallower than what is listed in Table 1.

Table 1. Minimum Depth Requirements for Water Mode 4 Profiling

Freq. (kHz)	Bin Size (m)	Blank (m)	Depth (m)
1200	1	0.5	6.0
600	2	1.0	12.0
300	4	2.0	23.0
150	8	4.0	46.0
75	16	8.0	92.0

Recommendation: Use Mode 4 in all applications except very dynamic environments (Mode 1) or very shallow environments with low flow conditions (Mode 5). Mode 4 is the default mode for firmware versions 3.xx and later.

5.3. Mode 5

Mode 5 (Shallow Water mode) uses a pulse-to-pulse coherent processing. These pulses are virtually independent of each other. In Mode 5, the second pulse is not sent until the first has died out. This creates a very long lag with extremely low velocity standard deviation. A long lag will cause a problem with *residence time*.

Residence time is the time a group of scatterers needs to remain in a region for both pulses to pass through it. If the velocity is very slow, most scatterers will remain in the same region for the time it takes both pulses to pass. A

slight bit of decorrelation, a lowering of the correlation between the two pulses, will occur because some new scatterers enter the region as others leave. Nevertheless, if the number of scatterers entering and leaving is small we still have high correlation, and therefore, valid data. If the velocity is too high, most of the group of scatterers will be replaced by new ones. The decorrelation is now high and the data is invalid.

The advantage of Mode 5 is its very precise measurement capability. This allows the use of minimum depth cell sizes five times smaller than the minimum depth cell size for Mode 4 (e.g., 5 cm for a 1200-kHz system). The limitations, however, are that the profiling range for Mode 5 is only 10-20% of the normal maximum profiling range available with Mode 4, and the maximum measurable velocities are lower than Mode 4. The exact numbers depend on the ADCP frequency and the profiling environment. See Tables 2 and 3.

Mode 5 does not work well in fast water or in water that has shear. It is intended for places with uniform flow from the surface to the bottom. Mode 5 is intended for 300, 600, and 1200-kHz ADCPs only.

Most of the results of using water profiling Mode 5 for 30° transducer beam angles (and default settings for the rest of the commands in the ADCP) are shown in Table 2 and 3. ADCPs with transducer beam angles of 20° can expect a decrease in range of 50%, an increase in standard deviation of 1.5 times (50%), and an increase in the maximum velocity of 1.3 times (30%).

Please note the values for the suggested maximum velocity and maximum range of the ADCP in Mode 5 operation. The suggested maximum velocity refers to the total apparent water velocity, which is the addition of vessel speed and the actual water speed. We recommend always setting the WZ-command to WZ02. If the bottom depth increases past the maximum range listed in Table 2 and 3, then the maximum velocity the ADCP can measure decreases. The standard deviation for the settings in these tables is about 1.5 cm/s.

Table 2. Default Setup results using Mode 5 operation with 30° beam angles

Freq. (kHz)	Bin size (cm)	Max Velocity (m/s)	If Max Range Is (meters)	Ambiguity velocity WZ-command
1200	5.0	3.50	2	WZ02
600	10.0	3.20	4	WZ02
300	20.0	2.10	8	WZ02

Table 3. Setup Results by Increasing Maximum Range by 2 (with 30° beam angles)

Freq. (kHz)	Bin size (cm)	Max Velocity (m/s)	If Max Range Is (meters)	Ambiguity velocity WZ-command
1200	5.0	1.75	4	WZ02
600	10.0	1.60	8	WZ02
300	20.0	1.05	16	WZ02

Recommendation: Use Mode 5 in very shallow water environments that have low velocity flows. Mode 5 is available in firmware versions 4.xx or later.

5.4. Mode 6

Mode 6 (Dual Water/Bottom mode) allows bottom-tracking on the same ping as the water-track ping. The mode requires a “valid bottom”, otherwise it produces no data (it enters a search mode). This mode ignores the BP setting, but uses the BA and BC commands. Mode 6 outputs bottom-track data in the bottom-track format.

The ambiguity velocity in firmware version 5.27 is fixed at 520 cm/s. In later versions, the WV-command (same as Mode 1) will set the ambiguity velocity. Setting lower ambiguity velocity will decrease the valid data range. This mode uses a percentage of the range to the bottom to set the bin size. This is done through the WR-command. The WN-command is ignored. The number of bins is set based on what is needed to reach the bottom with the WR-command (set bin size). This mode is not useful for Self-Contained (SC) BBADCPs unless there is a bottom. This mode is not useful for blue-water (VM-BBADCPs) or upward facing applications where the bottom is lost.

NOTE: RDI programs do not support the graphical display of this mode. *BBLIST* can display the data in a tabular format.

Recommendation: Mode 6 (Dual Water/Bottom mode) is ideally suited for moving platform situations where the range to the bottom can vary over an order of magnitude.

