ADCP Data Collected from a Liquid Robotics Wave Glider®

Jerry Mullison, Darryl Symonds
Teledyne RD Instruments
San Diego, CA
jmullison@teledyne.com

Neil Trenaman
Liquid Robotics, Inc.
Sunnyvale, CA
neil.trenaman@liquidr.com

***Abstract*—Liquid Robotics, Inc. (LRI) has developed an autonomous vehicle, the Wave Glider®, which utilizes wave energy for propulsion, Iridium® Satellite for command, control and data exfiltration and GPS satellite transmissions for positioning. The vehicle consists of a low-profile surface float outfitted with solar panels, energy storage and shore communication infrastructure and a subsurface wing located at approximately seven meters depth connected to each other by a sophisticated tether. The wing is designed to respond to the wave energy at its depth in such a way that it provides propulsion for the vehicle toward any location chosen by the operator. The wave energy thus harnessed by the vehicle can be used for locomotion to any point of interest as well as for station keeping (by driving in a tight circle) once that position is reached. Real time communication with the shore-based operator allows monitoring of platform's location and data gathered, commanding movement to a new position, or even complete repurposing of the mission. The capability of the Wave Glider® to accomplish its mission in a variety of environments with a variety of mission profiles is now well proven.**

In addition, the Wave Glider® is of course capable of carrying a variety of sensor payloads. LRI and Teledyne RD Instruments (TRDI) have now partnered to provide current profile measurements from the vehicle. An initial encouraging field test in 2009 showed the feasibility sufficiently to merit further work, though there was some indication that asymmetric motion of the surface float (it tends to skate on wave faces in some sea states) combined with low resolution GPS sampling could be biasing the velocity measurements. This led to additional testing of a Wave Glider® equipped with an ADCP, higher resolution GPS and an Inertial Motion Unit in 2010. Once the extensive integration project was completed sufficiently, a new field campaign was launched for comparison of the new, more integrated Wave Glider® ADCP measurements with those of a bottom mounted Workhorse ADCP that was deployed as an independent reference. The mission profile for this field campaign included programming the Wave Glider® to circle between the shallow water in which the reference ADCP was deployed to the deeper water of a submerged canyon. In this way measurements could be taken in shallow water, where bottom tracking capability could be effectively relied upon to remove platform motion, and in deeper water where the bottom was out of range and the relative motion of the platform removed by other means. Given the change in depth, there is no reason to assume the reference ADCP measurements are valid in the deeper water. However, comparison of the reference instrument in the shallow water with the relative velocity removed by bottom track and by the other methods can prove the utility of the other methods, and continuity of measurement between the shallow, referenced and deep, unreferenced regimes would indicate that the measurement in both instances is correct. We report on the initial results of the field testing, and on the current status of the integration.

Keywords-Wave Glider®; ADCP; AUV; ASV; UMV

I. Introduction

Teledyne RD Instruments (TRDI) and Liquid Robotics, Inc. (LRI) have teamed to provide near surface current measurements from the LRI Wave Glider® vehicle. The Wave Glider® is a wave-powered unmanned maritime vehicle (UMV) that represents a novel and unique approach to persistent ocean presence. Wave Gliders harvest the abundant energy contained in ocean waves to provide essentially limitless propulsion while two solar panels continuously replenish the batteries that are used to power the vehicle's control electronics, communications systems, and payloads. Wave Glider® is a hybrid sea-surface and underwater vehicle in that it is comprised of a submerged "glider" attached via a tether to a surface float. The surface float of the Wave Glider® has a continuous view of the sky, allowing it to use GPS for precise navigation and communication with shore via Iridium or radio for data transmission as well as command and control.

The Wave Glider® is well suited for air-sea surface investigations because it is a configurable platform designed to support a wide variety of sensor payloads while either operating as a vessel covering long distances in the ocean or as a station-keeping platform for indefinite periods of time. There has been considerable interest from this community to integrate an Acoustic Doppler Current Profiler (ADCP) with the Wave Glider® to obtain current measurements in the near surface.

An ADCP was integrated into a Wave Glider® system with a notebook computer to handle the data acquisition for the ADCP and GPS. This system was deployed along with a bottom mounted reference ADCP on two consecutive days in the near shore off the coast of La Jolla, California. The first deployment cruise plan was to navigate in a closed box in the near-shore near the reference ADCP, which allowed comparison of the two commonly applied corrections for platform motion: bottom tracking and GPS. The second deployment added an XSENS accelerometer compensated compass for comparison to the ADCP compass and also changed the cruise plan to range farther out to deep water to make repeated short transects in an area less subject topography driven current changes prevalent in the first deployment site.

