

## Summary Results from Horizontal ADCP tests in the Indiana Harbor Canal and the White River

This report summarizes results of tests of horizontally deployed ADCPs in the Indiana Harbor Canal and the White River at Indianapolis. The objective of these tests was to compare observations made by the Acoustic Doppler Current Profilers (ADCPs) with observations from already-installed Acoustic Velocity Meters (AVMs).

ADCPs obtain current profiles by measuring the Doppler shift of backscattered sound; AVMs use reciprocal travel times to obtain the average velocity along acoustic paths. AVMs routinely monitor flow in rivers, but ADCPs have been used for routine monitoring only rarely. ADCPs are rarely left deployed on the bottom because bottom sediments could erode under them, cover them up or damage them. One can avoid these problems by deploying a horizontally oriented ADCP at the side of the river, but then one worries that the bottom or surface could interfere with the acoustic beams. However, results from these tests suggest that horizontal ADCP measurements can be at least comparable in quality to an AVM, and may even have advantages over AVMs.

### Harbor Canal Data

The Indiana Harbor Canal is a man made ship canal in northwestern Indiana that flows northward from its confluence with the Grand Calumet River and into Lake Michigan. The canal is about 8 km long, surrounded by major industries and heavily traveled by ships and barges. Flow in the canal is variable and bi-directional on short time scales, but mean daily discharge has been observed over the past four years to remain a relatively constant  $20 \text{ m}^3/\text{s}$ .

The Harbor Canal site is about 1 km from Lake Michigan at a constriction in the canal. Figure 1 shows the site, and approximate ADCP and AVM beam locations. One ADCP beam was inside the constriction and the second was in the wider part of the canal. The constriction was about 10 m deep and 20 m wide, with vertical walls at each side (Fig. 2).

We carried out two tests in the Harbor Canal because we concluded after the first test that the AVM was defective. We carried out a second Harbor Canal test after we installed an upgraded AVM at the site. The test dates are listed in Table 1.

*Table 1. Harbor Canal Test schedule*

<b>Test</b>	<b>Duration</b>
Winter-spring test	14-31 March, 1997
Summer test	13 June-7 July 1997

The ADCP was a standard 1200 kHz Workhorse Monitor (the same for both tests; Fig. 3), about 3 m deep. The two Harbor Canal tests were mostly identical (other than the change in AVM). One minor difference was that different beam pairs were horizontal (beams 1 and 2 in the first test and 3 and 4 in the second test). This change of beams is inconsequential. A second difference is that the ADCP attitude changed an unknown amount. The attitude (heading, tilt and rotation around the ADCP cylinder axis) was set visually, and we believe it was consistent within

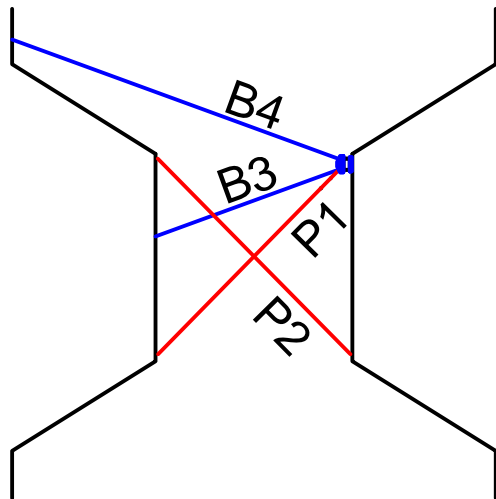


Figure 1. Sketch of ADCP and AVM installation in the second Harbor Canal test. The distance across the canal is about 20 m. B3 and B4 locate beams 3 and 4 (blue) of the ADCP, and P1 and P2 locate paths 1 and 2 (red) of the AVM.

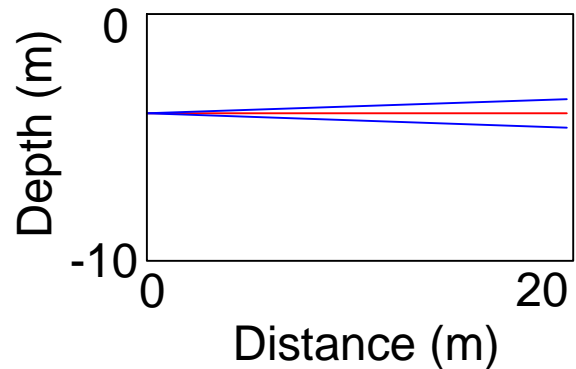


Figure 2. Harbor Canal crosssection showing the approximate placement of the horizontally oriented beams. The blue lines indicate the approximate beam width of the 1200 kHz beams.



