Enabling Shallow Water Flight on Slocum Gliders

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Abstract— **Underwater gliders are a disruptive technology capable of transforming our understanding of the ocean. Efficient vehicle flight is critical for proper data collection, allowing successful completion of project goals. Slocum glider flights in less than 15 m of water have been only marginally successful, as use of deep water flight coefficients disables proper inflection at shallow depths. Groundings can damage sensors, degrade data, halt progress, and ultimately endanger the vehicle. To correct poor flight performance, sensor parameters responsible for inflection were individually analyzed and adjusted. Tests were conducted on repeated flights in the shallow state waters of New Jersey with glider RU28 while conducting dissolved oxygen surveys for the New Jersey Department of Environmental Protection (NJDEP) and the United States Environmental Protection Agency (USEPA); further verifications were conducted off the shoaling areas of Delaware with glider OTIS while searching for tagged sturgeon and sand tiger sharks. As a result of these tests, flight performance has been drastically improved, with efficient flight in 8 m of water, including several promising instances in water as shallow as 6 m. Prior to adjustments, gliders would make little forward progress and spend 50-100% of a flight segment grounded. With the new parameters loaded, groundings have been eliminated from coastal missions. Enabling shallow water flight for Slocum gliders allows vehicle operations in an area largely unexplored by this type of platform, opening up coastal areas to new project ideas and sampling schemes. Shallow water flight parameters can be shared with the community to increase sampling density in areas previously off limits to these vehicles**.

Keywords—Gliders; Slocum gliders; Shallow water; AUV operations; Glider flight parameters

I. INTRODUCTION

In 1989, Henry Stommel penned a science fiction article published in the journal Oceanography entitled "The Slocum Mission"[1]. In it, he elaborated on an idea conceived by Douglas C. Webb about a fleet of autonomous underwater vehicles driven by buoyancy changes, dubbed Slocums, that traversed the oceans while profiling in a sawtooth pattern, surfacing at regular intervals and sending data back to a control center via satellite. Today the Slocum glider is no longer a myth, but a reality with purposed missions, monitoring both deep ocean basins [2] and shallower coastal regions [3]. While the former presents its own suite of challenges, the latter has presented glider operators with a unique set of issues to overcome merely to enable continuous flight in a limited water column. Standard flight coefficient settings work well in depths of 15 meters or greater, but often fail in depths below that, causing the vehicle to strike the bottom. Several separate factors can lead to these groundings with differing severity. Short duration groundings are affectionately termed "bottom sampling" (Fig.1), while longer duration groundings are referred to as "dredging" (Fig. 2). Both are capable of degrading the data set, and can cause damage to the vehicle and payload sensors. As work in these regions expands, finding a solution becomes imperative.

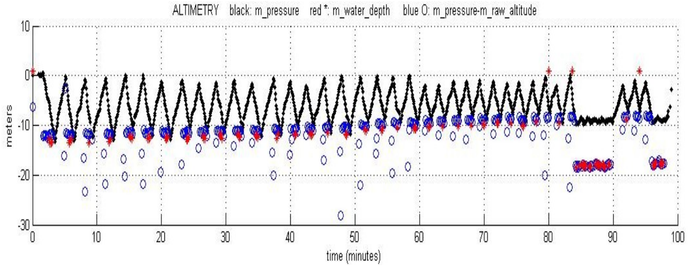

Fig. 1. *Pressure record from University of Delaware glider "OTIS". Towards the end of this segment, the otherwise uniform sawtooth pattern is interrupted by " bottom sampling"..*

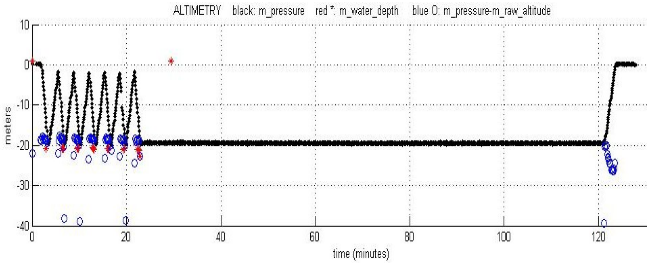

Fig. 2. *Pressure record from Rutgers University glider "RU28". In this example of "dredging", once the glider strikes the bottom, it is unable to recover and stays on the bottom for the remainder of the segment.*