The first deployment showed good agreement with the reference ADCP, particularly on large scale features. Both deployments showed features of oceanographic interest.

We report in more detail on the integration, the data acquired, and the next steps planned to more tightly integrate the ADCP into the platform.

II. THE INTEGRATION AND TEST SETUPS

As this is still a proof-of-concept system, the ADCP data acquisition and processing routines were not yet embedded in the Wave Glider® processor. Instead a special payload section in the Wave Glider® was made to accommodate an off-the-shelf laptop computer running TRDI acquisition and processing software. This limited the possible test deployment time length to the battery life of the computer, which was approximately eight hours. The laptop collected all ADCP, GPS, and XSENS data asynchronously and logged all to its internal hard drive. Fig. 1 shows the data flow, Fig. 2 shows the laptop, GPS and XSENS units as installed in the payload section. The ADCP was mounted through the hull of the float, and a fairing constructed to streamline the flow around it as shown in Fig. 3. The float is shown underway with ADCP installed in Fig. 4.The test plan for the integrated system involved two deployments that took place on consecutive days in July of 2010 off of the coast of La Jolla, California. A reference ADCP was deployed on the bottom for each test. Though it is well known that the topography of this area makes it poorly suited for current measurement comparisons, it had the undeniable advantage of easy access for TRDI and LRI personnel to accomplish the testing.

The primary goal for the first deployment was to establish if the GPS referenced velocity of the surface float could be used effectively to remove the motion of the platform from the relative velocities measured by the ADCP. For this deployment the Wave Glider® was programmed to accomplish multiple circuits around a box drawn just offshore of the reference ADCP. This kept the Wave Glider® in water shallow enough for the ADCP to maintain a signal lock on the ocean bottom and calculate the Doppler shift of the signal off the

