

Pure coherent Doppler systems – how far can we push it?

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Abstract- The excellent space-time resolution of pure coherent Doppler system has led many scientists to select this processing technique to solve his or her measurement problem. There is nothing in the acoustic Doppler world that can beat the information content of a pure coherent system. The high vertical and temporal resolution give an instantaneous picture of the flow field with photographic clarity; slow moving lake flow looks like something out of a physics text book and boundary layers come alive as you observe bottom sediments being ejected into the flow. Still, in the transition between the scientific prototype and the commercial implementation we tend to stumble. Instead of being a commonly used approach to oceanographic observations, successful deployments using pure coherent techniques are disappointingly few and far between. When we want to explain why, we quickly point to the inherent ambiguity problem of the pure coherent technique, which can be expressed as a limitation on the product of the profiling range and the unambiguous velocity we can resolve. In other words, the faster the flow, the shorter the profiling range, which effectively limits the technique to low-energy environments. Since high energy environments generally are the most interesting, the push is to operate where ambiguity limitations are exceeded. This has again led to the search for “ambiguity resolution schemes” that allow us to measure phase shifts larger than $\pm\pi$. Mathematically, this is not a hard problem to solve and methods for solving the ambiguity problem were suggested by Lhermitte as far back as the early 1980s. In the lab, with tow carriages moving back and forth across a quiet body of water, these schemes work well. When measuring in the field, however, these schemes have at times failed miserably, much to the chagrin of both the scientists and the support departments at commercial vendors. This paper provides an overview of the key operational elements of the pulse-to-pulse coherent system and addresses some recent findings that explains what previously has been unexplained differences between laboratory and field experiments. It also details some of the performance limitations we should realistically expect with pure coherent systems.

I. INTRODUCTION

Many physical processes in open waters occur at scales or velocities that make them undetectable with conventional Doppler sonars. High-resolution current profilers attempt to obtain the ultimate possible performance capability in order to observe these motions. Resulting implementations are both more limiting and more troublesome than conventional Doppler sonars, but the reward is new insight into the physics of underwater flow. This is especially true for process studies, where the higher temporal and spatial resolution potentially opens up a new physical universe for the observer (Fig. 1).

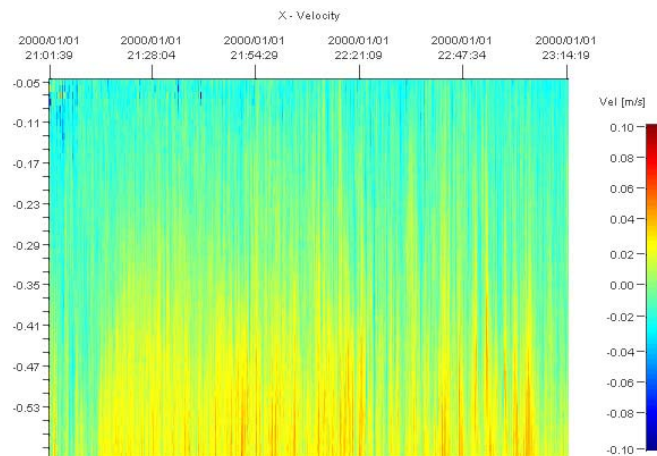


Figure 1. The color contour plots shows 15-s average data collected with 1-cm vertical resolution. The horizontal scale is about two hours and the vertical scale is about 0.5 m

A. High resolution Doppler measurements

Doppler velocity measurement works by observing the changing distance to particles in the water, typically by transmitting two or more pulses and comparing the echoes. The time required for the echo to return gives an approximate distance to the particles, while phase changes provide a sensitive means to detect small *changes* in this distance. For Doppler measurements to work, phase patterns must be recognizably similar from one ping to the next, that is, the echoes must be correlated. Lhermitte [1] was one of the first to explore an approach in which he waited for the first echo to die down before he transmitted the second pulse. This allows the limiting correlation to approach 1.0, and correlation approaching 1.0 dramatically reduces velocity variance (c.f. [2]). Doppler systems that rely on obtaining correlations near 1.0 are often called “pulse-to-pulse coherent”, and they are often able to achieve velocity variance orders of magnitude lower than in standard incoherent sonars [3]-[7]. The “term pulse-to-pulse coherent”, “HR”, and “pulse coherent” is used interchangeably in this description.

