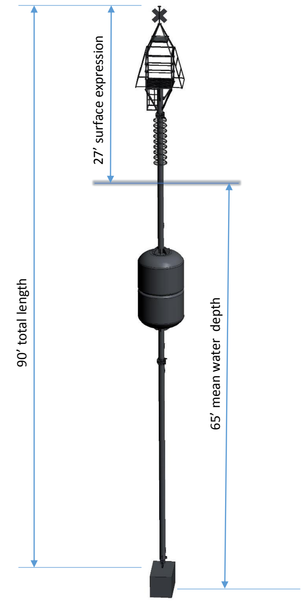
Status of USF Shallow Water Geodetic Buoy

November 10, 2018

USF has been funded by the NSF-OTIC (Ocean Technology) program to develop a high precision sea floor geodetic system suitable for shallow coastal regions (<200 meter water depth). The system would be especially useful for subduction zone applications, where offshore strain accumulation and release processes are currently poorly monitored. In principle strain measurements in these offshore areas would be useful for earthquake and tsunami forecasts, and improved understanding of earthquake processes. In some subduction zones, including Central America, the continental shelf area that is shallower than 200 meters covers 30%-40% of the area between the coastline and the trench. Measurements here could significantly expand the reach of high precision geodesy in this critical region. We have called the project **SUBGEO**, for Shallow Underwater Buoy for Geodesy.

Our system design is based on the successful design of INGV/Italy, who have used the system to monitor vertical deformation of the sea floor in the Gulf of Pozzuoli in southern Italy, adjacent to the Campi Flegrei volcanic area. We propose to augment this system to include measurement of horizontal deformation, by performing heading and tilt measurements and using these data to correct the raw GPS position data. If successful, the system will be capable of recovering the full three-dimensional displacement vector of a point on the seafloor to an accuracy of 1-2 cm averaged over 24 hours.

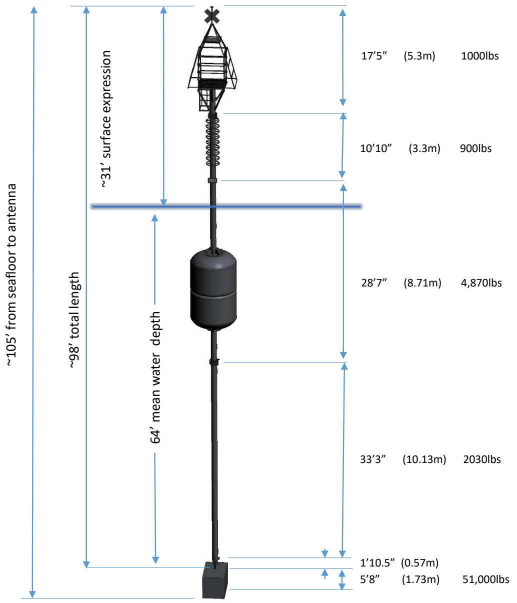
Figure 1 shows the initial buoy design, provided by Hydro Solutions LLC . Figure 2 shows the final specifications after construction, which closely followed the initial design. The system was deployed on August 23, 2018, and has been collecting data since then.



Buoy orientation in the water.

Beacon +float buoyancy: 10,865kg + 1110kg = 11,975kg
Ballast weight (in air): 20,000kg
Ballast weight (in water): 12,000kg
Beacon + float weight: 2,491 + 1,180kg = 3,671kg
Net ballast of system: ~3,000kg

Figure 1. Initial design specifications.



Buoy Specs:

Anchor weight in air:	51,000 lbs	(23 MT)
Anchor Weight in seawater:	29,000 lbs	(13 MT)
Buoy weight in air:	9,000 lbs	(4 MT)
Buoy weight in seawater:	7,000 lbs	(3 MT)
Gross Float Buoyancy:	26,500 lbs	(12 MT)
Net Float Buoyancy:	24,000 lbs	(11 MT)
Net buoyancy of entire buoy:	19,500 lbs	(9 MT)
Net Ballast (anchor) weight:	9,500 lbs	(4.3 MT)

Figure 2. Final specifications of the buoy as constructed.

From top to bottom, the main elements of SUBGEO are:

The superstructure that hold the GPS receiver, antenna, batteries and solar panels (Figure 3).

Figure 3. Buoy superstructure. This part of the buoy is above the waterline, and is designed to be lightweight and with low cross-section area to minimize wind stress. The GPS and associated electronics are mounted inside this framework (grey box; see Figure 3 for close-up) while the solar panel is mounted externally. The GPS antenna is mounted at the top (left–hand figure).