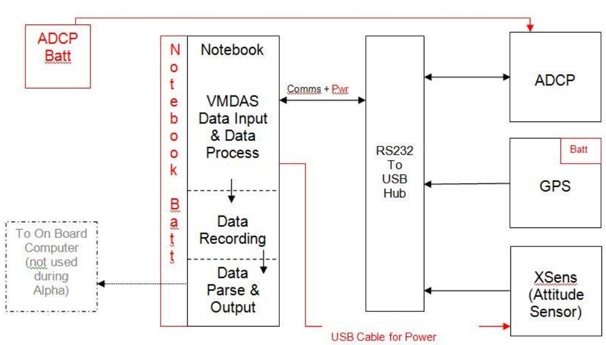

Figure 1: Data flow for system under test

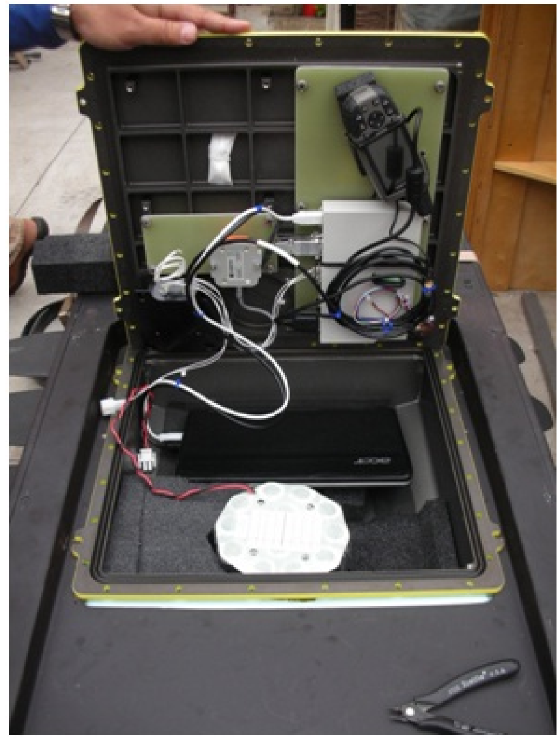

Figure 2: Computer payload section

Figure 3: Fairing for ADCP

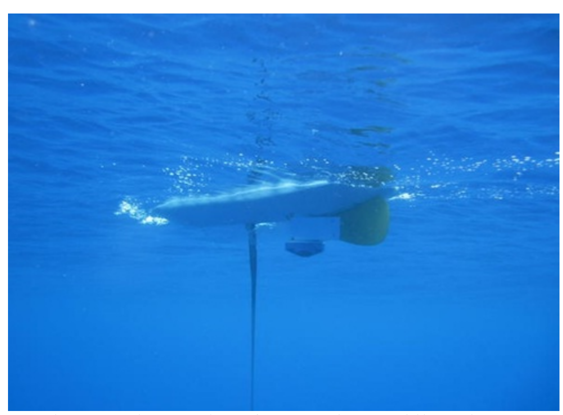

Figure 4: Float portion of system shown while underway

bottom for comparison to the motion of the platform calculated from successive GPS fixes.

In the second deployment the Wave Glider® XSENS sensor was implemented and logged. It is known that the Wave Glider® float can experience strong accelerations in some environments which could possibly lead to incorrect heading measurements from the ADCP compass. For this deployment the Wave Glider® was programmed to traverse to water deep enough the bottom was well out of range of the ADCP and then to make a series of back and forth transects to conclude the deployment. Unfortunately, during much of the deployment the data logged from the XSENS was intermittent, and too sparse to be of much use for the intended purpose. Fortunately, the weather conditions for the day were benign and the compass readings were sufficient for further analysis.

III. Analysis

A. Deployment One

The Wave Glider® track and location of the reference ADCP for the first deployment is shown in Fig. 5. ADCPs measure relative velocity profiles. That is, it is not possible for an ADCP to differentiate a five knot current flowing past it while stationary from itself making measurements while travelling at five knots (in the opposite direction) through still water. The ADCP can compensate for the relative motion of the float relatively easily with Bottom Tracking, as long as the ocean bottom remains within the effective range of the ADCP. To Bottom Track, the ADCP isolates the strong signal reflecting from the ocean bottom and calculates its Doppler shift. Under the assumption that the bottom is not moving, it is straightforward to use the bottom track velocity to remove the ADCP motion from the velocity profiles. Bottom tracking has the added advantage that the same compass heading from the ADCP is applied to both the bottom track and the current profile measurements, so any error in the compass is automatically subtracted from the final current measurement.

However, the portion of the ocean shallow enough to be within range of the ADCP signal is relatively small, so much of the world ocean requires an alternate method to remove the ADCP motion to obtain the true current profile. Typically in these cases GPS fixes are used to obtain the velocity of the platform. The disadvantage of this technique is that any compass errors are no longer automatically compensated, and any offset between the compass measurement and the true orientation of the vehicle must be compensated to obtain accurate measurements.

Figure 5: Position fixes from Wave Glider° during Deployment One.

A primary purpose of this deployment was to compare the two methods of removing platform motion from the ADCP measurements. The answer to this question is critically impacted by how well the ADCP heading sensor measurements compare to the absolute reference frame of the headings calculated from concurrent GPS fixes. There are two types of possible errors of concern: rotation errors that affect all headings equally and directionally dependent errors that do not. An example of a rotation error is the local magnetic declination (because GPS fixes are by definition relative to True North). An example of directionally dependent error would be the presence of ferrous material in the platform or mounting arrangement.

The rotation error is the simplest to correct as tables of magnetic declination by location are readily available. The current magnetic declination at the deployment site is 13° East. Directionally dependent errors are ideally removed prior to deployment using standard single and double cycle calibration routines for the ADCP as mounted into the platform. However, this was not possible for this deployment. In principle a post-processing correction can be determined with an appropriate cruise track and knowledge of the true direction of travel relative to the direction of travel calculated using the compass [1].

The presence of both types of errors can be detected by comparing the distance between GPS fixes and comparing to the distance calculated by dead reckoning using the bottom track fixes [2]. Fig 6. shows that the ADCP in the Wave Glider® has both rotation error as shown by the "tilt" of the boxes relative to the GPS calculated distances and heading dependent errors as shown by the "tilting" of the dead-reckoning boxes relative to the GPS fixes, and directionally dependent errors as shown by the successive offsets of the dead-reckoning boxes relative to the GPS fixes. Applying the known declination of 13° East appears to remove the rotation bias (though of course not the offset) as shown in Fig 6.

Data corrected for this magnetic declination is shown in this paper, while an attempt to correct the directionally dependent errors is deferred for further work.

