Current Velocity Mapping Using an AUV-Borne Acoustic Doppler Current Profiler*

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Abstract

An Acoustic Doppler Current Profiler (ADCP) has been mounted on an Odyssey II class Autonomous Underwater Vehicle (AUV) and used to measure current velocities. By merging data acquired by the ADCP with those acquired by other AUV-borne instruments such as a Conductivity-Temperature-Depth (CTD) sensor, as well as a long baseline (LBL) acoustic navigation system, we can better observe and interpret the underwater processes of interest by utilizing a mobile platform. This capability was demonstrated in a field experiment at Haro Strait, British Columbia, Canada, in the summer of 1996. This paper develops ADCP data acquisition and processing methods for AUV mounted use. A 307.2 kHz broadband RD Instruments Workhorse Monitor ADCP is mounted at the midsection of an AUV in a downward looking configuration. The velocity data are recorded in the ADCP's internal memory and downloaded after missions. At Haro Strait, the ADCP was programmed to map a 100-meter column of water which was subdivided into fifty 2-meter depth bins. During a yo-yo mission, the AUV crossed the front and significant contrasts of temperature and salinity between the two sides of the front were detected. The ADCP data processing results show that the water flowed mostly southward. The eastward velocity plot demonstrates a layered structure. Alternating upwellings and downwellings illustrate the spatial and temporal scales of the mixing process. Current velocity mapping is shown to provide insight into the tidal mixing process.

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I. Introduction

Haro Strait is part of a narrow channel between Washington State, U. S., and Vancouver Island, British Columbia, Canada. Haro Strait links the Strait of Juan de Fuca with the Strait of Georgia. This is an area with vigorous tidal mixing [1] of fresh water from the Fraser River and sea water from the Pacific Ocean. To study tidal mixing utilizing state-of-the-art technology, researchers from MIT and four other institutions led an expedition into Haro Strait in the summer of 1996. Through the experiment, two Odyssey class Autonomous Underwater Vehicles (AUVs) [2] designed by the MIT Sea Grant AUV Lab demonstrated their important role as cost-effective and high-performance mobile instrumentation platforms. An Acoustic Doppler Current Profiler (ADCP) manufactured by RD Instruments was employed on one of the vehicles, named Xanthos. In this paper, ADCP data acquisition and processing methods are presented, and results of one mission are shown.

The ADCP employed at Haro Strait was a 307.2 kHz RD Instruments Workhorse Monitor ADCP. The ADCP is mounted on Xanthos at the midsection in a downward looking configuration, as shown in Figure 1. With measurements from its four beams, water current velocities relative to the ADCP are obtained. As the vehicle flies through the water volume, the current velocities to a depth of 100 meters below the ADCP can be mapped. Since the ADCP's platform, the vehicle, is moving, the vehicle's velocities must be removed to obtain the current velocities relative to the Earth. As bottom-track was not available for Workhorse ADCPs at the time of the experiment, long baseline (LBL) navigation data [3] are used to estimate the vehicle's horizontal velocity. The vehicle's depth sensor enables the estimation of its vertical velocity.

Data processing results are interesting and helpful for a better understanding of the tidal mixing. One example is given. During mission 14 on June 25, the vehicle yo-yo'ed between the surface and a depth of 20 meters. The vehicle crossed the tidal front, recording strong contrast in temperature and salinity between the two sides of the front [3]. ADCP measurements show a mostly southward current flow with upwellings and downwellings. The eastward velocity plot demonstrates a layered structure.

