Novel Underwater Glider-Based Absolute Oceanic Current Observation Solutions

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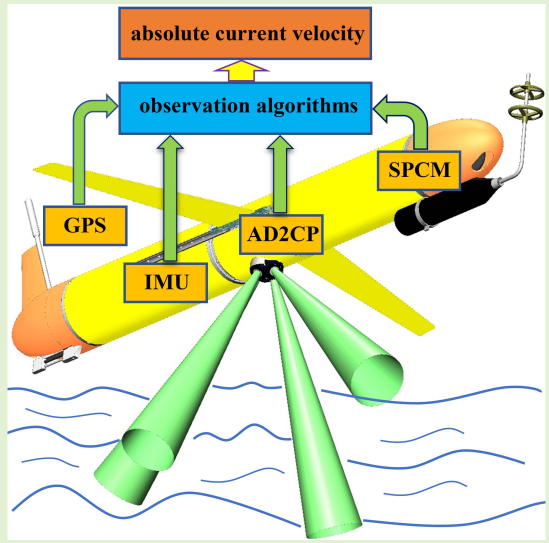
***Abstract*—This work indicates two novel ocean current observation methods that based on a glider type mobile platform. Glider with current meters are ideal current observation solutions for marine scientists since they have merits of large dynamic area and low power consumption, but their measurement accuracy is insufficient now. The proposed 1st solution, single point current meter compensated inversion method (SPCMCIM), is a revolution of the conventional inverse method by solving the acoustic Doppler to current profiler (AD2CP) induced turbulence problem. It's a cooperated AD2CP and single point current meter (SPCM) algorithm that compensates the contaminated first AD2CP layer data. The physical position of the SPCM is also optimized according to a finite element analysis (FEA) study to minimize the interference generated by the SPCM. The 2nd method is solving the area restriction problems that AD2CP can just apply to non-pure water environment namely single point and inertial measurement inversion method (SPIMIM). It utilizes the SPCM as the only current observation source and takes advantages of physical properties of ocean currents. The currents are constitute of stable layers and each of them has a stable velocity, so the glider's velocity variation can be obtained by reading the SPCM. The velocity variation in the transition process between layers can be acquired by the low cost inertial sensors. Finally, these theoretical studies were verified in an onsite sea trial. The SPCM and AD2CP was mounted to an underwater glider to measure the currents and a ship equipped AD2CP was used to provide the arbitrary data. Both of the proposed method can effectively measure the current velocity and induced significant enhancement than the classical inversion method. In particular, the first method conducted improvement of 70% accuracy by average. The 2nd one also shows an obvious improvement and has the advantage to deploy to high purity water area like deep lakes or north pole.**



***Index Terms*—Ocean current observation, single point current meter, AD2CP, inversion method, underwater glider.**

I. Introduction

CURRENTS constitute one of the most important elements in oceans. It plays an important role in the energy transfer and exchange of oceans which significantly influence the global atmosphere, climate, fishery and environment [1]. Thus, the accurate current observation is highly desired for marine scientists to essentially characterize and investigate the principle of the oceanic physics [2].

Remote sensing data from the satellites is an effective way to capture the ocean currents and eddies. The satellite-based altimeter can characterize surface properties of macro and meso-scale currents include trajectory, diameter and center point [3], [4]. By properly processing the altimeters' original data, the induced meso scale data can reach a resolution of 0.1 ° and 1 day in the spacial and time domain. Synthetic aperture radar (SAR) is another favorite remote sensing method for scientists because it has higher resolution than the altimeter and provides 3D information of the surface [5], [6]. Other remote sensing methods like ocean color satellite [7] and radar [8], [9] are also feasible to provide useful data for the oceanic scientists. Nevertheless, remote sensing is more suitable for characterizing the surface properties of larger scale currents [7], [10], [11].

As the sub-meso scale and micro scale currents become the hot topic in the marine science, the scientists are increasingly encouraging the in-situ observations since they can provide

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more reliable, much higher resolution both in timely and physical dimension manners [12]. Though the famous Argo network is designated as an in-situ way, its daily current observation that based on the Lagrange principle is only suitable for investigating macro and meso scale phenomenon [13]. The acoustic Doppler to current profiler (AD2CP) that load on scientific research vessels, or namely lowered AD2CP (LAD2CP), tend to be a good compromise between the requirement of resolution and observation range [14], [15]. The advantage of this LAD2CP method would be its has the access to the GPS that can compensate the errors introduced by the movement of the vessel. However, LADCP is very expensive for long duration and large range observation. The research vessel typically has multiple missions on one voyage and the LADCP task normally just share a some portion of it [14].

Mobile platform, like gliders, autonomous underwater vehicles (AUVs), based current observation has the great potential to solve this contradiction between the data effectiveness and economic efficiency [16]–[18]. Oceanic gliders are considered as the ideal candidates for this task because it has significant advantages of ultra power consumption, long endurance and outstanding deep water performance [16], [19]. The biggest challenge of mobile platform observation would be that the inertial frame of the glider is unknown [20]. The measurement results are superposed by the current velocity and the glider velocity which is very difficult to decouple, since high resolution inertial sensors are unaffordable for scientific research purposes. There are few published solutions to improve the accuracy that can be summarized as inversion method [21] and shearing method [22].

These methods, in particular the inversion method, do not require expensive inertial sensors to provide the velocity of the platform, but utilizing the currents' physical properties to build constraints to estimate the currents' velocity in each layer. The essence of the inversion method is the accurate measurement of the AD2CP. However, the AD2CP on the mobile platform has 2 issues. The first one would be that the mounted AD2CP will break the streamline of the glider and the induced turbulence will interfere the AD2CP's measurement. More importantly, an AD2CP can only work at non-purity water environment because its fundamental principle is processing the echos of its sound beams [23]. A single point current meter (SPCM) can adapt to this environment, but it's not compatible with neither inversion method or shearing method because its output dimensions are limited [24].

