Extracting Fish and Water Velocity from Doppler Profiler Data

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***Abstract* - Doppler current profilers are optimised for measuring water velocities but they have the demonstrated capability to measure fish swimming speeds. This is possible when fish form schools that are large enough so that the multiple Doppler sonar beams are sampling the fish speeds at the same time. In situations where fish are not present in at least three acoustic beams, it is impossible to extract fish velocity with the data processing algorithms normally used to extract water velocity. We present an alternative method of analysing Doppler sonar data that treats data from individual acoustic beams independently so that velocities can be extracted when fish occur intermittantly in the sonar beams. The algorithm is applied to extract both water and fish velocities from Doppler profiler observations of overwintering Atlantic cod in Smith Sound, Newfoundland. Currents in this enclosed coastal area are slow (about 10 cm s^{-1}) and the fish appear to move passively with the water much of the time. However, there are times when the fish have velocities different than those of the water and profiles averaged over 20 days shows clear differences in fish and water velocities.**

I. Introduction

The Doppler sonar technique allows determination of velocities radial to a single point transducer and by using narrow acoustic beams, this allows measurement of a single velocity component. In the case of Doppler current profilers, multiple diverging beams must be used in order to recover three component velocities. In order to invert the resulting data, it is necesary to assume that the water flow is homogeneous over the sampling volume of the instrument. Given that these instruments have acoustic beams that are directed at of order 50° to each other (in the vertical sense), the sample volume can be many 10's of meters across. The occurrence of fish moving independently of the water creates a situation where the assumption of flow homogeneity is violated contaminating the velocity estimates (see [1]and [2]). For low concentrations of fish, these events can be detected by comparing backscatter levels between the various acoustic beams and rejecting data when anomalies exceed a prescribed threshold [3]

In situations where large concentrations of fish exist over an extended area and are moving with the same average velocity such as in a fish school, it is possible to measure the swimming speed of the fish school. [4]provide an example of this technique using a vessel mounted Dopper profiler, and [5]demonstrate the technique using a moored system.

At intermediate concentrations of fish, the requirement for velocity homogeneity precludes the extraction of fish velocities. Water velocities can sometimes still be extracted but only by rejecting that data where fish signals are present in one or more of the acoustic beams. In this situation, the actual component measurements made by the beams are by themselves good and it is only that the usual velocity extraction algorithm cannot separate the coexisting information on fish and water velocities. This paper presents a method that allows retention of data from both fish and water backscatter and then allows that data to be reconstructed into two separate velocity estimates.

II. Conventional processing scheme

In a typical velocity extraction scheme, data from the various Doppler profiler beams are combined to form an instrument referenced velocity. For example, for a four-beam instrument in an upward looking orientation with beams directed at 20° to vertical the orientation of the beams relative to the instrument can be identified by the unit vectors:

$$\begin{aligned}\hat{b}_1 &= \{0, \sin 20, \cos 20\}\\ \hat{b}_2 &= \{\sin 20, 0, \cos 20\}\\ \hat{b}_3 &= \{0, -\sin 20, \cos 20\}\\ \hat{b}_4 &= \{-\sin 20, 0, \cos 20\}.\end{aligned} \tag{1}$$

where, $\hat{b}_1$, $\hat{b}_1$, $\hat{b}_1$, $\hat{b}_1$ refer to beams 1, 2, 3, 4. Each beam measures a velocity component (relative to the instrument) given by,

$$v_{bi} = \hat{b}_i \cdot \vec{V}, \tag{2}$$

where $\vec{V}$ is the water velocity and $i = 1, 2, 3, 4$ is the beam number. These measurements are combined to extract the velocity relative to the instrument as:

$$\vec{V}_{in} = \{(v_{b2} - v_{b4})/(2\sin 20), \\ (v_{b1} - v_{b3})/(2\sin 20), \\ (v_{b1} + v_{b2} + v_{b3} + v_{b4})/(4\cos 20)\}. \tag{3}$$

All Doppler profilers must employ some averaging of data to reduce estimate variance inherent in the technique (for example, see [6]If the instrument is deployed so that it is held fixed, then either the individual beam measured velocities ($v_{b1}, v_{b2}, v_{b3}, andv_{b4}$), or the resolved instrument velocity V_{in} can be averaged. The final instrument referenced velocity can then be rotated to correct for instrument orientation. More generally, these instruments are deployed so that they may move continuously (as in cable moored or ship mounted applications). In this situation, the instrument must measure its orientation using a compass and tilt sensors so that the individual instrument referenced velocity estimates V_{in} can be corrected to an earth referenced coordinate system by appropriate rotations. It is these earth referenced velocity estimates that can be averaged.

