

# Evaluations of a 600 kHz RDI Phased Array System ADCP and a wave module operating on a G2 Slocum Glider

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**Abstract**— The University of Maine Ocean Observing System (UMOOS), a member of the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS), has been operated by the University of Maine's Physical Oceanography Group (PhOG) since 2001. UMOOS currently maintains five real-time data buoys in the coastal Gulf of Maine (GoM) and two in the offshore GoM. Since September 2013, PhOG has been intermittently deploying Teledyne Webb Slocum G2 gliders to study spatial variability near, and between, several UMOOS data buoys in two principal branches of the Gulf of Maine Coastal Current, the Eastern Maine Coastal Current (EMCC) that extends along the eastern coast of Maine to Penobscot Bay, and the Western Maine Coastal Current (WMCC) that extends westward from Penobscot Bay toward outer Cape Cod. The gliders are equipped with a standard sensor suite that measures salinity, temperature, pressure, chlorophyll 470/695 nm), turbidity, and a dissolved oxygen optode. This manuscript evaluates two of the most recent sensor packages added to the potential payload of gliders: a Teledyne RDI 600 kHz phased-array ADCP and a wave module developed by PhOG in collaboration with Ocean Science and Technology (OST).

**Keywords**—*Glider, ADCP, Waves, Wave Module, OST, Coastal Processes, Currents, Ocean Observing System*

## I. INTRODUCTION

The University of Maine's Ocean Observing System (UMOOS) was designed and fabricated in 2000, and deployed in the summer of 2001. The system consists of a real-time data buoy array that collected oceanographic and meteorological measurements in a 24/7 operation at as many as 11 locations in the Gulf of Maine (GoM). The Gulf of Maine sensor array has had a data return of approximately 90% over more than a decade of operation and provided more temporal oceanographic data than available from the previous century. The observing system has revealed marked seasonal and inter-annual variability of the circulation and physical properties that suggest occurrences of regime shifts in the GoM over the last decade [1], [2], [3].

Despite reduced UMOOS funding starting in 2007, the removal of most optic sensors, and a reduction in the number of operating buoys, the majority of the array has remained in service. The buoy array includes surface current meters, Doppler current profilers for subsurface currents, and temperature, salinity, and dissolved oxygen at multiple depths. In addition, wave and meteorological sensors are deployed on the buoys including air temperature, wind speed and direction, atmospheric pressure, and atmospheric visibility.

While the buoy array can monitor circulation and physical properties at high temporal resolution at seven locations within the GoM, spatial variability is only weakly observed. Significant fronts form and fluctuate in the spring-fall seasons between several of the real-time data buoy locations. General circulation transport events occur over scales significantly smaller than distance between buoys. However the shipboard surveys that could resolve these events are neither logistically nor economically feasible via the Integrated Ocean Observing System (IOOS®) that funds NERACOOS, and thus UMOOS.

Gliders can operate as the fast response survey fleet of IOOS®, responding to oceanographic events, and can also provide more affordable sustained marine surveys necessary to observe spatial variability between data buoys, the workhorses of ocean observing. Gliders can supply the 3-dimensional spatial structure to complement the vertical/temporal structure obtained from buoy observations. There is increasing recognition of the role of subsurface events, such as mixing and nutrient injections from inflows, in driving episodic productivity and bloom collapse in the GoM that represent rapid carbon drawdown events [4].

To provide UMOOS with routine spatial gradients of circulation and transport episodes, our gliders require Doppler current profiling capabilities that we are evaluating in this manuscript. In addition we are also performing the first stage testing and evaluation of a wave module recently designed by the University of Maine Physical Oceanography Group (PhOG) and Ocean Science and Technology, LLC (OST) to

provide wave measurements by glider surveys. The wave field is particularly important during storms.

In the early fall of 2013 the “Penobscot” glider was deployed in the Eastern Maine Coastal Current (EMCC) near UMOOS Buoy I and flew southwest (along the EMCC flow) and then west in the Western Maine Coastal Current (WMCC) toward UMOOS Buoy E (Fig 1). The glider then continued in a rectangular survey pattern back to Buoy I, and finished with a second survey southwest from Buoy I to E. The transect pathways are shown in Fig 1 by black hatched arrows.

The glider survey successfully showed noteworthy spatial variability and gradients in the measurements of the standard sensor suite between Buoy I and E (not shown) in the convergence water properties of the EMCC and WMCC. This manuscript will focus on the assessments of the operation of the novel ADCP and wave module integration in the G2 Slocum glider.