The GPS and related electronics were mounted and tested for several months prior to deployment (Figure 4). These tests indicated that the Iridium system, used for data transmission, introduced significant noise. It was therefore disconnected and alternate communications were designed, involving a Freewave modem. This system will be satisfactory for distances out to about 15 km from the coast, but not for farther distances. In 2019, we will test alternate Iridium configurations, including a new GPS receiver (Xeos Technology) that incorporates an Iridium transmitter within the receiver itself, with appropriate filters.

Figure 4. GPS and related electronics in the weather-proof enclosure, mounted on the buoy superstructure.

The access ladder (Figure 5), which attaches immediately below the buoy superstructure.

Figure 5. Access ladder

The float section, which provides the primary buoyancy for the system (Figure 6).

Figure 6. Float, prior to integration with buoy main section (below).

The main buoy which comprises two pieces (Figure 7a) with the attachment point on the bottom (Figure 7b).

Figure 7 (top) main buoy; **(base)** close-up of attachment point, which connects with the seafloor ballast through a large shackle (Figure 8).

The shackle, which connects the main buoy to the bottom ballast (Figure 8).

Figure 8a. Shackle to connect main buoy to seafloor ballast.

Figure 8b. Shackle after deployment on the sea floor, connected to ballast.

In addition to the main buoy elements, a custom trailer was built to move the buoy to the deployment position on the pier (Figure 9).

Figure 9. Trailer for moving individual buoy elements to deployment area.

The ballast, which anchors the buoy to the bottom (Figure 10).

Figure 10a. Four views of ballast on pier. Clockwise from upper left: Concrete form (note rebar reinforcement); two views immediately after concrete is poured (note lifting hooks); ballast after form is removed.