B. Bistatic Pulse-coherent HR implementations

Acoustic Doppler Velocimeters transmit short pulses with a narrow acoustic beam and sample the echo when it propagates through the focus volume of the acoustic receivers. With sufficient separation between the pulses, there is no cross interference between the pulses and pulse-to-coherent processing works well. The ability to use this processing scheme is one of key reasons for the success of velocimeters, which are used to explore small temporal and spatial scales in hydraulic research and in oceanographic process studies. However, commercial implementations using the bistatic geometry still only provides point velocity measurements so applications in oceanographic studies are still limited.

C. Signal processing

In pulse-to-pulse coherent Doppler systems, the processing takes place by calculating the complex autocovariance function between the two echoes. Without going into details, the mathematical process is very similar to finding the angular difference between two vectors of length unity. Each sample produces one such “difference vector” and averaging over space or time is equivalent to summing all the “difference vectors” and finding the angle of the mean vector. The length of normalized vector is the “correlation”, a much discussed but not very well understood parameter that is used a proxy for the quality of the velocity estimate.

D. Ambiguity velocity

The precision of velocity observations improves if you increase the echo correlation, and it also improves if you wait longer between pings. Unfortunately, these two means of improvement are at cross-purposes because a longer wait reduces our ability to measure large velocities. The reason is the source of confusion that arises as phase changes approach $\pm\pi$. A sine wave with phase $-\pi$ looks the same as a sine wave with phase $+\pi$ so an “unambiguous” resolution of phase can only take place when the phase change is in the range $[-\pi, \pi]$. Outside this range, additional information is required in order to determine the real phase change and hence the velocity. For profiling systems the ambiguity problem translates [5] into a limit on the product of the velocity range multiplied with the profiling range. In other words, the shorter the profiling range, the higher the maximum velocity that can be measured. This limit depends on the frequency so that low frequency sonars have a higher limit on the range-velocity product than do high-frequency systems. In many natural oceanographic flows, the range-velocity limitation will be impractical or undesirable so Doppler systems routinely try to cope with velocity ambiguity by using various ambiguity resolution methods to determine just how many times the phase has wrapped around π . The trouble is that the wrong number of wraps gives you a large velocity error.

II. AMBIGUITY VELOCITY

Several methods have been developed and tested in order to work around the problem of ambiguity velocity. In the case of the velocimeters, the purpose of the scheme is simply to increase the velocity range. For profilers, the purpose is to increase the range-velocity product so that the instrument can become a practical tool for studying a larger range of oceanographic phenomena.

A. Multiple pulse pairs, long-long

The prototype RDI HR-ADCP and the Nortek HR-ADP (introduced in 1998 and discontinued a few later for commercial reasons), used a scheme first proposed by Lhermitte [1]. The transmit sequence in case consisted of two pairs of two pulses each, each pair with a different time lag. Each pair produced a phase shift inversely proportional to the lag between the two pulses so with some careful choices of lag times and a little algebra it was possible to extend the maximum measurable velocity a factor of three compared with the use of one pulse pair [4].

B. Multiple pulse pairs, short-long

The simplest and most straightforward ambiguity resolution scheme uses a “short lag - long lag” approach. It was used in the early implementations of the RDI BB-ADCP and it is also used in the recently released Nortek HR-Aquadopp and in the Nortek Vectrino/Vector single-point instruments. The first lag is short and has the desired (large) velocity range but, in the case of a profiling system, also has a short profiling range. This first pulse-pair is used to establish a coarse estimate of the velocity close to the instrument. A few ms later, a second pulse pair with a longer time lag provides more precise phase shift information over a longer profiling range. The information from the first pulse pair is then used to resolve any potential ambiguity in the phase shift that may have occurred when estimating phase from the second pulse pair.