## II. GLIDER ADCP EVALUATIONS

Teledyne Webb Research now supplies the 600 kHz Teledyne RDI Explorer Doppler Velocity Log (DVL) as an optional sensor for the Slocum G2 glider. The Explorer DVL can be upgraded to provide a profiling capability and can serve as a phased-array acoustic Doppler current profiler (ADCP). For this preliminary evaluation, a Slocum G2 glider equipped with the Explorer DVL/ADCP was flown within 5 km of an ADCP-equipped UMOOS data buoy on the Eastern Maine shelf for a 72 hour period (Fig 2, Fig 4).

Current profile measurements from UMOOS Buoy I have been collected continuously at this location since 2001, over a depth range of 10 to 90 m with a 4 m bin spacing. There are several key differences between the ADCP sampling parameters on the mooring and those on the glider.

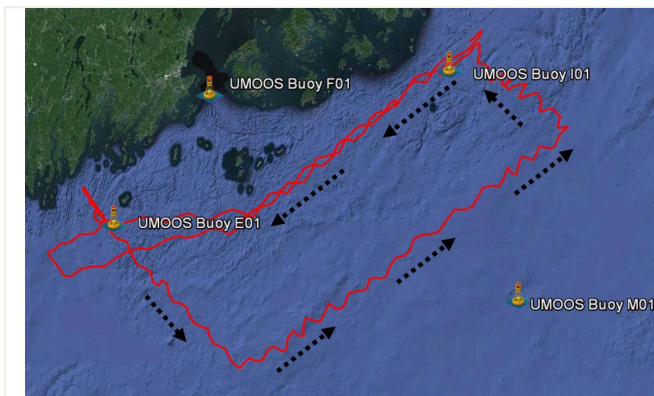


Fig 1. UMaine glider ‘Penobscot’ survey track - Sept 9<sup>th</sup> to Oct 16<sup>th</sup>, 2013. Deployed at the northeast corner of the plot in the vicinity of UMOOS Buoy I, Penobscot flew southwest in the Maine coastal current system. It then flew offshore, northeast and back onshore to buoy I. Three days of surveys were performed around Buoy I. Penobscot then performed a second pass of the coastal current between Buoy I and E and was picked up on Oct 16<sup>th</sup> in Muscongus Bay.

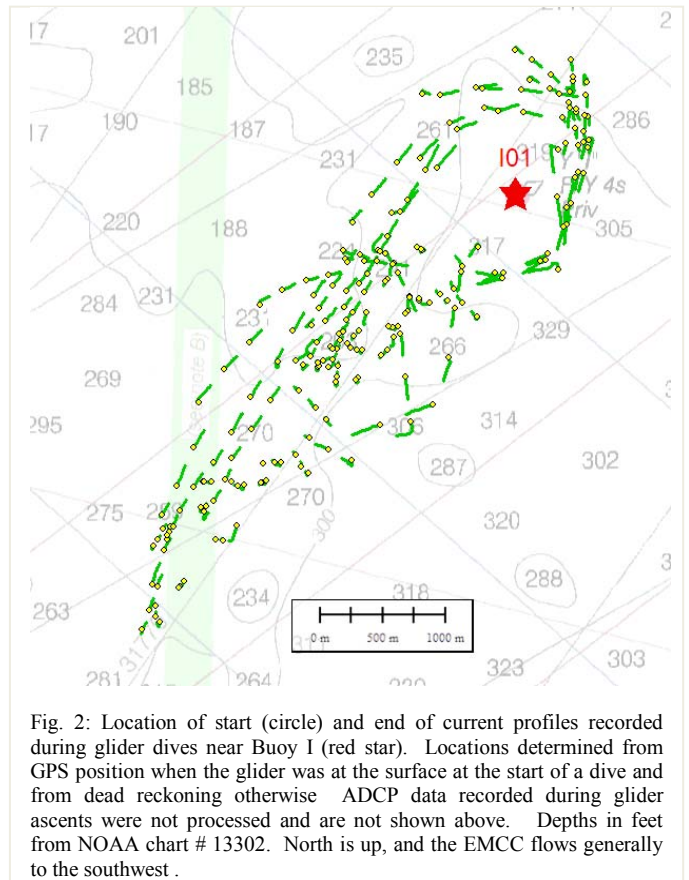


Fig. 2: Location of start (circle) and end of current profiles recorded during glider dives near Buoy I (red star). Locations determined from GPS position when the glider was at the surface at the start of a dive and from dead reckoning otherwise. ADCP data recorded during glider ascents were not processed and are not shown above. Depths in feet from NOAA chart # 13302. North is up, and the EMCC flows generally to the southwest.