Algorithms designed to remove fish contamination from Doppler data must identify that condition before values are added into the averaging process. When data from one of the beams is identified as being "corrupted" by the presence of fish, data from all 4 beams is effectively rejected because equation (3) cannot be used to determine velocity. In fact, redundancy in the four beam system does allow for a unique solution based on three good beams, but a three beam system has no such redundancy.

The problem with averaging data using equation (3) is that it requires that measurements for all (in this case) four beams be made with the same instrument orientation. If this requirement could be eliminated, then both the fish and water observations could be accumulated into respective averages. An algorithm that enables such a sorting of data is presented by [7]and this allows extraction of both fish and water velocities when fish are seen intermittantly by the Doppler sonar acoustic beams.

III. Least squares algorithm

Instead of solving directly for the velocity from a given set of observations, it is possible to consider the observations from each beam independently. When taking this approach, the observations no longer depend on each other with the specific advantage that the loss of data in one beam does not effect the ability to use data from the other beams.

The velocity component sampled from any Doppler sonar beam can be expressed as,

$$v_j = \vec{V} \cdot \hat{k}_j = V_x k_{xj} + V_y k_{yj} + V_z k_{zj} \tag{4}$$

where $\vec{V} = \{V_x, V_y, V_z\}$ is the velocity to be measured and $\hat{k}_j = \{k_{xj}, k_{yj}, k_{zj}\}$ is a unit vector defining the instantaneous orientation of the j'th component measurement. If a sufficient number of these observations are available with a range of orientations then it is possible to employ a least squares fitting approach to solve for the underlying true velocities V_x, V_y, and V_z and the associated estimate variance ([7]). Details of this algorithm are provided in the Appendix where velocities are given by (9).

There is no magic in this approach, if all of the data are utilised the resulting answers are identical to those provided by the conventional algorithm. The method is more computationally involved because of the need to account for position and orientation of each measurement. However, Doppler profilers of necessity provide the information required: $\hat{k}_j$ can be calculated by combining the beam orientation relative to the instrument with the heading, pitch and roll information that is recorded. In addition to defining the exact velocity component being measured, $\hat{k}_j$ can also define the exact depth of a measurement by using the configured sample range bins. In the end, each velocity measurement has associated with it a time, depth, and orientation ($\hat{k}_j$) and at this point, there is no need to recognise which beam was responsible for collecting the data. In applying Equation (9), the observations are sorted into time and depth intervals of interest and this subset of values is used to form the required averaging sums (Equation (8)) that produce a given velocity estimate.

The algorithm was tested and verified using synthesised data sets but a more complete test can be achieved using actual field data. For this purpose a test deployment of an RDI WorkHorse ADCP was used for which no data averaging had been applied and data had been recorded as beam referenced velocities. The instrument was lowered from a boat to a depth of 50 m and was towed at about 0.5 m/s in directions of 15°, 115°, 195°, and 270° true for 10 minutes each. The data were collected in 2 m depth bins sampled once every 2 seconds and these data were averaged into 10 m depth intervals every 60 seconds using both the conventional processing algorithm ((3)), and the least squares approach. Example time series from the 70-80 m depth interval for both algorithms are shown in Figure 1, the agreement between the two approaches is sufficiently close that the Least Squares values have been displaced upward in Figure 1 to allow them to be distinguished. Remaining slight differences result because of beam depth effects: the Least Squares algorithm corrects the depth of observations accounting for instrument pitch and roll while no such correction was configured in the conventional calculations.