To improve the measurement accuracy and expand the glider based framework to broader ocean areas, this article provides 2 novel solutions. The proposed 1st solution is a revolution of the conventional LADCP method that fused by a SPCM and the 2nd one is a brand new algorithm without using AD2CP. The contributions are summarized as follows:

(1) The mechanism of AD2CP induced turbulence is discussed and a solution of single point meter fusion namely single point current meter compensated inversion method (SPCMCIM) is proposed, investigated and optimized. The finite element analysis (FEA) verified that the mounted AD2CP will contaminate the AD2CP results. Thus, an AD2CP and SPCM cooperated algorithm is designed to compensated the errors. The Optimized installation position of the SPCM is also analyzed through a series of FEA simulations.

(2) A novel area free current observation method is firstly proposed by just utilizing SPCM as a state-of-the-art. This single point and inertial measurement inversion method (SPIMIM) takes advantages of ocean currents' physical properties that they are constitute of different layer with stable velocity as a key constraint. The transition process is short enough to entrust the low cost micro inertial sensors.

(3) The proposed methods were implemented and verified through an onsite ocean experiments. An AD2CP and a SPCM were mounted on an oceanic glider for the onsite trial. By comparing with the arbitrary data, both methods show satisfied measurement performance.

The remainder of this article gives the details.

II. Novel Inverse Method With SPCM Compensation

A. Basic Principle and Challenges of Inverse Method

The biggest challenge for mobile platform based ocean current measurement would be the superposition of the velocity of the current and the AD2CP that attached to the platform, which can be described by a fundamental equation:

$$U_{AD2CP} = U_{current} - U_{glider}, \tag{1}$$

where U_{AD2CP} is the AD2CP measured value, $U_{current}$ and U_{glider} are the unknown values of absolute ocean current velocity and speed of the platform [21], [25]. Though the glider's velocity can be obtained through high precision inertial sensors, it's not affordable for gliders designed for scientific discovery purposes. So the inverse method is a classical alternative approach to compromise this limitation and reaches a reasonable estimate of the real ocean currents.

In the real practice, the AD2CP is a multi-dimensional sensor that captures multi-layer information, so that the fundamental equation (1) can be generalized into the following form:

$$U_{AD2CP}(i, j) = U_{current}(i, j) - U_{glider}(i), \tag{2}$$

where i is the sample number of AD2CP data and j represents the current layer number in the ith measurement sample.

There are large amount of samples during one measurement task, so it would be convenient to describe the overall data by using a matrix operation:

$$\boldsymbol{d} = \boldsymbol{Gm} + \boldsymbol{n}, \tag{3}$$

where $\boldsymbol{d}$ is composed of $U_{AD2CP}(i, j)(i = 1, \ldots, N, j = 1, \ldots, nbin)$, $\boldsymbol{G}$ is the corresponding sparse matrix, whose column is $M + N$ and the row is $nbin \times N$. The values of M and N are determined according to the maximum glide depth of the glider and time scale resolution. $\boldsymbol{m}$ contains the unknown absolute current velocity $U_{currenti}(i = 1, \ldots, M)$ and the absolute glider speed $U_{glideri}(i = 1, \ldots, N)$, $\boldsymbol{n}$ represents the noise due to the imperfect estimates and measurements.

Here's an instance to better illustrate the elements in (3). In this research, the value of $nbin$ is taken as 3, so that $\boldsymbol{d}$, $\boldsymbol{m}$ and $\boldsymbol{G}$ can be embodied as the following form:

$$\boldsymbol{d} = \begin{bmatrix} U_{AD2CP}(1,1) \\ U_{AD2CP}(1,2) \\ U_{AD2CP}(1,3) \\ U_{AD2CP}(2,1) \\ U_{AD2CP}(2,2) \\ \vdots \\ U_{AD2CP}(N,1) \\ U_{AD2CP}(N,2) \\ U_{AD2CP}(N,3) \end{bmatrix} \quad \boldsymbol{m} = \begin{bmatrix} U_{current1} \\ U_{current2} \\ \vdots \\ U_{currentM} \\ U_{glider1} \\ U_{glider2} \\ \vdots \\ U_{gliderN} \end{bmatrix} \tag{4}$$

$$\boldsymbol{G} = \left[\begin{array}{ccccc|ccccc} 1 & 0 & 0 & \ldots & 0 & -1 & 0 & 0 & \ldots & 0 \\ 0 & 1 & 0 & \ldots & 0 & -1 & 0 & 0 & \ldots & 0 \\ 0 & 0 & 1 & \ldots & 0 & -1 & 0 & 0 & \ldots & 0 \\ 0 & 1 & 0 & \ldots & 0 & 0 & -1 & 0 & \ldots & 0 \\ 0 & 0 & 1 & \ldots & 0 & 0 & -1 & 0 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & \ldots & -1 \\ 0 & 0 & 0 & \ldots & 1 & 0 & 0 & 0 & \ldots & -1 \end{array}\right] \tag{5}$$

It's obvious that (3) can be solved by the least square estimation method but is no exact solution.

The formula in (3) is an overdetermined equation, but its least square solution can be obtained [26]. A useful approach to improve the estimation accuracy would be adding constraints to the system (3). The additional constraints can bound estimation and make sure that it is close enough to the real value. To add these constraints, the vertical average velocity V_{DAV}, which means the averaged value of the absolute velocity of each current layer experienced by the glider, needs to be captured. In this case, we will add one row to equation (3) as:

$$\hat{\boldsymbol{d}} = \begin{bmatrix} \boldsymbol{d} \\ wV_{DAV} \end{bmatrix}$$
$$\hat{\boldsymbol{G}} = \begin{bmatrix} & & & \boldsymbol{G} & & & & \\ w\Delta t_1 & w\Delta t_2 & \ldots & w\Delta t_M & 0 & 0 & \ldots & 0 \end{bmatrix}, \tag{6}$$

where w is the weighting coefficient determined by the accuracy of the additional information, the $\Delta t_i (i = 1 \ldots M)$ is the time spent by the glider in each layer, which is determined by the height of the layer and the speed of the glider. Finally, the estimated $\hat{\boldsymbol{m}}$ could be given as:

$$\hat{\boldsymbol{m}} = \left[\hat{\boldsymbol{G}}\hat{\boldsymbol{G}}^T\right]^{-1} \hat{\boldsymbol{G}}^T \hat{\boldsymbol{d}}. \tag{7}$$

Thus, V_{DAV} would be an important information to assure the reliability of the estimated results. V_{DAV} can be computed by making vector difference between the displacement of the glider relative to the ground and relative to water. The solution of vertical average velocity is given as:

$$V_{DAV} = \frac{D_{GPS} - Ddr}{\Delta t}, \tag{8}$$

where V_{DNV} is the vertical average velocity to obtain finally, D_{GPS} is the displacement of the glider relative to the ground and D_{dr} is the displacement of the glider relative to water and Δt is the observation time.