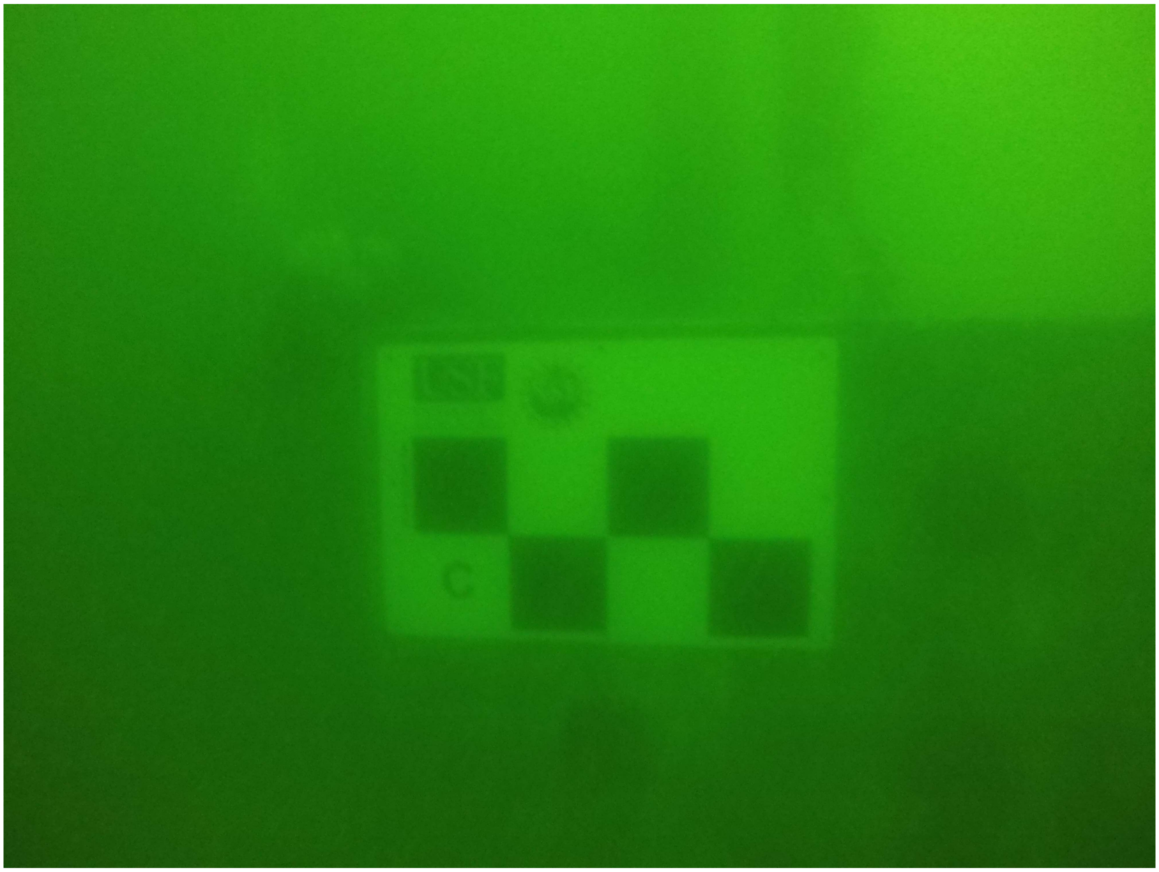


Figure 10b. Ballast after deployment in 65 feet of water near Egmont Key, Florida. Each side has sign affixed with USF and NSF logos, and four black squares 20 cm on a side. The four sides are labeled A, B, C, D (C is visible in the lower left).

The concrete ballast was poured and allowed to cure for about one month prior to deployment (Figure 10a). Because of its large mass, it is important to form rebar throughout the structure and tie it directly to the lifting hooks, to avoid material failure during lifting. Signs with a geometric pattern were secured to the four sides prior to deployment to allow detailed photo-based measurements of position and orientation, to insure that the ballast does not shift after an initial settling in period (approximately three months).

Deployment. Our first test buoy was deployed on August 23, 2018 (Figures 11-18). We used the services of Orion Marine, who had a large barge and crane available. The concrete ballast and buoy were loaded separately, transported to the site, and then joined just prior to deployment. The deployment went smoothly, but it was preceded by several months of planning and calculations. One lesson is that deployment issues need to be considered early on, including during the initial design of the buoy.

Figure 11. Buoy and ballast on sea wall prior to loading.

Figure 12. Barge approaching sea wall for loading operations.

Figure 13. Barge crane beginning to load the buoy**.**

Figure 14. Two views of the barge deploying the buoy.

Figure 15. Buoy immediately after deployment, prior to installation of electronics. Note top of float (yellow) approximately 2 meters below the surface.

Figure 16. Jay Law installing the GPS antenna on the highest point of the buoy.

Figure 17. The buoy with electronics, solar panels and signage installed. Egmont Key is in the background. Note tilt of buoy, reflecting strong tidal current.

Buoy location. We initially planned to deploy the buoy at a site farther offshore, with minimal tidal current. However, this would incur large deployments costs (long transit time for the deployment barge) and make servicing more difficult. We therefore chose a site within the tidal channel of Tampa Bay (Figure 18). This area is subject to large tidal currents, allowing a rigorous test of our tilt correction approach.