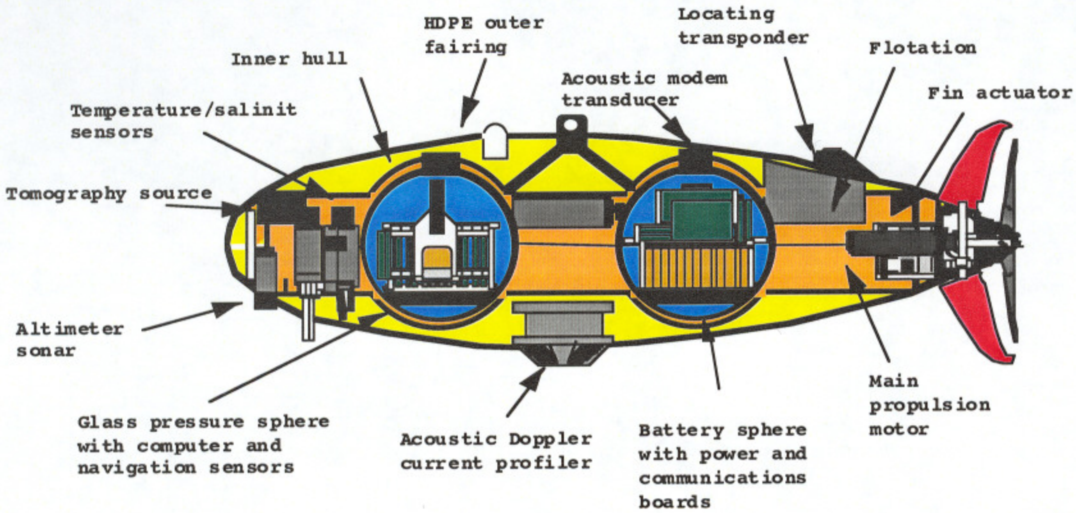

Figure 1. AUV Xanthos in its Haro Strait configuration with downward facing RDI ADCP in its midsection (courtesy of Dr. James Bellingham).

II. ADCP Data Acquisition and Processing

2.1. ADCP setting and data logging.

Table 1: ADCP setting

Ensemble period	No. of pings per ensemble	No. of depth sells	Depth cell size	Distance to the first cell
2 seconds	1	50	2 meters	4 meters

Mission specific ADCP setting is written into the AUV mission file. Each time right before the vehicle launch, a software command wakes up the ADCP for pinging via an additional small circuit board. The ADCP unit is powered by the vehicle's battery pack and the communication with the vehicle's computer system is through an RS-232 port. The ADCP's internal data recorder was enabled and its serial output was disabled. Data output was binary. The ADCP has 10 MB of memory space. With the setting outlined in Table 1, 20 minutes data logging requires about 1 MB of storage. For a typical mission day of less than 200 minutes operation at Haro Strait, the ADCP memory was enough to hold all the data. At the end of the day, the data would be downloaded onto a PC via an external RS-232 cable.

Ensemble cycling and ping cycling were both set to be automatic. For recording current velocity data in the ADCP's beam-referenced frame, there cannot be more than one ping in each ensemble, so the number of pings per ensemble was set to 1. The time that the ADCP takes to transmit each ping plus the overhead needed for processing [4] determines that the minimum ensemble interval is 2 seconds. This was the setting used. With fifty 2-meter depth cells, a water column of 100-meter depth can be mapped. Considering that Haro Strait has a water depth of about 200 meters or less depending on locations, and that the vehicle ran at depths within the upper 100 meters, the selection of 100-meter ADCP range is reasonable.

2.2. ADCP Data processing in combination with LBL and CTD measurements.

The ADCP data processing includes the following steps:

i) Time synchronization among different instruments. At Haro Strait, LBL and CTD data were stamped with the vehicle's GPS-referenced time. The ADCP had a separate clock from the vehicle, and its clock was set to GPS time by hand before each ADCP mission. The approximate one-second error introduced by hand setting is eliminated in data processing by careful alignment of the attitudes measured by the ADCP and the vehicle. Thus the vehicle's CTD and LBL data are synchronized with ADCP data on the common GPS time reference after processing. Currently, the ADCP clock is automatically synchronized with the vehicle clock at the beginning of each mission, removing the need for data synchronization in post-processing.

ii) Depth bin number correction. During a yo-yo mission, for any particular water depth, the ADCP's depth bin number varies as the vehicle goes up and down. So a bin number correction should be made to map current velocities in a rectangular box of water below the vehicle. Actually, even for missions with a designated depth, the vehicle may still deviate from the commanded depth due to the current, so depth bin number correction is done for all the data.

iii) Removal of the AUV's velocities to obtain the Earth-referenced current velocities.