C. Other methods

Ambiguity resolution schemes based on multiple discreet tones have been discussed and implemented in the field of medical ultrasound. Since each discreet frequency provides a slightly different phase, it is theoretically possible to resolve the ambiguity velocity using least squares methods. Multi-tone systems have not played a significant role for ambiguity resolution in oceanographic research but this may change (ref. presentation at “Underwater Acoustic Measurements 2007” by A. Hay, Dalhousie University, Halifax, Canada).

III. DECORRELATION

In spite of the very best attempts on the part of the instrument developers, the application of pulse-to-pulse coherent profiling systems still has been limited to low energy environments. The main reason is that the ambiguity resolving schemes generally do not work as well as we hope and we often find that the best performance is obtained when we restrain the instrument configuration to measure within the limits of a single ambiguity range, i.e. without ambiguity resolution. This is in contrast to bistatic implementations such as the Vector and the Vectrino, which are routinely operated at velocity ranges two or three times the basic ambiguity velocity. In effect, we have only found two significant limitations for point velocimeters: Low particle concentrations (low signal strength) and highly turbulent water jets, both of which leads to a reduction in correlation parameter.

A pulse-to-pulse coherent system is tolerant with respect to the exact shape of the transmit pulse or the particle scattering processes because we are essentially comparing two sonic images. So even if the transducer has imperfections, like an optic lens has imperfections, the two images that are produced will be very similar. The technique is thus robust with regard to small differences in manufacturing processes and even with respect to the electronic hardware implementation. The construction technique is thus not a limiting factor for the instrument performance.

There are three known mechanisms that can reduce the correlation and significantly disturb the phase estimate.

A. Pulse-to-pulse interference

HR profilers operate by transmitting a pulse, listening to the echo for a specified amount of time, then transmitting a second pulse and then listening to the second echo. The time between the two pulses is referred to as "time lag" or "time delay". As explained in the introduction, the velocity is proportional to the phase shift between the two echoes.

The first step, transmitting an acoustic pulse and recording the echo, is normally a trouble-free process. The second pulse is transmitted only a short time after the first one (of order ms) and recording the echo from the second pulse is the critical process in any HR system. If the echo from the first pulse, for any reason, overpowers the echo from the second pulse, we have a situation commonly referred to as "pulse-to-pulse interference". Avoiding this type of situation is one of the main difficulties in properly configuring a HR profiler and the user is normally forced to make several trade-offs.

1. System oriented downward and mounted at a known distance above the bottom.

If practical, this is normally the best way to get good data from a HR profiler. The configuration software can use the distance to the bottom as the key input parameter and the spacing between the acoustic pulses is usually set to be slightly larger than the distance to the bottom. Because the strong bottom echo from the first pulse reaches the transducer right after the second pulse is transmitted, the acoustic interference does not affect the velocity close to the bottom. Also, if the bottom consists of mud, silt or sand, the first pulse will often die out once it hits the bottom. As a result, there is no pulse-to-pulse interference. If the bottom is made from strong acoustic reflectors such as rock, coral reefs, etc., the first pulse will generally not die out and some level of interference should be expected.

Care has to be taken so the distance to the actual distance to the bottom matches the distance used in the software configuration. If the distance to the bottom is set to be smaller than true distance, the second pulse will be transmitted too early and the data close to the bottom will not be valid. If the distance to the bottom is set to be larger than the actual distance, the second pulse will be transmitted too late. The normal consequence is that data will be lost in a band close to the instrument.

Normally, the data close to the bottom is more important than the data close to the profiler so if the distance is not precisely known, it is better to err on the side of overestimating the distance to the bottom.