To compare the velocities calculated from GPS fixes to

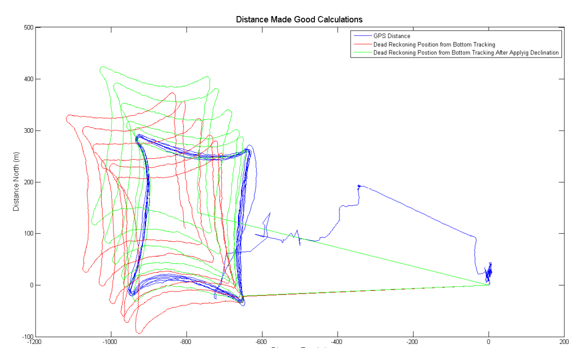

Figure 7: Blue lines represent the distance travelled using GPS fixes, red lines are the dead reckoning distance from bottom track measurements with no correction applied; green lines are the dead reckoning distance travelled from bottom track measurements after applying the magnetic declination.

those calculated by the ADCPs bottom tracking required interpolation of the GPS data to the times of the ADCP data. A simple linear interpolation was used to accomplish this. Linear fits of the GPS calculated velocities to the raw bottom track velocities resulted in:

$$East_{GPS} = 0.9931*East_{BT} - 0.0113 \text{ cm/s;}$$

$$North_{GPS} = 0.9514*North_{BT} + 0.0097 \text{ cm/s}$$

Applying the 13° East magnetic declination results in least squares fits of:

$$East_{GPS} = 1.0202*EastBT - 0.0087 \text{ cm/s;}$$

$$North_{GPS} = 0.9787*North_{BT} + 0.0118 \text{ cm/s}$$

This rotation improves the correlation to the east at the expense of that to the north, but results in a better overall alignment of the two measurements.

Contours of the Northern and Eastern velocities are shown in Fig. 7 and Fig. 8. Three contour plots are shown in each: two minute ensemble averages of the reference ADCP velocity at the top; ten minute ensemble averages of the Bottom Track corrected Wave Glider® ADCP in the center; and ten minute averages of the Wave Glider® ADCP rotated by 13° East before correcting with calculated GPS velocities. There are several points to note:

1. The ADCP measurements from the Wave Glider® are much noisier than the reference ADCP measurements, even with the additional averaging. One possible explanation for this is that any tilting motion of the float in response to waves results in a disproportionate velocity offset with depth (correcting for surface motion with the GPS will apply too small a correction to the deeper measurements, and correcting for surface motion with the bottom track velocities will result in a too large correction to the near surface velocities).

2. The glider is evident in the Wave Glider® ADCP measurements at about six meters depth (note that the glider will bias the velocities toward zero since its

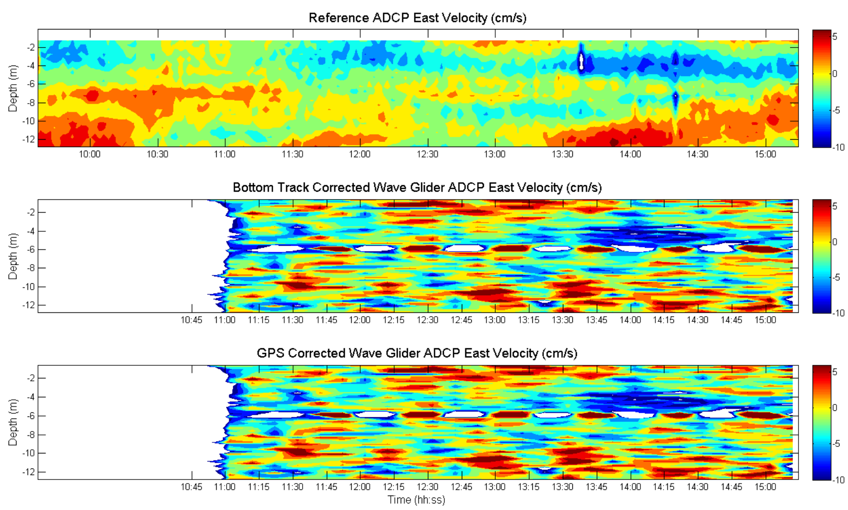

Figure 7: Contours of East velocity. The top contour is from the reference ADCP, the middle from the Bottom Track corrected Wave Glider® ADCP and the bottom from the GPS corrected Wave Glider® ADCP.