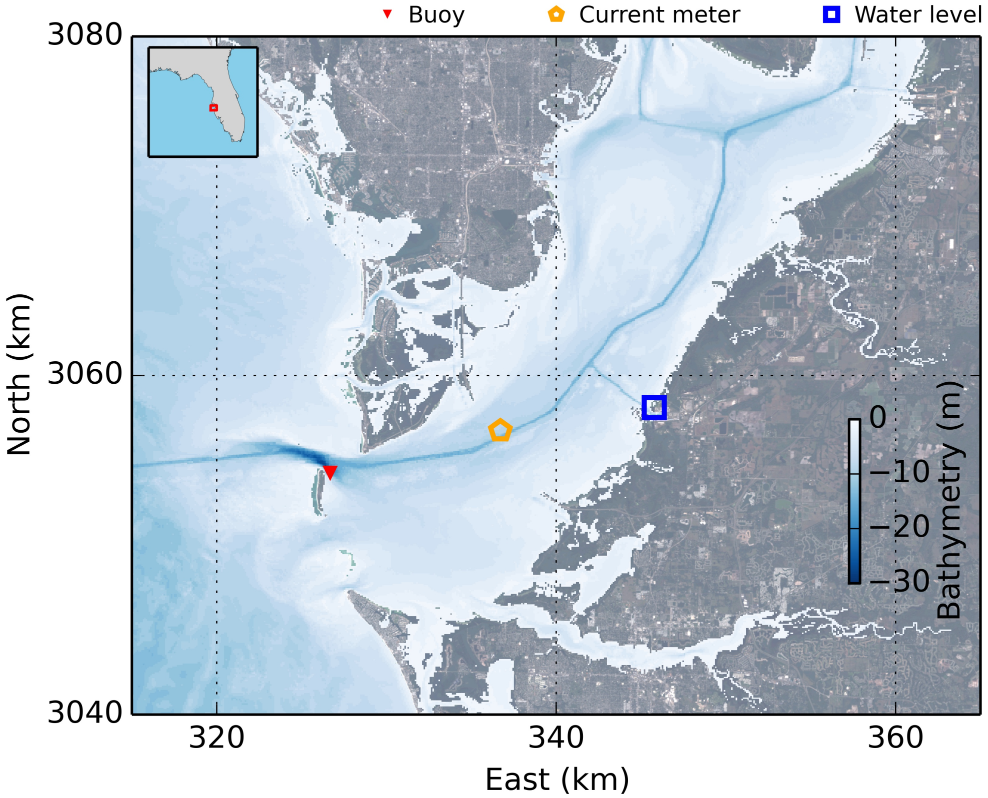
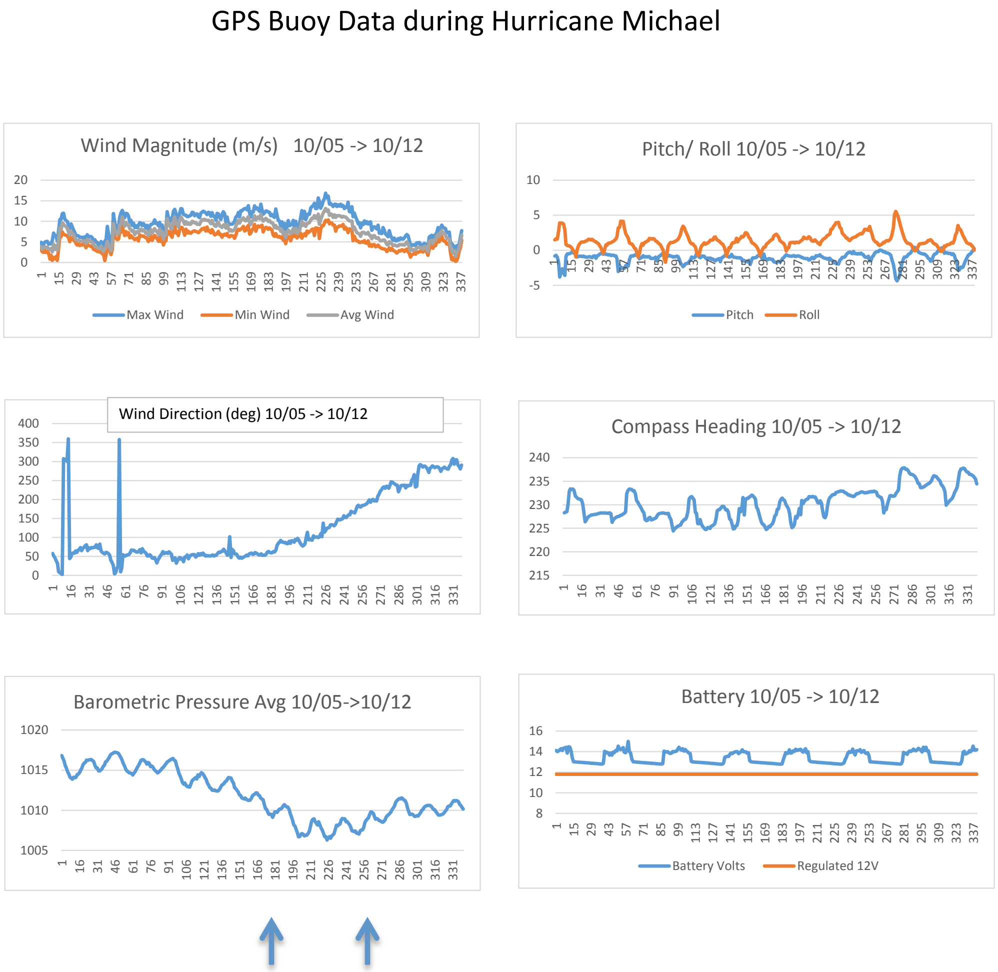


Figure 18. Bathymetric map (darker blue = deeper water) showing buoy location and other nearby instrumentation. Note location of buoy close to tidal outflow channel for Tampa Bay.

Data Analysis. Raw data from the various sensors are downloaded once per week. An example data set from the tilt, met and battery sensors are shown for a one week period that includes passage of Hurricane Michael (Figure 19). The met data are useful for trouble shooting and noise analysis for the GPS data.