Figure 3. Workhorse Monitor 1200 ADCP.

a few degrees. The two Harbor Canal tests were mostly identical. The only substantial difference was the weather: the second test was performed in warm summer weather while the first was in windy, snowy weather.

### Harbor Canal Tests

The Harbor Canal site was a good site to conduct the first horizontal ADCP trials because it is deep and narrow. Because the deep bottom is unlikely to contaminate the water echoes, it should be a relatively easy site in which to interpret the data. We observed complex flow structure, however, likely caused by stratification.

We had expected the AVM to perform well at this site, but we found in the first test that the AVM malfunctioned. For the second test, a new, upgraded AVM was installed, which appeared to remedy the malfunction.

### Harbor Canal echo intensity

Figure 4 shows echo intensity in beams 3 and 4 during the second test. Beam 3 is pointed at the wall on the other side of the constriction, and shows a distinct echo intensity peak at the appropriate range. Beam 4 extends past the wall into the wider part of the channel, and it shows only a small perturbation at the same range. In the first test, beams 1 and 2 are horizontal, and they show similar behavior.

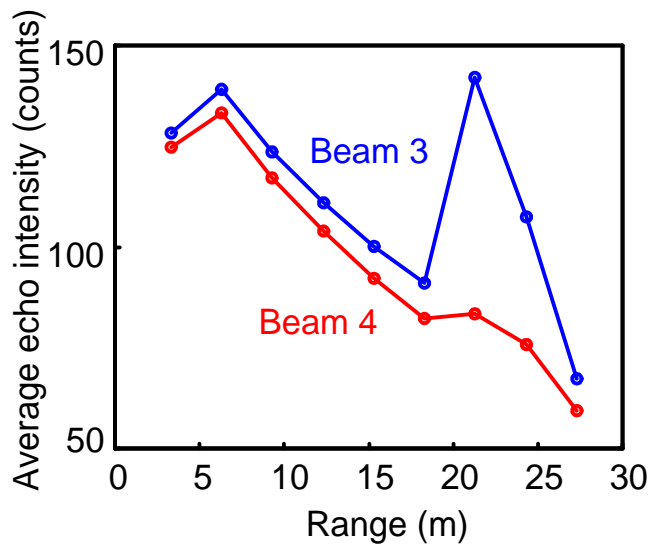


Figure 4. Echo intensity from the second Harbor Canal test. The peak at 20 m in beam 3 corresponds to the beam hitting the opposite wall. Beam 4 lacks a similar peak because it points into the wider canal instead of the constriction; it does not hit a wall. Data shown are from bins 1-9, with bin 1 at the far left on the beam.

### Harbor Canal velocity data

The Harbor Canal ADCP data were corrected from beam to along-channel velocity using:

$$V_{\text{corrected}} = V_{\text{beam}} / \cos(\Theta)$$

where  $\Theta$  is the angle between the mean flow direction and the beam direction (nominally 70 degrees plus or minus a small offset). Positive velocity is flow toward Lake Michigan. The small, unknown offset was computed assuming uniform flow through the channel, using the equation:

$$\langle V_{\text{beam1}} \rangle / \langle V_{\text{beam2}} \rangle = \cos(70^\circ + \text{offset}) / \cos(70^\circ - \text{offset})$$

where brackets  $\langle \rangle$  denote averaging over time and across bins. The computed offsets are summarized in Table 2.

Table 2. ADCP heading offsets  
(relative to a line normal to the flow)

Test 1	5.7°
Test 2	3.1°

In both cases, the ADCP was pointed to the right relative to a line normal to the flow. The headings of the two installations were within 2.6 degrees of one another in spite of the 6-month interval between them.