Since the ADCP's platform, the vehicle, is moving, the vehicle's velocities must be removed to obtain the current velocities relative to the Earth. Bottom-track was unavailable with the Workhorse Monitor ADCP at the time of the experiment. Consequently, LBL navigation data are used for estimating the vehicle's horizontal position and velocity. The vehicle's vertical velocity is estimated by the time derivative of the depth measurements made by its depth sensor.

iv) Data smoothing. To reduce the current velocity estimation errors, appropriate averaging over depth bins or over time is carried out in data processing. The bias of the ADCP's velocity measurement is typically less than 1 cm/s and it is not yet possible to calibrate or remove the bias in post-processing[4]. The standard deviation of velocity measurement is 7.0 cm/s for horizontal and 1.8 cm/s [4] for vertical with the setting outlined in Table 1. For the LBL navigation using four sonar beacons, the position accuracy is better than 10 meters and the precision is better than 2 meters when the vehicle's distance from the center of the 4-beacon array is less than the array aperture [3]. The vehicle's depth sensor (Paroscientific Model 8B-4000) has an accuracy of 0.4 meter, and its precision is much better than 0.2 meter [5]. The length of the smoothing window is determined based on the measurement errors introduced by the ADCP, the LBL navigation system, and the vehicle's depth sensor. The window length is adjustable to get a good trade-off between the temporal resolution and the estimation error relative to the maximum current velocity.

v) Corrections on the ADCP's heading and attitude measurements. As shown in Table 2, the ADCP-measured heading and attitude [4] were not as accurate as the AUV's heading-and-attitude measurements made by KVH Digital Gyro Compass and Digital Gyro Inclinometer[6]. For ADCP data recorded in the Earth-referenced frame after its internal coordinate transformation, corrections are made in data processing using KVH's measurements as better references. For ADCP data recorded in its raw beam-referenced frame, the Earth-referenced current velocities can be computed off-line directly using KVH's more accurate heading and attitude measurements. Note that "Earth-referenced current velocities" here are still relative to the vehicle. The magnetic variation at Haro Strait was 18.9 degrees, and this has been taken care of in data processing.

Table 2: Heading and attitude sensor accuracy

	heading	attitude
ADCP	±1°	±2°
KVH	±0.5°	±1°

III. Mission Analysis

During mission 14 on June 25, The vehicle yo-yo'ed between the surface and a depth of 20 meters. Its commanded heading was 108.9 degrees (True) for 1200 s and then a reciprocal course of 288.9 degrees (True) for 900 s. The vehicle's horizontal and vertical trajectory is shown in Figure 2. Its horizontal speed component was about 1.3 m/s. Figure 3 shows the Earth-referenced current velocities after removing the vehicle's velocities. The water flowed mostly southward with the maximum southward velocity of 40 cm/s. Alternating upwellings and downwellings of up to 5 cm/s illustrate the spatial and temporal scales of the mixing process. The eastward velocity plot demonstrates a layered structure: the upper 40 meters of the water column flowed to the east at about 10 cm/s while the water below flowed to the west with velocity up to 30 cm/s. This kind of layered current structure is attributed to the mixing process.

In Figure 4, the vertical current velocity, the vehicle's depth, and the measured temperature and salinity are compared. At time 600 s, the vehicle crossed the front, entering a lower-temperature and higher-salinity water mass. Then at time 1200 s, the vehicle turned around, and at time 1700 s it crossed the front again and came back to the higher-temperature and lower-salinity water. These signatures were well recorded by the temperature and conductivity sensors. The vertical current velocity shows that within the lower-temperature and higher-salinity region, there were downwellings on the order of 5 cm/s, while in the higher-temperature and lower-salinity region, upwellings on the order of 5 cm/s existed. Alternating upwellings and downwellings demonstrate the complexity of the mixing process.