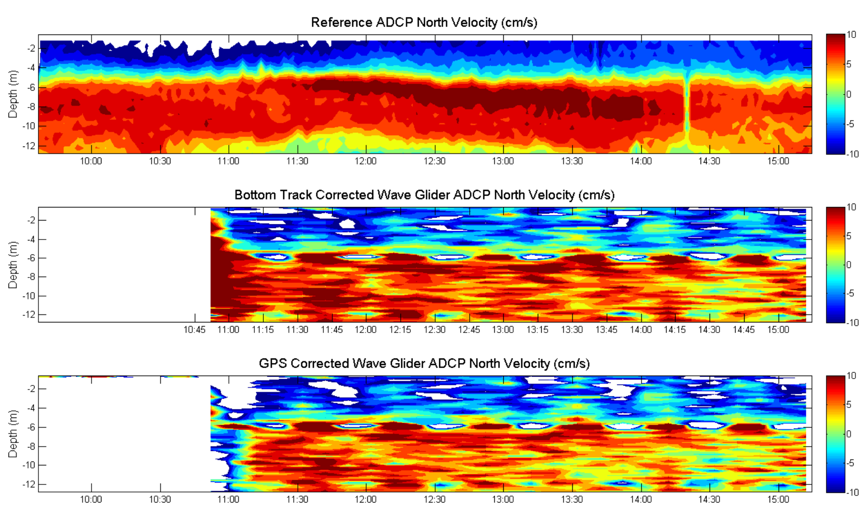

Figure 8: Contours of North velocity. The top contour is from the reference ADCP, the middle from the Bottom Track corrected Wave Glider® ADCP and the bottom from the GPS corrected Wave Glider® ADCP.

velocity will match well with the ADCP in the float, but when the bottom tracking or GPS corrections are applied it becomes a maxima in the velocity profiles).

3. The current velocities are quite small, lessening any expectation that current measurements not collocated in space as well as time will be the same.
4. There is very good agreement between the two different methods for correcting the Wave Glider® ADCP velocity profiles. Small scale and large scale features are both comparable, though the GPS velocities appear to have slightly larger magnitudes, particularly on the North axis.
5. There is also good agreement between the Wave Glider® and reference ADCP, at least on the large scale features.
6. There is a current reversal in the northern velocity whose depth coincides roughly with the glider depth. If not for the reference ADCP also showing this reversal, this data would likely have been discarded. Flood tide in this area is generally to the north, and the southward flow in the near surface is consistent with a moderate onshore wind that is typical of the area - with that day being no exception.

Because the course track was a series of closed boxes, a time series of east and north velocity profiles from the Wave Glider® ADCP averaged over each closed box are compared with the averaged velocity from the reference ADCP over the identical time frame. The “corners” of the box were determined by eye and are presented in Fig. 9. Should this technique prove useful, the corners can easily be taken on the fly from the Wave Glider® navigation system as each change in way point destination is logged. There were six closed box circuits during this deployment, and Fig. 10 and Fig. 11 show the averaged current profile comparisons. Each shows reasonable agreement in the near surface (between the float and the glider) given the low velocities involved, but less so below the glider – particularly in the north direction. One possible explanation is

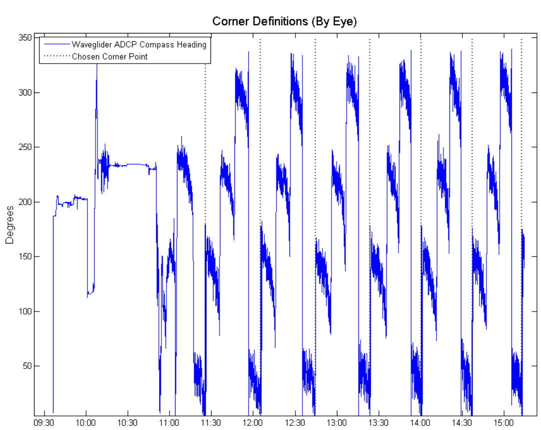

Figure 9: The blue line is the Wave Glider® ADCP compass heading, the vertical black lines are the defined (by eye) beginning points of successive circuits.

