Glider Performance During Hurricane Gonzalo

BIOS, Bermuda

David Aragon
Scott Glenn, Travis Miles
Rutgers University Department of Marine & Coastal Sciences
New Brunswick, NJ
dkaragon@marine.rutgers.edu

Ruth Curry
Bermuda Institute of Ocean Sciences
MAGIC Lab
St. George's, Bermuda
rcurry@whoi.edu

I. INTRODUCTION

Hurricane Gonzalo was 2nd in a series of sequential Atlantic tropical cyclones to hit the island of Bermuda during the 2014 season. Hurricane Fay landed as a Category 1 hurricane October 12 and the resulting efforts helped pre-condition the island for Gonzalo. Less than a week later on October 18, Hurricane Gonzalo made landfall as a Category 2 storm. It had peaked in intensity as a Category 4 storm less than 500 miles south of Bermuda [1].

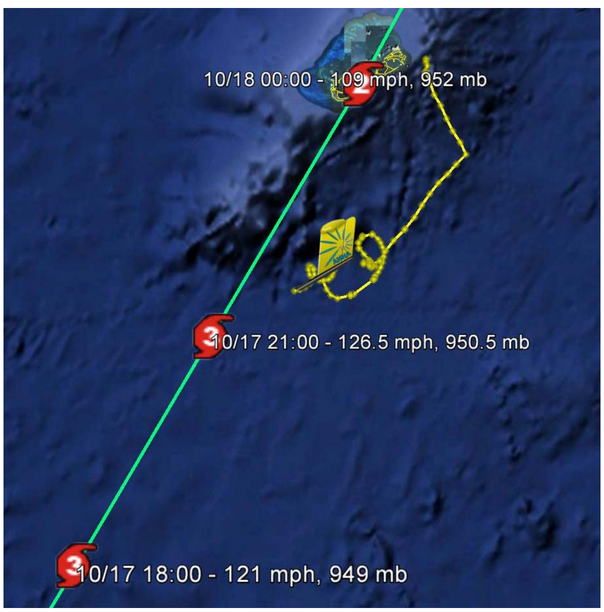

Fig. 1. Hurricane Gonzalo track with wind and pressure. Glider Anna path. (*Google Earth, NOAA*)

A Teledyne Webb Research Slocum G2 glider, owned by BIOS (Bermuda Institute of Ocean Sciences) was opportunistically deployed ahead of the storm, after being recovered before Hurricane Fay. The glider was equipped with CTD, optical backscatter and fluorescence, and a dissolved oxygen meter. The glider flew for a short time before and after the storm giving a snapshot of the post-Hurricane Fay ocean properties and Hurricane Gonzalo induced effects.

Noted during the flight of the glider under the hurricane, was strong turbulence as seen in attitude variables from the vehicle. The measurements were taken using the glider's onboard attitude sensor which measures pitch, roll, and magnetic heading. This turbulence was seen during peak storm intensity as the hurricane crossed over the glider and extending quite deep into the water field. The glider also experienced decreased communication reliability as well as damage to the tail from the storm or debris.

With gliders increasing presence and availability, unique events such as hurricanes will be sampled in ways never before seen. Sensors of greater complexity and quantity are being added to such vehicles and may be susceptible to extreme conditions such as seen during Hurricane Gonzalo.

II. METHODS

Gliders have become robust tools for sampling the ocean during both normal and episodic events such as storms [2] [3]. Slocum gliders are capable of operating in shallow waters (5+ meters) to open ocean (up to 1000 m). By changing buoyancy they are able to descend or ascend vertically through the water column. Incorporating a pitch angle into their ascent or descent allows forward progress upwards of 35 cm/s. Steering mechanism and onboard attitude measurements allow navigation underwater for specified lengths of time.

Sensor payloads are added primarily to the center of the vehicle and data is collected during the ascent, descent, or surfacing phase of the glider's flight. Logged at a maximum rate of 1 Hz, gliders provide relatively high density sampling spatially and vertically. Low power allows operation across seasons and certainly during the durations of most storms or episodic events.