2. System oriented toward the surface, deep water.

If the water depth is larger than twice the profiling range, pulse-to-pulse interference is rarely a problem for high-frequency Doppler systems (>1 MHz). However, this assumes that the scattering conditions are uniform. If we define R to be the position of the depth cell of interest, L is the distance between the two pulses, α is the water absorption in dB per meter and Sv is the volume scattering function for pulse 1 or 2, the SNR for the second echo is:

$$\text{SNR} = 20\log_{10}([R+L]/R) + 2\alpha L + \text{Sv}(2) - \text{Sv}(1) \quad (1)$$

If the scattering conditions are uniform, $\text{Sv}(2) = \text{Sv}(1)$ and the SNR is defined in terms of the absorption ($2\alpha L$) and geometric spreading terms. For systems profiling over 1 m and operating at 2 MHz, the geometric spreading corresponds to about 6 dB and the absorption corresponds to about 2 dB for a sum of 8 dB. This relatively low SNR is in itself a form of pulse-to-pulse interference and it will reduce the correlation from an ideal value of 1 to a value of about 0.9. If the scattering conditions are not uniform, as can happen if there are fish or zooplankton

layers in the water column, the correlation can be reduced even further.

To alleviate this particular situation, it is possible to differentiate the transmit power for the two pulses in a pulse-pair.

3. System oriented toward the surface, shallow water.

Shallow water means that we have to worry about acoustic interference from the surface echo. Intuitively it may seem that this situation is similar to the downward looking profiler positioned at know distance above the bottom but the water surface is acoustically different from the bottom:

- The echo does not die out when it hits the surface.
- The surface position varies with tide and wave motion.

A conservative approach to this situation is to set the profiling range to be a little less than half the distance from the instrument to the surface. This ensures that it possible to listen to echo from both pulses without interference and it simulates the “deep water” scenario described above. Unfortunately, this means that an upward looking system can only safely measure the lower part of the water column as defined by half the distance to the deepest wave trough. A more aggressive approach in this situation would be to pretend that this case is similar to the situation where the profiler is mounted downwards. However, this approach will give high quality data only when the surface is very smooth – as it was in the tidal channels where Lhermitte [1] tested his first coherent Doppler system. When waves from local boat traffic propagated above the bottom mounted instrument, the measurement process would completely break down.

B. Flow field effects

Several known decorrelation mechanisms, or “spectral broadening effects”, are due to the interaction between the flow field and the acoustical sampling volume.

Beam Divergence: An acoustic beam is not cylindrical and the pressure field is not parallel to the face of the transducer. For this reason, the flow field will be sensed at slightly different angle as we move off-center from the beam axis. This introduces a small broadening of the velocity spectrum that will reduce the measured correlation. The effect is quite small for the narrow acoustic beams that are used in Doppler systems.

Shear: If the flow field varies within the acoustic sampling volume, the flow is not defined by a single phase shift but rather as distribution of phase shifts. This can give rise to reduced correlation, especially in the bottom boundary layer. For profilers, which are difficult to operate in the immediate

vicinity of the bottom, this effect is usually quite small. It is also quite easy to assess the magnitude of the effect by varying the size of the sampling volume.

Turbulence: The effect of turbulence on the correlation of pulse-to-pulse coherent systems has been the subject of much speculation, both for profiling and single-point systems. As mentioned previously, we see a reduced correlation with velocimeters when we measure in water jets. This has been attributed to a possible reorientation of the scattering particles that can take place over the time delay between the two pulses. While enticing, this hypothesis has never been rigorously tested and it is not known to what extent this effect should be taken into account.

