Design and Applications of a Vertical Beam in Acoustic Doppler Current Profilers

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***Abstract*—This paper provides an overview of the design parameters and performance considerations of a vertical profiling beam in an acoustic Doppler current profiler (ADCP) instrument. Typically ADCP instruments employ an array of beams that are used in concert to determine three-dimensional velocity estimates at various ranges from the instrument. The vertical profiling beam is an additional beam, supplementary to this array, which is dedicated solely to the measurement of the vertical component of the velocity. This separate beam offers enhanced performance versus the typical ADCP beam array. Also, the vertical beam must be configured in a different manner from the typical ADCP array, and has different performance considerations. These trade-offs are explored and sample data is presented.**

Keywords—Acoustic Doppler Current Profiler, ADCP, vertical beam

I. INTRODUCTION

Acoustic Doppler Current Profiler (ADCP) instruments have long been used to collect time series data of current profiles in oceanographic research. In addition to their core function of measuring currents at various distances throughout the water column, ADCPs can also monitor the return signal level to assess the backscatter level in the water as well as the range to surface. Spectral analysis can be applied to ADCP data, consisting of velocity data as well as range to surface data as determined by pressure readings and/or acoustic signal intensity, to analyze the wave fields in the vicinity of the instrument.

Typically ADCP instruments have employed an array of beams to develop a solution for the three-dimensional velocity. At a minimum three beams, in a non-coplanar arrangement, are required to develop this three-dimensional velocity solution. In many instruments four beams are employed in opposing pairs, known as a Janus configuration, to provide a more robust solution. In these instruments the individual beams are used to measure beam-wise velocity components, which are then mathematically transformed into Cartesian coordinate velocities (X/Y/Z or East/North/Up) or into a polar coordinate velocities (velocity magnitude and direction).

Since the measurements taken by the individual acoustic beams are physically separated, the resultant three-dimensional velocity measurements are predicated on the assumption that the velocities are homogeneous, *i.e.* that the three-dimensional velocity detected by one beam at a certain distance from the instrument is identical to the three-dimensional velocity detected by other beams at that same distance from the instrument. Certain conditions can invalidate this assumption: for example phenomena such as turbulence and ocean waves can cause the velocities to vary on a spatial scale small enough to be significant with respect to the instrument's beams. It can be advantageous to obtain a direct measurement of a velocity component in order to eliminate this source of measurement degradation.

The Sentinel V is a new ADCP which, in addition to its standard 4 Janus beams, also offers an optional fifth beam which is oriented on the vertical axis of the instrument. This beam can be used to improve spatial resolution of velocity measurements, offer direct measurement of the vertical component of the water velocity, and enhance detection of the water's surface.

II. MOTIVATION FOR VERTICAL BEAM

A. *Direct Measurement of Velocity*

With the traditional transducer array, the vertical velocity that is measured by the instrument is derived from the individual beam-wise measurements. Specifically, in the case of a four-beam Janus array of transducers, the vertical velocity is calculated as the average of the four beam-wise velocities, with a scaling factor to account for the beam angle:

$$Z = \frac{b_1 + b_2 + b_3 + b_4}{4\cos\theta}$$

Where b_1 through b_4 are the individual beam velocities and θ is the Janus angle (i.e. angle of the beam with respect to vertical).

The points at which the four beam velocities are measured are physically separated, so if the Z-component of the velocity is not uniform at all four of these measurement points (due to turbulence, interference, or phase of an orbital wave velocity at one or more measurement points) then the resultant Z velocity solution will have a corresponding error. Specifically, the calculated Z velocity is an average of the four physically separated beam velocities, and so it represents a spatial average of the velocities detected in that region.

The Z velocity of a vertical beam is measured directly along that beam, and so the spatial averaging effect mentioned no longer applies. This mitigates the need for homogeneity of current; the beam only detects the vertical velocity component in that local region.

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B. *Enhanced reflection off specular surface*

In many applications it is desirable to use the amplitude signal from the acoustic beam to determine the distance to the water's surface or bottom. Specifically, the amplitude profile is examined to find the local maximum in the echo which corresponds to the specific boundary.

The reflection from the water's surface (air-water interface) is often highly specular. As such, beams which strike the surface at a non-perpendicular angle will have the majority of their energy reflected away, with only a small portion of the energy reflecting back toward the instrument. By contrast, a vertical beam will strike the water's surface at a nearly perpendicular angle, and so the majority of the acoustic energy is reflected back toward the instrument.