**Instruments and Sampling Parameters:** To conserve power, storage space and communication bandwidth, the 300 kHz Teledyne RDI Workhorse ADCP used on the UMOOS coastal GOM mooring records the ensemble average of 170 pings during an 8 minute window centered at the top of each hour. Data from the built-in orientation sensor is used for coordinate transformations on board the Workhorse ADCP on the mooring, converting ensemble-averaged data to earth coordinates. The 600 kHz Explorer ADCP on the glider receives orientation information from the glider navigation computer rather than onboard sensors. During this test, it was configured to record single pings with a 1 m bin spacing as fast as possible (with a typical ping interval of about 2 seconds) continuously while profiling in the water column. This allows later processing and bin averaging to deal more effectively with uncertainties in orientation, speed, and vertical position in the water column of the moving vehicle.

The Explorer DVL on the glider uses a single beam-forming phased-array transducer rather than the individual piston transducers more commonly seen on fixed moorings in ocean observing systems such as UMOOS. The phased-array transducer is smaller, weighs less, and can be incorporated into the glider with less drag than an array of piston transducers. Phased-array transducers sometimes have a lower signal-to-noise ratio than comparable piston transducers.

Finally the Workhorse ADCP on the mooring is mounted in a cage facing downward in a near vertical position, with the 4 acoustic beams symmetrically arranged about the vertical axis, with only minor departures from this orientation. The

downward-looking transducer face of the Explorer DVL is tilted at  $11^\circ$  to the long axis of the vehicle, so that the transducer face is angled to be slightly forward looking. This configuration reduces drag, but complicates standard ADCP processing because during a typical dive ( $26^\circ$  pitch) the four beams are centered around an axis that is nearly  $15^\circ$  off vertical. During a typical dive only the forward facing and two side looking beams are roughly symmetrical with the vertical axis, while the aft-facing beam is nearly  $45^\circ$  to the vertical.

*Absolute velocity reference:* An ADCP measures motion of reflectors in the water column relative to the instrument. In the case of an ADCP on a moored buoy this is sufficient to estimate current speed and direction. In the case of a moving instrument, however, an absolute velocity reference is needed to convert the relative velocities measured by the instrument to meaningful earth-referenced current velocities.

GPS positions at the start and end of a dive and ascent cycle can constrain absolute depth-averaged velocity and provide a reference for velocity inversion [5], [6].

However, for the Slocum glider, surfacing and acquiring a GPS position fix involves inflation of an air bladder, consumes power and requires time on the surface. In a shelf environment with shallow water depths, and particularly with strong surface currents, Slocum gliders fly much more efficiently when the glider can make multiple dives between surfacings.

*Bottom Tracking:* During this evaluation, we used the bottom tracking capability of the Explorer DVL as an absolute velocity reference. The bottom track capability of the Explorer DVL provides a measurement of the vehicle motion relative to the water bottom. This earth-referenced absolute velocity can be subtracted from the relative velocities in the ADCP profile to obtain a direct velocity measurement for each depth bin associated with a bottom track ping. Although the ADCP profiling range of the Explorer ADCP during this evaluation was only 10-15 m, we saw bottom tracking ranges of approximately 60-70 m, limiting direct velocity measurements to depths 60-70 m from the water bottom. Since water depths in the near buoy area ranged from about 70-100 m, direct velocity measurements from the upper portion of the water column were unavailable in deeper areas.

*Velocity Inversion:* To estimate velocities in the upper portion of the water column beyond the range of bottom tracking, a velocity inversion routine was developed. The method used was based on the inversion routine described by Visbeck [5], for inversion of lowered CTD-mounted ADCP (LADCP) data. Key differences between LADCP and glider-mounted ADCP data make direct application of LADCP software and methods difficult [7]. Velocity inversion involves simultaneous solution of a set of linear equations incorporating vertical shear derived from water profile data, bottom track data, and independent estimates of vehicle speed through water. The observed variables used to generate the linear equation can be weighted to reflect relative uncertainty or relative importance. For this evaluation, depth-averaged velocity bins, were used as velocity input to the inversion routine.