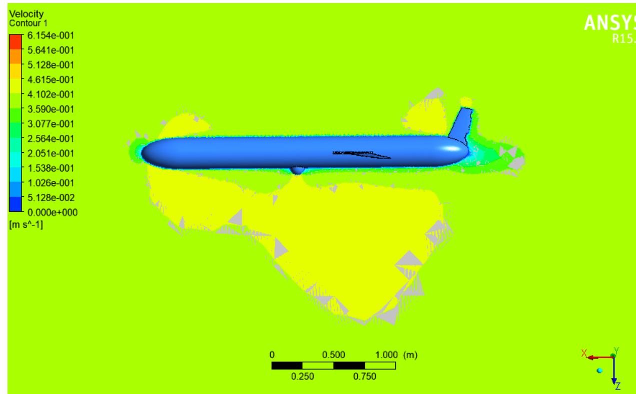


Fig. 1. Analysis of the current field around the glider which at the state of $-6°$ attack angle and $0.4m/s$ speed.

B. Distortion Problems

In (8), D_{GPS} can be obtained through the position information of the outlet and inlet points, and D_{dr} can be obtained by "AD2CP first layer velocity" method in the conventional way. However, this has the severe defects that affects the measurement accuracy.

This method is based on the assumption that the AD2CP measured first layer velocity is equal to the moving speed of the glider relative to the ground, which is not true. There's always a measurement dead area between the glider body and AD2CP echo for its first layer data, so this will introduce a velocity residual to the conventional inverse method. Another drawback of this arrangement would be the AD2CP induced turbulence. The mounted AD2CP would break the streamline shape of the glider and lead to the velocity measurement error.

A FEA simulation example is given in Fig.1. The glider in this simulation is namely "OUC-III", which is a product that manufractured by Ocean University of China. The length of the glider is 2600mm and the diameter is 250 mm. The glider with an attack angle $-6°$ and speed 0.4 m/s is simulated, which can be seen that AD2CP working is obviously affected by the turbulence flows around the glider body.

C. Proposed Solution With SPCM Compensation

1) Optimal SPCM Configuration: To solve this problem, a novel solution is proposed by using a single point type current meter to provide the first layer velocity. The SPCM has an overall streamline shape and its probe is small enough, so its induced turbulence around the glider is eliminated compared to the ADCP in the first clue. Under these principles, the overall layout scheme of the integration of AD2CP, SPCM and glider is shown in Fig.2, where the distance between the center axis of SPCM probe and the nose of glider is X, which is needed to be determined the optimal value ensuring the security of equipment and avoiding the turbulence of glider. The reference SPCM in this simulation is the Nobska MAVS-3 3 axis current meter. An optimization about X is processed to minimize the turbulence under a normal working condition.

As mentioned before, the probe of SPCM does not have the streamline which generates distortions to affect the velocity measurement, but it can be minimized by properly choosing X. In the simulation of this work, the velocity difference between

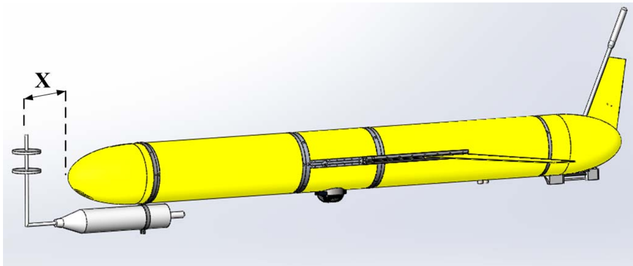


Fig. 2. The overall layout scheme of the integration of AD2CP, SPCM and glider.

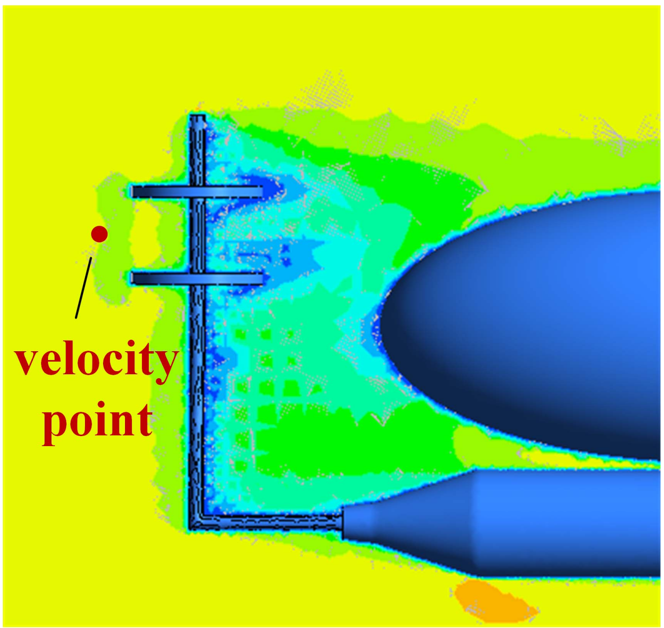


Fig. 3. The location of sampling point of current velocity.

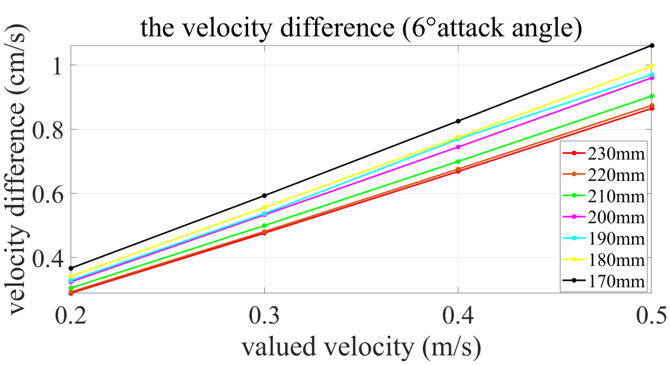


Fig. 4. The difference of current velocity in the states of different attack angles and X.

the inlet and the sampling point is used as the analysis basis of the disturbance as shown in Fig.3. The simulation is setting the point that $3cm$ away from the center of the probe as the velocity point to fit the real instrument and reduce the numerical errors.