C. *No sidelobe rejection region needed*

The acoustic signal reflected at a boundary (the water's surface or bottom) has a high return level, far greater than the acoustic return generated by the scatterers within the water column. Because of this, the vertical range to the boundary limits the useful profiling range of the instrument due to acoustic sidelobes.

As shown in figure 1 below, when a signal is transmitted from a Janus beam (at an angle of 25 degrees in this example) there is also energy propagating vertically due to transducer sidelobes. The acoustic signal within the sidelobe has a much lower amplitude than the signal in the main lobe – roughly 35 decibels lower – and so it does not affect the measurement when both the sidelobe and main lobe signals are being reflected off scatterers within the water column. However, when the sidelobe signal strikes the boundary, the sidelobe signal is reflected with much more efficiency than the main lobe signal, which is still reflecting off of scatterers within the water column. Because of this, the sidelobe signal return becomes significant with respect to the main lobe signal, and the overall measurement becomes corrupted by sidelobe interference, and the data beyond this point is no longer usable.

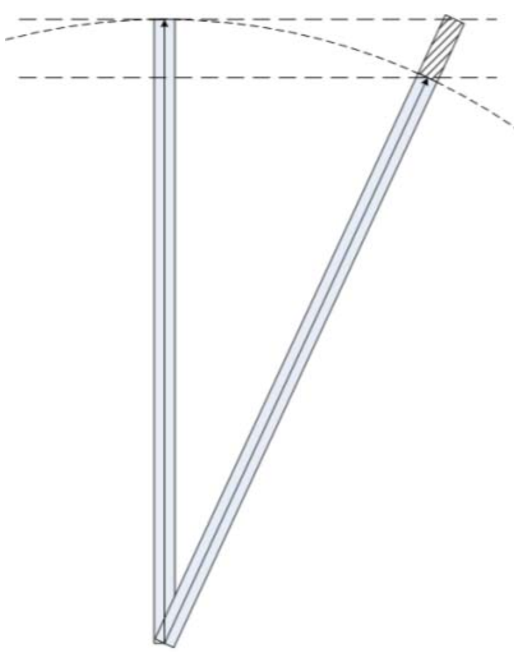

Fig. 1. Range of a Janus beam can be truncated by vertical sidelobe interference

In summary, the range of a slant beam is limited because its side lobe strikes the surface before the main lobe of the beam. In the case of the vertical beam, however, the main lobe will strike the surface before the side lobes, and so useful data may be obtained much closer to the surface.

III. Design Considerations

A. *Beam diameter / beam width*

A key source of long-term error (measurement bias) in ADCP instruments is the way in which the beam intersects with any stratification in the return signal. This can be due to the sea surface or bottom (i.e. the air-water interface or the water-bottom interface) or non-uniformity of the return within the water column. The latter is sometimes designated as a "life layer" and causes a horizontal stratification of the scatterers within the water column.

When a beam intersects such a stratification boundary, it intersects over a range of angles as determined by the beam width. Each of these intersection angles generates a different Doppler shift, and any directional dependence in the return signal will generate a measurement bias. Because of this, it is typically desirable to minimize the width of the beam in order to minimize these bias effects.

Since stratifications are most commonly horizontally distributed, a vertical beam will strike at a perpendicular angle nominally, and the angles of intersection will be centered about zero. Because of this, the vertical beam is much more tolerant of a wider beam width.

Since a vertical beam is commonly used to detect the range to the boundary (water's surface or bottom), having a wider beam is beneficial since it makes the overall range-to-boundary measurement more tolerant to instrument tilt. It also has the practical benefit of allowing for a smaller transducer, which in turn allows for a more compact overall design. As shown in

Fig. 2. The vertical beam transducer in a Sentinel V ADCP

figure 2, the Sentinel V employs a vertical beam transducer that is roughly one-half the diameter of the slant beam transducers.

IV. Performance Considerations

A. Noise

As discussed in [1] there are various sources of measurement noise (standard deviation) in the instrument measurement. These manifest themselves as a variation in the velocity measured along the transducer beam. In most applications the ADCP instrument is primarily used for the measurement of horizontal velocities, and as such the noise specifications are typically transformed to be representative of a horizontal velocity measurement. The net result is that a beam-radial noise component will be multiplied by a moderate amount – a factor of roughly 1.2 for a 25-degree system – when transforming to the horizontal.

In the case of the vertical beam the velocity being measured is the along-beam component only. As such, no scaling factor is required and any measurement noise is translated to the output by a unity factor. Therefore the noise of this velocity measurement does not require any transformation nor any scaling factor, unlike the corresponding horizontal velocity measurement from the Janus beams.