Table 3 lists the mean velocity computed for the duration of each test. The mean ADCP data were computed using bins 2-5 (i.e. the measurement cells nearest the center of the canal) from both horizontal beams. The heading correction affects the mean velocity only to second order—an uncorrected heading offset of 5.7° would change the computed mean by only 0.5%.

Table 3. Mean velocities

Instrument	Test	Mean velocity
ADCP	1	100 mm/s (0.33 ft/s)
ADCP	2	111 mm/s (0.36 ft/s)
AVM, path 1	2	137 mm/s (0.45 ft/s)
AVM, path 2	2	122 mm/s (0.40 ft/s)
AVM, average	2	130 mm/s (0.42 ft/s)

### Harbor Canal flow regime

The Harbor Canal has an average flow of roughly 100 mm/s toward Lake Michigan with roughly 200 mm/s quasi-periodic fluctuations (roughly 1-hour time scale) imposed by industrial usage. The mean flow is controlled by the steady input of water where the canal begins at the Grand Calumet River. Figure 5 illustrates an 8-hour segment of typical flow. The hourly fluctuations appear to have roughly the same size and phase, but there are relative offsets.

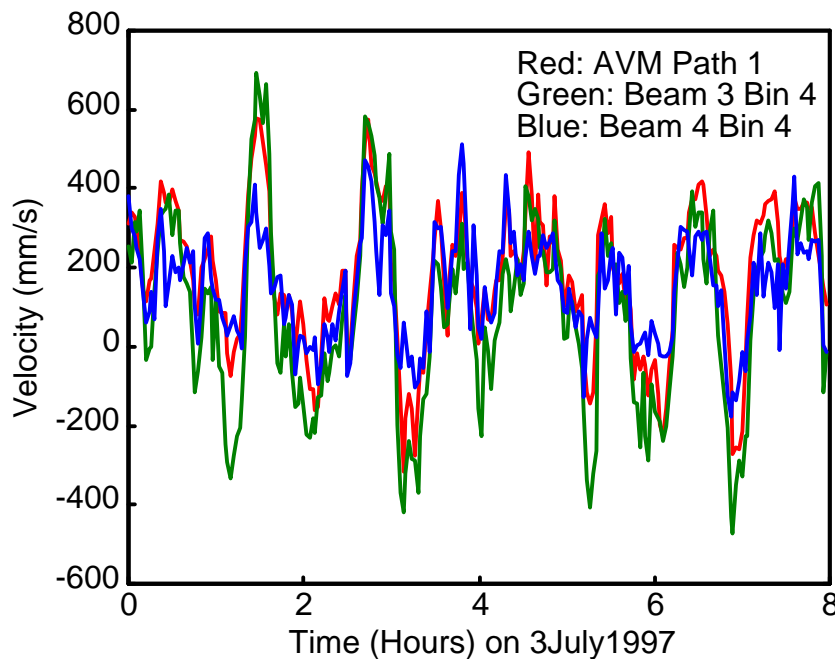


Figure 5. Three unfiltered 8-hour time series from the second test. Two of the time series are from bin 4 (in the middle of the canal) of the horizontal beams (3 and 4). The third time series is from the AVM.

Figures 6 and 7 present low-passed time series of flow from different bins along the ADCP beams plus the average of all the bins. Figure 7 also includes the AVM data from its two paths. The variability of the AVM data is comparable to the variability in the ADCP bins and there is a

mean offset between the two AVM paths (which are separated vertically by about 0.3 m). The ADCP data vary more in the second test than in the first test, and the mean ADCP data (the average of four bins in both beams) shows the most constant flow of all.

