

Using Three Acoustic Technologies on Underwater Gliders to Survey Fish

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Introduction

There is significant interest among federal, state, academic, and private research scientists in developing new fishery-independent sampling systems to assist resource managers. Although the bulk of fishery ecosystem assessments are conducted by well-staffed research teams on large fishery research vessels, recent advances in autonomous platforms show potential for increasing the coverage and extent of ocean ecosystem surveys. Utilization of new technologies and methods provide new data sets that may be more efficient than traditional methods. Studies involving remotely operated vehicles (Patterson et al., 2009), ship-towed systems (Cryer, 2015; Williams et al., 2010; Lembke et al., 2017), autonomous underwater vehicles (AUVs; Clark et al., 2010), satellites (Hostetler et al., 2018), and even ships are being used in collecting fisheries data in new ways.

Fisheries-based applications for underwater profiling gliders, hereafter

ABSTRACT

Autonomous platforms and vehicles are a growing component of the ocean research fleet, producing data sets crucial to our understanding of oceanographic and fishery ecosystem processes. One emerging tool for making these measurements is underwater gliders that autonomously sample the water column for weeks to months at a time. Although originally designed to measure temperature and salinity, underwater gliders can now support a myriad of sensors. For the demonstration project described within, three complementary acoustic technologies were integrated into an underwater glider for mapping fish on the continental shelf: an acoustic telemetry receiver, a passive acoustic monitoring recorder, and a fisheries echosounder.

The demonstration project was designed to evaluate the effectiveness of each sensing technology. Sixty-one fish were implanted with acoustic tags near the Gulfstream Natural Gas pipeline in the eastern Gulf of Mexico in advance of planned underwater glider missions. The glider was deployed four times over 12 months, with all three acoustic technologies to traverse the pipeline and surrounding habitat. Glider detections were compared to detections of fish at moored acoustic tag telemetry receivers and passive acoustic recorders co-located at the tagged fish locations. All three technologies identified fish along the targeted hard-bottom pipeline habitat, as well as previously uncharted areas of hard-bottom reef. The results of this study demonstrate the utility of gliders integrated with acoustic sensors as a potential tool to identify areas that merit deeper investigation to assess fish stocks.

Keywords: glider, acoustic tag telemetry, passive acoustic monitoring, fisheries echosounder, ocean observing systems

called *gliders*, to date have been exploratory but are rapidly evolving. In recent years, three types of acoustic sensors have been incorporated to provide data relevant to fisheries assessments. Passive acoustic monitoring (PAM) recorders record ambient sound, including sounds of soniferous fish within range (Wall et al., 2012). Acoustic telemetry receivers are capable of detecting fish implanted with acoustically transmitting tags (Oliver et al., 2013). Fishery echosounders can provide indicators of fish and zooplankton biomass within their field of view (Guihen et al., 2014;

Taylor & Lembke, 2017; Benoit-Bird et al., 2018). By demonstrating the utility and cost efficiency of gliders to obtain this information, these sensors could become part of the broader ocean observing infrastructure to provide data sets useful for stock assessments.

Gliders are robust, proven platforms designed for water column data collection. Typically, gliders vertically migrate the surface to depth repeatedly using buoyancy and attitude adjustments to propel themselves at horizontal speeds of 0.7–1 km/h (Rudnick et al., 2004). Gliders stay deployed for weeks to

months at a time, traversing hundreds of kilometers, working in conditions that can often be impractical for shipboard operations due to weather limitations. They come to the surface several times a day at user-controlled intervals to obtain GPS positions, transmit the data being collected, and receive any commands the user deems necessary. Originally designed to collect water column density data, the gliders are increasingly being incorporated into the national ocean observing system backbone to constrain data-assimilative ocean models (IOOS, 2014; Testor et al., 2010). Sustained glider operations, with nearly continuous coverage in regions such as southern California, have by now lasted well over a decade (Johnston & Rudnick, 2015). Similar operations geared toward collecting biological parameters could provide valuable context to understand the ecological health prior to and following episodic events, such as oil spills, harmful algal blooms, tropical storms, or anoxic zones.

This effort integrated and evaluated three complementary acoustic technologies in providing indicators of fish abundance using an underwater glider. To demonstrate the utility of this approach, we first selected a test area of known and unknown habitat. We then tagged fish and seasonally deployed the glider in the region. Finally, to provide comparison to more traditional methods, moored acoustic telemetry receivers and passive acoustic recorders were deployed in the same region.