B. Beam divergence decorrelation

One key source of noise discussed in [1] is known as beam divergence decorrelation. Briefly, this noise is due to the non-uniform angle of reflection of the acoustic signal. Ideally, the acoustic signal generated by the ADCP would reflect off the scatterers and surfaces within the water column at a known angle, i.e. the Janus angle of the instrument. In reality, the beam has a non-zero width and so these reflections occur at a range of angles as defined by that beam width. This causes a spread in the Doppler shift of the return signal, which manifests itself in the resulting measurement as a short-term uncertainty.

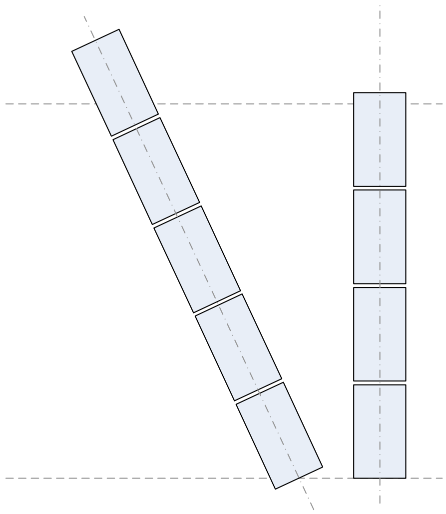

Fig. 3. Transmit pulse length for the Janus beam is longer than that for the vertical beam.

As mentioned above, the vertical beam of the Sentinel V has a wider acoustic beam width than the corresponding slant beams. This means that the beam divergence decorrelation component of the measurement noise will be correspondingly higher. However, this is offset by the fact that the vertical beam is measuring a beam-wise velocity component, which does not undergo any scaling due to transformation into another coordinate system.

C. Bin size / lag size

The depth cells of the instrument, also known as bins, are by convention measured in terms of distance along the instrument's Z-axis. As such, the along-beam distance of a depth cell is larger than the Z-distance by a factor of $1/\cos\theta$, where θ is the angle of the beam with respect to vertical.

As discussed in [1], the ambiguity velocity of a broadband measurement (i.e. the largest velocity that can be measured in an unambiguous fashion) is determined by the transmit lag of the instrument. By accounting for the speed of sound in the water, this lag can be expressed as a physical distance within the water column. In a broadband measurement system the transmit signal is a repeated coded pulse, where the length of the code is equal to this transmit lag.

The transmit signal is scaled to fully ensonify the desired measurement bin. In a broadband system, this is accomplished by repeating the transmit code enough times to provide an overall transmit length that is greater than or equal to the bin length.

Figure 3 illustrates a system using a vertical beam and a slant beam with the same transmit lag and bin size. Since the overall along-beam size of the bin is larger for the slant beam by a factor of $1/\cos\theta$, the slant beam quite often requires a larger number of code repetitions. So the overall transmit length, in terms of vertical distance, is most often different for the slant beams versus the vertical beams, with the slant beams often having the longer transmit.

V. Recommended configurations

In many applications the vertical beam will serve a dual purpose. In addition to providing a direct measurement of the vertical velocity profile, the amplitude return signal from the vertical beam will be used to determine the range to the surface. For this amplitude profile, it is desirable to have the transmit pulse length of the vertical beam well-matched to the size of the measurement bin, in order to enhance the fidelity of the surface finding algorithm.

Figure 3 shows an example of transmit configured for a Janus beam and vertical beam. This example corresponds to a configuration where a 983kHz instrument has been configured to have 30 cm bins and an ambiguity velocity of 350cm/s. As shown in the diagram, the bin is always measured in depth units (i.e. as a vertical distance from the instrument), so the beam-radial distance of the depth cell is longer for the Janus beam than for the vertical beam. This configuration is tuned to provide a transmit length that is well-matched to the bin size for the vertical beam – in this specific case the transmit length is 31cm versus a bin size of 30cm. In the Janus beam, an additional code repetition is needed to completely fill the bin, so the overall transmit length is noticeably larger than the bin, but this is not a concern in the Janus beams.

VI. Sample Data

In April 2013 a Sentinel V system, with the vertical beam transducer, was deployed off of Scripps Pier in San Diego. The system had a 983kHz center frequency and was configured with 30cm bins. The data obtained were analyzed for their beam-wise amplitude returns and the velocities were transformed into U-V-W coordinates, along with the direct measurement of vertical velocity which is denoted as W5 (indicating the instrument's fifth beam). The resultant data are shown in figures 4, 5, and 6.