In this study, an attack angle in 6° is assigned to the glider to better simulate the real behaviors. The results of turbulence influence are calculated by taking the difference between the given arbitrary current flow and the velocity point that accompanied with different values of X that varies from 170mm to 230 mm, which is shown in Fig.4. It is very clearly that the velocity difference is increasing with larger X, which means that the SPCM probe should be as far as possible from the head of the glider. It's also notable that an over length of X will cause the attitude instability and installation failure issues. More specifically, the fixing point of the SPCM to the glider is too close to its tail, the front part will generate a large torque to make a mechanical peel off of the SPCM. Considering that X larger than $220mm$ will rarely reduce the error, we take a compromised X that equals to $210mm$ to reach a reasonable measurement accuracy and mechanical reliability.

2) Enhanced Velocity Estimation With SPCMCIM: By using the SPCM to replace the AD2CP's first layer measurement, the results can be significantly improved. The SPCM current meter can convert its measured original data into a three-dimensional velocity in the geodetic coordinate system, which has an advantage of immune to the influence of the glider's attack angle. SPCM always contacts the observed water area before the glider, and the measured current velocity can accurately represent the moving speed of the glider relative to the current layer where it is located, and overcame the limitations of the "AD2CP first layer velocity" method.

It can be seen from equation (8) that the vertical average velocity can be obtained by the vector difference between the ground displacement D_{GPS} and the water displacement D_{dr} during one profile measurement cycle. The current velocity observed by the SPCM is the velocity of the current relative to the airframe, which also indicates the opposite of the speed of the glider against the water. Thus, the displacement of the glider relative to the water can be obtained by integrating the negative value of SPCM outputs during one profile cycle, which can be written as:

$$D_{dr} = -\int U_{SPCM} dt, \tag{9}$$

where U_{SPCM} is the velocity of the current relative to the airframe. Combining the information of GPS position of the glider's entry and exit points of a single profile cycle, and the cumulative time t of the full profile process, the vertical average velocity can be computed by (8).

The glider triggers AD2CP and SPCM at a rate of 1 Hz to synchronize the outputs, though their original sampling rate is higher. To compromise the contradiction between spacial coverage, efficiency and accuracy, the AD2CP stratospheric layer height can be set to $1m$, and the number of depth units involved in the calculation in each frame is 3.

Reconstructing the vector $\hat{\boldsymbol{d}}_1$ by the replacing the AD2CP first layer data with the SPCM outputs:

$$\hat{\boldsymbol{d}}_1 = \begin{bmatrix} SPCM(1,1) \\ AD2CP(1,2) \\ AD2CP(1,3) \\ SPCM(2,1) \\ AD2CP(2,2) \\ AD2CP(2,3) \\ \vdots \\ SPCM(n,1) \\ AD2CP(n,2) \\ AD2CP(n,3) \\ wV_{DAV} \end{bmatrix}. \tag{10}$$

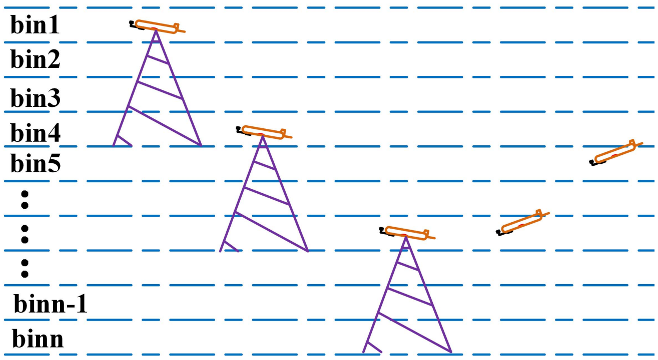


Fig. 5. Illustration of AD2CP detecting the current velocity in the rising phase.

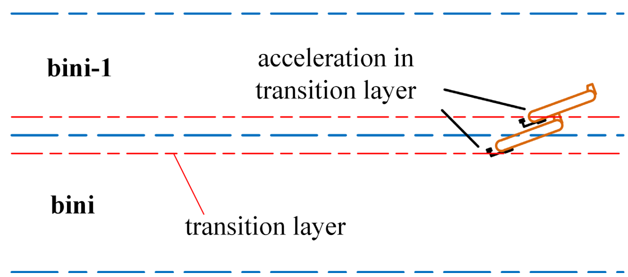


Fig. 6. Illustration of the two stable current layers and their transition layer.

and substituting back to (11) to get the enhanced least square solution:

$$\hat{\boldsymbol{m}} = \left[\hat{\boldsymbol{G}}\hat{\boldsymbol{G}}^T\right]^{-1}\hat{\boldsymbol{G}}^T\hat{\boldsymbol{d}}_1, \tag{11}$$

The most significant feature of this novel algorithm would be improving the ocean current estimation accuracy from the system level by minimizing the influence of the turbulence. In addition, if the samples are overlarge, (11) can be alternatively solved a recursive formula to avoid the memory shortage issues.

III. Absolute Velocity Estimates From Glider Equipped With MAVS

A. The Crucial Motivation

Though the proposed method can obviously enhance the results of the conventional inverse method, this method has some fundamental defects that requires highly innovative solutions.

The first challenge is the glider attitude control problem. In the inversion type method, the main data source is still the AD2CP, though the SPCM is an important contributor in our proposed solution. A AD2CP generates 3 axis sound beams and captures the echoes of the beams to reverse the currents' velocity, and this principle requires high stable attitude of the vessel. According to the manual of the AD2CP product, the optimized pitch and roll angles of the glider are 17.5 ° and 0°, respectively. This requirement can be partially accomplished by our proposed glider attitude control systems [27], [28], but the desired attitudes are not reliable in the diving phase. The rising phase is relatively more reliable and the AD2CP keep detecting, which illustrated in Fig.5. In this framework, half of the profile cycle is wasted to avoid any unreliable measurement to contaminate the whole data set.