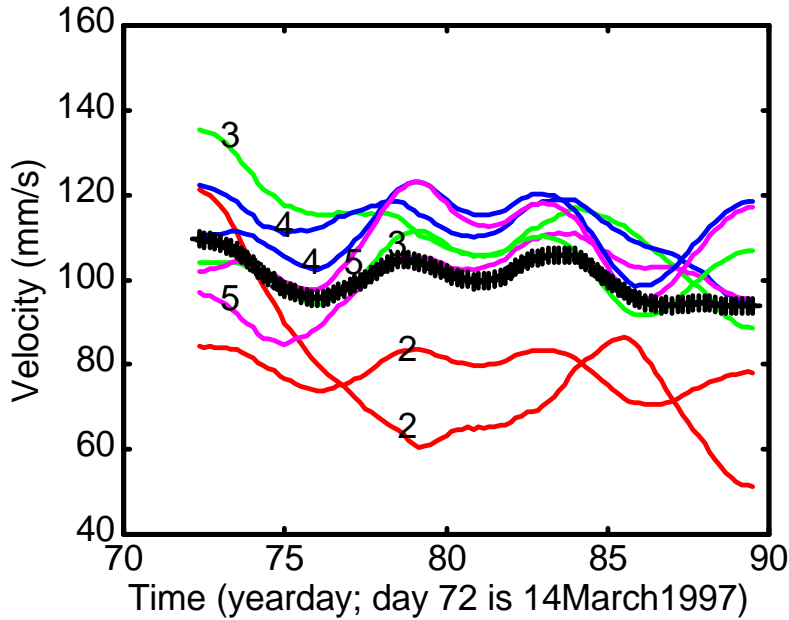


Figure 6. Low-passed time series, first test; ADCP beams 1 and 2, bins 2-5. Data from different beams are not distinguishable on the figure. The number on each trace gives the bin number. The heavy black line is a time series of the average of all eight ADCP traces.

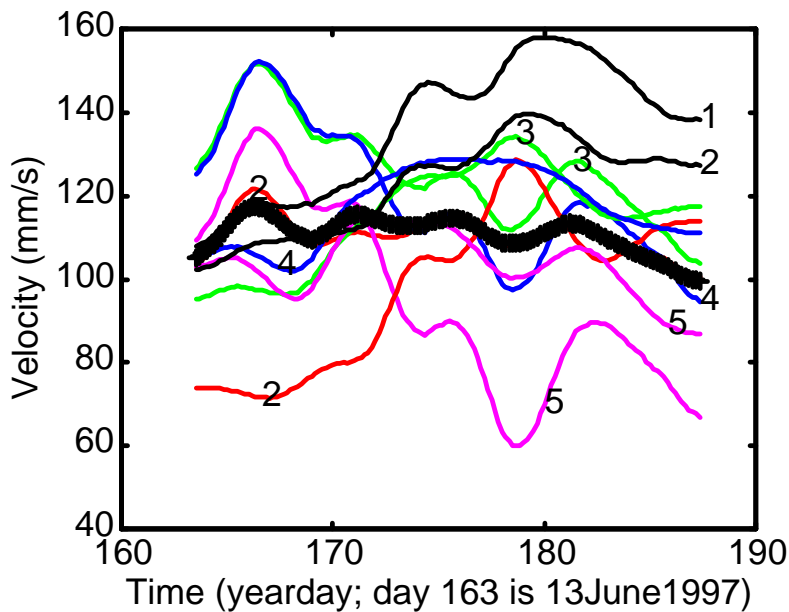


Figure 7. Low-passed time series, second test. The data are from ADCP beams 3 and 4, bins 2-5. The heavy black line is a time series of the average of all eight ADCP traces. This figure also includes data from the two AVM paths (in black, marked by numbers 1 and 2 at the upper right on the figure).

### Cross-sectional Flow Variation

Flow variations from one bin to another in the ADCP data were greater in the second test than they were in the first. The following are two possible sources for this variability:

1. Instrumental error. Given the channel geometry, the ADCP data should be unaffected by the boundaries at either the surface or the bottom. There was no evidence in the data itself to suggest there was any problem with the ADCP—the data appeared to be good.

2. Stratification. Appendix A shows that the data are at least consistent with stratification as the source of the observed flow variations.

We have no independent means to verify either possibility.

### White River Test

The White River is a medium-sized upland river that drains about 5000 km<sup>2</sup> upriver of the test site. The river is subject to large flow variations typical of natural upland rivers. Annual mean flow is 58 m<sup>3</sup>/s; observed daily flows have varied from 2.5 to 850 m<sup>3</sup>/s. The lowest flows at the test site are usually observed during summer and fall. We carried out tests in the White River during a low flow period in the summer (20 August to 8 September 1997).