*Preliminary results:* Along-shelf current speed profiles determined from the glider-mounted ADCP for each of the dives during this period are shown in Figure 3a. For comparison, along-shelf current speed profiles measured at UMOOS Buoy I during the same time period are shown below in Figure 3b. The hourly data from the mooring is linearly interpolated in time to correspond to the time period of each dive. The blank areas in the upper part of Figure 3a correspond to that part of the profile beyond the range of bottom tracking. Figure 3c shows the along-shelf current speed determined by preliminary velocity inversion to estimate velocities in the upper part of the water column.

The comparisons of current profiles from the glider-mounted ADCP and the current profiles from the UMOOS buoy was encouraging. The glider-mounted ADCP clearly imaged the structure of tidal flow in the area.

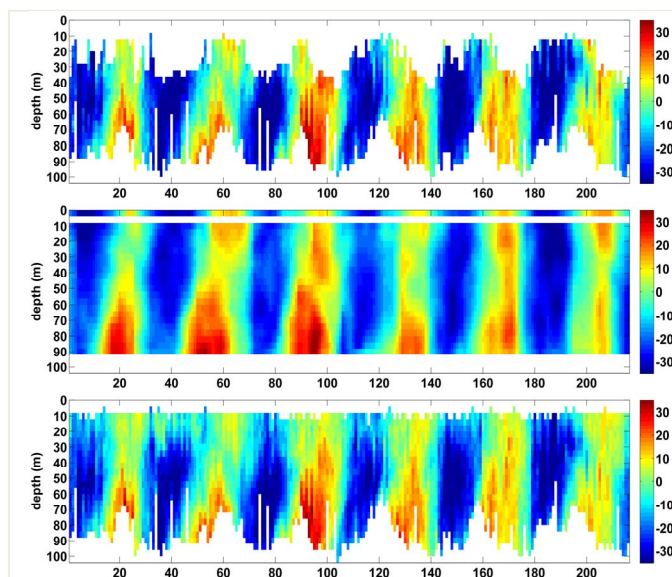


Fig 3. Comparison of glider mounted ADCP profiles with ADCP data collected at UMOOS Buoy I. Along-shelf currents are shown (positive to the northeast). The horizontal axis lists glider dive number – dives are roughly equally spaced in time.

a)(top) direct velocity measurement computed by removing bottom track velocity from depth-averaged bins. The blank area in the upper part of the water column is out of range of the Explorer bottom tracking.

b) (middle) hourly ADCP data from UMOOS Buoy I. Data is interpolated in time to correspond to each of the glider dives

c) (bottom) result of preliminary velocity inversion to provide estimate of currents in upper part of water column



Fig 4. UMaine glider 'Penobscot' deployed offshore of Southwest Harbor, ME, Sept 9<sup>th</sup> to Oct 16<sup>th</sup>, 2013. Equipped with integrated RDI ADCP. Note - attached to the top of the glider is a VEMCO VMT Acoustic receiver, used for fish tag detection.

### III. GLIDER WAVE MODULE EVALUATIONS

Ocean Science and Technology's (OST) Wave Module is based on an inertial system that includes a tri-axial accelerometer, a tri-axial MEMS gyro, and a tri-axial magnetometer. It was developed in collaboration with the Physical Oceanography Group at the University of Maine. This system, which includes onboard processing, is used in the UMOOS buoy array to measure significant wave amplitude, dominant wave period, and wave direction once per hour with a 20 minute measurement period and 40 minutes in a sleep mode. The current usage is 80 mA in operation and 30  $\mu$ A in sleep mode. We have recently installed OST Wave Modules in five Slocum G2 gliders (four of which are part of the CINAR Tempest program). The Wave Modules begin operation after the glider surfaces and stabilizes, gather data for 5 minutes, and then calculate the wave statistics. At the present time the raw data and wave statistics are not available in real-time. Comparisons of wave statistics between the UMOOS buoys and the gliders have been very encouraging.

### IV. METHOD AND ENGINEERING APPROACH

OST Wave Modules have been in use in the UMOOS buoy array in the Gulf of Maine, the CARICOOS buoy array in the Caribbean and CICESE buoy array in the Gulf of Mexico. On these buoys, they run concurrently with TRIAXYS wave measurements (CARICOOS and CICESE only) and wave measurements using a Summit accelerometer, since 2008. Comparisons of data from the different instruments consistently show very strong agreement (Figs 5, 6).