Another important motivation would be the AD2CP environmental adaptability issue. The inherent principle of AD2CP is detecting the echoes that reflected by the scatters in the water. This measurement will fail in the pure water environment, which is particularly true in the north/south pole areas.

B. Concepts and Assumptions for SPIMIM

Based on the above considerations, the SPCM would be the only sensor option since it is free to the glider attitude and immune to the water quality. Recalling that the biggest challenge of mobile platform current observation is that the velocity of the platform itself is hard to be determined, the proposed new method shouldn't use the unaffordable high precision inertial sensors, while low cost ones cannot fulfill the duty in a 30 minutes profile detection mission.

The way to build a reliable current velocity observation system only with a single point type meter on a glider has to successfully utilize the unique physical properties of the oceans.

The fundamental assumption for the breakthrough idea would be that the currents are relatively stable during a glider profile measurement task. During the observation, the sea can be divided into several layers in the vertical direction and each current velocity is considered to be stable, and this has been already applied to AD2CP based measurement [21]. Thus, this concept can be adopted to the SPCM based measurement task, too. The velocity of the glider in each layer can be calculated by reading the outputs of the SPCM, if the initial condition is known.

More importantly, there's a small concept of transition layer between two stable current layers to fit the reality. During the transition, the glider velocity that calculated by the SPCM readouts becomes invalid since the current velocity is no longer stabilized. It's the time for the on-board low cost inertial sensor to provide the glider velocity. The transition process is on the 10 seconds level, so the low cost sensors can accomplish this mission and the errors are not accumulated between each transition layers.

C. Complete Solution of SPIMIM

Based on the above assumptions, the velocity variations of the glider within one stable layer can be obtained by taking the difference of the SPCM outputs:

$$U_{glider}(i) - U_{glider}(i+1) = U_{SPCM}(i+1) - U_{SPCM}(i). \tag{12}$$

Between 2 stable current layers would be a transition layer, where (12) becomes invalid since the current velocity is unorganized. In this circumstance, the glider speed measurement must be assisted by the on-board inertial sensors to prevent generating outliers or inducing data sample discontinuity. The transition process in about 10s level so even the lost commercial MEMS inertial measurement units (IMU) can

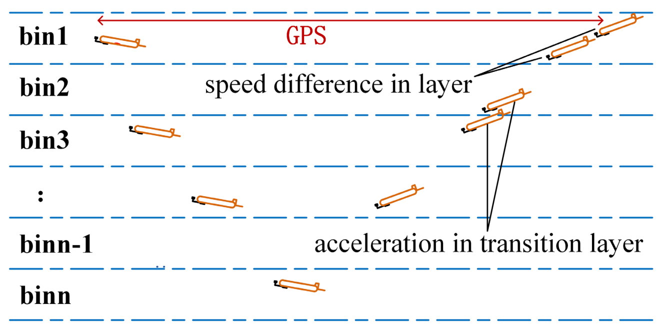


Fig. 7. The diagram of current observation of glider equipped with SPCM.

accomplish this task which can be described as:

$$U_{glider}(i+1) = U_{glider}(i) + a_i \Delta t \tag{13}$$

where $U_{glider}(i)$ and $U_{glider}(i+1)$ are the speeds of the glider at the current and next time points, a_i is the acceleration of glider obtained by the IMU, Δt is the sampling time. After the glider enters the next stable current layer, the SPCM measurement in (12) is replacing (13) again until it reaches the next transition layer. The above process is repeated until one profile task is finished and the glider reached the exit point, where the entire process is illustrated in Fig.7.

The major challenge of this proposed method would be that the initial velocity, $U(0)$, is typically unknown. Gliders typically take 3 minutes to enter the V shape trajectory with some initial velocity. Without an accurate initial condition, the iteratively computed velocity would be superposed with the initial condition induced error. The absolute velocity $U_{glider}(i)(i = 1 \ldots N)$ of the glider during the entire profile can be described by the following equation:

$$U_{glider}(i) = U_0 + V(i) \tag{14}$$

where $V(i)$ is the "reference value", which is obtained by this way that assuming the first glider speed to zero and using the velocity differences obtained from SPCM readouts to compute $V(i)(i = 2 \ldots N)$.

The key to identify the difference between "true value" $U_{glider}(i)$ and "false value" $V(i)$ depends on how to correctly estimate U_0. Given that the attitudes, particularly the yaw angle, of the glider is well controller, U_0 can be well estimated by observing the displacement of the entry and exit point that acquired by the GPS:

$$D_{GPS} = \int_{t_0}^{t_1} U_{glider}(1)dt + \int_{t_1}^{t_2} U_{glider}(2)dt + \ldots + \int_{t_{i-1}}^{t_i} U_{glider}(i)dt + \cdots + \int_{t_{N-1}}^{t_N} U_{glider}(N)dt \tag{15}$$

Therefore, the initial speed U_0 can be obtained by combining (14) and (15). Moreover, the absolute glider speed $U_{glider}(i)$ at each time point of the full profile can be obtained by combining (14). Finally, the absolute current velocity at each time point of the full profile is obtained by the following equation:

$$U_{current}(i) = U_{glider}(i) + U_{SPCM}(i). \tag{16}$$

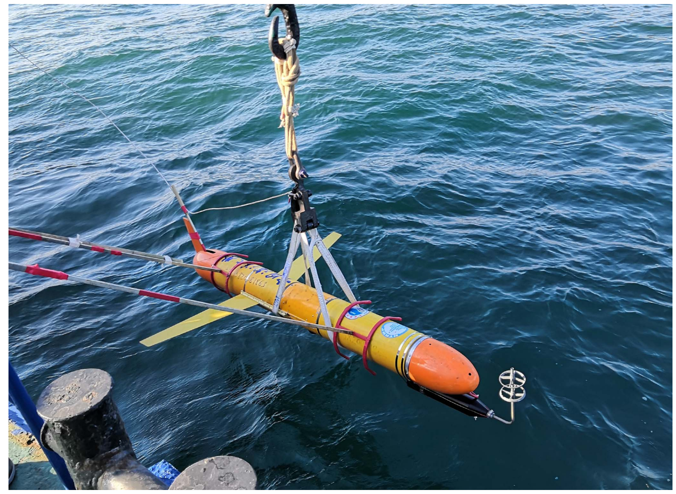


Fig. 8. The deployment of OUC-III glider equipped with AD2CP and SPCM to ocean area.