II. BACKGROUND

A. Glider Configuration

The Slocum glider, manufactured by Teledyne Webb Research Corporation (TWRC), is modular in design and available in several different configurations [4]. Aside from the payload bay that can be configured with a variety of different sensors, the primary differences lie in the depth rating of the buoyancy pump – currently 30 m, 100 m, 200 m, and 1000 m, with others well on the way. For very shallow coastal areas, the 30 m pump configuration is ideal, with a theoretical operational depth of between 4 m and 30 m of water. With the standard flight coefficients, the 30 m pump has not performed any better in shallower water than the deep rated 100 m pumps.

B. Applicaitons Requiring Efficent Shallow Water Flgiht

1) New Jersey Dissolved Oxygen Monitoring

With the arrival of the warm summer weather, the coastal waters of New Jersey often experience areas of low dissolved oxygen at depth. [3] These areas are of interest to and are occasionally monitored by the New Jersey Department of Environmental Protection (NJDEP) and the United States Environmental Protection Agency (USEPA), often leading to an “impaired” classification for the coastal waters of the region. Rutgers University has since partnered with these agencies to pilot a Slocum glider through the state’s coastal waters, monitoring dissolved oxygen at a much higher spatial resolution than previous shipboard surveys. Data collected for the USEPA has a previously specified resolution and format, specified in a Quality Assurance Project Plan (QAPP), and state waters lie within three nautical miles from shore. The convergence of these constraints require reliable operation and data collection of a glider in very shallow water, in this case approaching as near to the seabed as possible without risking the glider.

2) University of Delaware Shark Tagging Project

The University of Delaware pioneered the integration of a Vemco VR2C hydrophone into a Slocum glider, effectively allowing the glider to receive information from sand tiger sharks, sturgeon, and other tagged species in the area while mapping out the physical properties of the associated preferred water masses [5]. Rutgers University partnered with the project team to pilot the glider, primarily in the shallow coastal region off Delaware, known for its shoaling. A glider in this area can often find itself operating in 6-8 m of water while winding its way through the navigable waters between shoals. Flight dynamics adjustments are necessary to successfully gather data in these regions.

III. METHODS

Two gliders were flown for separate projects off the coasts of New Jersey and Delaware – RU28 to monitor areas of low dissolved oxygen off New Jersey, and OTIS in a search for tagged sharks and sturgeon off Delaware. While instances of bottom sampling and occasionally even dredging have been seen before, both became common occurrences during these flights. Glider pilots were not able to coerce the gliders to make headway, and the project data sets were in jeopardy. It was at this point that in-depth analyses of flight data were conducted in an attempt to pinpoint the root cause of the issues.

“Live” plots that update with the newest flight data after every surfacing were poured over time and time again, as were higher density datasets transferred directly from the glider representing suspect segments. Several plots began to point toward altimetry issues, both in the collection and processing of the sonar returns. The master file containing all sensors aboard the glider, masterdata was scoured for all sensors and settings related to the altimeter. Upon reasoning through the default settings, the root cause of bottom sampling had been found.

A rather specific set of criteria applies to altimeter returns to be considered “good”, and thus be accepted by the glider. As the glider begins a dive in shallow water, a good altimeter return may be received and rejected, as the glider is still considered to be “on surface”, or it may still be too soon after an inflection. As the glider continues its dive, it reaches a window where an altimeter return is recognized as “good”, and that value is stored. The glider continues its dive, and receives another good return, but it may be rejected because the glider is too close to the bottom. The glider requires two valid altimeter returns to determine height above bottom and then inflect, but in very shallow water, it may only receive one, which is then ignored, and the glider strikes the bottom. (Fig. 3.) Fixing the bottom sampling issue requires taking multiple flight parameters into consideration at once, with an understanding of their interactions between each other and the glider. The initial step is to disable the filtered altimetry:

```
sensor:   u_alt_reqd_good_in_a_row(nodim)         1
sensor:   u_alt_filter_enabled(bool)              0
sensor:   u_alt_reduced_usage_mode(bool)          0
```

