Dual-RiverSonde Measurements of Two-Dimensional River Flow Patterns

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***Abstract*—Two-dimensional river flow patterns have been measured using a pair of RiverSondes in two experiments in the Sacramento-San Joaquin River Delta system of central California during April and October 2007. An experiment was conducted at Walnut Grove, California in order to explore the use of dual RiverSondes to measure flow patterns at a location which is important in the study of juvenile fish migration. The data available during the first experiment were limited by low wind, so a second experiment was conducted at Threemile Slough where wind conditions and surface turbulence historically have resulted in abundant data. Both experiments included ADCP near-surface velocity measurements from either manned or unmanned boats.**

Both experiments showed good comparisons between the RiverSonde and ADCP measurements. The flow conditions at both locations are dominated by tidal effects, with partial flow reversal at Walnut Grove and complete flow reversal at Threemile Slough. Both systems showed complex flow patterns during the flow reversals. Quantitative comparisons between the RiverSondes and an ADCP on a manned boat at Walnut Grove showed mean differences of 4.5 cm/s in the u (eastward) and 7.6 cm/s in the v (northward) components, and RMS differences of 14.7 cm/s in the u component and 21.0 cm/s in the v component. Quantitative comparisons between the RiverSondes and ADCPs on autonomous survey vessels at Threemile Slough showed mean differences of 0.007 cm/s in the u component and 0.5 cm/s in the v component, and RMS differences of 7.9 cm/s in the u component and 13.5 cm/s in the v component after obvious outliers were removed.

I. INTRODUCTION

The RiverSonde is a UHF radar system operating near 435 MHz. It provides continuous, non-contact measurement of river surface velocity by processing radar echoes from surface water waves [1]. Typically, a single unit is placed on a bank of a river or channel with straight, parallel banks, and it measures the flow along the channel [2]. However, in some situations, such as the confluence of two channels or a single channel with a sharp bend, the flow is more complicated and it is quite difficult to quantify the large-scale two-dimensional flow pattern. In this paper, the two-dimensional surface flow patterns are measured using two RiverSondes operated in close proximity with overlapping spatial coverage [3], [4]. A pattern of total flow vectors is constructed by combining the radial flow vectors from the individual RiverSondes.

Recently two experiments were conducted to investigate dual-RiverSonde operation. The first experiment was at Walnut Grove, California on 23–25 April 2007, and the second was nearby at Threemile Slough on 10–11 October 2007. Both locations were in the Sacramento-San Joaquin River Delta in central California, and both locations were near junctions between two water channels, with the flow dominated by tidal effects. The dual RiverSondes were in continuous operation for several hours which encompassed at least a complete tidal cycle, and both experiments included detailed surface and near-surface ADCP water velocity measurements. The RiverSondes produced radial vectors spaced one degree in azimuth and 15 m in range out to 200 m every 15 minutes. At Walnut Grove, the ADCP measurements were made from a small manned boat and produced measurements half-hourly, while at Threemile Slough two ADCPs were carried on small unmanned autonomous vessels and produced nearly continuous measurements during the tidal reversal and maximum-velocity portions of the tidal cycle.

The operation of the RiverSonde depends on the presence of surface water waves of 35 cm wavelength, which can be generated either by the wind or by turbulence caused by bottom roughness. Wind during the Walnut Grove experiment was low, and the required waves were present only about half of the time. Wind and turbulence effects at Threemile Slough provided the required waves almost all of the time. Data from both experiments have been processed and show good results.

II. WALNUT GROVE

The experiment at Walnut Grove was conducted during 23–25 April 2007. A map of the experiment site is shown in Fig. 1. The experiment took place at the junction of the Sacramento River and Georgiana Slough. This area is on the migration path of juvenile fish, which have limited ability to swim against a strong current. The current pattern can be influenced by controlled water releases upstream of the experiment location. The flow in the Sacramento River is mostly unidirectional, as indicated in the figure, but the flow is strongly affected by the ocean tide and can reverse direction during a small part of the tidal cycle. Flow in Georgiana Slough is unidirectional toward the south during the entire tidal cycle.