IV. Example Data Set

The example of processing water velocities shown in Figure 1 demonstrates that the Least Squares algorithm can be used to extract water velocities but a test deployment to extract fish velocities was required. An opportunity for such a test was provided in Smith Sound, Newfoundland, in an area where aggregations of overwintering northern cod (*Gadus morhua*) can reach

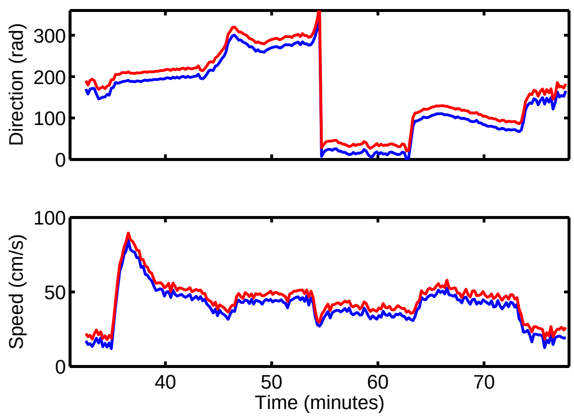

Figure 1: a) Apparent flow direction and b) speed observed from an ADCP towed at 0.5 m/s in directions 15°, 115°, 195°, and 270°. Conventional algorithm results are shown in blue and Least Squares approach in red: least squares speeds are displaced by 5 $\mathrm{cm\,s^{-1}}$ and directions by 20°.

concentrations as high as 1 $\mathrm{m^{-3}}$ (as determined from data presented in [8]).

Smith Sound located on the east coast of Newfoundland, is about 30 km long and 2 km wide with a depth of around 200 m. Figure 2 shows the location of Smith Sound on the Newfoundland coast. During the winter of 2004-05, a pair of RDI 150 kHz WorkHorse Acoustic Doppler Current Profilers (ADCPs) were deployed in Smith Sound with the purpose of tracking the movement of these fish; the location of the deployment site is indicated by the × in Fig. 2. Two instruments were deployed as an upward looking, downward looking pair to provide more complete coverage through the 200 m depth of Smith Sound but also because of sampling restrictions imposed because these instruments were configured to sample fish rather than water velocities.

When using the instrument to detect fish, comparatively short (1.2 m) depth bins were selected to increase the chances of isolating individual fish. Small depth bins translate into reduced velocity accuracies when profiling water. However, backscatter from a single fish should behave as a coherent signal and produce more accurate velocity estimates than might normally be achieved from volume reverberation [9]

For a short deployment, frequent unaveraged profiles are possible but the Smith Sound deployment was planned for 6 months and instrument data storage limits constrained the number of profiles that could be recorded. In order to compromise on this problem and collect enough samples to provide reasonable accuracy, the instruments were configured to sample a rapid series of 15 pings (an ensemble was sampled in under 6 seconds). The idea with this approach was that in 6 seconds, the moored instrument would not have moved much so that averaging in beam coordinates is possible. In addition, fish movements were not expected to be rapid and it was hoped that the 15 pings would (largely) resample the same fish when they occurred in the beam.

Even employing the burst averaging, memory requirements resulting from frequent ensembles and small bins constrained the deployment duration and two instruments were used to share the storage requirements. The two instrument were positioned at a depth of about 150 m with one looking up and the other looking down. For both instruments, the depth bins were 1.2 m but the sample averaging time was staggered between the two instruments: the upward instrument sampled every 5 minutes while the downward instrument sampled every 3 minutes. The staggered sampling approach was both for memory considerations (the upward looking instrument sampled more bins) but also to avoid acoustic interference between the two instruments. The deployment geometry is shown in Fig. 3 and the instrument configurations are summarized in Table I. The instruments were deployed for a 7 month period starting on December 1, 2004.