The White River site was under a freeway bridge in Indianapolis between two bridge supports. Nearly all the flow passes between these supports. In contrast to the Harbor Canal site, the White River was shallower and wider. While boundaries were unlikely to affect the ADCP data at the Harbor Canal, the beams certainly touch the bottom in the White River. The White River tests used a 300 kHz Workhorse ADCP specially modified for horizontal use (Fig. 8). Modifications include reorienting the beam geometry to create two pairs of parallel beams and reorienting the compass for horizontal operation. The pairs of parallel beams should combine to create a narrower transmit beam.



*Figure 8. 300 kHz ADCP specially modified for horizontal profiling.*

### White River echo intensity

Figure 9 shows the echo intensity in all four beams in the White River. In comparison to the equivalent profiles from the Harbor Canal (Fig. 4), these profiles are puzzling. There is no consistent recognizable structure in these data. The standard deviation of all the data in Figure 9 is only 1.2 counts or 0.5 dB. In contrast, Figure 4 has a 50-count (22 dB) echo from the opposing wall in the channel. The river width is about 40 m at this site, so data within the river correspond to ADCP bins 1-9.

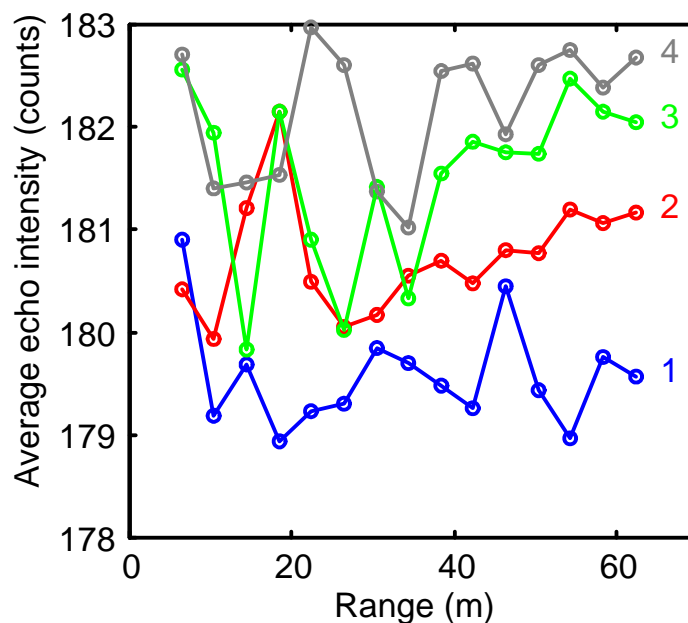


Figure 9. Echo intensity from the 300 kHz Dog House ADCP in the White River. The far side of the river is about 40 m from the ADCP.

### White River flow regime

The White River velocity data were processed the same as the velocity data from the Harbor Canal. The beam angle offset was computed to be much smaller than 1° and it was treated as zero.

Figure 10 shows velocities in three cells across the White River. The detailed velocity structure is largely consistent across all three cells, but the magnitude of the velocity is largest near the ADCP and smallest at the other side of the river. This variation across the river is illustrated in Figure 11, which shows that the mean velocity falls almost linearly across the river.

The AVM data from this test were noisy, and one path did not work at all. We processed the AVM data by removing data in which the velocity magnitude exceeded 152 mm/s (0.5 ft/s), then averaging the remaining data into 2-hour intervals. Figure 12 shows that the AVM data, processed this way, compare well with the average flow (bins 1-9) measured by the ADCP. The AVM is a new model, and this is the first installation; the AVM will require further calibration and verification before it is accepted for routine flow monitoring by the US Geological Survey.

Nevertheless, the AVM and ADCP mean flow measurements (using the data in Figure 12) agreed closely with one another: the mean difference was 2 mm/s (the AVM was higher) and the standard deviation was 13 mm/s.