GPS Buoy Data during Hurricane Michael

Wind Magnitude (m/s) 10/05 -> 10/12

Pitch/ Roll 10/05 -> 10/12

Wind Direction (deg) 10/05 -> 10/12

Compass Heading 10/05 -> 10/12

Barometric Pressure Avg 10/05->10/12

Battery 10/05 -> 10/12

Figure 19. Data from met sensors on the buoy (wind speed, direction and atmospheric pressure) for an example week of operation (October 5-October 12, 2018). Horizontal axis is time, labeled in number of 30 minute data samples from beginning of week. Note passage of Hurricane Michael (between arrows, October 9-11, data samples 180-260), when atmospheric pressure reaches a minimum, and wind speed reaches a maximum. Water level was also significantly higher during this period (Figure 23).

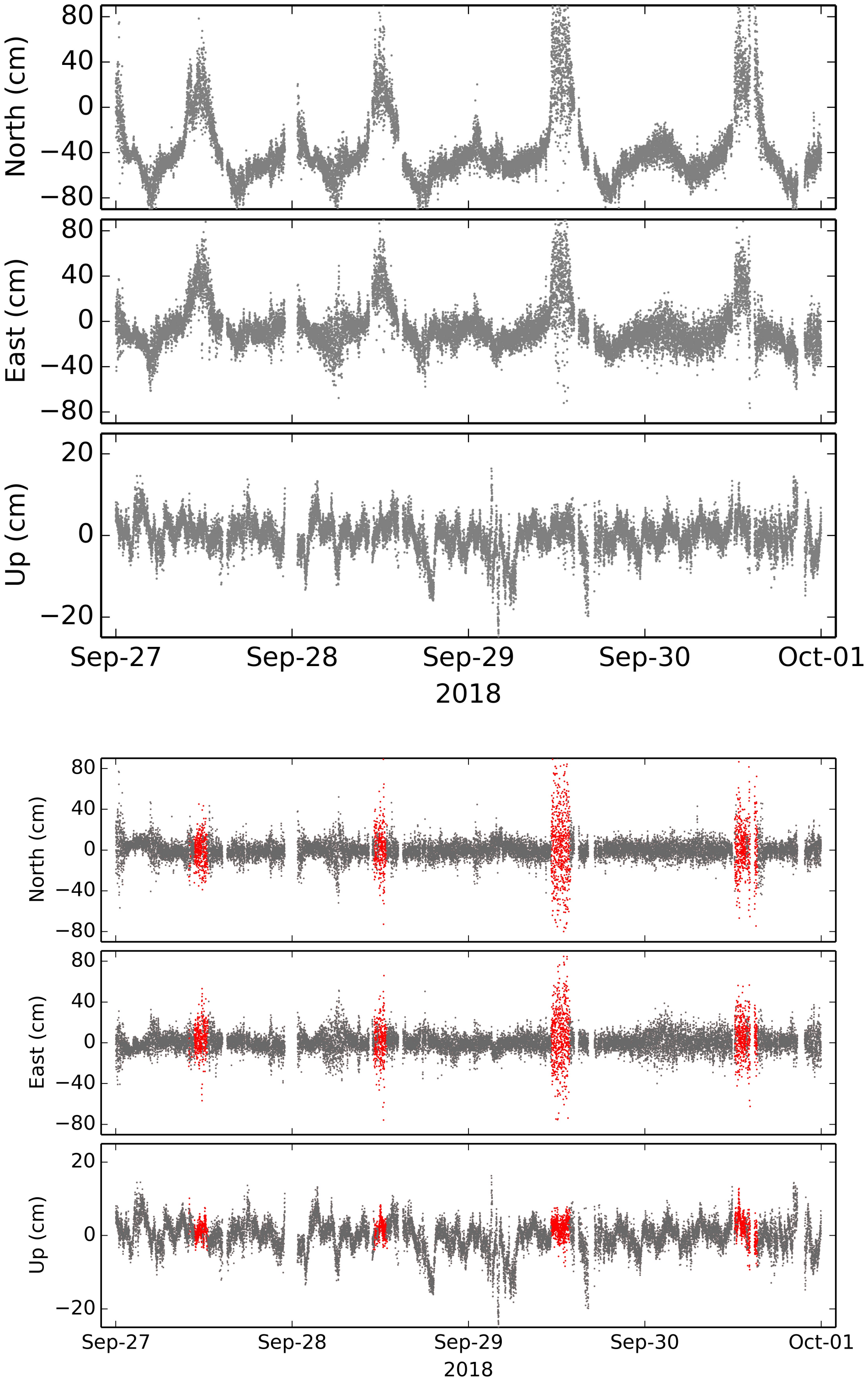


Figure 20. Four days of data showing "raw" GPS horizontal data (top) and tilt-corrected data (bottom). Red areas show data where tilt exceeds 3 degrees.