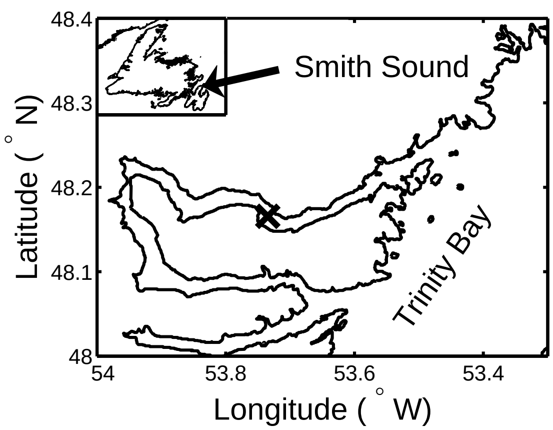

Figure 2: Inset shows location of Smith Sound on the Newfoundland coast, and × identifies the mooring location in Smith Sound.

TABLE I
Profiler Sampling Configurations

Depth (m)	Bin Size (m)	Pings	Ping Interval (s)	Sample Interval (min.)	Bins	Beam Orientation
152	1.20	15	0.36	5	76	Upward
156	1.20	15	0.23	3	41	Downward

V. Observations

An overview of the 7 month deployment is provided in Fig. 4 from the backscatter intensity records of the

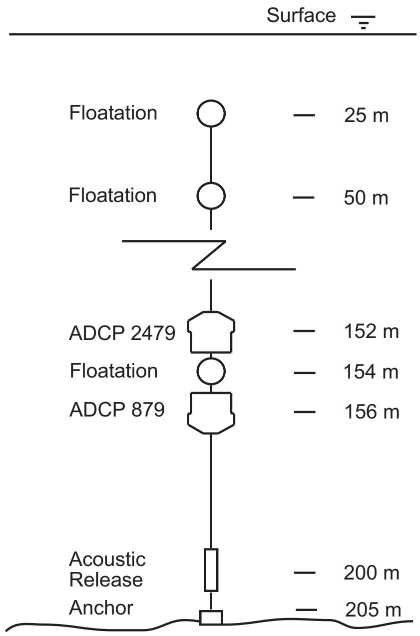

Figure 3: Schematic diagram of the Smith Sound mooring: depths (in meters) are provided for each component. Note the large gap between flotation at 50 m and ADCP 2479 at 152 m.

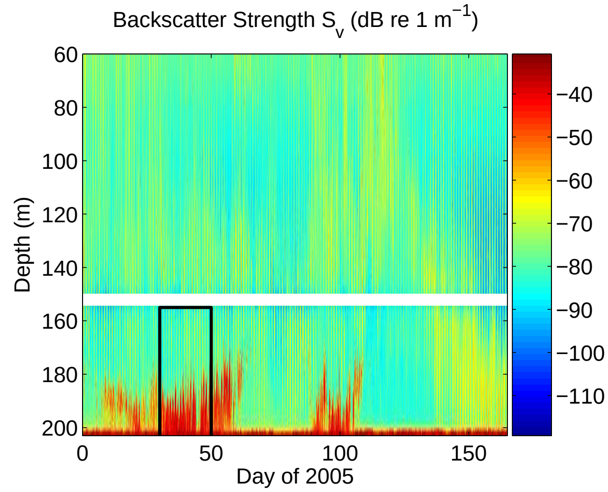

Figure 4: Backscatter record for both upward and downward looking Doppler profilers. The instruments are located near 155 m depth and this accounts for the lack of data in the band between 150 and 158 m. The bottom is at 203 m. Overwintering cod appear as regions of increased backscatter near the bottom between year days 10 and 60 and then again near year day 100.

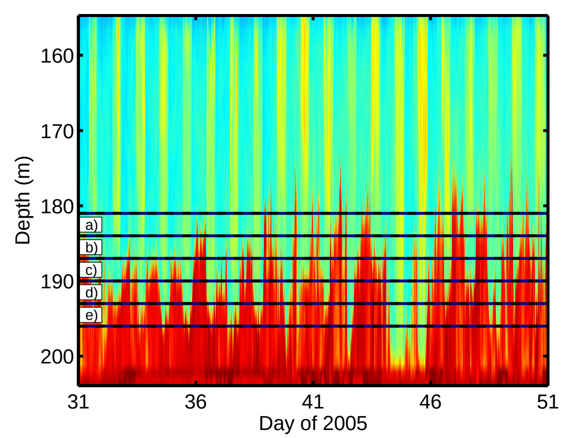

Figure 5: Backscatter record from the downward looking Doppler profiler from the 20 day period beginning on year day 31. The colour scale is the same as used in Figure 4. The bands labeled a-e identify the depth intervals from which velocities shown in Fig. 6 have been extracted.