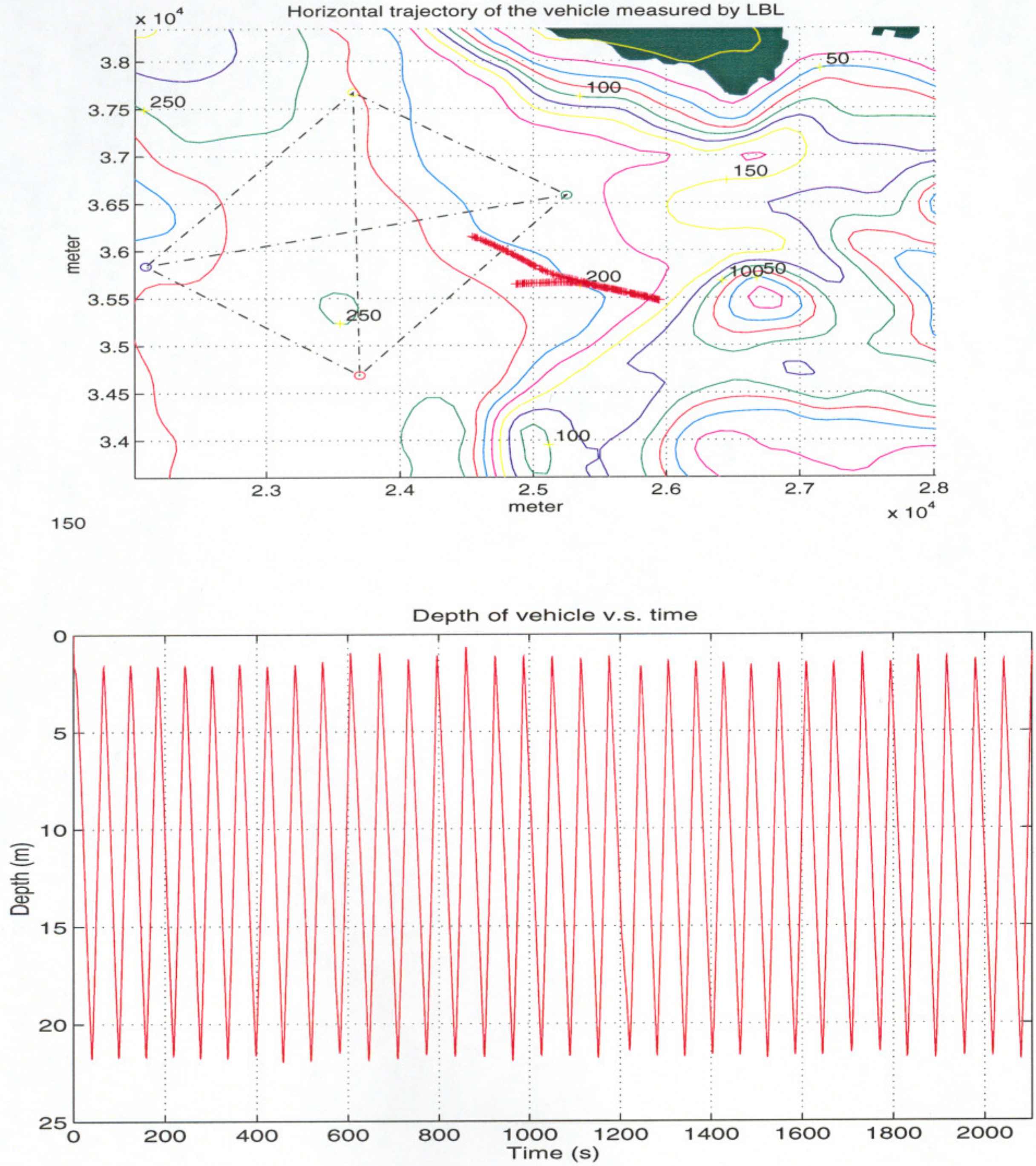

Figure 2. During mission 14 on June 25, the vehicle ran southeast and then turned around, while yo-yoing.