5.5. Mode 7

Mode 7 (Extended Range mode) increases profiling range by 10 to 15%. The signal-to-noise ratio is improved by reducing the system's bandwidth (thus allowing for increased range). However, the standard deviation of a single ping will be increased by a factor of 2.5 over a Mode 4 ping with the same bin size. This mode is intended for the 300, 150, and 75-kHz frequencies when they are used in open waters and maximum range is required. The WB-command (bandwidth control for Mode 1) has no effect.

Recommendation: Set the bin size to 4 meters for 300-kHz, 8 meters for 150-kHz, and 16 meters for 75-kHz frequencies. Never set the bin size to less than one-half of the recommended bin sizes in Table 4 as the performance will be poor. Use this mode when ranges *beyond* those in Table 4 are required.

Table 4. WT Mode 7 Range

Frequency (kHz)	Bin size (meters)	Transmit power	Range (meters)
300	4	Low power	100
150	8	Low power	220
150	8	Hi power	280
75	16	Low power	400
75	16	Hi power	480

5.6. Mode 8

Mode 8 (Close-In mode) uses pulse-to-pulse coherent mode. Mode 8 operates very similar to Mode 5. It uses a pulse-to-pulse coherent mode to calculate velocity. Mode 8 has ten times the standard deviation of a Mode 5 ping with the same bin size. This mode is intended for 300, 600, and 1200-kHz ADCPs only. Use the same setups for Mode 5 with Mode 8.

Recommendation: Mode 8 is still under development. We recommend using it whenever Mode 5 will not work.

6. BOTTOM-TRACK PROFILING MODES

Bottom-profiling modes are similar to water-profiling modes except that these modes measure the velocity of the bottom in relation to the ADCP. The system default is Bottom-Track Mode 4 (BM4) for firmware versions 4.xx and later.

6.1. BT Mode 4

Bottom Mode 4 (Default Bottom mode) is similar to Water Mode 4 in that a single series of pulses is used, and the proprietary RDI algorithm resolves ambiguities. It differs in that this single series contains several pulses. Since the pulses within a series are identical, several lags are available for processing (i.e., a one-pulse lag between each successive pulse; a two-pulse lag between successive pairs of pulses, etc.). This enables Bottom Mode 4 to get the best estimate possible of vessel velocity over bottom.

Recommendation: Use Bottom Mode 4 in all bottom-track applications except very shallow environments with low flow conditions (Bottom Mode 5). This mode has a minimum bottom tracking depth. The minimum depth is frequency dependent as shown in Table 5.

Table 5. Absolute Minimum Bottom Mode 4 Bottom Tracking Depths

Frequency (kHz)	Depth (meters)
1200	0.8
600	0.8

Frequency (kHz)	Depth (meters)
300	1.5
150	3.0
75	5.0

The bottom-track mode will automatically switch to Mode 5 operation when the depth becomes shallower than the ranges shown. The standard deviation of Mode 4 increases as the depth decreases. In areas where the water is shallow, Mode 5 will improve the standard deviation by as much as a factor of ten.

6.2. BT Mode 5

Bottom Mode 5 (Shallow Bottom mode) is similar to Bottom Mode 4, but has a lower variance in shallow water by a factor of up to four. In very shallow water at slow speeds, the variance is lower by a factor of up to 100. Mode 5 also has a slightly slower ping rate. This mode has a very precise measurement capability. When the water becomes too deep for Bottom Mode 5 operation, the ADCP automatically switches to Bottom Mode 4.

Table 6. BT Mode 5 Minimum Tracking Depths

Frequency (kHz)	Minimum Tracking Depths (m)
75	5.0
150	3.0
300	1.5
600	0.8
1200	0.8

Recommendation: Use Bottom Mode 5 in very shallow water environments that have low velocity flows. Bottom Mode 5 is available in firmware versions 4.xx or later.