Doppler profilers. This data has been calibrated to absolute backscatter using the method described in [10] and only data for one beam (from each of the ADCPs) is presented in Fig. 4. The overwintering cod (identified by regions of increased backscatter in Fig. 4) typically remain within 10 or 20 m of the bottom but there are large variations both in the depth interval and concentration (based on backscatter strength) of the fish. The choice of a threshold for the detection of fish is somewhat arbitrary for this application, we have chosen to identify fish when volume backscatter levels (S_v) exceed -55 dB (re 1 m^{-1}).

The overview shown in Figure 4 identifies the extended presence and depth of occurence for the fish but does not reveal any of the fish behaviour. The richness of detail recorded in the backscatter record is shown in Figure 5 which expands the data for a 20 day period starting on year day 31 (January 31, 2005). When expanded to this level, the data in Fig. 5 demonstrate a clear diurnal signal in the fish movements with the fish tending to stay closer to the bottom during daylight hours.

Bands labeled a through e in Fig. 5 identify 3-m depth intervals where velocities have been extracted based on 1 hour averages: the East component of these velocities is shown in panels a-e of Fig. 6. For each interval, both water and fish velocities are shown: water velocities (in blue) are displaced upward by 10 $cm\,s^{-1}$ and fish velocities (in red) are displaced down by 10 $cm\,s^{-1}$. Velocities are only plotted if the calculated standard deviation is less than 5 $cm\,s^{-1}$. Farther from the bottom (panels a and b), fish velocities become sparse due to the intermittent presence of fish (consider Figure 5). This situation is reversed close to the bottom (panel e) where water observations become scarce. Observed velocities are generally low (less than 10 $cm\,s^{-1}$), water motions in Smith Sound at these depths are driven by a weak tidal component interupted by occasional wind forcing responses.

The occurrence of regular diurnal movements patterns in fish depth seen in Figure 5 suggests that some coherent vertical motion of the fish might exist. In the present case, the fish are moving a vertical distance of order 10 m in perhaps a 1-hour time period: that would suggest a vertical velocity of only 0.3 $cm\,s^{-1}$: this is a small signal to detect but the pervasive nature of the movements makes consideration of those movements worthwhile. The 5-day period beginning on

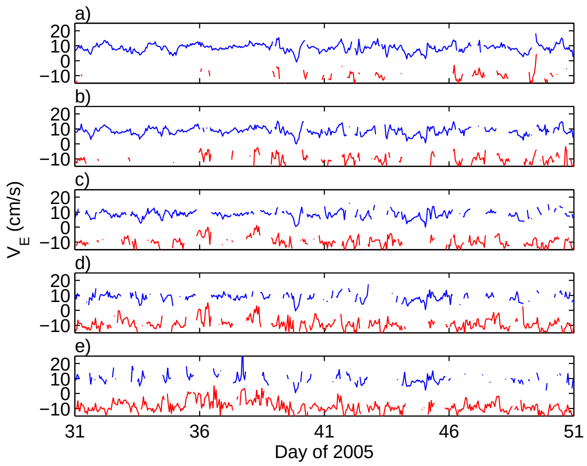

Figure 6: East component of velocity extracted for depths of 182.5, 185.5, 188.5, 191.5, and 194.5 (panels a through e). Water velocities are displaced up by 10 $\mathrm{cm\,s^{-1}}$, fish velocities are displaced down by 10 $\mathrm{cm\,s^{-1}}$.