Two RiverSondes were installed at locations indicated in Fig. 1 designed to construct total flow vectors from the

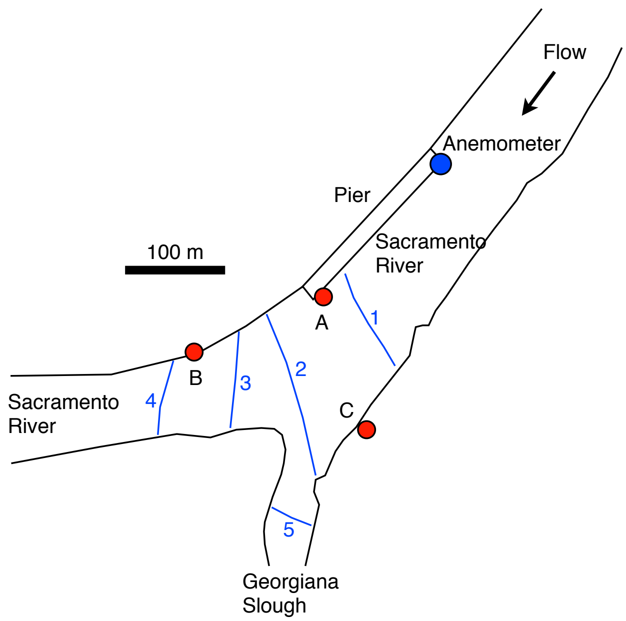


Fig. 1. Experiment layout at Walnut Grove. One RiverSonde was at location A throughout the experiment. The other RiverSonde was at location B for the first two days and was moved to location C on the last day. The ADCP made measurements on the Sacramento River near the RiverSondes and in Georgiana Slough along paths 1–5. Wind was measured by the anemometer at the end of the pier.

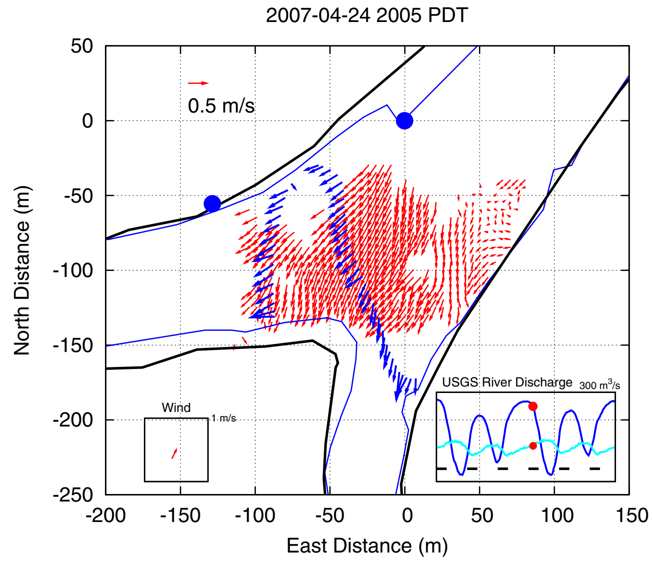


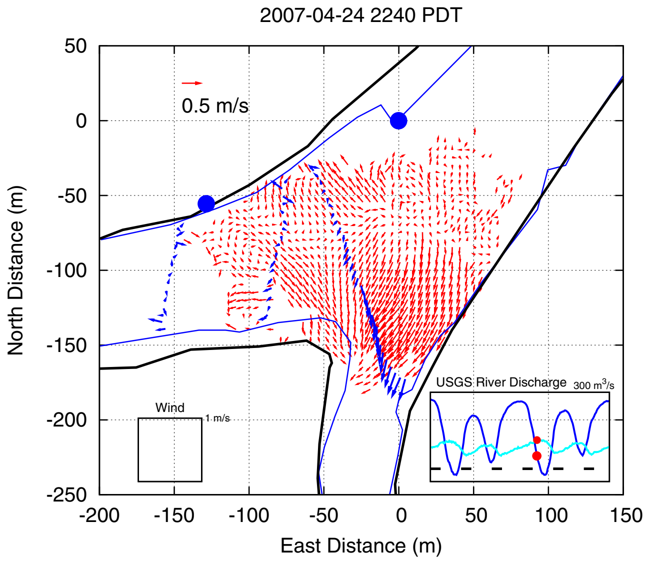
Fig. 2. RiverSonde velocity vectors (red) and ADCP velocity vectors (blue) for 20:05 PDT on 24 April 2007. The inset on the left shows the wind measurement, with the surrounding box corresponding to 1 m/s. The inset on the right shows the volume discharge measured by the USGS for the Sacramento River to the west of the experiment area (blue) and Georgiana Slough (cyan), with the discharges for 20:05 indicated by the red dots. The discharge in the river is near its maximum value, while the discharge in Georgiana Slough is rising toward its maximum value.