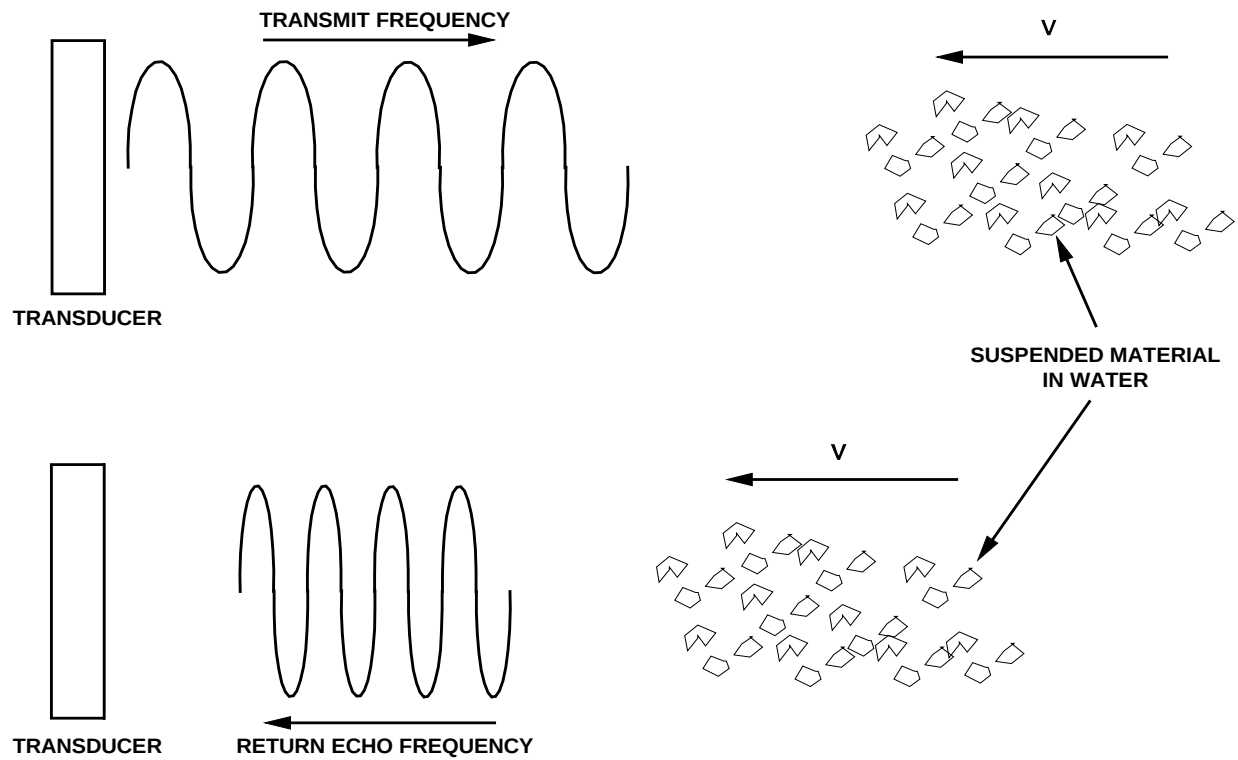


Figure 2. Frequency Change Caused by Doppler Effect

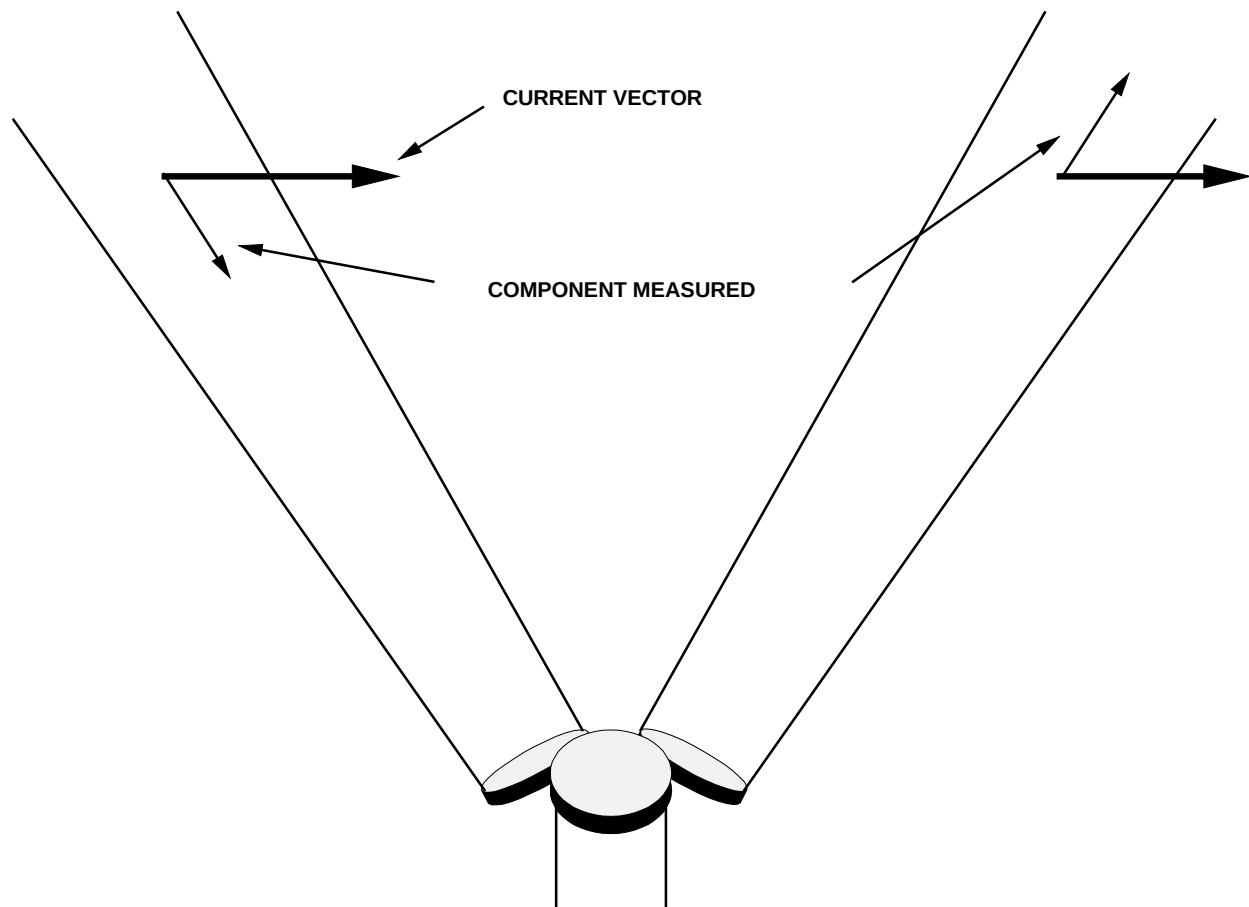


Figure 3. ADCP Beam Geometry