This step disables the built-in filter, turns off the standard reduced usage mode, and requires only one “good” return in a row to register as a valid altimeter return. Otherwise, valid returns are rejected. The second step requires changing parameters that effectively increases the size of the water column to the glider’s altimeter.

```
sensor:  u_reqd_depth_at_surface(m)                  2
sensor:   u_alt_min_post_inflection_time(sec)      4.0
sensor:  u_alt_min_depth(m)                        1.0
sensor:  u_min_altimeter(m)                        1.5
```

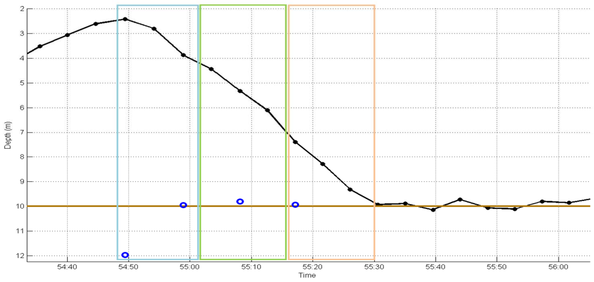

Fig. 3. Obtaining returns in very shallow water. The 2 initial returns are rejected, one valid return is accepted, and another later hit is rejected, causing the glider to ground.

The depth at which the glider considers itself on surface is reduced to 2 meters instead of 4, immediately increasing the depth in which valid returns can be obtained. The post-inflection time filter is reduced to 4 seconds, letting the glider take readings earlier after it inflects. The minimum depth the glider must obtain before taking altimeter readings is reduced to 1 meter, effectively keeping the altimeter on for the majority of the flight. The minimum reading the altimeter may return is then reduced to 1.5 meters, allowing the glider to reach as low as 1.5 meters above bottom prior to inflecting. Below this altimeter readings can be unstable, spiking up into unrealistic values. So the general summary of steps to avoid bottom sampling is to a) disable the filtering of valid altimeter returns and b) increase the depth of the water column in which the glider is able to receive returns. Should these fail, an additional safety can be added:

```
sensor: u_max_water_depth_lifetime(yos)      2
```

Setting this sensor allows the glider to use the measured altimetry from the last dive should it fail to obtain a valid measurement on the current dive. While not accurate, it can serve as a safety if the depth hasn't changed drastically.

Further refinements can be made to increase altimeter accuracy and nullify false hits:

```
sensor:   u_sound_speed(m/s)                        1510.0
sensor:   u_max_bottom_slope(m/m)                      3.0
sensor:   u_min_water_depth(m)                           0
sensor:   u_max_water_depth(m)                        2000
```

The speed of sound can be set to match as closely as possible the physical properties of the water mass in which the glider will be flying. Although the difference may not appear drastic, all attempts to increase altimeter accuracy had to be taken into consideration. The maximum slope of the seabed can be adjusted; this value is presented in vertical meters per horizontal meter. Strong caution is urged in reducing this value, as it may be acceptable where topography is generally flat, but can filter out valid returns in an environment with a more dynamic terrain, such as rocky coasts, reefs or wrecks. The final two sensors listed above are included as an altimeter fix for a very specific situation; their inclusion here will be clarified later in this section. Several glider flights have produced false altimetry hits, causing the glider to inflect up in the water column instead of down near the seabed. Although this has been seen occasionally off New Jersey in the shelf waters, it is primarily an issue in the colder waters of Antarctica. General speculation points towards masses of krill acting as a false bottom, giving the glider false returns. Setting the minimum water depth deeper than the false returns filters out any returns prior to the preset depth. Again caution must be used, especially if entering shallow water. This can inadvertently trigger a grounding. Setting the maximum water depth avoids null returns from the altimeter; i.e. generic placeholder values such as 9999. This is not an issue, as this is the default setting, and is included here only for completeness.