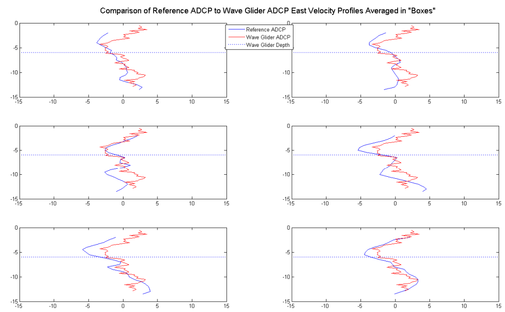

Figure 10: Comparison of the average East velocity profile between the Wave Glider® ADCP (red) and the reference ADCP (blue) over the six closed boxes traversed by the Wave Glider® .

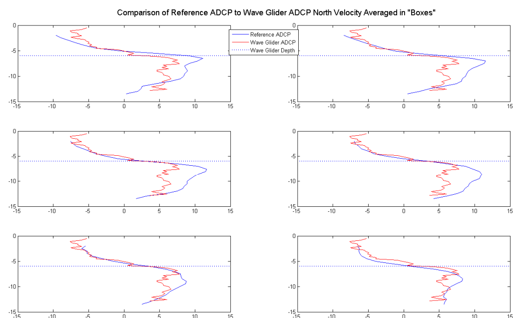

Figure 11: Comparison of the average North velocity profile between the Wave Glider® ADCP (red) and the reference ADCP (blue) over the six closed boxes traversed by the Wave Glider® .

that the glider is influencing the measurements, though this is not evident in Fig. 7 and Fig. 8. Another possibility is that the deeper currents are smaller for the Wave Glider® ADCP because it was averaged over the circuit where a substantial portion of the circuit is over water much deeper than where the reference ADCP is located. If the shoaling of the shelf increases the tidal velocities then the lower velocities offshore would decrease the average.

B. Deployment Two

The Wave Glider® track for the second deployment is shown in Fig. 12. In this deployment the Wave Glider® was commanded to go to deeper water and do a series of short back and forth transects. The Wave Glider® only passed by the reference ADCP briefly, so it is not shown here. In addition, most of this deployment took place well outside of the ADCP bottom tracking range, so GPS corrections are the only input

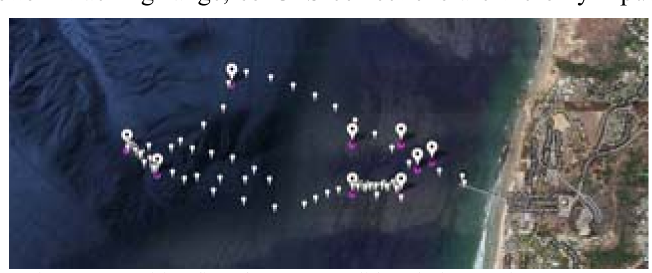

Figure 12: Position fixes from Wave Glider° during Deployment Two.

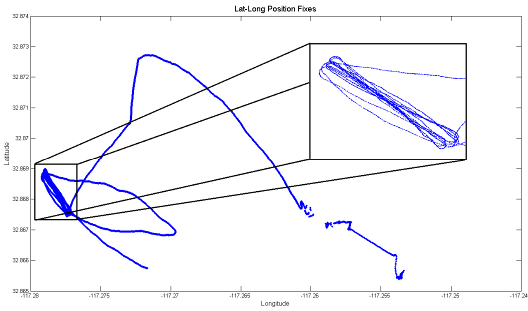

Figure 13: GPS position fixes from the Wave Glider° with the area of repeated transects expanded.

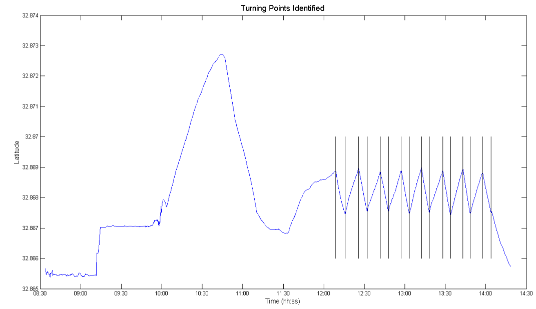

Figure 14: Time series of GPS latitude from the Wave Glider° (blue) with the defined (by eye) end points of the repeated transects (black).

available during the entire deployment. Because the Wave Glider® was commanded to do repeat transects - as shown from the GPS fixes in Fig. 13 - it was worthwhile to investigate the behavior at the turning points. These points were again chosen by eye as shown in Fig. 14. The GPS corrected East and North velocity current profiles are contoured in Fig. 15. In addition, the end points of the repeat transect are marked with vertical lines. A few points are worth noting:

1. Several features of interest span across the float direction reversals, adding confidence that the current measurements are not biased by the direction of travel of the Wave Glider®.
2. The glider itself remains clearly visible at about six meters below the float.
3. The velocity measurements are much less noisy than those of deployment one. This is probably because these transects were made over deep water, where topographic effects no longer dominate the spatial and temporal variability seen in deployment one.
4. There is a subsurface south bound current maximum on the velocity profiles that is deepening over time as the transect repeats.