Acoustic telemetry is the most widely used method to track the movements of marine fish (Heupel et al., 2006; Hussey et al., 2015). With tag telemetry, submersible receivers with omnidirectional hydrophones are deployed and constantly monitoring for signals from tagged fish within range of a re-

ceiver. Detection data includes the transmitter's identity, date and time of detection, and any additional sensor data built into the tag, such as temperature, pressure, or acceleration. Detection ranges vary depending on depth, ambient noise, habitat (i.e., barriers to sound), and environment, ranging from 100 m in high relief habitats (Selby et al., 2016) to 400 m or more in coastal habitats (Lowerre-Barbieri et al., 2016). However, there is increasing interest in telemetry-enabled mobile platforms such as AUVs (Oliver et al., 2013), which allow for detections in areas difficult to monitor with fixed receivers or over larger scales. Tags are most commonly attached to animals through surgical implantation in the body cavity (Cooke et al., 2010), but external attachment is also used. Each tag is coded so that individual fish can be tracked, and often tags are fitted with additional sensors, such as temperature or pressure (for depth). Data from acoustic telemetry have been used to inform a wide range of processes important to fisheries management, including stock structure, natal homing, spread of invasive species, the efficacy of Marine Protected Areas (MPAs), spawning frequency and mortality (Young et al., 2013; Hernandez et al., 2013; Lowerre-Barbieri et al., 2014, 2016; Crossin et al., 2017).

The use of PAM to detect soniferous fish and map spawning habitat (Luczkovich et al., 2008; Walters et al., 2009; Ricci et al., 2017) has been well demonstrated and is another approach to track and quantify the presence of sound-producing fish. For example, red groupers (*Epinephelus morio*) produce a distinctive species-specific sound throughout the day and night (Nelson et al., 2011; Wall et al., 2014). Past efforts have used an array of fixed passive acoustic recorders and recorders

on gliders to study the distribution of fish including red groupers over very large spatial scales (Wall et al., 2012). These efforts have resulted in spatial and temporal maps of grouper and other fishes. In essence, the sounds produced by red groupers act as a tag to indicate their presence.

Fishery echosounders have been used to survey biological components of the marine ecosystem from the smallest plankton to the largest fish. Using rapid transmissions of high-frequency sound (>38 kHz), echosounders detect reflections of particles and animals in the water column. When deployed from research vessels, surveys can cover large areas mapping the distribution of biomass of plankton and fish throughout the water column over a continuum of spatial scales (Simmonds & MacLennan, 2005). Adapting echosounders for use in autonomous platforms like ocean gliders is relatively new (Guihen et al., 2014; Moline et al., 2015; Taylor & Lembke, 2017; Benoit-Bird et al., 2018). New small-size, low-power echosounders and miniaturized acquisition computers are now deployed on AUVs for surveying remote areas of the ocean. Electric gliders overcome a few challenges of echosounder surveys from large ships, including interference from engine noise that potentially disrupts the behavior of fish (De Robertis & Handegard, 2013). Although species identification is not possible with single frequency echosounders alone, surveys of acoustic backscatter can provide indicators of fish density to direct additional research.

Methods

Study Overview

To evaluate the efficacy of using a glider with acoustic sensors to detect fish abundance, it was important to

choose a study region able to be standardized and included at least some known habitat. To do so, we selected an area which included ~70 km along the Gulfstream Natural Gas pipeline (GNGP), from the 30–50 m isobaths in the eastern Gulf of Mexico. The GNGP originates in the northern Gulf and traverses SE and into Tampa Bay and is known to provide habitat for important bottom fish species (Figure 1). The pipeline's presence on the bottom can be categorized in several ways: completely covered with sand; partially submerged with or without rock piles alongside; and sitting up on top of the seabed fully exposed, again with or without rock piles alongside.

In addition, there are areas of natural hard bottom in proximity to the pipeline, all of which provide habitat for red groupers (*E. morio*) and American red snappers (*Lutjanus campechanus*), our target species for acoustic telemetry. These species were selected based on their role as an important fishery in the Gulf of Mexico and because they exhibit high site fidelity (Coleman et al., 2011). Red groupers were also targeted because they are known to make distinctive sounds that can be picked up by both fixed and glider-mounted passive acoustic recorders (Nelson et al., 2011; Wall et al., 2012, 2014). Red snappers are not known to produce sounds.

In choosing this region for a glider path, the study area has the advantage of traversing well-documented diverse artificial habitat as well as the surrounding region, which is less understood. This provides an opportunity to understand the performance of the sensors cost effectively, within the glider's designed capabilities, and in a manner consistent with how sustained

glider observations may be applied in an observing system capacity.