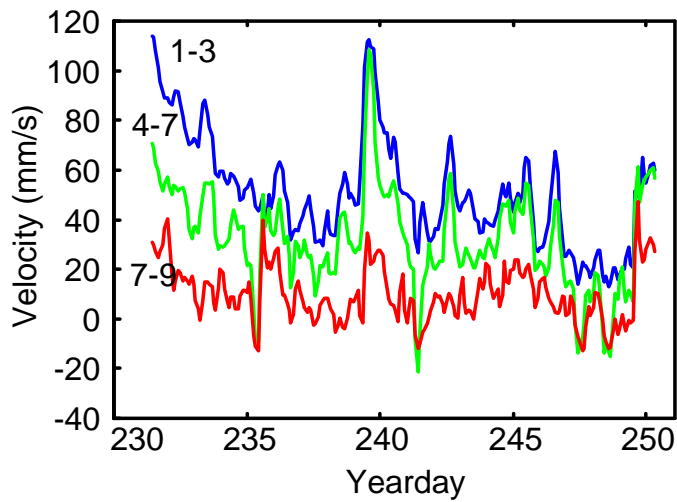


Figure 10. Velocity in three cells across the White River. The cells are averages of bins 1-3, 4-6, and 7-9, each corresponding to about 1/3 of the river width.

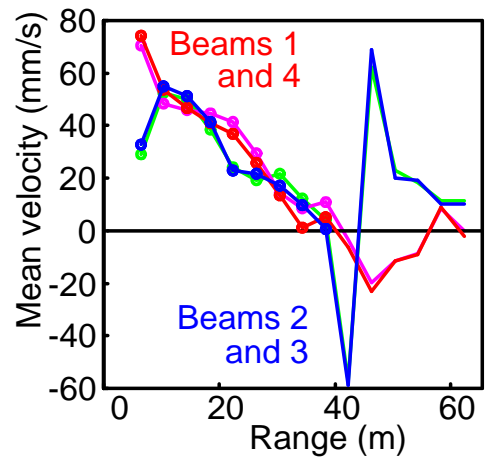


Figure 11. Mean velocity versus position across the White River.

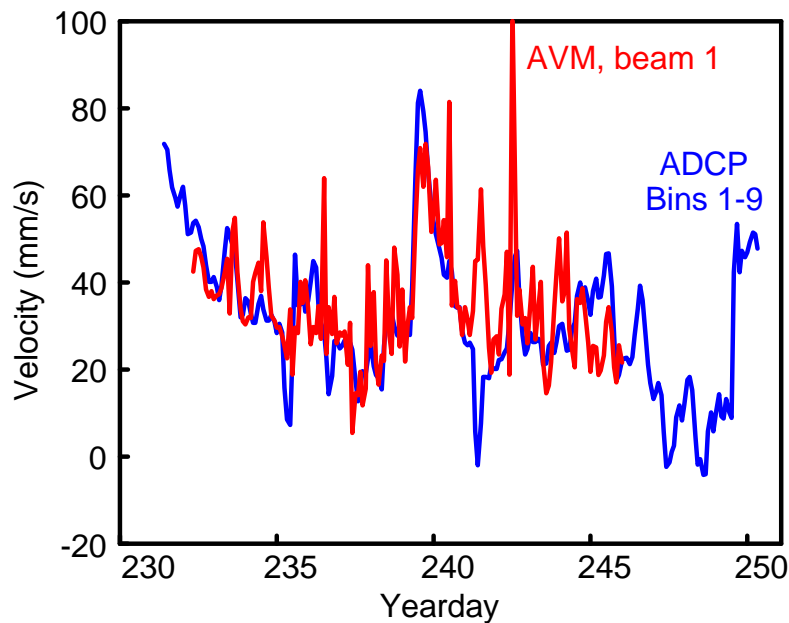


Figure 12. Comparison of AVM path 1 velocity data with the average of ADCP data across the White River (bins 1-9).

## **Appendix A. Could stratification cause the flow variation observed in the second Harbor Canal test?**

This appendix demonstrates that stratification could reasonably cause the spatial variation observed in the second Harbor Canal test. We show that temperature stratification at the site is sufficient to account for observed velocity variations. We hypothesize that stratification is imposed by Lake Michigan and reduced as it flows through the canal. We test for this stratification indirectly through its effects on velocity variability and conclude that stratification is a reasonable source of the observed variability. The consequence of this hypothesis is that one cannot rely on velocity at a single level to obtain mean discharge.