A. Reflection off surface has higher amplitude

Figure 4 below shows, for a representative profile, the intensity profiles for the four Janus beams, the intensity profile of the four beams averaged together, and the intensity profile of the vertical beam. The range from the instrument increases up the y-axis, and the signal intensity (in instrument counts, roughly 0.5 decibel per count) increases to the right along the x-axis.

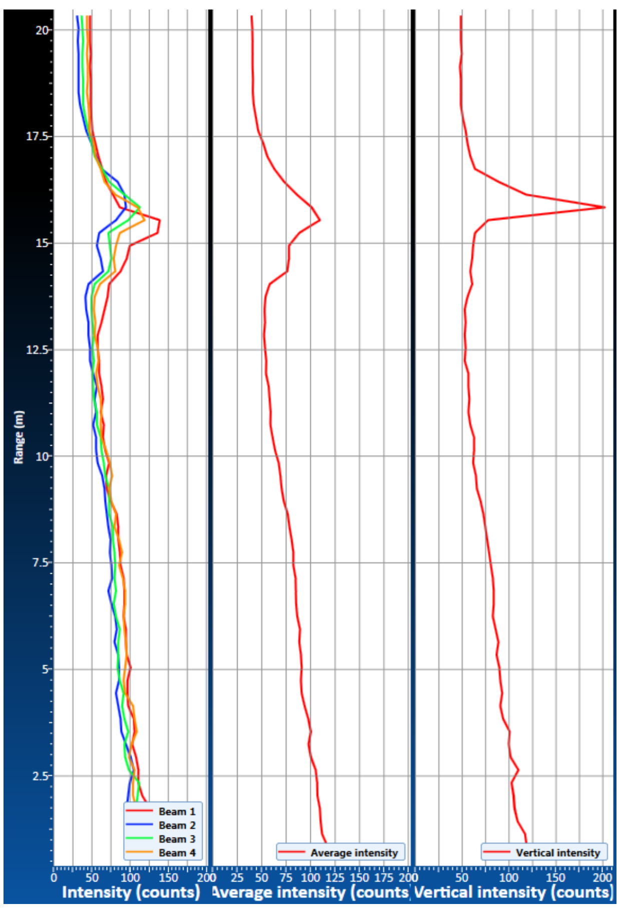

Fig. 4. Amplitude return for Janus beams and vertical beam

In all of the amplitude profiles the local maximum due to the surface reflection can be readily discerned visually. However, in the four beam-wise profiles on the left-most graph, as well as the four-beam average in the center graph, there is a noticeable increase in intensity prior to the maximum that occurs at the surface. This is due to the sidelobe reflections mentioned previously. This sidelobe interference reduces the fidelity of the surface reflection and makes the location of the surface more difficult to discern via automated processing.

The vertical beam return, as shown in the right-most graph of figure 4, shows a stark difference from the slant beams. The vertical beam signal has much higher peak amplitude, which is due to the near-perpendicular reflection of the vertical beam signal. Also, the graph illustrates that the vertical beam has a more well-defined peak, since it is not subject to the sidelobe reflection effects previously mentioned. As such, the amplitude return signal from the vertical beam provides a much more robust means of detecting the water's surface when compared with the slant beams.

It can also be seen that the individual amplitude profiles of the four beams show local maxima at a moderately different ranges. This can primarily be attributed to instrument tilt; the range, which is a distance along the instrument's Z-axis, is an estimate determined by multiplying the slant range of the beam by the cosine of the beam's angle with respect to the instrument's Z-axis. If the instrument is tilted with respect to vertical, then this Z-distance estimate can differ from the true range to surface. As figure 4 illustrates, the maximum of the vertical beam signal occurs at the approximate center of the maxima of the four individual beam measurements.

B. Vertical velocity measurement

Figures 5 and 6 are visualizations of the velocities measured by the instrument. Figure 5 is a high-frequency time series which displays the orbital wave velocities seen, while