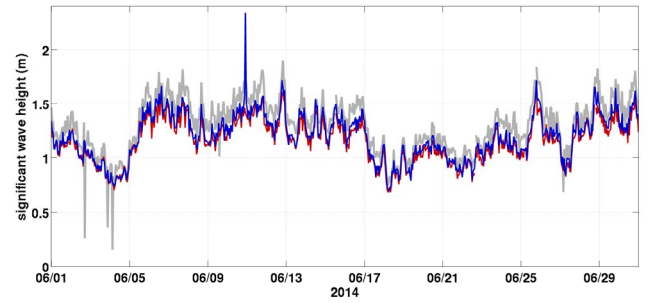


Fig 5. Comparison of significant wave height measurements from TRIAXYS (red), Summit (grey) and OST Wave Module (blue).

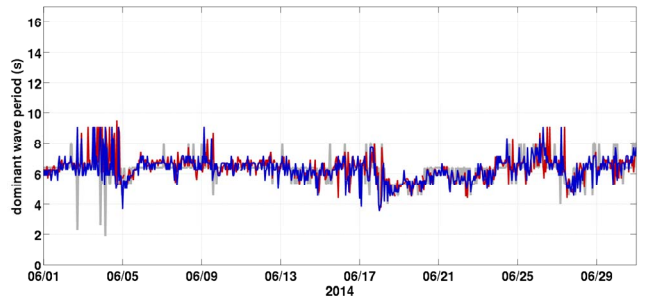


Fig 6. Comparison of measurements of mean wave direction from TRIAXYS (red), Summit (grey) and OST Wave Module (blue).

The OST Wave Module is a compact, lightweight system built using the very low power Persistor CF2 CPU module. The CPU is interfaced with the Microstrain 3DM-GX1, a nine axis inertial system using the UMaine PhOG serial bridge (developed in-house at UMaine). The statistical processing methods that the Wave Module uses to produce buoy wave measurements are based on those of Teng et al [8] at the NDBC. The Wave Module implementation used in the gliders can run in multiple modes, allowing for different sample periods and power requirements. Instrument raw data is stored internally on a 2GB storage card with a report of calculated wave parameter values produced for real-time telemetry, if available.

As part of the CINAR storm project, to monitor the interplay between the coastal ocean and Hurricanes and to aid in forecasting of Hurricane intensity and risk of wind damage and inundation, UMaine has incorporated OST Wave Modules into the CINAR storm gliders and CINAR storm buoys. Additionally, the University of Maine, which has been running the UMOOS/NERACOOS buoy program in the Gulf of Maine since 2001 has recently started performing spatial surveys connecting buoy sites to further elucidate coastal ocean processes including the wave field, in the Gulf of Maine.

Operating the Wave Module in a glider introduces several operational considerations:

1. *Energy efficiency:* Efficient use of power is essential to glider operation. The Wave Module uses very little power; drawing 30 microamps of current sampling in sleep mode and less than 80 milliamps while sampling. Thus each sample uses less than 10 milliamp-hours of power, which, operationally translates to less than 2% of our glider power budget, assuming the glider takes 5 minute surface wave samples every two hours.

2. *Size and Weight:* The Wave Module weighs under 300 grams, including the mounting hardware. It fits into the existing science bay and did not complicate the normal ballasting procedure on the five G2 gliders.

3. *Power stability:* Diagnostic data from several years of operation on moorings has demonstrated no adverse power issues on the platform control systems. The Wave Module runs at from 7.5 - 20 volts and is transient protected with a TVS zener diode. Three load switches and regulators are used to produce a true power down state for the 3DM-GX1 in quiescent mode, which further minimizes power consumption.

4. *Software integration:* Sampling behavior is controlled through the normal glider instrument configuration files. At this time, the data can only be queried in real-time, manually. The next upgrade, under development, will incorporate wave data into the normal glider science data flow, permitting 'real-time' automatic transfer of data.

The Teledyne Webb Slocum glider is an ideal platform for integration of the OST Wave Module measurement system into a glider as it is designed to allow end user maintenance and installation and configuration of instrumentation. The software platform and interface is also flexible enough to allow for addition of new instrument types. Initial field trials of the integrated Wave Module have not required any software updates, involving only the choice of appropriate configuration options in the normal glider mission and instrument configuration files. To facilitate incorporation of a Wave Module into a Slocum glider, we modified the board profile and mounting system to fit exactly into the glider science bay, using a standard Teledyne Webb science board mounting kit which meant that no further alteration to the glider science bay housing was necessary. The Wave Module was connected to the instrument power and data connectors that are provided, natively, in the glider science bay and main bays.