day 31 (of 2005) was analysed for this purpose because of the regular nature of the vertical movements on these days. Figure 7 shows horizontal speeds (7 a), vertical speeds (7 b), and backscatter (7 c) for this period. To provide a continuous comparison of water and fish speeds in this case, a characteristic water velocity was extracted from a 3-m interval about 180 depth where fish are not observed, fish velocities were extracted from the 3-m interval about 195 m depth. In Figure 7, fish speeds are indicated in red while water speed are indicated in blue. Over this time period, horizontal speeds are between 5 and 15 $\mathrm{cm\,s^{-1}}$with the fish speeds noticably larger that the water speeds on day 34 and 35. The corresponding vertical velocities are only of order 1 $\mathrm{cm\,s^{-1}}$with fish velocities slightly larger than water velocities (in Figure 7, water velocities are displaced up by 1.5 $\mathrm{cm\,s^{-1}}$while fish velocities are displaced down by 0.5 $\mathrm{cm\,s^{-1}}$). There does appear to be some periodic character to the vertical motions but it is impossible to see any clear correlation with displacements of the backscatter layer: any signal is not strong enough or consistent enough to draw any definitive conclusions.

For the velocity components shown in Figure 6, and 7, the concentration of fish remains high but varies with depth. Another condition of interest is when the concentration of fish is changing so that a range of fish concentrations are observed. An example of such a condition is provided by the 6 day period beginning on year day 60 of 2005 shown in Figure 8 . Backscatter for this period 8c) shows fish have moved clear of the bottom and the concentrations are decreasing. At this time, fish are present in the backscatter but they occur intermittantly. Velocities were analysed in the 5 m depth interval from 175-180 m (this interval is indicated by black lines in Figure 8c), the east and north components of the water and fish velocities for this interval are shown in Figures 8a and b by green

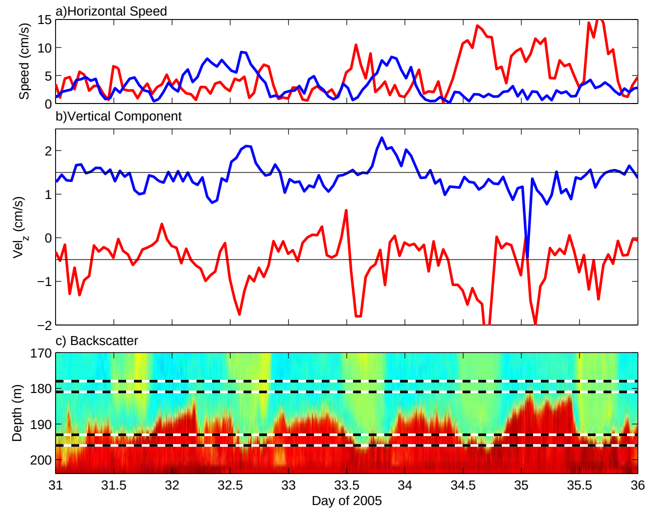

Figure 7: Expanded view of a) horizontal speeds, and b) vertical velocity components for fish at a depth of 195 m (red), and water for a depth of 180 m (blue), for the five day period beginning on day 31, 2005. In b), water velocities are displaced up by 1.5 $\mathrm{cm\,s^{-1}}$and fish velocities are displaced down by 0.5 $\mathrm{cm\,s^{-1}}$. c) shows the backscatter signal for this period and identifies the depth intervals used to extract fish and water velocities.

and blue lines respectively. Water velocities can be extracted for all data over an averaging interval period of 1 hour. The reduced fish density required a longer averaging period of 3 hours to provide reliable fish velocity estimates: with shorter averaging intervals, standard deviations in the fish velocities become excessive.

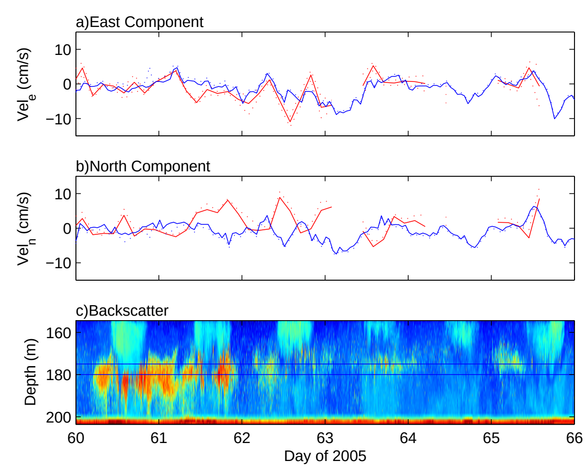

Figure 8: Six day time series of data starting on March 1, 2005 (year day 60) for the depth interval 175-180 m. a) East component of velocity, b) North component of velocity, c) Backscatter intensity. Fish velocities are indicated in red, water velocities are indicated in green, confidence intervals for fish are indicated by red dashed lines, confidence intervals for water velocities are not distinguishable on this scale. The sampled depth interval is indicated by lines in panel c.