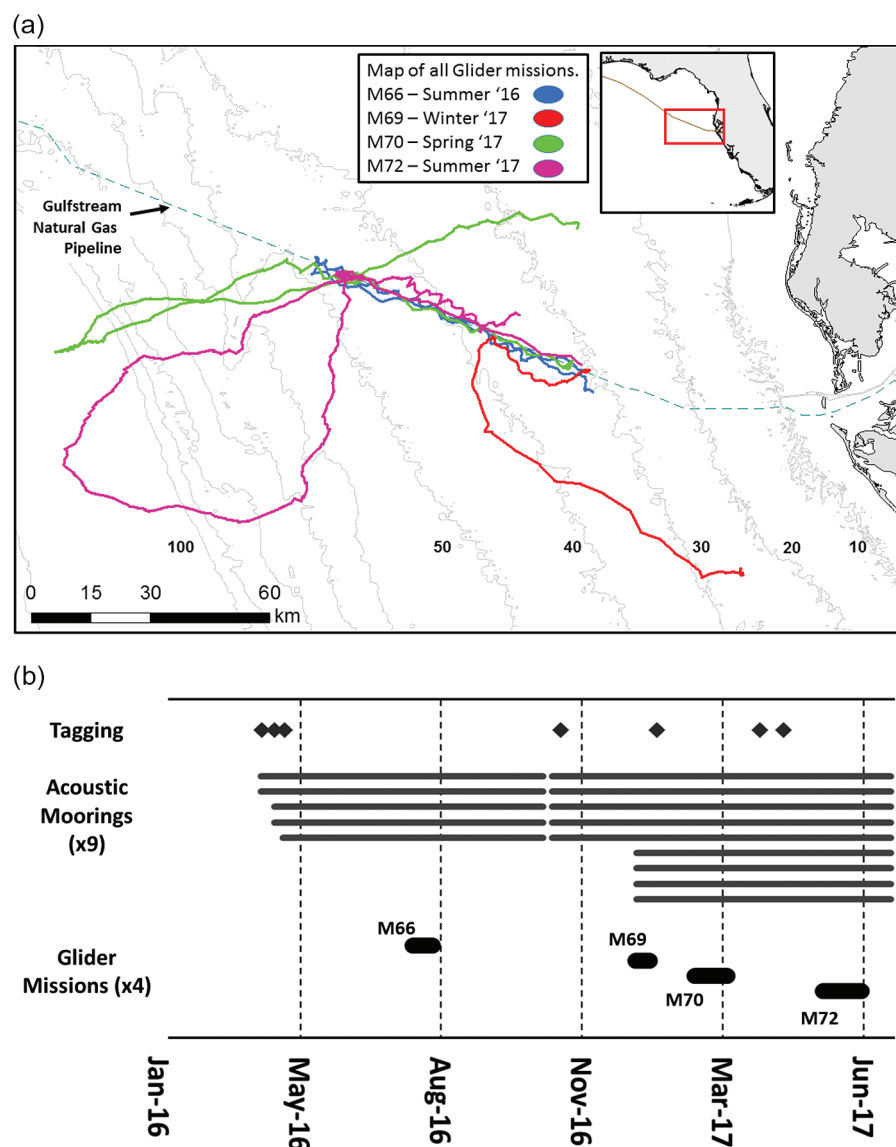
Subsurface Glider

A Slocum Electric G1 200-m glider manufactured by Teledyne Webb Research and owned by the University of South Florida's College of Marine Science was equipped with a standard alkaline battery pack for each of the

four deployments. The intent was for the glider to traverse the pipeline region. The biggest challenge to this piloting strategy was the occasional currents that were stronger than the glider's maximum speeds. During the deployments, flight and oceanographic variables were monitored for performance. For these deployments, the glider was equipped with a Seabird

FIGURE 1

(a) Tracklines of all glider missions relative to the pipeline. (b) Timeline of fish-tagging activities, deployments and recoveries of the acoustic moorings, and glider deployments. Breaks in the mooring data sets are exaggerated for clarity, actual time with mooring out of the water was less than an hour per mooring.