IV. Results and Discussions

A. Instrumentation and Deployments

The methods proposed by this work were verified through OUC-III glider that developed by Ocean University of China. OUC-III had an optimized mechanical structure that can improve the maneuverability for high dynamic motion. There were multiple actuation mechanisms inside the glider that can fully adjust the attitudes and the redundant actuators can significantly improve the control efficiency. The main mechanism inside the body includes a oil bladder, the battery, motor and control electronics. Thus, its attitude can be adjusted by control the bladder and position of the battery. The advanced control algorithm along with the effectively mechanical driving systems can guarantee the glider working at the desired attitude (pitch angle equals to 17.4°, yaw and roll angle equal to 0 0°). The attitudes and acceleration were provided by a XSens MTi-100 inertial measurement unit (IMU) with a data output rate of 100 Hz. The reliable mechanical design and materials enabled this glider to dive to the deep sea up to 2000 meters.

The MAVS has a sampling frequency $5Hz$ was mounted at the head the glider. The AD2CP with continuous mode with a data rate $1Hz$ was installed at load cabin that underneath the glider. The AD2CP was configured with 3 sampling layers and each layer had a depth of $3m$ for the consideration of detection accuracy and range.

In order to verify the feasibility and accuracy of two algorithms, the absolute current velocity data for comparing was required. In this experiment, we used the sentinel-type self-contained ADCP (WHS-600) developed by TRDI company to provide the arbitrary ocean currents. It was fixed on the experimental ship during the measurement process of glider equipped with AD2CP and SPCM. The arbitrary AD2CP was working at the continuous mode with a sampling rate with a $30s$ interval and the depth layer depth was set to $1m$ to maximize the resolution and accuracy.

The Yellow Sea located on the southeast side of Shandong Peninsula of China was selected as the trial area in

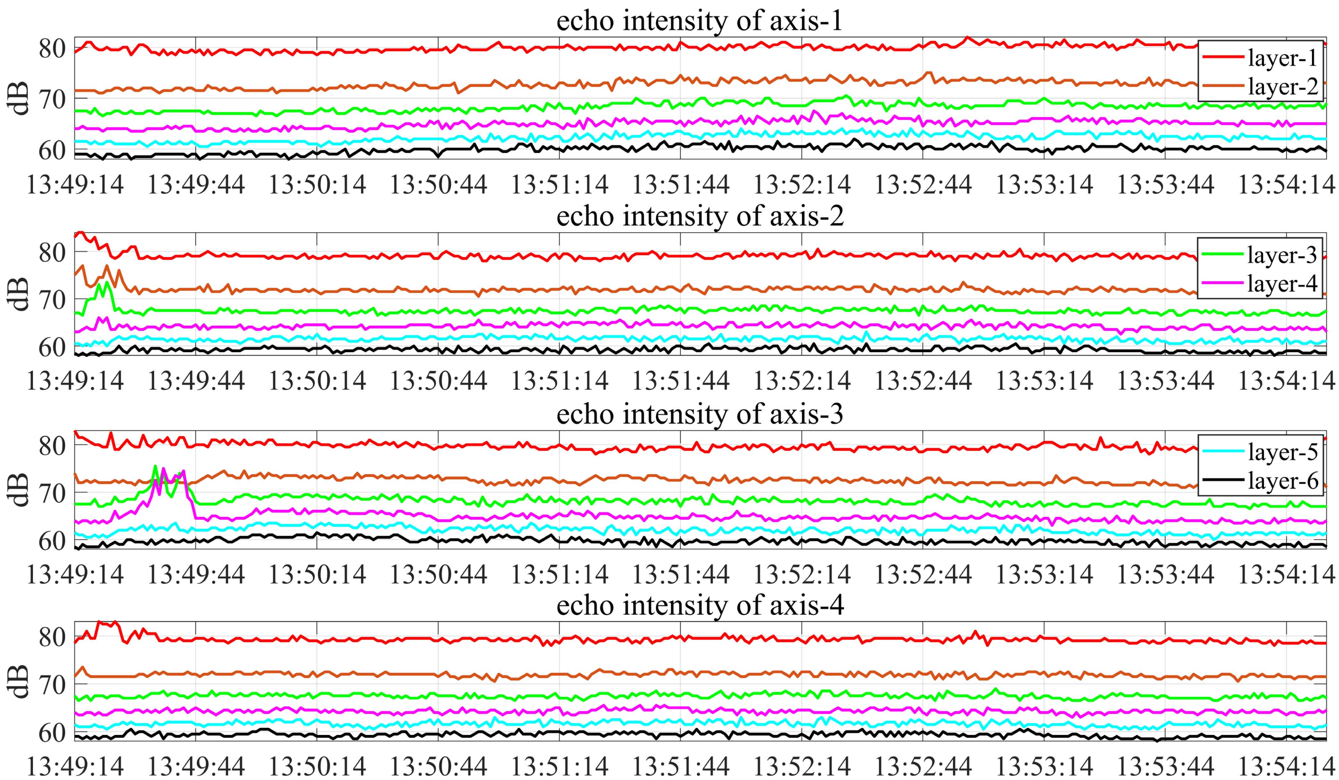


Fig. 9. The echo intensity of each sound axis of AD2CP.