The detailed data shown in Figure 8 demonstrates that significant differences in fish and water velocities can be extracted. It is however hard to identify any systematic behaviour in the fish from such short data records. A summary view of the data can be gained by averaging over an extended period to identify net movements (of fish and water). Figure 9 presents profiles of velocity data averaged over the 20 day period starting on year day 31 (this is the same data as presented in Fig. 6. In Fig. 9 green vectors (joined at the ends) show the velocities derived using a conventional processing approach (with no attempt to reject fish contaminated data), the blue vectors are least-squares water velocities and the dashed red vectors are fish velocities. For the least-squares extracted velocities, error bars shown at the tip of each vector indicate the computed standard deviation. The conventionally processed data shows a flow reversal within the bottom 10 m of the profile but there is no obvious physical cause for such a reversal. The least-squares extracted water velocities agree with the conventional processing above 180 m, below that depth they continue to show the North West drift seen higher in the water column. The bias that appears in the conventionally processed data is caused by the fish movement that at this time is into the current.

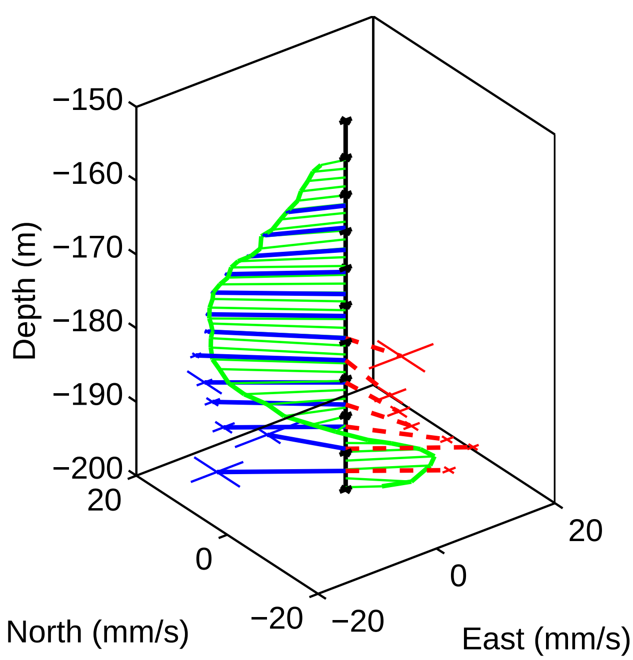

Figure 9: Velocity profiles: light vectors with ends joined in a profile are water velocities derived using conventional processing, bold vectors are least-squares water velocities, and dashed vectors are least-squares fish velocities. Error bars indicate standard deviations for least-squares computed velocities.

VI. Summary and Conclusions

We have presented a new approach to processing Doppler profiler data that allows extraction of both fish and water velocities from the same data. The key to this method is the treatment of data from each acoustic beam as independent so that the nature or quality of data in one acoustic beam does not depend on or have to be processed with data from the other beams. We have distinguished signals from fish as those for which calibrated acoustic backscatter exceeded a threshold of $S_v > -55$ dB, and using this criterion, divided the data into two coincident data sets: one representative of water movements and the other representative of fish movements.

Performance of the algorithm in extracting velocities was verified using a test data set where the Doppler profiler was towed in a rectangular pattern. Comparisons between the least squares algorithm and the conventional processing showed that when all data are included both methods return the same velocities (Figure 1).

We have employed the method to extract fish and water velocities from data collected in Smith Sound Newfoundland where aggregations of overwintering Atlantic Cod reach densities as high as 1 m^{-3} (as determined from data in [8]). When highly localised concentrations of fish exist, the method can only extract either water velocities or fish velocities (see Figure 6) as would be possible using conventional processing (as done by [4], or [5]). However, when intermediate concentrations of fish occur, simultaneous fish and water velocities can be extracted as shown in Figures 7, and 8.