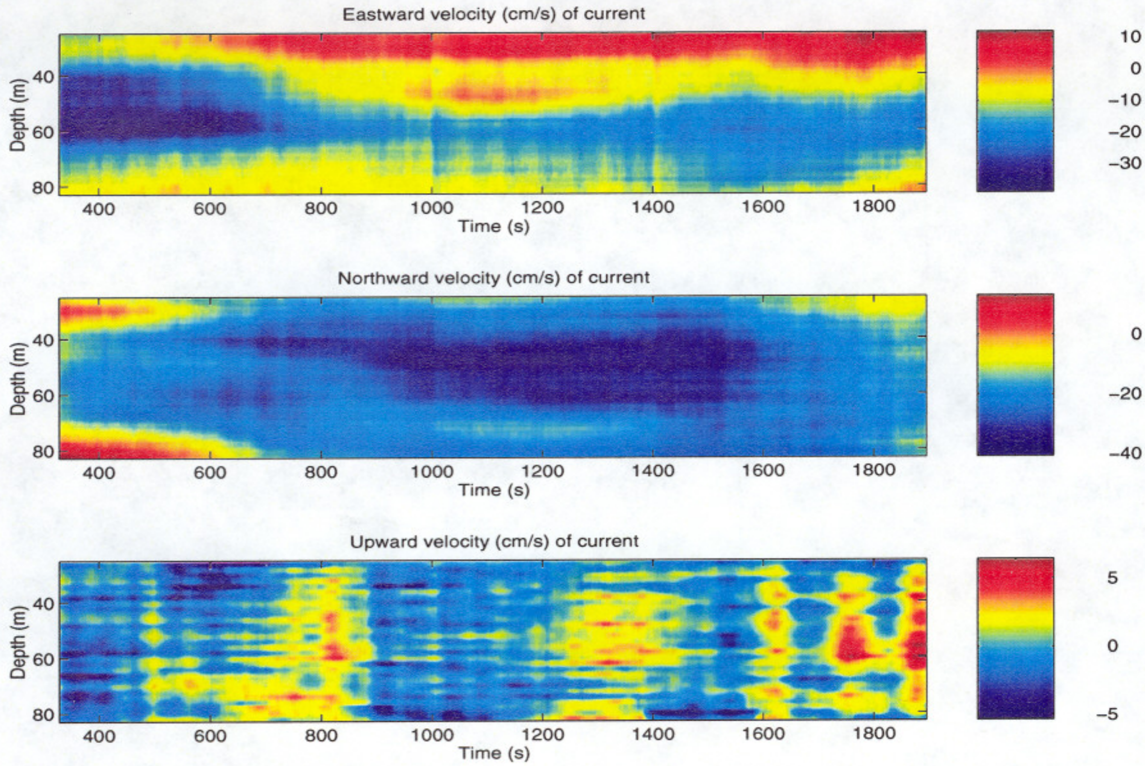

Figure 3. Earth-referenced current velocities.

To decrease velocity estimation errors to acceptable levels, 400-second smoothing and 200-second smoothing are done on the horizontal velocity and the vertical velocity, respectively. Based on the precision of the ADCP measurements and the LBL navigation, the overall rms error of the Earth-referenced horizontal current velocity is about 3 cm/s after smoothing, while the magnitude of horizontal current velocities is about 30 cm/s. It should be noted that the LBL navigation error is the dominant source of error in estimating horizontal current velocities. This necessitates the long smoothing window. Therefore the improvement on LBL navigation precision is an important task, and good progress is being made and tested in Cape Cod Bay while this paper is being written. For estimating the vehicle's vertical velocity, the time derivative of the depth sensor measurements is used. The vertical current velocity is small in this mission, on the order of only 5 cm/s. Considering the ADCP's vertical velocity rms error of 1.8 cm/s plus the vehicle's depth sensor error, a smoothing window of 200 seconds (100 ADCP samples) is applied, giving an overall rms error of less than 0.5 cm/s. During the Haro Strait experiment, the ADCP's depth bin size was set to 2 meters. If we had sacrificed the depth resolution, say, by doubling the depth bin size to 4 meters, the ADCP's velocity measurement error would have been decreased by more than half. With smaller ADCP measurement errors, the length of the time smoothing window can be shortened, resulting in better temporal resolution. So there is a trade-off between temporal (horizontal) resolution and depth (vertical) resolution.