Preventing dredging, although related, is a separate issue. When bottom sampling, the groundings occur due to a lack of altimetry, but the glider can typically recover. When dredging occurs, the glider not only grounds, it remains on the bottom for extended periods of time, typically the remaining duration of the segment. On occasion, a trigger will cause the glider to recover, but the safeties in place often aren't enough to overcome the dredging. For example, the glider should attempt to surface if it has been at the same depth for a specified period of time, which seems plausible, as the glider is stuck on the bottom. However, in dynamic shallow water environments, the surge of the waves moving the glider around often creates enough of a pressure change that the glider's logic does not realize it is generally at the same depth. The underlying cause of dredging is yet another altimeter issue – surface reflections. When the glider is on the bottom, the ping of the altimeter reflects immediately off the seafloor, and again off the surface before returning to the glider. The glider registers these as valid returns, and continues trying to dive through the seafloor to reach the depth registered by the altimetry (Fig. 4). To circumvent this, one sensor is set:

```
sensor: u_max_altimeter(m)                  6.0
```

The maximum value allowed to be returned by the altimeter is set to less than the actual water depth. This is considered to be a workaround rather than a final solution, as it prevents the glider from dredging, but also limits altimeter returns in deep water to the same value; e.g. if the glider is flying to 80 m in 100 m of water, no altimetry will be returned, as 20 > 6, even though the altimeter is easily capable of measurement at that depth.

Throughout the initial troubleshooting process, the above sensors were individually adjusted and tested to gain better understanding of how the glider's flight behaviors changed with each setting, and how the sensors interacted with one another. Once a best-practice set of parameters was decided upon, the sensors were collected and placed into a mission file that is now included in Rutgers' default software version. Using a simple "loadmission" command via short-range

Freewave communications or even through TWRC's dockserver over the Iridium network, shallow water flight parameters can quickly and easily be loaded on a glider at sea, preventing nearly all groundings.

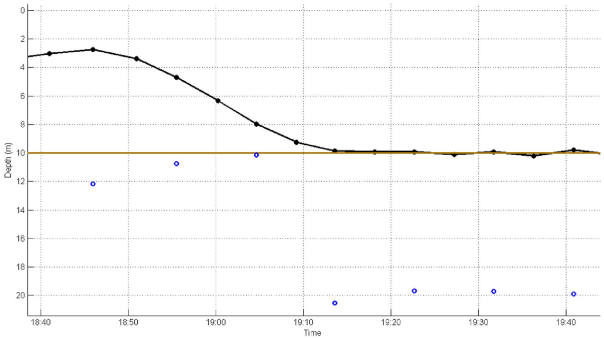

Fig. 4. Altimetry surface reflections during a grounding event. The glider remains grounded as it attempts to dive to the values returned by the altimetry.

IV. DISCUSSION

Slocum gliders are a powerful tool capable of sampling the marine environment with very high resolution, both vertically and horizontally. A standard suite of software included from the manufacturer generally enables glider flight across a range of pump configurations, providing the water depth is sufficient. This "one-size-fits-all" approach breaks down in shallow water, causing the glider to strike the bottom on multiple occasions, or strike the bottom and remain there for the duration of the segment. While adjusting sensors onboard the glider has lead to a software fix, not everything can be blamed on the software configuration.

A. Causes of grounding

Splitting the glider into two separate systems, denoting a hardware system and a software system, both have their faults that can result in groundings.

1) Hardware

Sonar altimeters, although used for decades and generally trustworthy, are not without their own idiosyncracies. As the physical properties of seawater (temperature, salt content) change, the speed of sound in that water mass changes, causing the altimeter's calibration to differ as well. Although this difference is typically small, it is still present.

In glider altimeters, as in many other lowered instrumentation packages, the altimeter will begin reporting erratic values when the altimeter reaches approximately one meter above bottom. Without filtering, the glider's logic would simply continue to send the glider on its dive, resulting in grounding.