The data reveal an environment with currents typically less than 10 $\mathrm{cm\,s^{-1}}$as expected given the protected nature of Smith Sound. Much of the observations show little difference between water and fish velocities consistent with a situation where the fish are conserving energy. However, there are times with local differences between fish and water speeds (Figures 7 and 8). When data are averaged over an extended time period, significant differences in motion between the fish can occur (Figure 9). The occurrence of such difference indicate that the fish do move systematically to maintain their position in Smith Sound.

Backscatter data do show that the fish tend to form high concentrations near the bottom and undertake small diurnal movements: during daylight hours, the fish press down to within 5 or 10 m of the bottom while at night, they rise up to 10 or 20 m off the bottom. An attempt to extract vertical velocities associated with these migrations did show some diurnal periodicity in vertical velocities (Figure 7). However, there was no clear correlation between velocities and the movements implied by the backscatter record. For these weak velocities (typically less than 1 $\mathrm{cm\,s^{-1}}$), the variability could well be due to changes in data quality related to backscatter conditions and not to the movements themselves.

Acknowledgment

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VII. Appendix

Following the derivation given in [7], the velocity sampled at some range by a beam of a Doppler profiler can be expressed as:

$$v_j = \vec{V} \cdot \hat{k}_j = V_x k_{xj} + V_y k_{yj} + V_z k_{zj} \qquad (5)$$

where $\vec{V} = \{V_x, V_y, V_z\}$ is the velocity to be measured and $\hat{k}_j = \{k_{xj}, k_{yj}, k_{zj}\}$ is a unit vector defining the instantaneous orientation of the j'th component measurement (in world coordinates).

The mathematical problem now is to find the best choice of the unknown V_x, V_y, and V_z that can explain the observed v_j's. Following the least squares approach outlined by [11]the sum square error is formed as:

$$\Sigma\epsilon_j^2 = \Sigma\big(V_x k_{xj} + V_y k_{yj} + V_z k_{zj} - v_j\big)^2. \qquad (6)$$

This is a standard fitting problem where the values of V_x, V_y, and V_z are chosen to minimize $\Sigma\epsilon_j^2$, that is we require:

$$\begin{aligned} \frac{\partial}{\partial V_x}\Sigma\epsilon_j^2 &= 0 \\ \frac{\partial}{\partial V_y}\Sigma\epsilon_j^2 &= 0 \\ \frac{\partial}{\partial V_z}\Sigma\epsilon_j^2 &= 0 \end{aligned} \qquad (7)$$

(7) can be written in a matrix form after substituting in the values for ϵ_j from (6):

$$\begin{pmatrix} \Sigma k_{xj}^2 & \Sigma k_{xj}k_{yj} & \Sigma k_{xj}k_{zj} \\ \Sigma k_{xj}k_{yj} & \Sigma k_{yj}^2 & \Sigma k_{yj}k_{zj} \\ \Sigma k_{xj}k_{zj} & \Sigma k_{yj}k_{zj} & \Sigma k_{zj}^2 \end{pmatrix} \begin{matrix} V_x \\ V_y \\ V_z \end{matrix} = \begin{matrix} \Sigma v_j k_{xj} \\ \Sigma v_j k_{yj} \\ \Sigma v_j k_{zj} \end{matrix} \qquad (8)$$

$$or$$

$$C\vec{V} = R$$

where the unknown velocities can be found by forming

$$\vec{V} = C^{-1}R. \qquad (9)$$

Variance in (for example) the x-component velocity estimate is found by forming

$$\sigma_{V_x}^2 = \sigma_v^2\, \Sigma\left(\frac{\partial V_x}{\partial v_j}\right)^2, \qquad (10)$$

where the sum is over all observations and σ_v^2 is the observed variance in individual (beam referenced) velocity estimates: expressions for V_y, and V_z variance are found by replacing the x-component with the y- and z-component respectively. The assumption of a common value for σ_v^2 is reasonable because all beams sample with the same operating parameters.

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