The glider deployed from Bermuda's BIOS MAGIC Lab (Mid-Atlantic Glider Initiative and Collaboration) was named Anna. This glider was a deep glider capable of descending to 1000 m. Science payload consisted of 3 oceanographic sensors. A Seabird pumped CTD unit for measuring temperature and salinity is a staple on all gliders. An optical Wetlabs ECO sensor, FLBBCD, measures proxies of phytoplankton abundance (chlorophyll fluorescence), total particle concentration (backscattering), and dissolved organic matter (CDOM fluorescence). An Aanderaa oxygen optode capable of measuring dissolved oxygen are installed at the rear of the vehicle.

Other observations from Bermuda include L.F. Wade airport, NOAA Station BEPB6 - 2695540 - Bermuda Esso Pier, as well as others mentioned in National Hurricane Center's Hurricane Gonzalo Report [1].

III. Results

A. *The Ocean, the Storm, and the Robot*

The storm approached Bermuda over the slightly cooled waters after Hurricane Fay had passed through. This likely weakened Gonzalo before making landfall, further giving Fay the credit of 'preparing' the island for another hurricane's landfall. Fay had also knocked most loose structures, limbs, and debris loose so that Gonzalo's impacts were limited on the island.

Gonzalo tracked over Bermuda, crossing the glider around 00 GMT October 18. The glider (Anna) was flown about 30 km from storm center. Anna continued to operate an additional 2 days after the storm departed before being recovered by R.V. Atlantic Explorer. At this point it was continuing to profile but was un-steerable due to damage from the- storm, thus recovery was a top priority. It would have been beneficial to continue flying beyond such date.

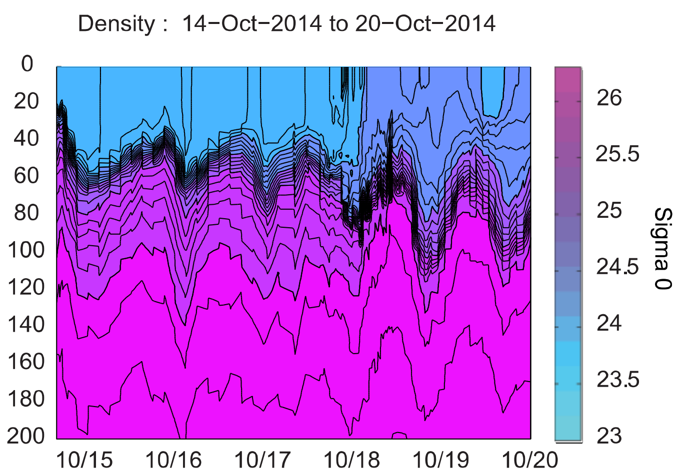

Fig. 2. Anna density, note: mix layer depth (credit: Ruth Curry, BIOS)

The passage of Hurricane Fay cooled the ocean 2-3 degrees C, likely weakening Gonzalo. A curiosity this brings is because both storms had similar tracks, how much effect of the cooling extended further south from the island along their paths. Finally, the mixing and turbulence layers as seen in temperature begin to show the picture of activity as deep as 80 m which affected the glider's attitude. Deeper scientific analysis of the glider data is ongoing and is outside the realm of this paper. This paper intends to focus on the performance of the G2 Slocum glider in an extreme event such as this.

B. *Rudder: Lost at Sea*

Underwater gliders steer using a variety of methods. Angling the glider about its roll axis (banking) allows gliders to steer during ascents and descents turning vertical motion into heading control. This is analogous to an airplane banking on a landing approach. Another method used is via a rudder or fin allowing the vehicle to turn by yawing. This changes heading much like a rudder in an airplane by rotating the glider about its heading axis. It is important to note vehicles that rely on yaw for heading control have no ability to roll or bank. Their only control methods are pitch and yaw. Roll can be induced by a rudder moment but is outside the scope of this discussion.

The rudder on the Slocum glider is an external moving part, essentially the only one besides an externally inflating and deflating buoyancy diaphragm. This urethane control surface can operate roughly +- 25 degrees for controlling heading. It is housed by a self-contained fin unit called the digifin. Also built into the fin are communication and GPS antennas.