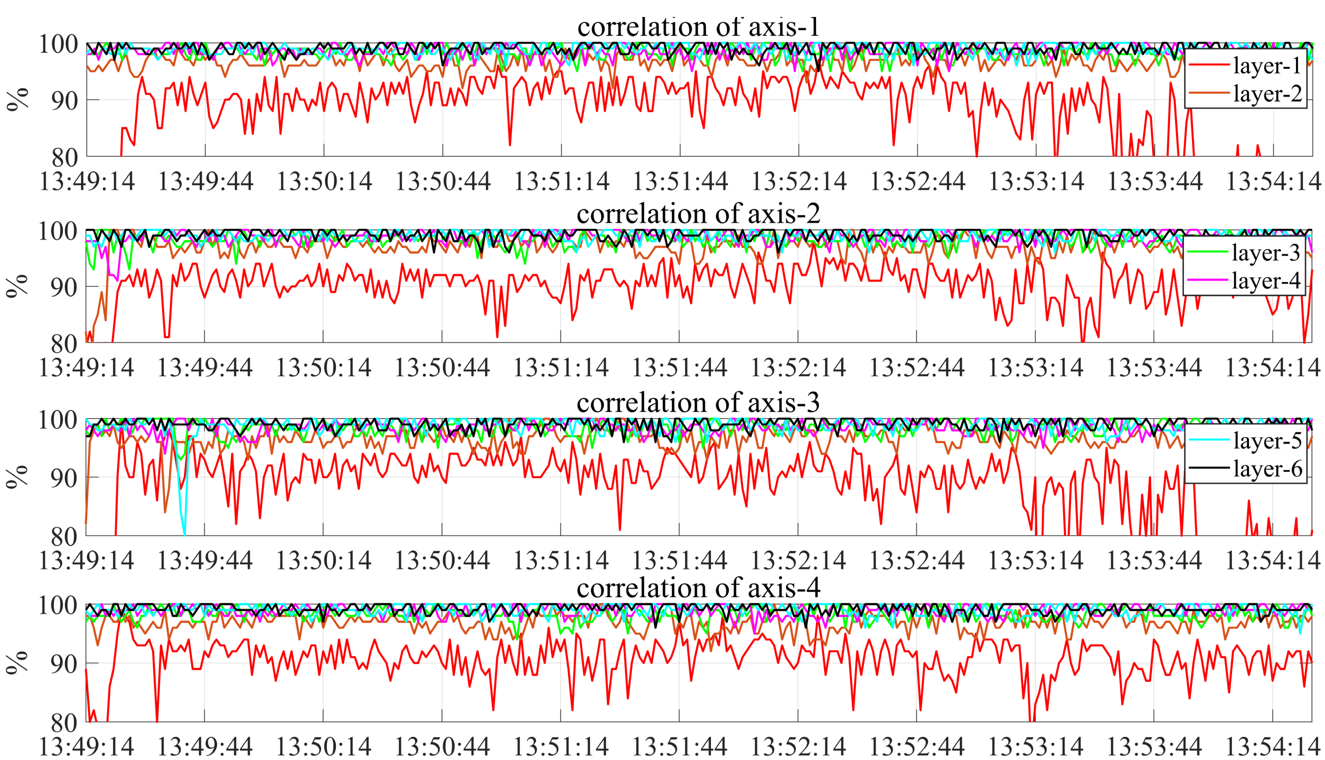


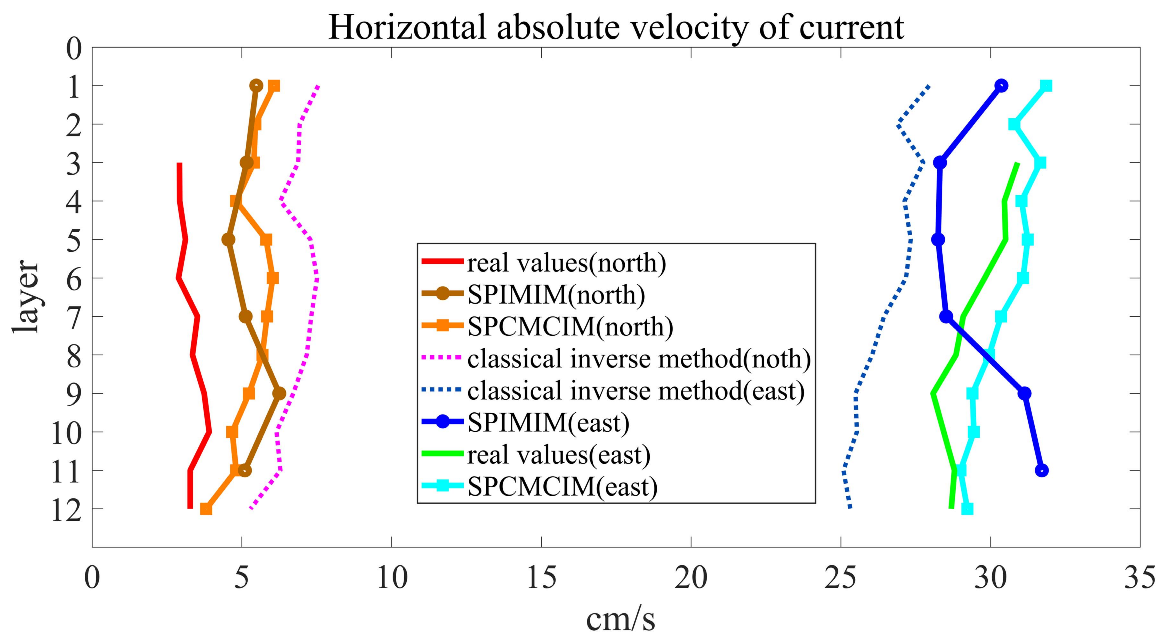
Fig. 10. The correlation of each sound axis of AD2CP.

Dec 9th, 2019. The detailed location was 36.185N 120.97E, whose average depth was 40m. To fit with this site, the glider was set to begin floating at 30m to prevent any risks.