During the spring field engineering test of the CINAR tempests storm project, three Slocum G2 gliders (from University of Maine, Woods Hole Oceanographic Institution and Rutgers University) were deployed in the Gulf of Maine and the Middle Atlantic Bight, equipped with OST Wave Modules. The data we present here is from the UMaine glider deployment which surveyed the coastal ocean in an area between Saco, ME, the Northwest edge of Wilkinson basin and Muscongus Bay (Fig 7). The survey path was chosen to investigate changes in the area of interest offshore of Saco and into Wilkinson Basin, before during and after a Northeaster system and to provide comparisons between glider wave data

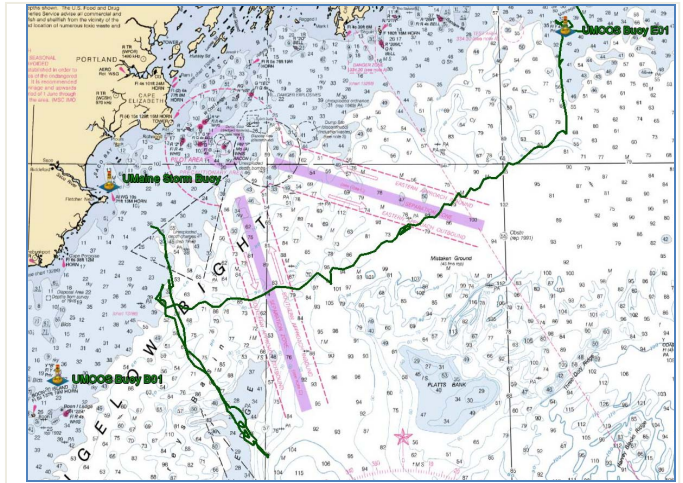


Fig 7. UMaine storm glider survey track - Spring 2014. As part of the spring storm glider test deployment, the UM Storm glider was deployed offshore of Saco ME to investigate the interplay between the coastal ocean and a Nor'easter storm system moving through the area. Wave data was captured approximately hourly in the western part of the survey, close to buoy B. The storm glider then flew to buoy E where wave measurements could be compared between platforms.

and buoy wave data from UMOOS buoys, B and E. Because of the mechanical differences between a glider and a moored buoy, more work needs to be done to verify the determination of wave direction from a glider. Thus analysis of wave direction is not discussed here."

## V. RESULTS AND DISCUSSION

The significant wave height and dominant wave period measured from the glider very closely matched the same the measurements from the OST Wave Module and Summit accelerometers on UMOOS buoys B and E (Fig 8 thru Fig 10). Measurements spanned a range of significant wave height amplitudes from 0.25 to 3 m (Fig 8) and dominant wave periods from 3 s to 12 s (Fig 10).

Careful timing of the sample period was crucial as valid surface wave measurements can only be obtained when the glider is on the surface and is in a state of constant buoyancy. This is normally achieved once the glider ballast pump and pitch battery has stopped moving and the air bag is fully inflated. The Wave Module used the glider sample state trigger to determine when to begin collecting statistical wave data. It was found from mission analysis and bench testing that a two minute delay had to be added to the sample start time to accommodate the time necessary for the glider to rise fully to the surface and finish adjusting its buoyancy. This two minute delay period may be different for gliders with configurations, particularly different ballast pump sizes. Future OST Wave Module versions will read key parameters from the glider systems, including ballast pump, depth and airbag state, to determine the optimal sample timing.