individual radial vectors from each unit. One unit was installed at location A at the end of a pier and operated from AC power for the duration of the experiment. The second unit was installed on the bank at location B on 23–24 April and was moved to location C on 25 April in order to compare the operation using two units on the same bank and on opposite banks. This second unit was operated on 24-volt batteries. An anemometer was installed on a houseboat (which provided logistical support during the experiment) at the north end of the pier, as noted in Fig. 1. The location for the anemometer was somewhat sheltered, so the wind readings may be somewhat lower than that right on the water near the RiverSondes; however, the wind was very low during the entire experiment, rarely exceeding 2 m/s.

An acoustic Doppler current profiler (ADCP) was mounted on a small manned boat which made repeated transects along paths 1–5 in Fig. 1 every 30 minutes for 12 hours on 24 April. The ADCP measures the water velocity below the water surface, at an average depth of about 1 m below the water surface, while the RiverSonde is sensitive to the water velocity in the top 3 cm ($1/2k$, where k is the Bragg-resonant water wavenumber) [5], so the two instruments measure water velocity from slightly different depths of the water column. Nevertheless, comparisons between the ADCP and RiverSonde measurements are valid. In addition to the ADCP measurements, the USGS routinely measures the river discharge in the Sacramento River north of the experiment location, in the river southwest of the experiment location, and in Georgiana Slough.

The operation of the RiverSonde depends on the presence of water waves of 35-cm wavelength (one-half of the radar wavelength), which have a phase velocity of 0.73 m/s. These waves usually are generated by the wind with a speed at least the phase velocity of the waves, or by surface turbulence caused mainly by bottom roughness. Unfortunately, the average wind measured by the anemometer during the experiment was 0.37 m/s, with a maximum of 2.24 m/s seen for only one hour, so the required surface waves frequently were spotty to non-existent. An experiment in a salt marsh in South Carolina in 2005 using a RiverSonde operating at 350 MHz in a low-turbulence setting showed that the number of radial vectors provided by the RiverSonde was roughly proportional to wind speed up to about 3.5 m/s and was independent of wind speed above 4.0 m/s [6]. When the wind was below 1.0 m/s, very few radial vectors were seen in the salt marsh. However, some waves were present at Walnut Grove during the times of the ADCP transects, so the motion of the survey boat may have helped generate waves by generating some surface turbulence. Waves also were seen during times of flow reversal, perhaps due to increased turbulence at those times.

Figure 2 shows the RiverSonde velocity vectors in red and the ADCP vectors in blue for 20:05 PDT on 24 April 2007. At this time, the river discharge was near its maximum value, corresponding to velocity in the river channel flowing toward the west, and the discharge in Georgiana Slough is approaching its maximum value, which is about $1/3$ of the



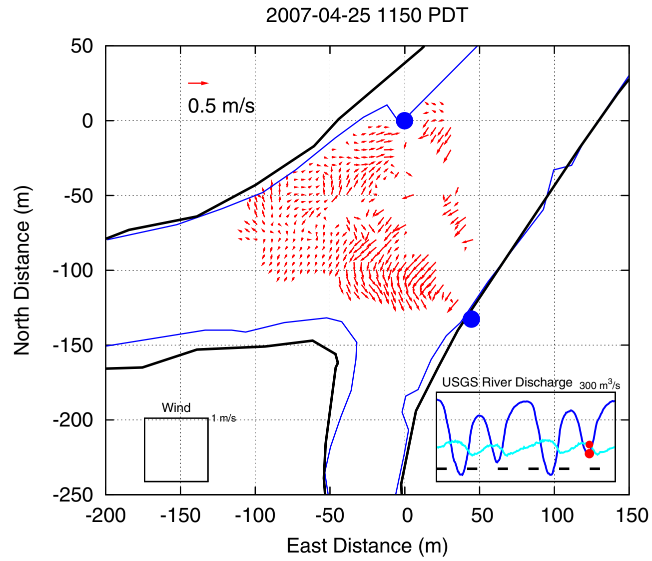


Fig. 3. RiverSonde and ADCP velocity vectors for 22:40 PDT on 24 April 2007. The discharge in the river is near its minimum value, while the discharge in Georgiana Slough is near its maximum value. As the flow in the river is about to reverse direction, the circulation pattern becomes complex.