To this date Rutgers University has had no major issues with the digifin system and rudder during its hundreds of individual deployments of gliders. Leading up to rudder loss were numerous reports from the glider that the fin was being pushed around by wind, water, and/or debris. It was expected the rudder would be able to continue to operate normally despite the warnings and conditions.

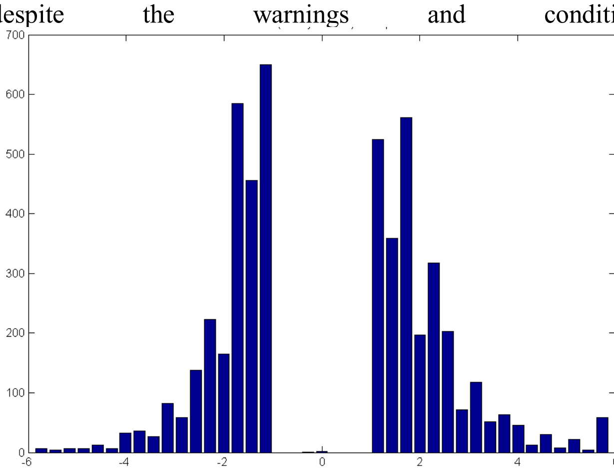

Fig.4. Rudder out of deadband histogram. Degrees rudder was found to be outside of +- 1 degree motor deadband

However, during the passage of Gonzalo over glider Anna the rudder system sustained complete loss minutes after surfacing. The loss occurred (10/17 18:30) several hours before the eye passed directly overhead. It is difficult to conclude the cause of rudder loss: options being biologic, wind driven debris or water. Given the path of the hurricane and wind direction during the loss, debris or flotsam density should be low. Biological loss is an option but would be highly coincidental given the timing and infrequency of rudder losses on previous glider missions.

C. *Communications Reliability*

Gliders rely on antennas in the top of the digifin (tail assembly) to maintain GPS and communication links. The tail of the glider is elevated out of the water by buoyancy provided from an external air bladder which inflates near the surface. This lifts the tail out of the water for antenna access to GPS and Iridium satellite constellations. The primary means of communication to a glider is via the Iridium system when out of range of radio communications.

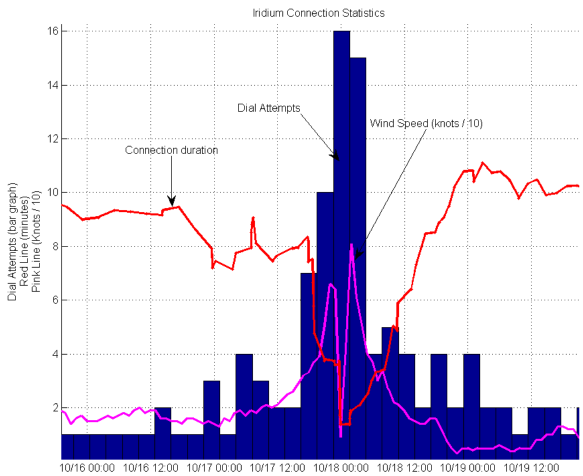

Fig 4. Iridium connection success rate

The mission plan had called for mixed sampling depths between 200 m and 500 m, alternating, during the storm. This was accomplished by changing mission parameters upon each surfacing via an automated scripting routine. Several hours prior to peak storm, communication success rate plummeted and thus dive depth cycling was halted for single 500 m yo's (a yo is a dive and a climb performed by glider) for the remainder of the mission.

Centered on 00 GMT 10/18 by about +- 3 hours, communications hit their low point with connections lasting less than 1-3 minutes. Such short connecting times made changing mission parameters difficult as well as transferring data. This also had an unintended effect of idle surface time perhaps better spent sampling rather than drifting in the dangerous winds.