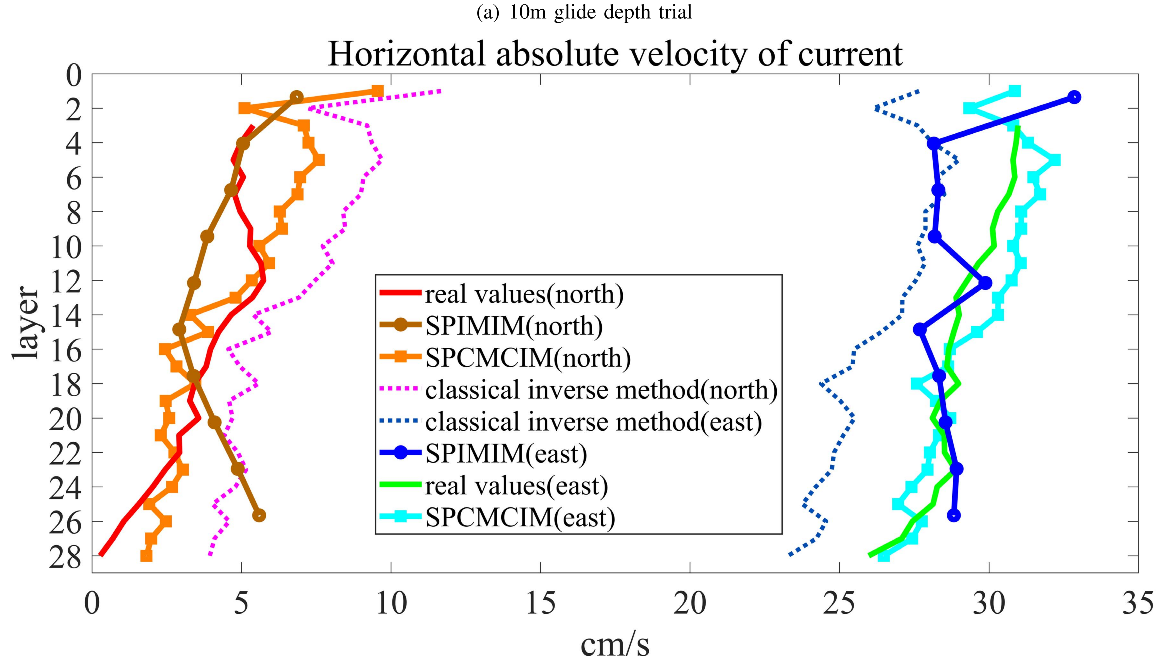
B. Preliminary Experiments

Before the turned the glider into the working mode, two preliminary experiments were performed. The first one was the echo intensity of AD2CP, which refers to the strength of the return signal of the beams. This indicates the power of the collected signal and the corresponding data is given in Fig.9.

It's clear that the echo intensity of the AD2CP first layer is at approximately 80dB, which is higher than any other layer. The strength decayed as layer increased as expected since deeper location will dissipate more energy. There was



(a) 10m glide depth trial



(b) 27m glide depth trial

Fig. 11. Comparison of absolute current velocity obtained by the two novel algorithms and arbitrary data.

an unusually signal magnification at 13:49:44 in layer 3-4 of axis-3. This unexpected reflection could be caused by an encountered by a large group of fish, but the following samples were stabilized which means this area was clear and the system was ready to begin.

The next analysis was verifying the AD2CP induced turbulence problem by examining the correlation of every 2 samples, which is shown in Fig.10. The theory is that the current under is ocean is relative stable and every 2 adjacent samples should be highly correlated. If not, the outputs of the instrument may not be reliable. In every axis, layer 2 to 6 were all highly correlated with a percentage very close to 100 %. In contrast, the layer 1 data in each axis was always far away from 100 %. This was an solid evidence to prove the existence of AD2CP induced turbulence.

By far, the echo intensity test verified that the instrument and site were ready for the formal current observation tests.

C. Absolute Current Velocity Estimation Results

After the preliminary experiments had been processed, the glider turned into the work mode with 2 profiles. The first trial and second trial had depth of 10m and 27m, respectively. During the trials, the on vessel WHS-600 ADCP kept sampling to provide the arbitrary measurement as the real value for the comparison, whose outputs were already compensated with the GPS. The glider recorded the SPCM and AD2CP data in a SD card for the offline computation.

The finalized results that generated by the proposed 2 novel solutions, classical inverse method and the WHS-600 ADCP measured ground truth are shown in Fig. 11. In each trial, the results were divided into north and east sub-values for a good demonstration. In the 1st 10m glide trial, it was clear that the classical inverse method resulted in a constant bias about 5cm /s compared to the ground truth in both north and east directions, which was caused by the AD2CP induced turbulence. In contrast, both of the proposed novel methods show the significant enhancement, since their results had 50 % reduced error in average. It was notable that the SPCMCIM show a better convergence since the AD2CP can provide more reliable information. The SPIMIM method illustrated a good improvement in average, but the total deviation was larger than SPCMCIM, particularly in the north direction.

The classical inverse method shows the same bias error trend in the 2nd 27m trial. The averaged errors in both directions were still around 5cm /s that once again validated the concerns about turbulence. The methods that we proposed once again induced the improved results. They provided at least 70% error reduction compared to the conventional one. The SPIMIM show a better convergence than the 1st trial, though it still shows big deviation at the beginning and finishing phase. The 1st method demonstrated a good repeatability such that it had a good fit in trend, small deviations and averaged error less than 1cm /s. The results in these two different trials followed the same clue. The novel methods that we proposed show clearly enhancement compared to the conventional inverse method since they cooperated with different sensors with effective information fusion solutions. The SPCM and AD2CP cooperated method is a competitive solution to replace the popular inverse method in normal sea environment because it replaced the inaccurate 1st layer data with the SPCM outputs. The SPIMIM was a surprise that its measurement accuracy is also 50 % better. Though its deviation was larger than the AD2CP/SPCM combination, it also had a great potential to play an important role in the current measurement tasks, especially if it was deployed in the polar areas.

V. Conclusion

Two novel mobile platform based current observation solutions were analyzed, designed and verified in this work. The SPCM and AD2CP fusion approach can solve the turbulence contaminated velocity data and improve the current estimation accuracy. The cooperated observation solution overcame the limitations of water purity and glider attitudes' dependency. The oceanic research works can greatly benefit from these methods since the onsite experiments validates the effectiveness and advantages that these can provide more accurate, large scale and economic ocean current observation solutions.

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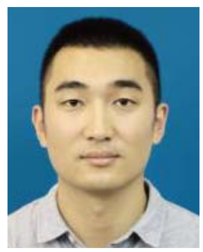

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