Although less common, there have also been instances where the altimeter calibration has been incorrect, and an offset occurs. This calibration offset has been seen in both the positive and negative direction, causing one glider to ground while another could not seem to find the bottom.

While calibration issues can often be survived at sea and solved in the lab, some are intrinsic issues that cannot be resolved.

2) Software

The standard altimetry settings onboard the glider allow flight in sufficient water, but can cause grounding in water depths less than 15 meters. This is a direct result of the glider's cycle time and ability to obtain altimeter returns combined with its filtering logic ignoring valid returns. Unlike the hardware system, the user has control over the software system, and these settings can be adjusted to enable shallow water flight. By disabling the standard altimetry filters, more altimeter returns are considered for inflection determination. By decreasing the top and bottom boundaries for altimetry data, more of the water column becomes available to obtain valid altimeter returns. The culmination of these changes result in enough valid altimetry to inflect effectively and continue to collect data in very shallow water.

B. Detriments of groundings

1) Vehicle/platform risk

Groundings present a series of risks to gliders and the sensors they carry. Striking the seafloor - or any number of objects on the seafloor – has the potential to scratch, break, or otherwise damage attached sensors such as the external CTD (Conductivity, Temperature, Depth) sensor and the exposed faces of integrated fluorometers and backscatter meters. As the glider is pushed around by the surge, sediment can build up in the nosecone, resulting in a loss of buoyancy. With enough additional sediment, it is possible this could lead to the inability to surface, eventually resulting in the glider releasing its ejection weight. At that point, the glider's mission is over and a typical recovery becomes a rescue. On one occasion, University of Delaware's glider OTIS had gathered enough sand in the nosecone during a bottom sampling segment that small pieces of gravel became lodged between the buoyancy pump and the diaphragm. As the pump moved during inflection, the small pieces of gravel ground against the diaphragm, eventually ripping through and causing a leak. This put the vehicle in immediate risk of total loss.

2) Data quality risk

Aside from the obvious physical dangers presented by groundings, data quality can be affected as well, even jeopardizing projects. Deployments monitoring dissolved oxygen for the NJDEP and USEPA require a predetermined and preapproved glider path, horizontal, and vertical data resolution. Groundings halt forward progress, thereby wasting battery and possibly jeopardizing the path. Horizontal resolution is reduced, often drastically, as the glider cannot make expected progress. Vertical resolution is also affected, as the glider may still be sampling and taking high resolution data, but at a single point on the seafloor rather than monitoring the water column.

C. Summary/results

The software solution outlined above allows a quick, easy method for loading shallow water flight coefficients on a deployed Slocum glider. The end result is confident flight and data collection in 8 meters of water, with examples of successful flight in as little as 6 meters of water (Fig 5.).

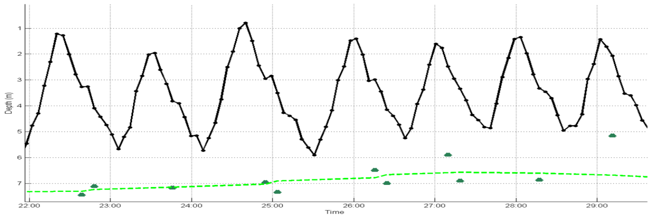

Fig. 5. Successful flight in 6-7 m of water after applying shallow water flight coefficients.

The ability to operate Slocum gliders in shallow water environments presents a new monitoring tool to the community. No longer are shallow coastal regions off limits to endurance sampling schemes. Future implications point towards the possible monitoring of harbors and bays, with the ability to transit to areas of interest, as opposed to single point moored arrays that require vessel intervention to reposition. Regions shallower than 6 meters currently pose flight mechanics issues, but shallower flight may be possible with further adjustments of flight characteristics such as pitch, pump flow rates, and stability. As the vertical speed of the platform is slowed, the ability to obtain altimeter returns is increased, possibly allowing full flight in the designed inflection range of 4 meters for the 30 m shallow pump configuration.

ACKNOWLEDGMENTS

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