Conductivity, Temperature, and Depth sensor (CTD), WETLabs fluorometer (Chlorophyll, CDOM, bb @ 650 nm), Aanderaa dissolved oxygen optode, and at least three acoustic sensors: one or two Loggerhead Instruments passive acoustic recorders, a VEMCO Mobile Transceiver (VMT) tag telemetry receiver, and an ASL Environmental Sciences AZFP water column echosounder operating a single-frequency single-beam 200-kHz transducer (Figure 2). Acoustic data sets could only be analyzed upon retrieval of the glider. Prior to the deployment each sensor was synchronized to Coordinated Universal Time (UTC) time to ensure timestamps across sensors and platforms could be matched. For the majority of deployments, the glider was programmed to surface on 3-h intervals. For positioning, the glider obtained a fresh GPS fix prior to submerging and again when it surfaced prior to transmitting through satellite. Glider subsurface positions between each 3-h surfacing were inter-

polated as linear. The four glider deployments discussed here are labeled M66 (summer 2016), M69 (winter 2017), M70 (spring 2017), and M72 (summer 2017), and are shown in Figure 1.

Acoustic Telemetry

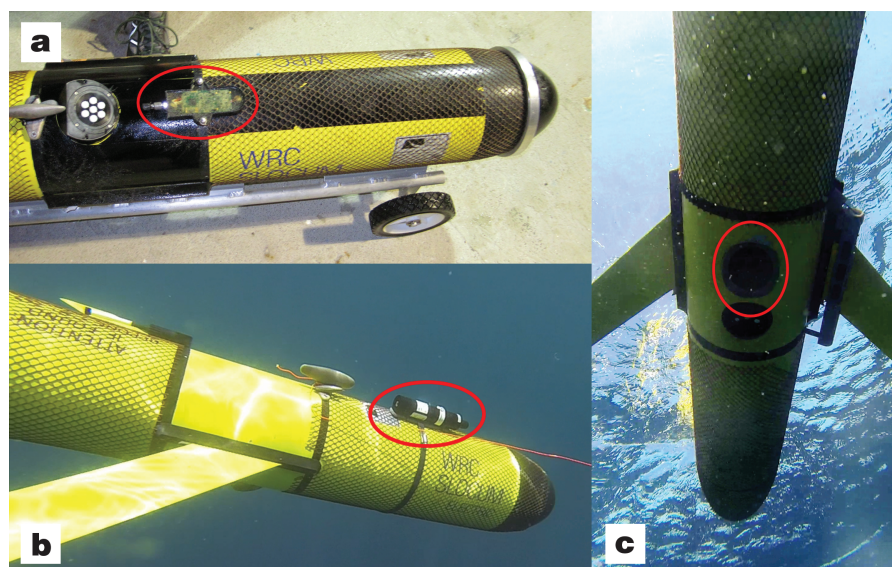
A total of 61 fish were implanted with Vemco acoustic tags (V13P L power, 968 d battery life, interpulse delay 60–180 with a mean of 120 s) from April 2016 to April 2017. This included 27 red groupers and 34 red snappers (Table 2). All fish were captured at locations close to the pipeline with hook and line and implanted with acoustic tags following the surgical process described in Lowerre-Barbieri et al. (2016). Releases were conducted with a seaqualizer to return fish to depth and video-recorded to assess the fish's health and if there was post-release predation. No predation events were observed. All red groupers and 29 of the red snappers were captured at a total of five natural hard-bottom sites

in proximity to the pipeline (<1 km). In addition, on April 18, 2017, five red snappers were captured and released directly on the pipeline to broaden the locations of fish tagged and see if site fidelity varied between the mooring locations and a pipeline location. Acoustic release receivers (Vemco VR2-AR) with passive acoustic recorders (to record courtship sound) were deployed at each location tagged fish were released ($n = 5$). These receivers also emit a signal every 10 min. In addition to the five acoustic receivers moored at release sites, four additional receivers were deployed in January 2017 between two of the permanent receivers to allow for finer scale monitoring. Telemetry data from the moored receivers were filtered to remove potential spurious detections ($n = 1$), which were defined as fish detected only on a single date with fewer than five detections. On the glider, a VMT was attached externally to the top of the hull using a band clamp and bracket (Figure 2b).

To assess the glider's efficacy at detecting the tagged fish within the tagging region, we had to first filter the moored detection data set for those times when the glider was in the area. Because the number of tagged fish at these sites varied with date, rather than assessing the number of detections, we assessed the number of unique transmitter signals (from tags implanted in fish or from the receivers) that were detected by either moored receivers or the glider. Because the AUV is moving, it was hypothesized that paths designed to increase the time spent in range of the receivers would increase detection efficacy. To assess this, we used linear regression to assess if the proportion of unique transmitters detected by the glider versus those in the area (determined

FIGURE 2

Slocum glider equipped with the following acoustic technologies: (a) an externally mounted passive acoustic recorder, (b) tag telemetry receiver, and (c) water column biomass echosounder.



by the moored receivers) increased with increased time in the area.