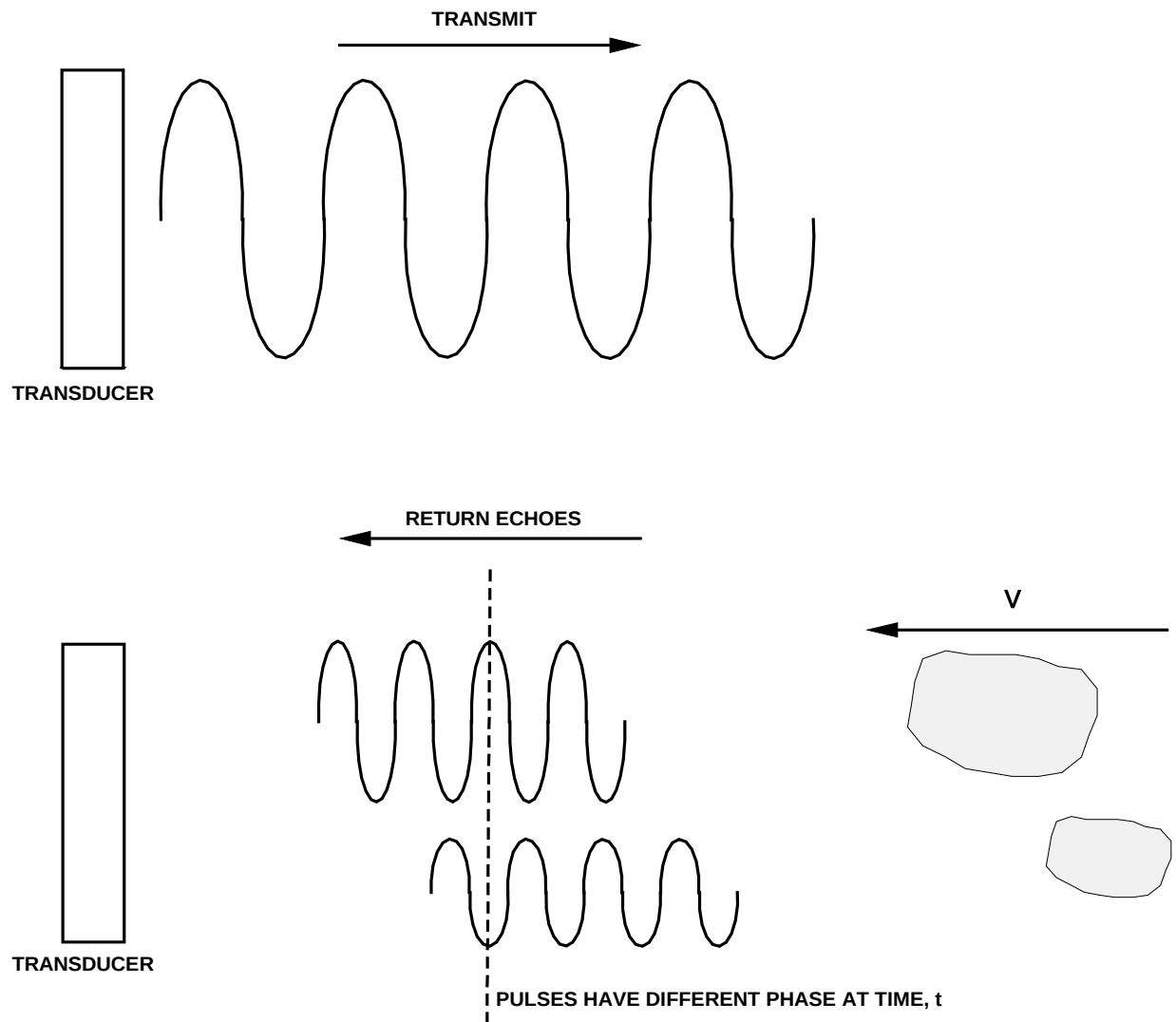


Figure 4. Return Echo of Two Scatterers

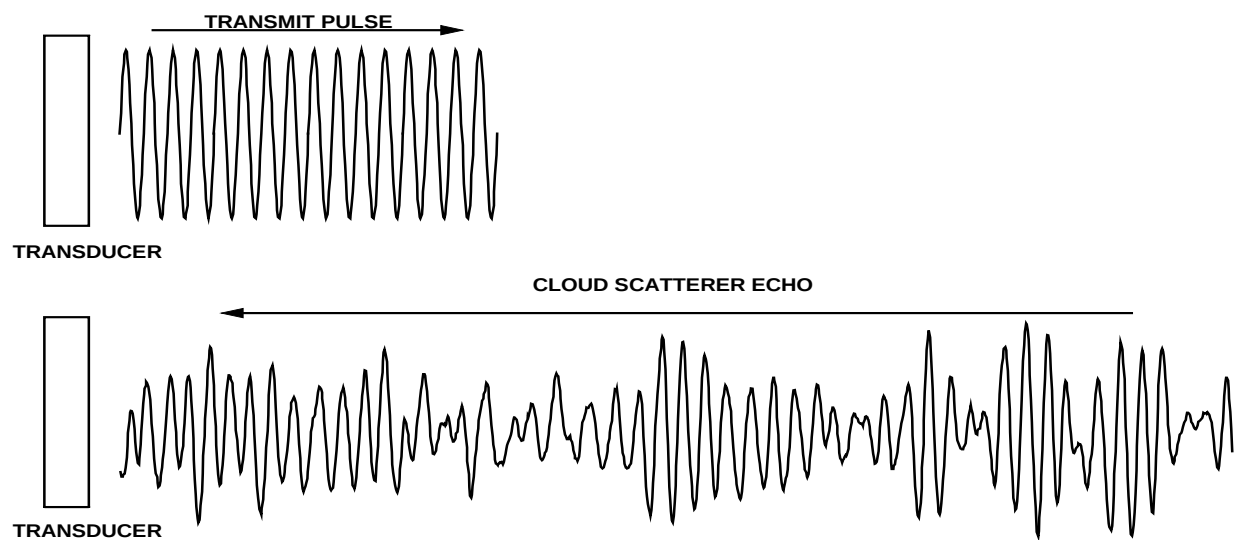