Fig. 4. RiverSonde velocity vectors for 11:50 PDT on 25 April 2007, near a minimum of river discharge. The second RiverSonde was moved across the river from the configurations of Figs. 2 and 3.

river discharge maximum. The velocity vectors in the river are strong and generally toward the southwest for both the RiverSonde and ADCP. A low-velocity region also is evident near the bank opposite the pier. This feature is seen in many samples and appears to correspond to the bathymetric features of this region. In general, the RiverSonde and ADCP vectors agree in both magnitude and direction.

Figure 3 shows RiverSonde and ADCP vectors for 22:40 PDT on 24 April. This time is near a minimum in river discharge, just before the flow in the river briefly reverses direction. The discharge in Georgiana Slough is near its maximum. The velocity pattern in the river is much more complex than that of Fig. 2 because of the impending flow reversal. Again, the RiverSonde and ADCP vectors generally agree qualitatively in both magnitude and direction.

Finally, Fig. 4 shows the RiverSonde vectors for 11:50 PDT on 25 April. The RiverSonde initially placed at location B was moved across the river to location C in order to compare the operation of a pair of RiverSondes deployed on the same bank or on opposite banks of a channel. No ADCP measurements were available for this configuration. The system was operated in this configuration for only a few hours, but little difference in the results were seen between the two configurations.

Figure 5 shows a scatter plot of the differences between the u and v components of the vector ADCP velocities and the RiverSonde velocities. The means of the differences of the raw data are 4.5 cm/s and 7.6 cm/s for the u and v components, respectively, and the RMS differences are 14.7 cm/s and 21.0 cm/s, computed over 1011 samples. After removing obvious outliers having u or v differences of more than 0.5 m/s, the means of the u and v differences are 3.7 cm/s and 5.3 cm/s, and the RMS differences are 13.5 cm/s and 16.2 cm/s for the u and v components, respectively, computed over 963 samples.

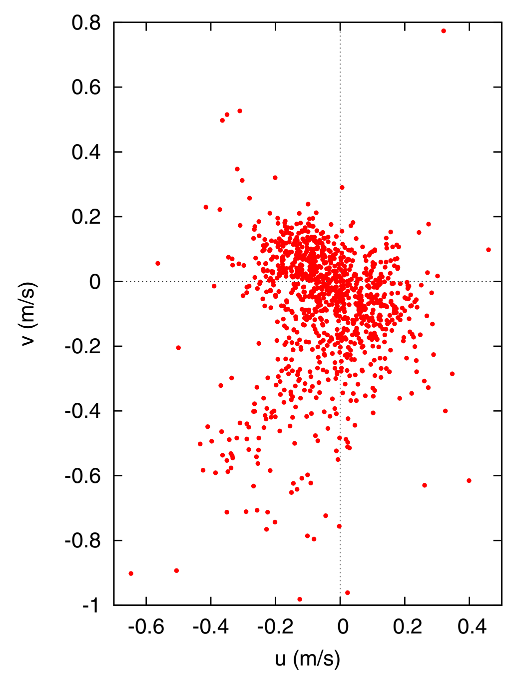


Fig. 5. Scatter plots of the u and v components of the vector differences between ADCP and RiverSonde velocities at Walnut Grove.

Because of the very low wind conditions at Walnut Grove, it was decided to conduct another experiment at Threemile Slough, where the wind conditions had been more favorable historically.