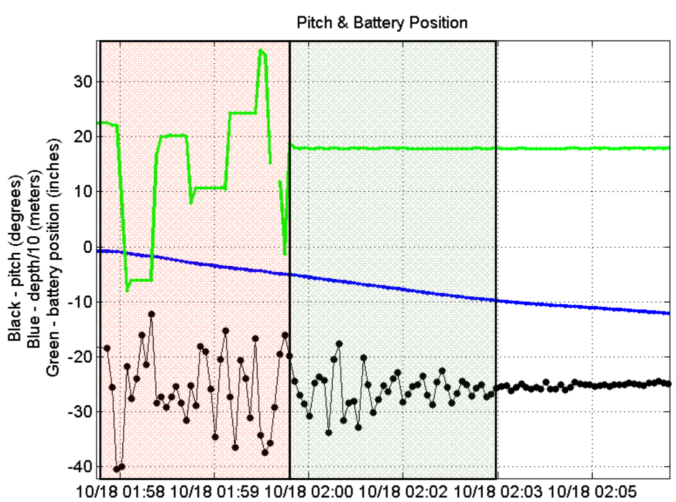

Fig 5. Glider pitch is in green, while depth is plotted in blue. Note even after pitch battery stops moving pitch oscillates down to 100 m

D. Rough Seas: Turbulence

The primary field for which we can look for turbulence in the glider flight is in the roll dimension of the attitude sensor. Roll is important to look at because it is the most independent of the glider's control surfaces. In other words the glider cannot directly control roll, thus most of the roll measurements are the result of the environment itself.

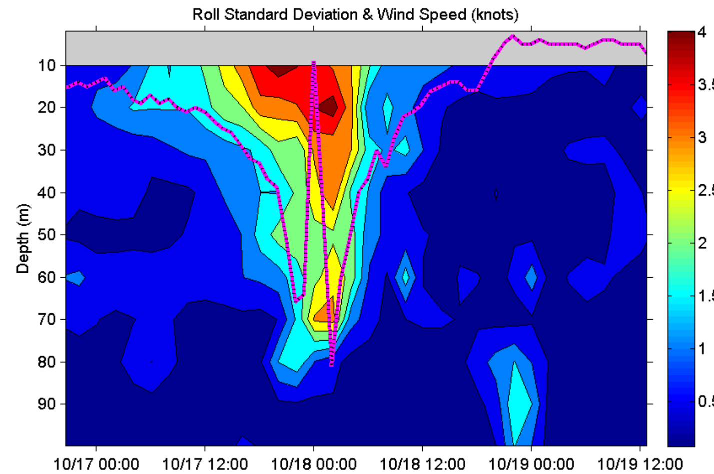

Fig 6. Vehicle roll (degrees) moving standard deviation

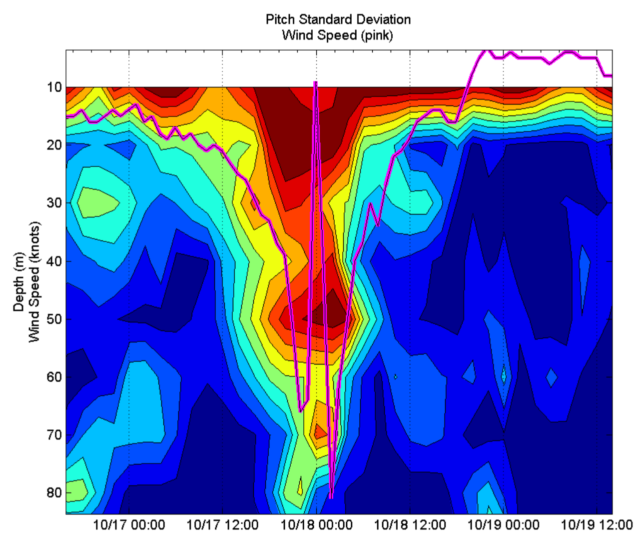

Fig 7. Vehicle pitch (degrees) moving standard deviation

The glider's ideally fly with 0 degrees of roll and outside of any influences should remain at 0 during all operating times. Of course turbulence, inflections, pitch changes, and rudder all create moments which roll the glider. Roll standard deviations of 5-10 degrees were seen during passage of the storm. Periods appeared to be 10-20 seconds in the roll data but further investigation needs to be done.

Pitch shows turbulence as well, but the glider is able to control this surface via a movable mass in the fore of the glider. This 9 kg mass is able to slide forward and aft to adjust the pitch angle. In Anna's case when the pitch error became too large (caused by turbulence) it began to move the pitch internal control surface (battery). Analysis should be done as independent of this as possible. Also worth noting is this may be an unintended consequence of the control system parameters as moving the battery may have contributed to higher pitch errors. A possible solution is flying with a fixed pitch battery or larger pitch deadband.