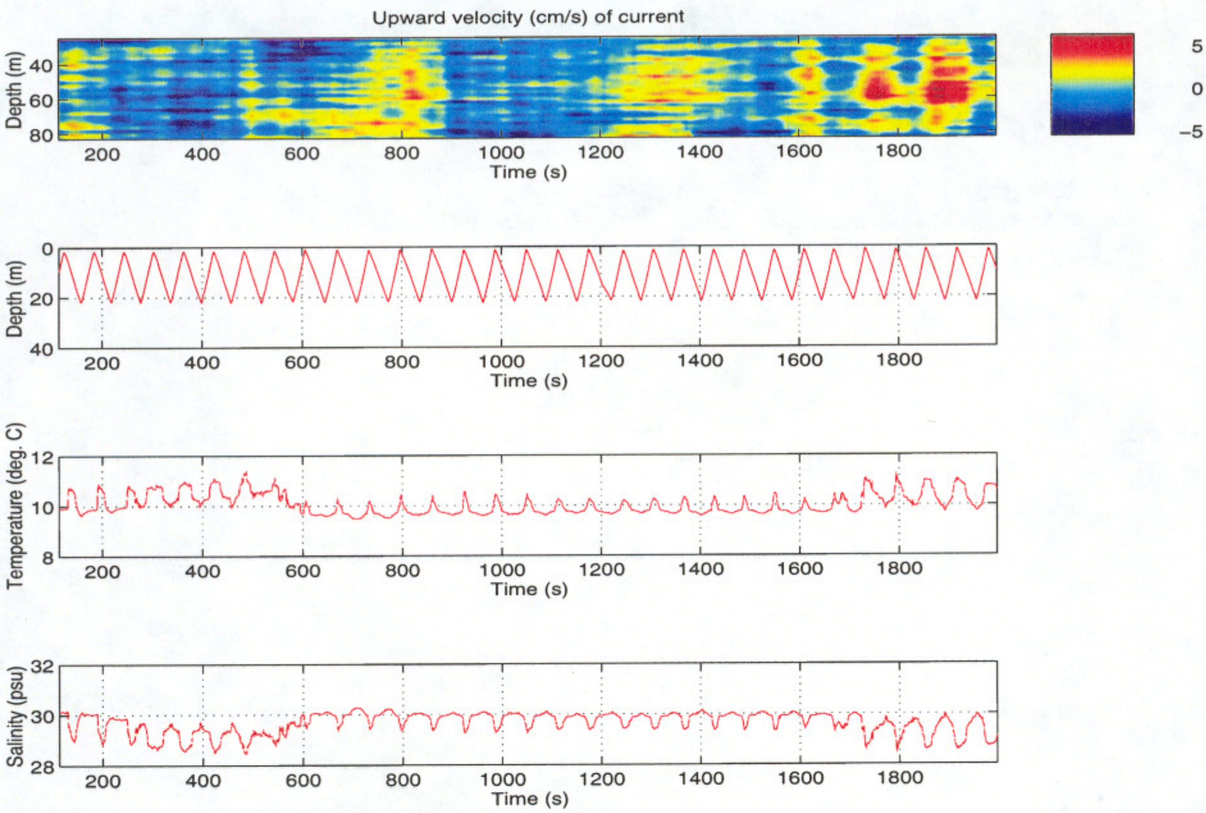

Figure 4. Earth-referenced vertical current velocity and CTD measurements.

IV. Conclusion

In the Haro Strait experiment, an RDI ADCP was put into use as one of the AUV's sensors. In such a tidal mixing area, the current velocity measurements are very important for understanding the physical process, especially when combined with the CTD measurements. Data processing techniques include: time synchronization, depth bin number correction, extraction of the vehicle's dynamics, data smoothing based on navigation and sensor error bounds, and correction for ADCP's attitude sensor errors. The results provide insight into the mixing process of different water masses. The AUV's role as a mobile instrumentation platform is well demonstrated.

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