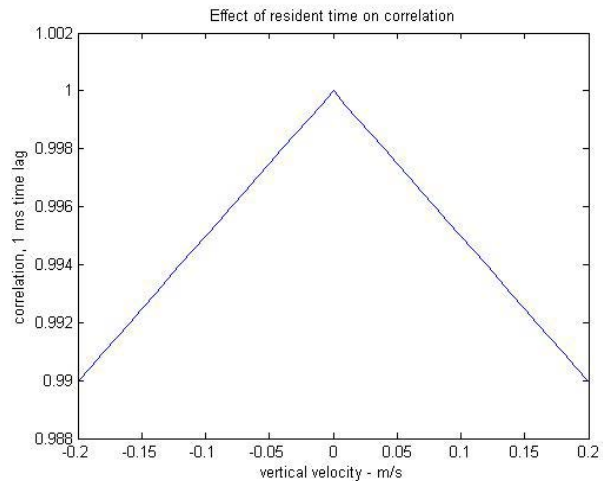


Figure 2. Resident time has little effect on the correlation parameter

Residence time: If the flow field moves fast, the particles contained in the sampling volume will not remain the same as the two pulses propagate through the volume. Again, this effect is quite small and Fig. 2 illustrates how the correlation is reduced as a function of the along-beam velocity for a system that profiles over 1m. As can be seen, the vertical velocity must be quite large to have an impact on the correlation.

Flow field effects are certainly relevant for our understanding of the decorrelation mechanism and they will reduce the correlation factor from an ideal value of 1 to a lesser, but very much acceptable value of 0.9 or above. So far, however, we have not been able to identify any such process that is as important as pulse-to-pulse interference.

C. Processing methods

Early implementations of the pulse-to-pulse coherent technique compute velocity by averaging the complex autocovariance over a period of 1-2 seconds and then extract the phase change that allows us to compute velocity. The velocity from each acoustic beam then goes through the standard coordinate transforms from beam coordinates to instrument

coordinates (V_x , V_y , V_z) and with the use of a compass and tilt reading to earth coordinates (V_e , V_n , V_u). Further averaging over longer time scales can be performed as proper vector averages, which is especially important if the instrument is rotating.

Given the detrimental effect of sudden ambiguity jumps, the Nortek HR-ADP was implemented with a different scheme for computing and averaging. Because ambiguity errors are relatively large, they dominate the resulting velocity averages. The HR-ADP, in contrast, averaged the complex autocorrelation over time scales that typically lasted for several 10's of seconds. Because measurements that would incur velocity ambiguity are normally associated with small correlation magnitudes, they are suppressed in the average. It turned out that this method remained robust and produced high quality estimates of the mean flow even in oscillatory flow (i.e. waves) in which velocities periodically exceeded the ambiguity limits. However, when the oscillatory motion exceeded the ambiguity velocity by a factor of 1.5-2, the correlation would drop and the estimates of the mean velocity were no longer reliable. The reason for this drop has remained unexplained until a recent study of the effect of sampling rate on the magnitude of the correlation parameter.

In a recent dockside study in Coconut Grove, Miami, a 2 MHz Aquadopp Profiler operating with pulse-to-pulse coherent firmware was attached to a ladder close to the surface and oriented so it looked down toward the bottom located approximately 2 m below. The mean current was less than 0.05 m/s and the surface waves had a period of about 1 s and amplitude of about 0.1 m. The instrument was first configured to collect data at 2 Hz in 5-cm depth cells over a range of about 2 meters and then later set to collect data at 8 Hz with 5-cm depth cells with a over a range of about 1.4 m. The secondary ambiguity range was about 6 cm/s for the 2 Hz data and about +/- 8 cm/s for the 8 Hz data. The surface velocity is shown in Fig. 3, where the environmental conditions can be seen to have remained unchanged during the data collection period but where the 8 Hz data obviously resolves the wave motion better than the 2 Hz data.

In Fig. 4, the correlation data for the same time period is shown. Surprisingly, there is a large difference between the correlation values associated with the 2 Hz and the 8 Hz data. Whereas the correlation values in the 8 Hz data are quite acceptable with values in the range 0.8-1, the corresponding 2 Hz data show a significant reduction in value.

The underlying data collection rate is about 30 Hz for both data sets and the only difference is how the data is averaged. In the 2 Hz case, the autocovariance function is calculated for 15 pulse-pairs and the average phase shift estimated. For the 8 Hz case, only about 4 pulse-pairs are averaged before the velocity is calculated.