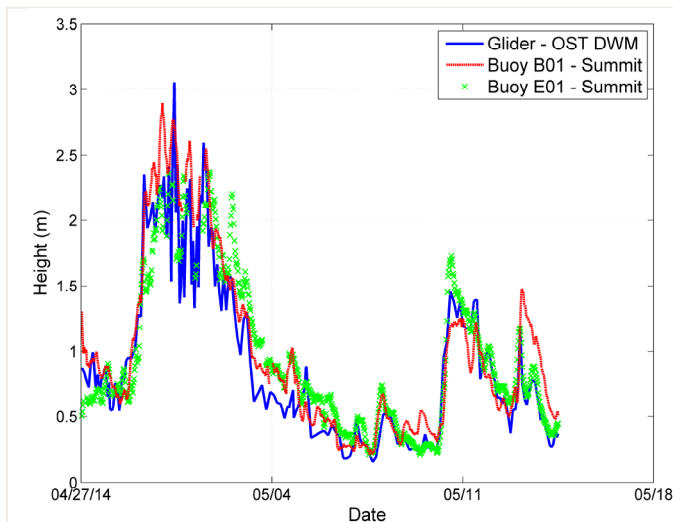


Fig 8. Comparison of significant wave height measurements from a glider and a buoy. The glider (thick blue line) performed 5 minute samples approximately every 1.5 hrs using the OST wave module. Buoy B / E (red dashes / green x) measured significant wave height using a Summit accelerometer system, sampling every 30 minutes. At the start of this time series the glider was SE of Saco, in the vicinity of Buoy B. The glider then flew NE and slightly offshore towards buoy E. The glider was within 5km of buoy E during the last day of the time series

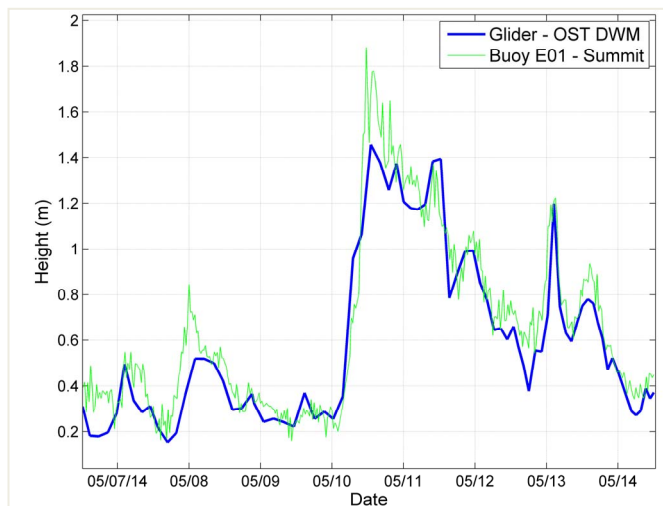


Fig 9. As in Fig 8. Close up of glider in region of Buoy E. The buoy (thin green line) measured significant wave height using a Summit accelerometer system, sampling every 30 minutes. At the start of this time series the glider is approximately 40 kilometers from buoy E. The glider was within 5km of the buoy during the last day of the time series.

Re-orientation of the glider on the surface in response to the local wind and wave field did not appear to affect measurement of wave period, frequency and amplitude but may be a significant factor in determination of dominant wave direction. Unique to glider instrumentation the Wave Module requires statistical analysis of data across a discrete sample period as opposed to the instantaneous measurements taken by other instruments. Lab testing and re-analyses of raw 20

minute buoy data indicated that five minute data periods would produce a reasonable approximation of wave state. The reduced sample windows was motivated by a need to minimize surface glider time to keep communication costs low and minimize risk of damage while on the surface. Once sampling on the surface is complete, the Wave Module can then performance statistical analysis of the data, independent of a particular dive state.

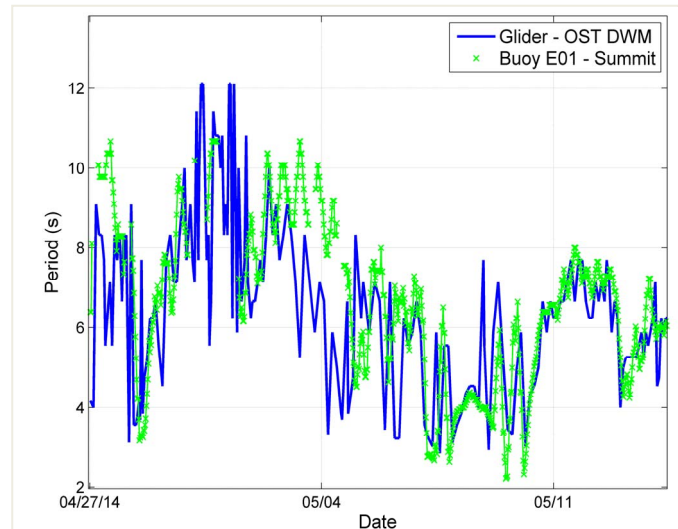


Fig 10. As in Fig 8 but showing the Period of the Dominant Wave (sec). The glider measurements (thick blue line) compare the most favorably with the measurements from Buoy E as the glider approaches the vicinity of the buoy.