Figure 5. Modulation vs. Time Plot for Many Scatterers

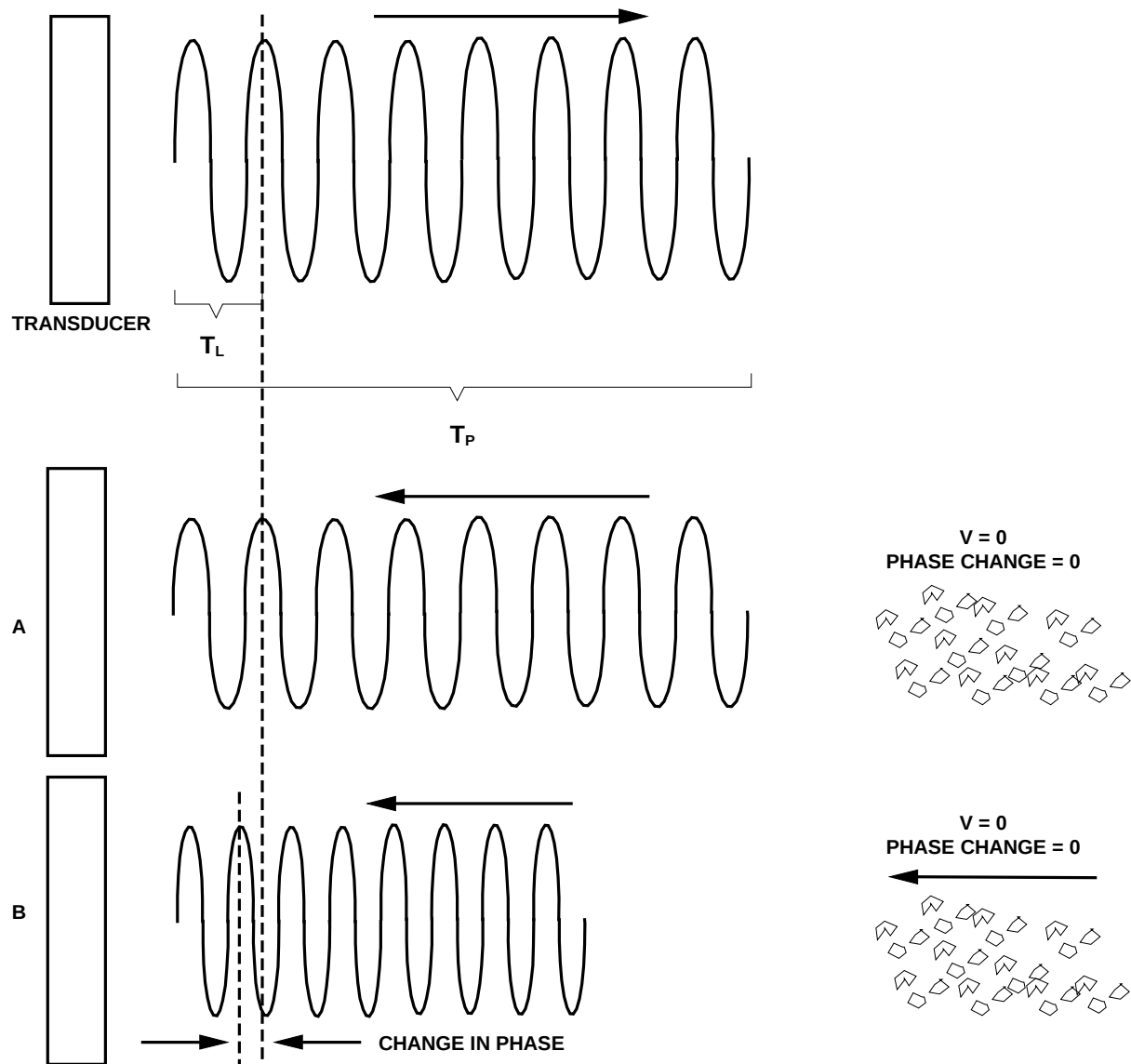


Figure 6. Phase Change Seen by the Narrowband System

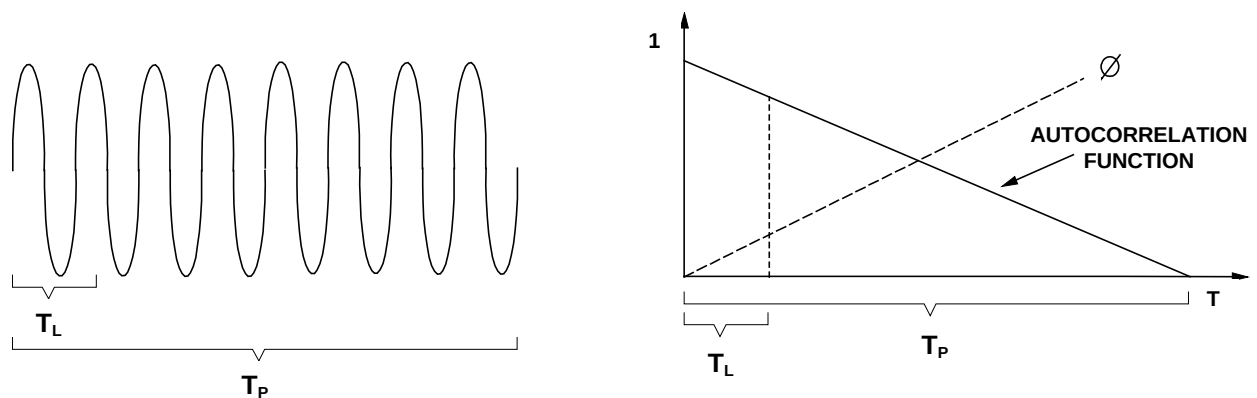