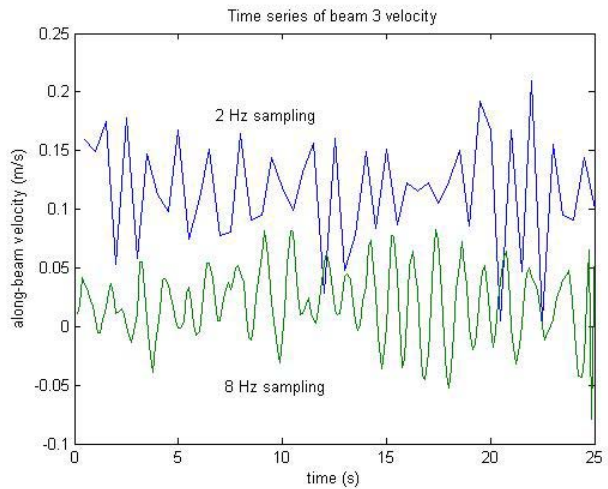


Figure 3.- Time series of HR velocity collected 25 cm below the surface. The top blue line (2 Hz sampling) is offset by 0.1 m/s for clarity

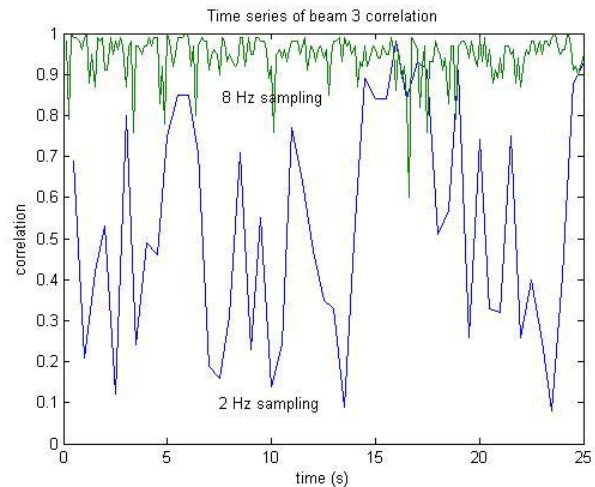


Figure 4. The correlation of the 2 Hz and the 8 Hz data shown on the same scale

Since the velocity varies within the averaging period, we can think of each pulse-pair as generating a resulting vector of length unity. The angle of the vector is equal to its phase and the average of several vectors is the sum of the vectors. In a limiting case, we can imagine four vectors with direction 0 , $\pi/2$, π , and $3\pi/2$. The sum is then 0, which means that the length of the resulting vector is zero (correlation = 0) and the phase is undefined. In other words, if the velocity variation within the averaging period is allowed to span a significant portion of phase space, the averaging process falls apart. This implies that the magnitude of the velocity variation can not be close the ambiguity velocity or the correlation drops. Our problem in Fig.3 is thus connected to the velocity variability within the averaging period. In effect, the shorter averaging period gives the better correlation.

This particular averaging effect can be modeled using an assumption of linear velocity variations within the sampling interval. Fig. 5 illustrates this with two data sets taken from the same periods shown in Fig. 3 and 4.

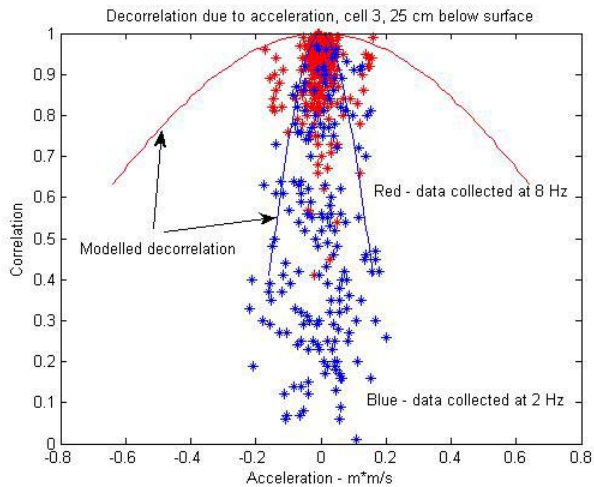


Figure 5. Correlation as a function of the acceleration between two subsequent velocity averages.