### **Stratification is a sufficient source.**

Stratification limits the maximum velocity gradient via the Gradient Richardson's Number ( $Ri$ ).  $Ri$  is the ratio of stratification (measured via buoyancy frequency) and vertical velocity gradient (also measured in units of frequency)

$$Ri = N/(dU/dz)$$

where  $N$  is the buoyancy frequency and  $dU/dz$  is the velocity gradient.  $N$  is defined by

$$N^2 = g/\rho(dp/dz)$$

Where  $\rho$  is density,  $g$  is gravity and  $z$  is vertical distance. As long as  $Ri$  stays above the critical value  $Ri=0.5$ , stratification inhibits the formation of Kelvin-Helmholtz instabilities. If shear increases and  $Ri$  falls below 0.5, Kelvin-Helmholtz instabilities form and generate turbulence which mixes the water and effectively prevents further increases in shear. Thus  $Ri=0.5$  sets the maximum velocity gradient.

Temperature is sometimes measured at this site, and it is not unusual to observe temperature changes of 3°C over 9 m depth. This temperature change corresponds to a density gradient sufficient to support a velocity gradient of 0.06 s<sup>-1</sup>; the observed gradient between the AVM paths was typically half this amount (10 mm/s over 1/3 m).

### **An indirect test of stratification**

*Hypothesis.* Because Lake Michigan is close to our measurement site and because flow can move in either direction, whatever stratification is present at our site is imposed by the lake. Lake Michigan is typically stratified, particularly in the hot summer months. In contrast, turbulent flow in the canal will mix the water and reduce the stratification. This mixing will not happen quickly because it is difficult to mix stratified water.

The above hypothesis leads to a simple test in which we compare the characteristics of flow in different directions. Water flowing from the lake will be more strongly influenced by the stratification of the lake when compared with flow going toward the lake. The reason for this is that water flowing toward the lake will have had more time to mix as it flows through the canal. Where water is more stratified, we will observe more flow variability (associated with the Kelvin-Helmholtz instabilities described above).

We will test the above hypothesis by comparing the variability of flow for the two different directions: from the lake and toward the lake.

Define

$$M_v(t) \equiv \text{mean}[V_{ij}(t)]$$

$$S_v(t) \equiv \text{standard deviation}[V_{ij}(t)]$$

Where  $V_{ij}(t)$  is the velocity for bin  $i$  and beam  $j$  (for five bins and two beams). We can define similar quantities  $M_a(t)$  and  $S_a(t)$  for the AVM data, except that standard deviation is replaced by a simple difference between the two paths. Now we compare  $S_v$  and  $S_a$  for positive flow (i.e. toward the lake) versus negative flow (i.e. away from the lake). We do this by computing the conditional means:

$$R_v^+ = \text{mean} [S_v/M_v \mid M_v > \text{threshold}]$$

$$R_v^- = -\text{mean} [S_v/M_v \mid M_v < -\text{threshold}]$$

where the threshold was 20 mm/s. Similar ratios,  $R_a^+$  and  $R_a^-$  were defined for the AVM data. The results are summarized in Table 4.

*Table 4. Comparison of flow variation for flow toward lake and flow away from lake.*

	<b>Toward lake</b>	<b>Away from lake</b>
ADCP	$R_v^+ = 0.42$	$R_v^- = -0.88$
AVM	$R_a^+ = 0.26$	$R_a^- = -0.40$

Table 4 demonstrates that flow variability is larger when flow comes from the lake rather than toward the lake. This result is consistent with our hypothesis and thus suggests that stratification is the source of our observed velocity variation.

## Discussion

Other data are consistent with stratification as the source of the observed flow variability. When compared with the summer data, the winter-spring data show less variability at a time when the cold, windy weather would have reduced stratification. Variability was greater when warm summer weather would have increased stratification in the lake.

Stratification can introduce mean offsets in velocity measured at a given level, relative to the mean flow. The situation at our Harbor Canal site is, on a small scale, similar to what happens in tidally dominated estuaries. In such estuaries, stratification is imposed by the ocean and reduced by tidal mixing. The result is a steady secondary flow in which water enters at the bottom and returns at the top (or vice-versa). The mean difference between the two AVM paths could be the result of such a steady secondary flow.

If our hypothesis is correct, then one cannot rely on measurements at a single level to obtain the mean discharge.