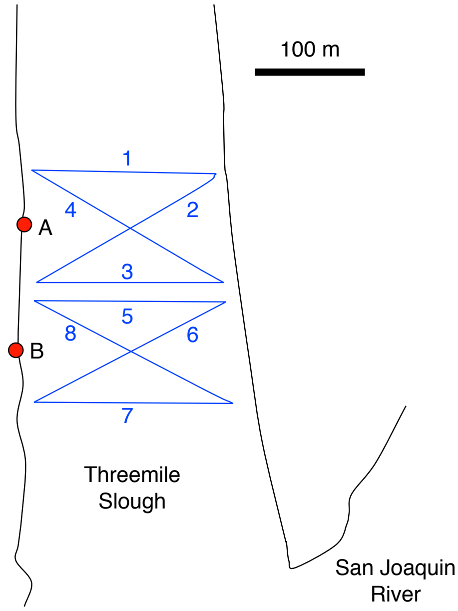


Fig. 6. Experiment layout at Threemile Slough. The RiverSonde at location A is on a DWR pier and has been in operation nearly continuously for over a year. The RiverSonde at location B was set up temporarily and operated from battery power. ADCP transects are shown by paths 1–8. Two autonomous vehicles were operated simultaneously, one covering paths 1–4 and the other covering paths 5–8.

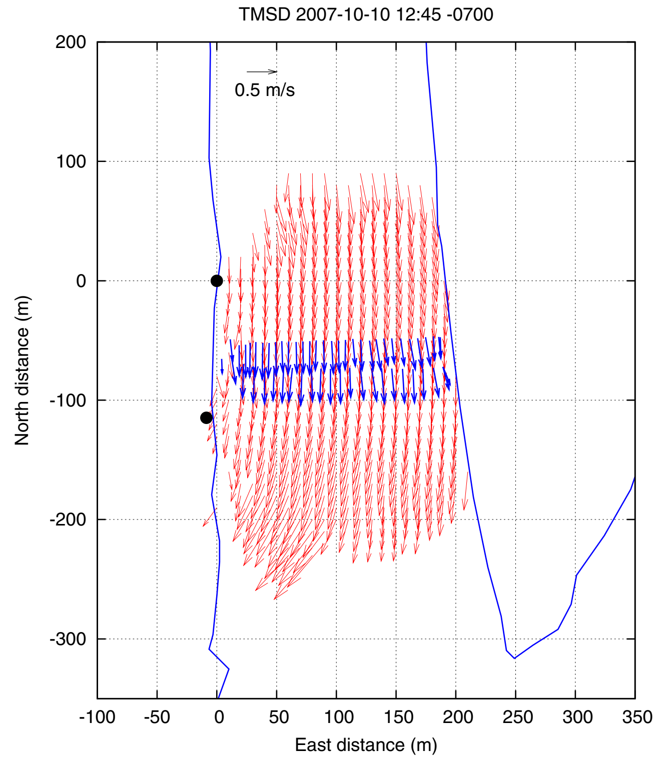


Fig. 7. RiverSonde velocity vectors (red) and ADCP velocity vectors (blue) from the unmanned survey vessel for 12:45 PDT on 10 October 2007 at Threemile Slough. Flow in in the slough was strongly to the south. The two ADCP tracks are from the two survey vessels which were operated simultaneously, and show good agreement.

III. Threemile Slough

A dual-RiverSonde experiment at Threemile Slough was conducted during 10–11 October 2007. A map of the experiment is shown in Fig. 6. Threemile Slough joins the Sacramento and San Joaquin Rivers, and the location of the experiment is at the southern end of the slough near the San Joaquin River. The slough runs north-south at its southern end. A RiverSonde has been in operation nearly continuously at Threemile Slough for several years at a Department of Water Resources, State of California (DWR) gaging station [2], and the site is accessible via the Internet for data access, remote operation and software updates. That RiverSonde was one of the two used in the experiment in October, and is shown at location A in Fig. 6. The second RiverSonde was installed temporarily at location B, 114 m south of the first, and operated on batteries for the duration of the experiment. Flow in Threemile Slough is dominated by tidal effects, with complete flow reversals and nearly equal flow magnitudes of approximately 0.8 m/s (max) in the north and south directions during the tidal cycle.

A pair of ADCPs made measurements on 10 October, with the paths indicated by 1–4 and 5–8. Each ADCP was mounted on an autonomous survey vessel which is controlled remotely by a computer via wireless technology. The operation of the ADCP surveys on autonomous unmanned survey vessels is described in a companion paper at this conference [7]. Abundant surface waves were present almost all of the time during this experiment, generated either by the wind or by surface turbulence caused by bottom roughness, so quantitative comparisons between the RiverSondes and ADCPs is possible. An anemometer was placed at the end of the DWR pier at location A for the duration of the experiment. Average wind speed measured by the anemometer was 2.0 m/s, with a maximum of 6.7 m/s.