The red '+' symbols show correlation of the 8 Hz data as a function of the acceleration. The corresponding decorrelation model is shown in red, and all the data points are within the upper bound of the model. The blue '+' symbols illustrates how the greater velocity variations in the 2 Hz data reduce the correlation. Most of the data points are below the predicted decorrelation model, although a few points are outside, most likely because of the uncertainty in the estimates of acceleration.

In Fig. 6, the same situation is shown for data collected further down in the water column. As can be seen, the oscillatory wave motion is no longer a factor and the correlation is about the same for both the 2 Hz and the 8 Hz data.

IV. CONCLUSIONS

The pulse-to-pulse coherent technique is great when it works but produces quite disastrous results when it doesn't. To ensure the best possible results, it is important to get ready for the specific measurement situations by carefully preparing the deployment configuration and the instrument orientation. It should also be accepted that the some of the data collected during a deployment may not always be of highest quality and that the varying environmental situation can have a significant impact on the data quality. It is also advisable to avoid high-energy environments. Despite our best effort, our ability to resolve velocity across multiple ambiguity ranges is quite limited. Finally, in dynamic situations it is much better to output data fast and then average afterwards. Failure to do so

comes at the penalty of a strong reduction in the data quality when the velocity variability within an averaging interval approaches the ambiguity velocity.

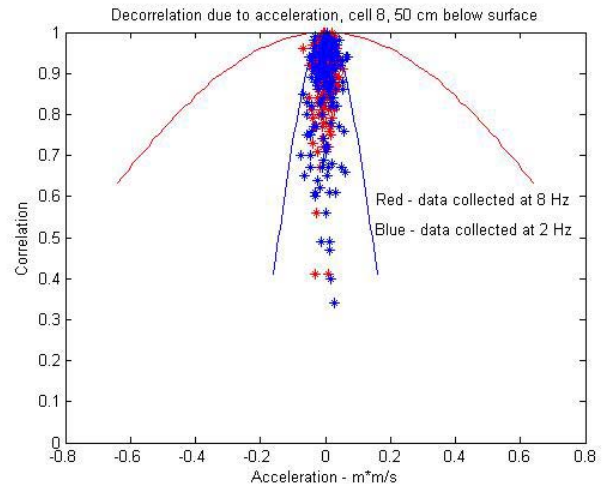


Figure 6. Deeper in the water column, the orbital wave motion is insignificant and the decorrelation effect of the averaging process is no longer noticeable

REFERENCES

- [1] R. Lhermitte and R. Serafin, "Pulse-to-pulse coherent Doppler sonar signal processing techniques," *J. Atmos. and Ocean. Technol.*, vol. 1, pp 293-308, 1984.
- [2] B. Brumley, R. Cabrera, K. Deines, and E. Terray, "Performance of a broad-band acoustic Doppler current profiler," *IEEE J. Oceanic Eng.*, vol. 16, pp.402-407, 1991.
- [3] R.L. Gordon, A. Lohrmann, A. and T. Jonas, "Internal Wave Generation in Lakes with very slow flow", IEEE Sixth working conference on Current Measurements, San Diego, March 1999.
- [4] A. Lohrmann, B. Hackett and L.-P. Røed, High resolution measurements of turbulence, velocity and stress using a pulse-to-pulse coherent sonar, *J. Atmos. and Ocean. Technol.*, vol. 7, pp. 19-37, 1990.
- [5] L. Zedel, A. E. Hay, R. Cabrera, and A. Lohrmann, "Performance of a single-beam pulse-to-pulse coherent Doppler profiler," *IEEE J. Oceanic Eng.*, vol. 21, pp.290-297, 1996.
- [6] J. T. Sherman and R. Pinkel, Estimates of the vertical wavenumber frequency spectra of vertical shear and strain, *J. Phys. Oceanogr.*, vol. 21, pp 292-303, 1991.
- [7] J. T. Sherman, Observations of the fine scale vertical shear and strain in the upper ocean, PhD thesis, Scripps Institution of Oceanography, SIO Ref. 89-11, 119 pp., 1989.