Figure 7. Narrowband Autocorrelation

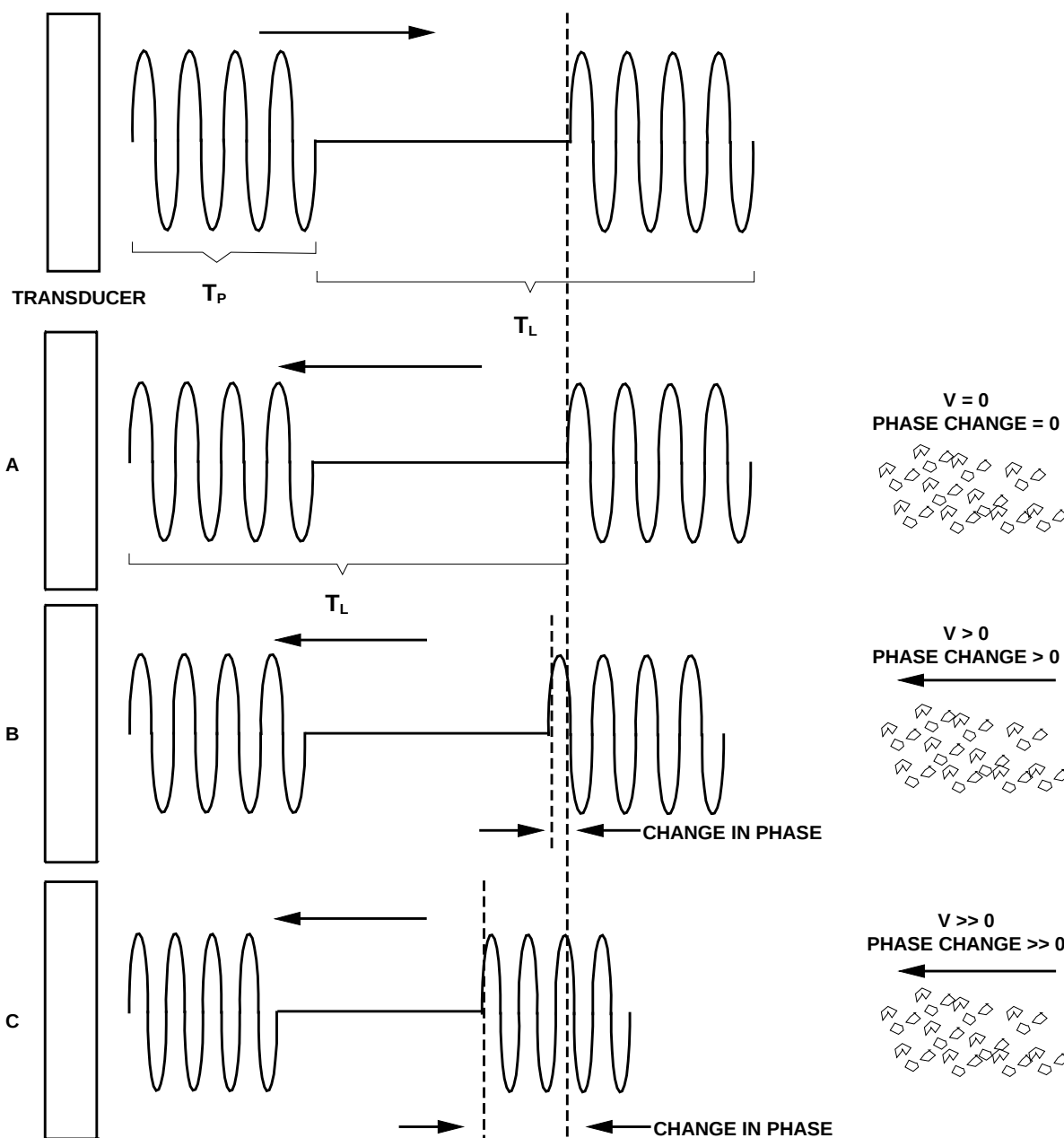


Figure 8. Phase Change Seen by the Broadband System