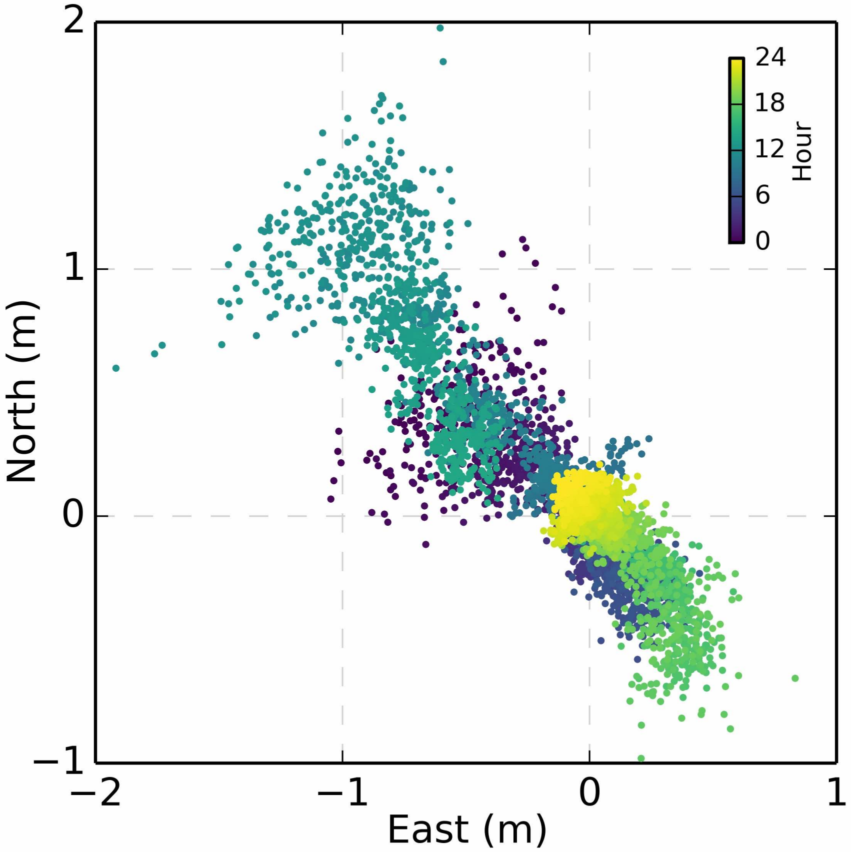


Figure 21. GPS position data for a typical 24 hour period (15 second sample rate), showing the influence of tidal currents, which tilt the buoy 1 – 2 meters off vertical in the northwest and southeast direction (the 0-0 position is vertical). Northwest tilts are larger than southeast tilts, since outgoing currents are stronger than incoming currents because of fresh water inputs to Tampa Bay.

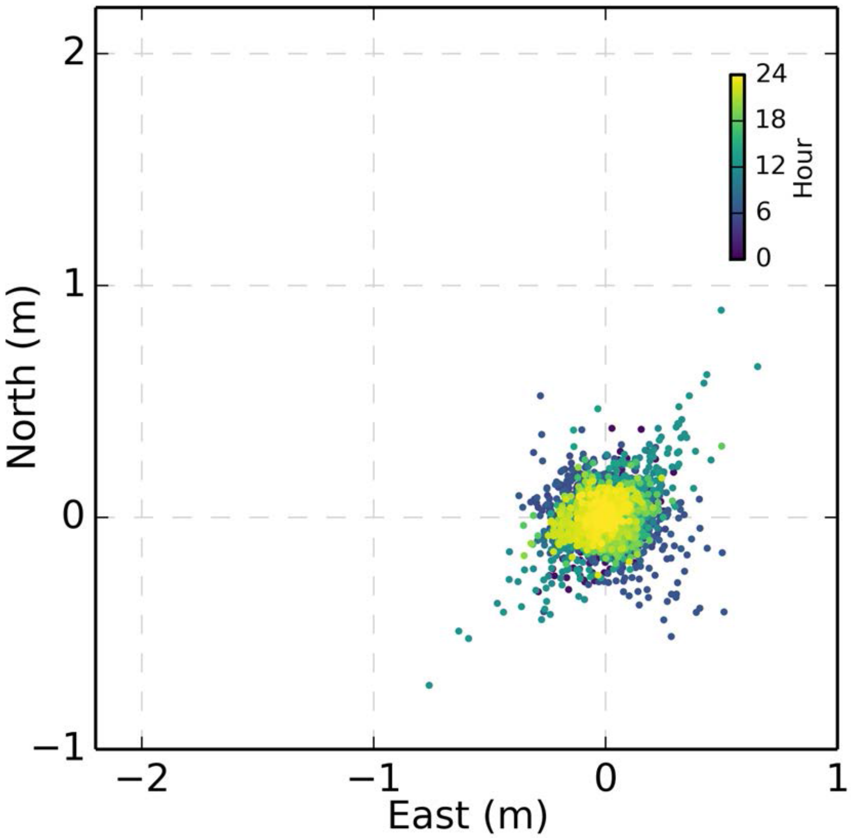


Figure 22. The same data as Figure 20, after tilt correction. RMS scatter is approximately 3 cm in the north and east components.