Figure 7 shows a typical southward-flowing pattern for 12:45 PDT on 10 October 2007, about 45 minutes after a flow reversal. The RiverSonde vectors are plotted using a grid spacing of 10 m. The two unmanned autonomous vessels were operating simultaneously, and their paths were close to each other for this data set. The vectors from the two ADCPs agree with each other and with the RiverSonde vectors.

Figure 8 shows RiverSonde and ADCP data for 12:00 PDT during the flow reversal. The two autonomous vessels were spaced about 100 m apart and showed similar patterns. There is some variation in flow across the channel, with counterclockwise circulation near the left bank and patches of somewhat stronger flow near the right bank.

Finally, Fig. 9 shows RiverSonde vectors along with ADCP

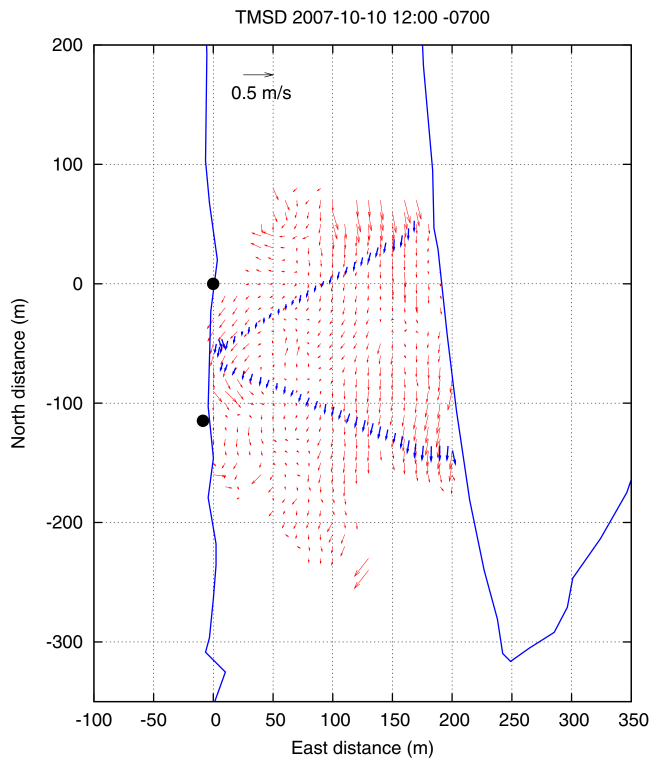


Fig. 8. RiverSonde (red) and ADCP (blue) velocity vectors for 12:00 PDT at ThreeMile Slough, just 45 minutes before Fig. 7. Flow in the slough was reversing direction from northward to southward. The data from the two ADCPs agree well with the RiverSonde data.

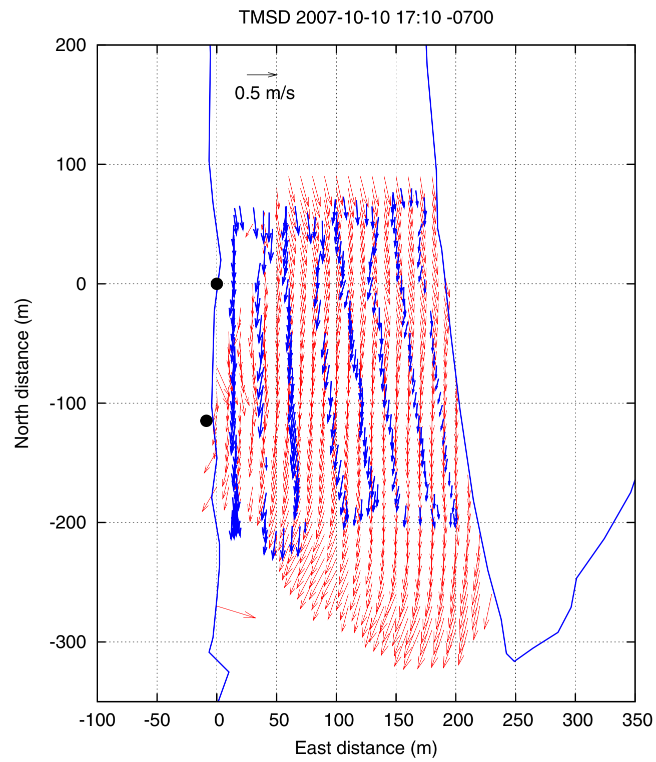


Fig. 9. RiverSonde (red) and ADCP (blue) velocity vectors near 17:10 PDT at Threemile Slough. One autonomous survey vessel was in operation at this time and covered a large number of tracks in order to map the bottom profile. The ADCP data were collected over about 40 minutes, from 16:50 to 17:31 PDT. Flow in the slough was toward the south.