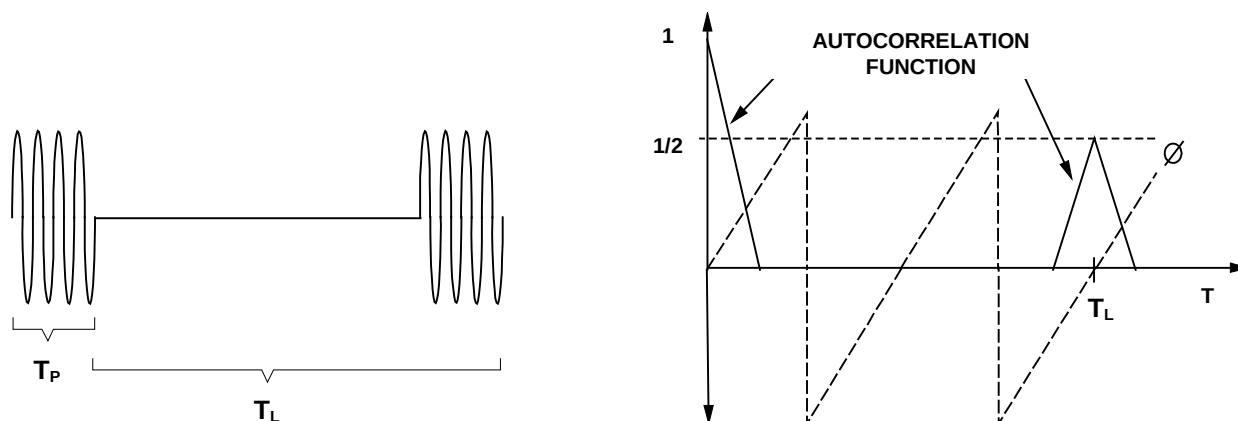


Figure 9. Broadband Autocorrelation

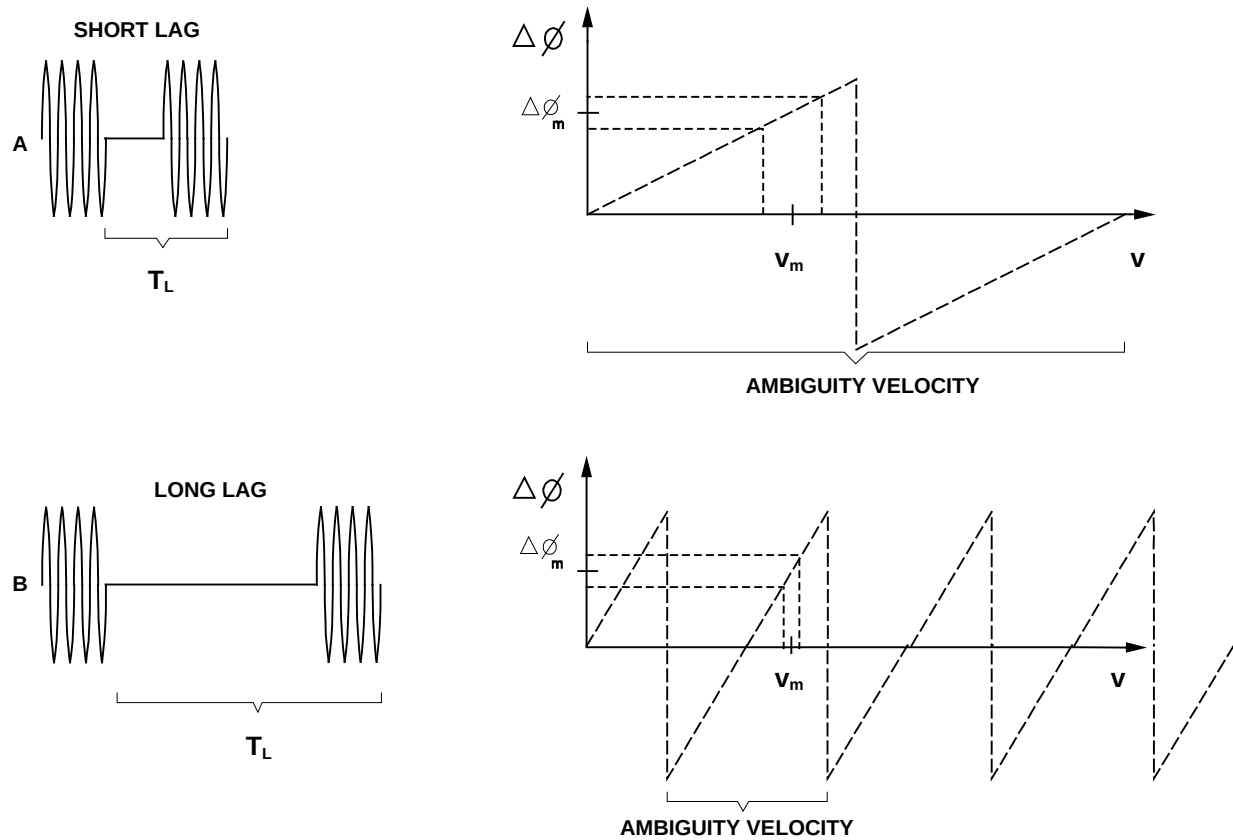


Figure 10. Phase vs. Velocity