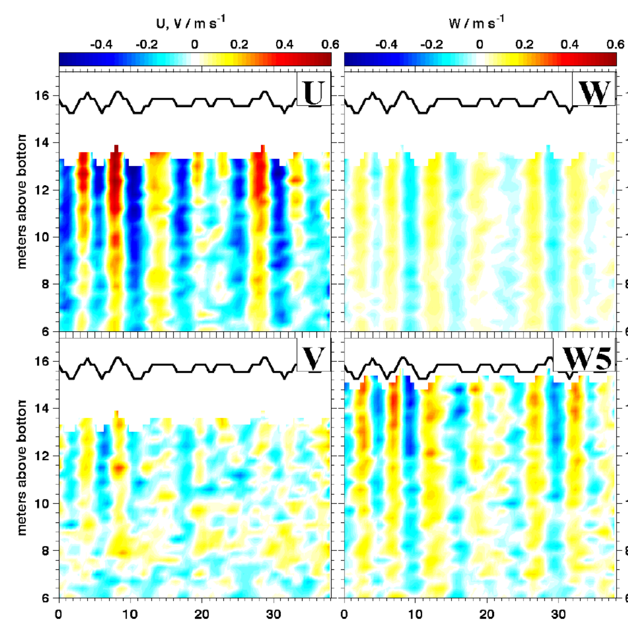

Fig. 5. Data from Scripps pier, short time series

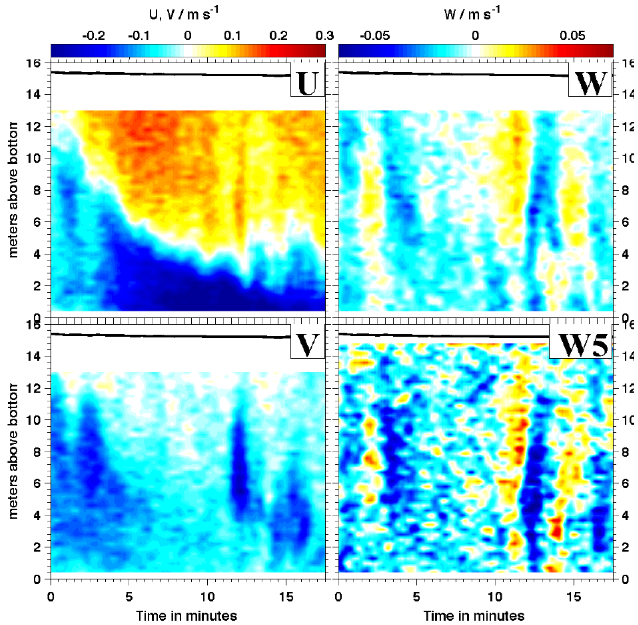

Fig. 6. Data from Scripps Pier, long time series.

figure 6 is a longer time series focused on an internal tidal bore.

In both figures 5 and 6 it can be seen that the vertical beam signal W5 has a greater useful velocity profile range than the slant beams. The U, V, and W signals have had their ranges truncated to avoid the signal contamination due to sidelobes, as discussed earlier. This truncation is roughly 15% of the overall profiling range. The W5 signal does not need this amount of truncation and so offers a means to see vertical velocities in near-surface regions that cannot be feasibly detected by the other beams.

In figure 5 the orbital wave velocities can clearly be seen in the U, W, and W5 components. The W5 component (vertical velocity as directly measured by the vertical beam) contains amplitudes that are noticeably higher than the corresponding measurement in the W component (vertical velocity as derived from the four slant beam measurements). This is due to the spatial averaging effects mentioned previously; the wave orbital velocities are being spatially averaged by the four beams, thus attenuating the overall velocities seen.

Figure 6 illustrates a similar phenomenon. This figure focuses on a tidal bore and some of the internal waves occurring therein. In the latter half of the time series some of these internal waves can be seen, and the components seen in the W5 have higher amplitude and greater resolution than the corresponding W component.

VII. Conclusion

The vertical beam offers a direct measurement of the vertical component of the water velocity, which provides a number of key advantages. This measurement of the vertical velocity component is not subject to the spatial averaging effects that are present in the Janus beams of the systems. Also this measurement is less sensitive to decorrelation and bias effects that are inherent in Doppler measurements. In addition, a vertical beam permits measuring a greater portion of the water velocity profile, since the main lobe of the acoustic beam reaches the surface prior to any of the side lobes.

In waves measurement applications it is often desirable to determine range to surface by the amplitude return signal of the beam. Having a vertical beam is a key advantage in this situation because the signal is being reflected off the water-air interface at a near-perpendicular angle. This results in a return signal that is both high-amplitude and is compact in the time domain.

To provide an optimal configuration for detection of the surface with the amplitude return signal, the length of the transmit pulse should be closely matched to the bin size. Due to the different beam angles and the means used to fully ensonify a bin, the overall length of the transmit signal for a given bin size will be different between the vertical beam and the Janus beams.

For a given bin size and transmit lag, the length of the pulse transmitted on the Janus beam can often be longer than the pulse transmitted on the vertical beam. The length of the transmit pulse of the Janus beams is typically not a major concern. For the vertical beam, however, it is often desirable to have the transmit pulse length closely matched to the bin size to enable detection of the surface via the amplitude return signal.

Acknowledgment

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