Pitch errors of +- 10 degrees were seen at depths as great as 80 m. This was centered on the storm and shallowed as the storm approached and departed. For a period of roughly 24 hours the glider showed turbulence in roll and pitch at depth, peaking just hours before the eye passed overhead.

IV. Conclusions

Operating remote platforms such as gliders in extreme events will continue to provide insightful measurements and observations. In parallel advancement, sensor development and integration will bring new sensors to AUV's that will help scientists answer questions they didn't have the means to observe prior.

New sensors often have increasing complexity as well since often scaling down is the largest technical challenge. Early gliders flew just a CTD sensor and that yielded some victories. However, multiple ADCP units by Nortek and Teledyne, as well as water quality sensors such as nitrate, and phytoplankton productivity (FIRE) sensors from Satlantic are all ready for glider use. Turbulence probes such as the Rockland Scientific Microrider can be mounted on top of gliders. Using these complex sensors in extreme events could have unintended effects and should be accounted for in operation. For example large roll and pitch movements could yield errors in ADCP measurements from gliders, especially in vertical water velocities [5]. Proper operation of the vehicle could alleviate some of the effects seen, especially in pitch fluctuations or at least allow predictive behavior. Onboard accelerometers may assist in understanding these effects and provide new insight. Additional understanding as to the response time and accuracy of the onboard attitude sensor will continue to be paramount. Open ocean current profiling gliders could perhaps benefit from upward looking instruments which would sense turbulent water while swimming in still water. This would only have benefits in situations where bottom track would always be impossible.

As the operational numbers of gliders increases so grows the percentage of risk of damage and unintended interactions. Gliders will hopefully continue to harden and become resilient amongst the many conditions they will face. Strong winds and similar incidents that lead to the rudder loss should be accounted for and tested against. Surface time should be limited to reduce risk to the glider.

It is important for scientists and operators of the gliders to understand the lessons from this paper. To summarize the conclusions for missions in the future:

1. Maintain maximum glider stability at all times. This will assist in mitigating external forces creating pitching, yawing, and rolling conditions to the vehicle and attached science sensors. Stability also plays a role in at surface communication success. The goal will be to minimize measurement errors and increase vehicle operability. Stabilizing surfaces are important as well, wings, canards, etc.

2. During episodes of extreme weather, less is more. Prepare to have your glider handle episodes of complete autonomy and make sure it continues to sample. Don't create an overly ambitious operating plan and be sure to sample more than what you need, in this case depths. When probing the unknown you can't predict what you will miss because you don't know what you will be measuring.

3. Limit surface times in the event it can't connect. Time at the surface is not only more dangerous, but it is also un-productive in that little useful data is being collected. Many Rutgers glider missions have had incidents happen at the surface yielding it is a dangerous place to be. Surface control scripts should have told Anna to immediately dive and forego data transfers until passage of the worst conditions.

4. Control algorithms for the glider optimized for normal flight may produce unintended consequences during storm flight. Simplifying or neutering such controls may be beneficial during instances of turbulence and high autonomy (not able to control vehicle). For example, increasing the pitch deadband, setting a fixed pitch battery position, or lowering the control gains could help the glider from trying to dampen turbulence caused pitch oscillations.

V. Future Work

Frequency analysis of the pitch and roll could be helpful to see if it somehow correlated with wave field experienced in the area. Work with a glider and an accelerometer would help augment the suite of useful data collected by the glider. Analyzing the pitch and heading controller during this time period to make a setup for the glider to operate more relaxed during a storm will prove useful.

Acknowledgment

Praise should go to the deployment crew from BIOS and R.V. Stommel who deployed Anna in less than ideal conditions prior to the storm. Also to the recovery team who were able to muster 2 days after the hurricane to rescue an un-steerable glider. This team consisted of the crew and scientists of R.V. Atlantic Explorer. Also special thanks for Ruth Curry and the MAGIC Lab for the opportunity to assist BIOS with their glider operations.

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