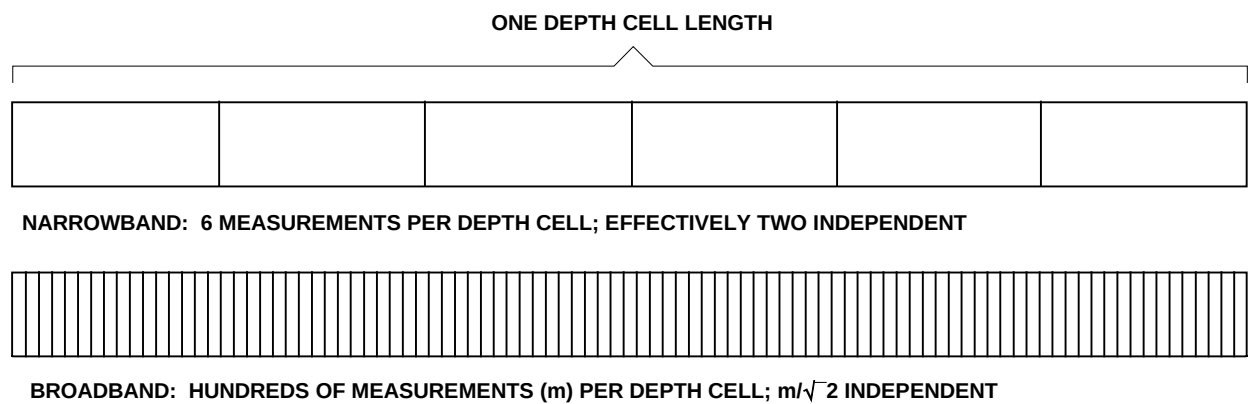


Figure 11. Comparison of Number of Measurements per Depth Cell

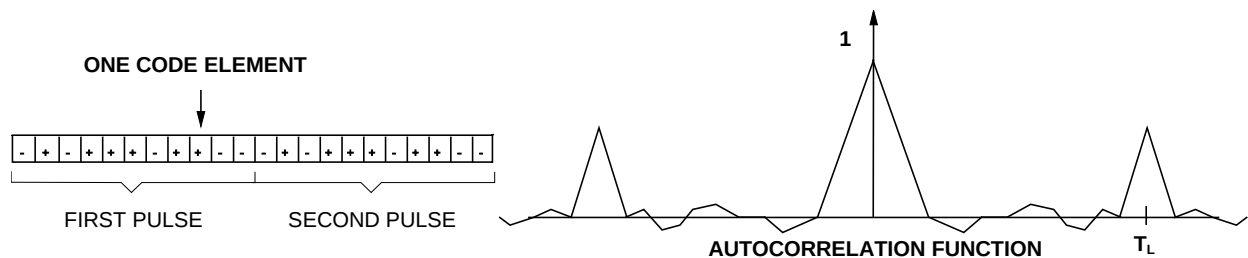


Figure 12. Sample Coded Pulse