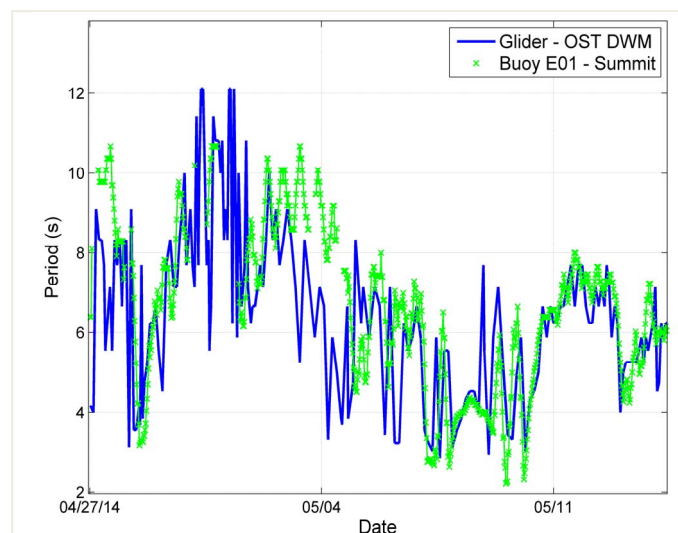


Fig 10. As in Fig 8 but showing the Period of the Dominant Wave (sec). The glider measurements (thick blue line) compare the most favorably with the measurements from Buoy E as the glider approaches the vicinity of the buoy.

## VI. CONCLUSION

The preliminary comparison with buoy-mounted ADCP data suggests the Slocum G2 glider with the integrated Explorer phased-array ADCP is suitable for direct velocity measurement of currents in a coastal environment. Processing glider-mounted ADCP data to provide velocities extending through the water column remains a challenge and involves careful data screening, integration of data from orientation, pressure, and position sensors, and may require development of methods of data handling tailored for this particular application.

We plan on further, more quantitative validation of the glider ADCP data during investigation of the coastal current system in the GoM. Velocity inversion shows potential as a means of extending absolute velocity measurements beyond the range of ADCP bottom-tracking, and incorporating information from other sensors and sources to constrain current measurements. We plan to continue work on refining these methods for our work in the GoM.

We are also planning field testing the effect of boosting the voltage supplied to the Explorer ADCP beyond the glider battery supply voltage to potentially increase the range of the instrument. An increase in profiling range can improve the accuracy of velocity measurements because of the nature of depth averaging redundant depth-bins from a descending profiling vehicle. In shallower coastal areas like the GoM, an increase in bottom-tracking range can provide an absolute velocity reference over a larger portion of the water column, improving both navigation and velocity measurement.

The significant wave height and dominant wave period measured from the glider tracked very closely the same measurements made from two independent wave sensors on nearby coastal buoys. The measurements used for the glider-mooring comparisons in this study spanned a range of significant wave height amplitudes from 0.25 to 3 m and dominant wave periods from 3 to 12 seconds. Extensive comparisons of these parameters and these instruments have been performed over several years by our group on several buoys in the Caribbean, Gulf of Mexico and the Gulf of Maine, validating the measurements in a range of conditions. Careful timing of the glider wave sample period was crucial to optimize surface sample time, minimize cost and risk of damage to the glider by limiting surface time. Measurement of wave period, frequency and amplitude did not appear to be affected by the response of the glider on the surface to the local wind and wave field. Future OST Wave Module versions will improve integration of the Wave Module with glider systems, reading key parameters to optimize sample and processing behavior and integrating with normal glider telemetry. Our group is working with Teledyne Webb to improve software and hardware integration of the OST Wave Module with gliders. We are investigating other applications of the inertial measurement capabilities of the Wave Module.

Our field testing later this year will include longer duration glider surveys around wave sensor equipped buoys. These tests will involve a glider equipped with both ADCP and Wave Module. The availability and range of smaller, lighter and more energy efficient sensors continue to open up the range of applications for autonomous vehicles. It is our hope that continued testing and validation of the integrated Teledyne RDI ADCP and OST Wave Module will further enable our group and other researchers to contribute to a broader understanding of the dynamics and spatial variability of coastal ocean processes.

## ACKNOWLEDGMENT

We gratefully acknowledge the help from all the staff at the Physical Oceanography Group at the University of Maine and the support of the glider folks at Teledyne Webb. We also thank the Maine Technology Institute and the NOAA CINAR Tempests Project for funding support.

## PATENT

The OST Wave Module implementation, described herein, is the subject of a provisional patent application.

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