High precision GPS results lag real time by about one week, because high precision satellite ephemerides (description of the satellite orbits) are not available in real time. Results from preliminary analysis of the time series are shown in Figures 20-24. Figure 20 shows details of a typical four day period. During initial analysis, we noted large errors (excursions from zero) in our tilt-corrected data, occurring during periods of maximum current speed and maximum tilt, likely reflecting errors in our heading sensor. This magnetic sensor is sensitive to variations in the local magnetic field, and the steel superstructure of the buoy likely causes a systematic bias. We now treat this bias as a variable, estimating a constant heading offset along with the north, east and vertical position estimates, obtaining a bias of 32°. Once this bias is applied to the tilt correction, RMS scatter in the position estimates is significantly reduced (Figure 20, bottom; Figures 22 and 24).

Hurricane Michael. A significant test of buoy design occurred around October 10, 2018 during passage of Hurricane Michael. The buoy experienced high wind speeds and water levels, and rotated by several degrees (Figure 19, 23), resulting in about

10 cm of translation of the sea floor ballast, some of which was subsequently recovered (Figure 24). Otherwise, the buoy experienced no ill effects.

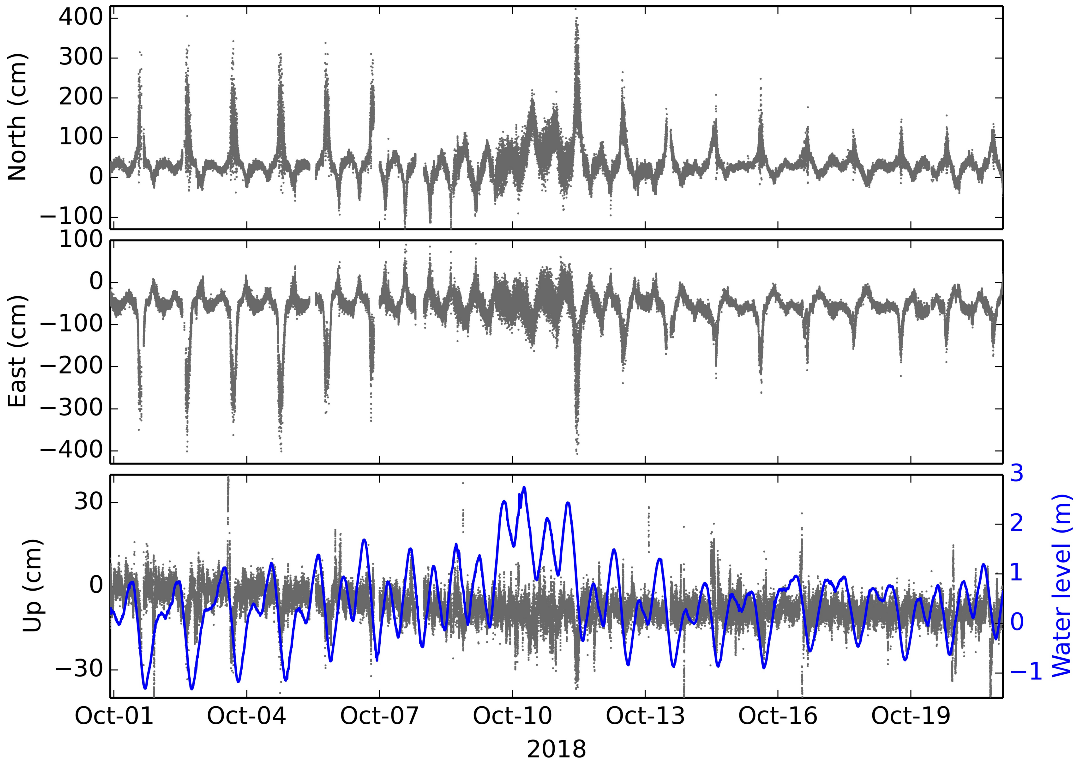


Figure 23. Water level and "raw" GPS position data (uncorrected for tilt) during passage of Hurricane Michael, October 9-11.