It was actually intended that the heading determined from the acceleration-compensated heading sensor be investigated with this deployment as well. However, the data from this sensor was too sporadic, particularly during the repeat transects to be very helpful. However, the sea state was calm enough that its use turned out not to be necessary during this deployment.

IV. CONCLUSIONS

These results are very encouraging, and certainly indicate that this integration has considerable potential to measure currents in an economical way – particularly in the top few meters of special interest to the air-sea interaction community. Effective removal of the Wave Glider® velocity from the measured contours is possible with both bottom tracking (when in range) and with GPS measurements. Large scale features agree well between a reference ADCP and the Wave Glider® ADCP during deployment one. Large scale features of oceanographic interest - such as a current reversal and a

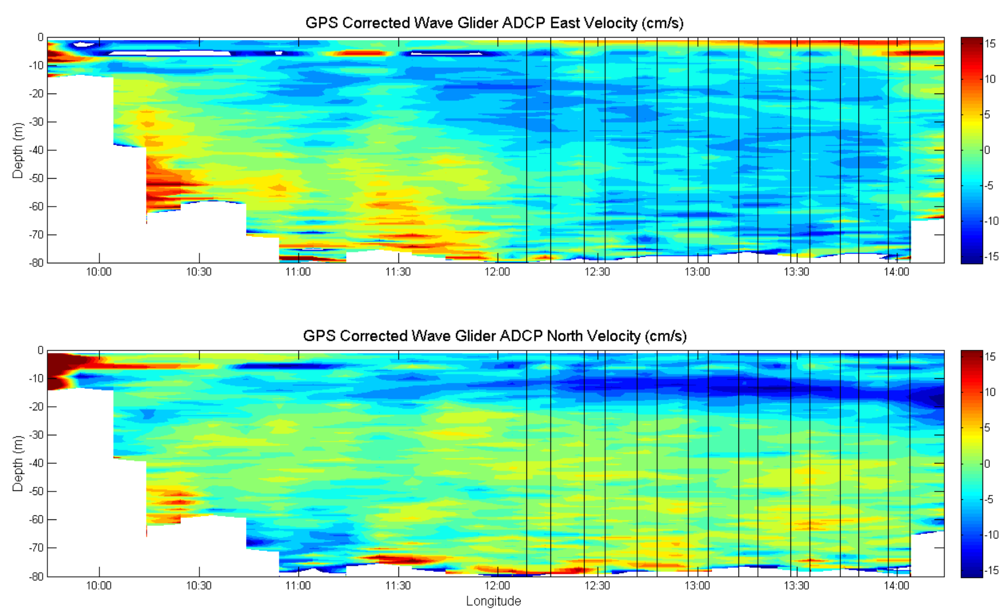

Figure 15: Contours of the GPS corrected East (top) and North (bottom) velocities from the Wave Glider° ADCP during Deployment Two. The vertical lines are those chosen in Fig 14.

subsurface current that deepens over time - can also be captured by the Wave Glider® ADCP by virtue of its persistence and capability to making repeat transects at a location of interest.

V. Future Work

LRI is currently embedding the data acquisition and processing software into the Wave Glider® on board computer system. During daylight hours, the Wave Glider solar panels continuously charge the 665 Watt hour Lithium ion battery pack. The ADCP will use the LRI batteries coupled to a capacitor driven power supply allowing longer deployments as well as removing the need for the standard ADCP battery pack. This will allow the Wave Glider® solar panels to provide power for much longer deployments than were limited by the laptop computer battery in our tests.

A process to ensure compass calibration when installed in the vehicle must be done to allow removal of the biases in the heading. The use of an external heading sensor still needs to be evaluated, but a much tighter integration between the timing of the ADCP and heading sensor measurements will be required.

Acknowledgments

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