vectors from a single vessel which was operating to cover the entire study area in about 40 minutes centered at 17:10 PDT and was designed to survey the bottom of the channel. However, velocity vectors also were measured and show considerable spatial variability. Again, the ADCP and RiverSonde vectors agree quite well.

Figure 10 shows a scatter plot of the vector differences between the ADCP and RiverSonde velocities for 2257 samples with differences of no more than 0.5 m/s. The means of the u and v differences are 0.007 cm/s and 0.50 cm/s, respectively, and the RMS differences are 7.9 cm/s and 13.5 cm/s, respectively. Clearly, the RiverSonde and ADCPs are giving very similar results.

IV. Discussion

The site at Walnut Grove was chosen because of its importance in the study of juvenile fish migration in the Sacramento-San Joaquin River Delta, and the experiment was scheduled for 3 days in April 2007 well in advance of the actual dates. Unfortunately, the wind during the experiment was very low, the river discharge was low to moderate, and the water flowing over the bottom did not result in enough surface turbulence to consistently generate the 0.35-cm wavelength surface waves required for the RiverSonde operation. Nevertheless, when ADCP data were available, often there were sufficient surface waves to provide good RiverSonde echoes. The flow patterns at Walnut Grove are quite complex, especially during periods of flow reversal. Comparisons between RiverSonde and ADCP vectors, when available, are quite encouraging.

Conditions at Threemile Slough were more favorable. The wind was higher during the experiment in October, with an average wind speed of 2.0 m/s, and the bottom of the channel is rough, which often generates surface waves even in the absence of strong wind (although historically there are periods of low flow and low wind conditions which sometimes result in very low surface waves). The unmanned autonomous vessels performed very well in these initial tests, and the quality of the ADCP data is quite good. RMS differences between RiverSonde and ADCP data of 7.9 and 13.5 cm/s were seen, with very little bias.

The use of two RiverSondes to measure complex flow

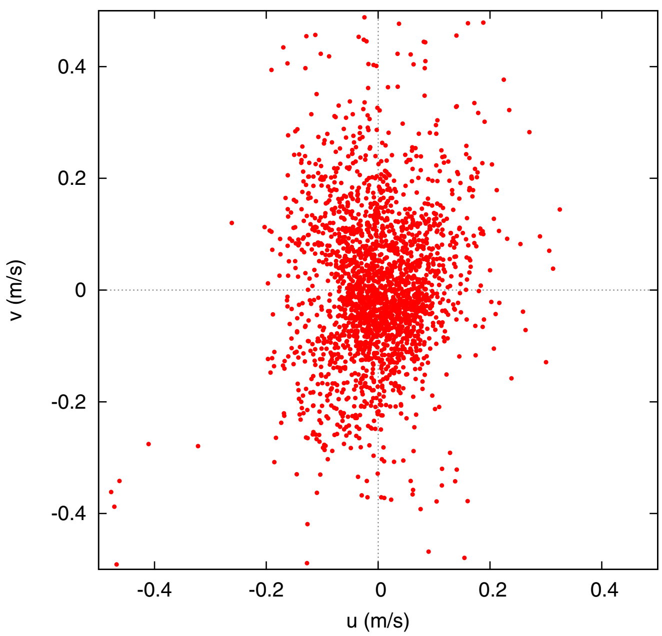


Fig. 10. Scatter plot of the vector differences between 2257 RiverSonde and ADCP measurements at Threemile Slough for 10 October 2007. Outlying samples with *u* (eastward) or *v* (northward) differences of more than 0.5 m/s have been removed.

patterns is attractive because of the spatial coverage which can be achieved, and the lack of contact with the water when the measurements are made. However, the RiverSonde does require some surface roughness, in the form of 0.35-m wavelength water waves, so the presence of those waves should be considered as an essential requirement when planning an experiment using the RiverSonde.

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