Long term motions. Figure 24 shows the long term motions of the ballast (anchor point). In the first few weeks, the system settled by several tens of cm and moved horizontally by about 3 m, and then stabilized except for slow subsidence (we expect up to one half meter of subsidence over a several month period). The high translation rate during the first few weeks may have been caused by tidal current scouring prior to settling into a stable position. RMS scatter of the three position components after Hurricane Michael is 3 cm or better.

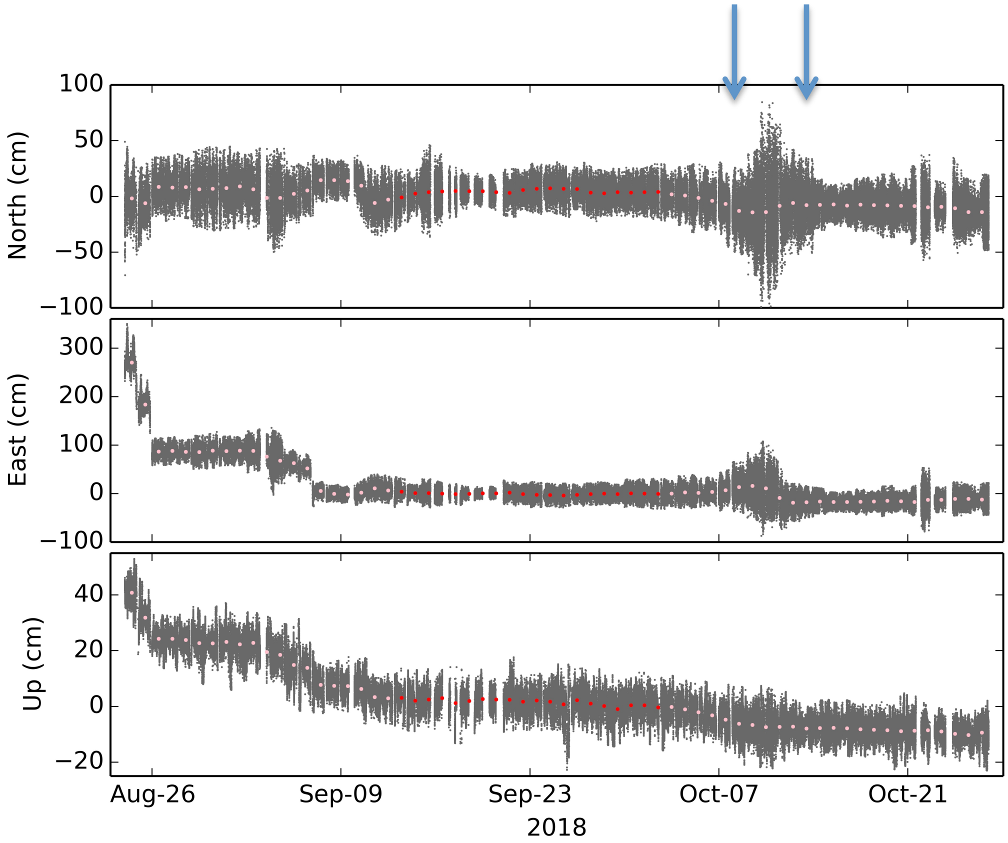


Figure 24. GPS results for anchor (ballast) position, corrected for buoy tilt, omitting periods when tilt exceeds three degrees, and using a median filter (dots show average 24 hr position). After the first few weeks, the ballast has been relatively immobile, except for ongoing slow subsidence, and passage of Hurricane Michael (October 10, arrows) when ~ 10 cm of horizontal displacement occurred. A total of about 0.5 meters subsidence is expected.

Future Work. The following issues have been identified as tasks for the next year:

1. Verify/understand the bias in the magnetic heading indicator; assess whether this is time-variable.
2. Monitor buoy subsidence; if greater than expected, come up with possible design changes in the ballast and/or overall buoy design.
3. Refine the tilt correction algorithm to recover the horizontal position components with improved precision.
4. Assess the sensitivity of the GPS position estimate to small (3° or less) tilts.
5. Data transmission: our Iridium transmitter for data recovery induces significant noise in the GPS data. We need to design an improved system, which may just involve alternate antenna locations for the transmitter or electronic filters on the GPS receiver.

6. Deeper water designs. The current system design is suitable for water depths up to about 40 m. In deeper water alternate designs will be required, which will likely involve a cabled component.

END