Passive Acoustic Recorders

A Digital Spectrogram Recorder (DSG) passive acoustic recorder (Loggerhead Instruments), which had been previously integrated into the glider (Wall et al., 2012), and an externally mounted Remora recorder (Loggerhead Instruments; Figure 2a) were used during this study. The DSG board was housed internally and powered by the glider batteries and the hydrophone (HTI-96-min sensitivity: $-170\text{dBV}/\mu\text{Pa}$) was integrated into the flooded aft cowling of the glider. The DSG recorded with a duty cycle of 1 min every 5 min with a sample rate of 50 kHz onto a 32-GB SD card. We also tested a self-contained acoustic recorder potted in epoxy that used a Soundtrap board (Ocean Instruments NZ) and spherical piezoceramic (Loggerhead Instruments). The Remora was powered by an internal lithium polymer battery (3.7V, 2500 mAh) and set to record for 1 min every 5 min at a 96-kHz sample rate. The Remora was mounted to the top surface of the glider with screws to mounting holes on the glider.

Fixed station recorders were deployed with the telemetry receivers and consisted of the same Soundtrap board as the Remora with a 128-GB microSD card that was powered by a rechargeable lithium polymer battery (3.7 V 850 mAh) and a primary lithium battery (3.6 V SAFT LS or LSH 20 Ah). The hydrophone was made from a spherical piezoceramic ($-211\text{dBV}/\mu\text{Pa}$; full-scale system sensitivity: $-178\text{dB re } 1\mu\text{Pa}$). Fixed recorders were set to record on a duty cycle for 1 min every 20 min at a 96-kHz sample rate. The duty cycle was selected so that the fixed recorders

would be able to run for 1 year. However, there was an issue with firmware shutting down recordings prematurely due to low voltage on all but one of the recorders, so only one full year cycle was recorded. This full year cycle was analyzed for this project.

The acoustic recorder data were analyzed with a combination of automated and manual analyses. A MATLAB (The MathWorks) script was written to identify potential red groupers sounds by comparing the energy in the red grouper band (40–300 Hz) to a reference band (600–900 Hz). A red grouper sound was detected if the red grouper band sound level was 3 dB greater than the reference band for between 0.6 and 2.5 s. The reference band was used to minimize false detections from glider rudder adjustments that covered a wider frequency range than red grouper sounds. Three decibels was selected as a low level that would enable detection of low amplitude red grouper sounds. For the glider, due to false detections of background noise, recordings of all potential red grouper sounds were manually inspected by plotting a spectrogram of the identified signals. For fixed recordings, after analysis of 100 signals showed no false detections, the data were analyzed entirely automatically.

Echosounder

The ASL Environmental Acoustic Zooplankton and Fish Profiler (AZFP) was integrated with the Slocum ocean glider as described in Taylor and Lembke (2017). The glider provided power, acquisition parameters, and clock synchronization, whereas the AZFP returned status and cumulative number of transmitted pings. The AZFP echosounder operated at a single frequency of 200 kHz

using a single beam 7° transducer. The transducer and AZFP received a calibration by the manufacturer using a standard hydrophone and calibration sphere of known target strength. The transducer was installed into the glider science bay and pitched forward 22.5° so that it would transmit downward and vertically when the glider was descending. The glider was then programmed to descend at a 22.5° angle. The AZFP transmitted short pulses (pulse length = 150 μs) at 1 Hz, logging data to 100-m range from the glider on glider descent. The AZFP was put into sleep mode during glider ascent. Files were logged for each hour and stored on the AZFP hard drive. Data were downloaded and processed upon recovery.

Data from the summer 2016 (M66), winter 2017 (M69), and summer 2017 (M72) were analyzed; the transducer failed during spring 2017 mission (M70), and data were not suitable for analysis. AZFP binary data files were read into Echoview (v. 8.0, Echoview Pty Ltd.). Position, attitude, and depth from the glider mission logs were used to (1) georeference acoustic backscatter, (2) convert acoustically measured range of targets and the seabed to depth below water surface, and (3) filter data using pitch information to eliminate unwanted and noisy data when the glider was at the surface or when the glider was initiating an ascent and angle when the transducer was not vertical. Salinity, temperature, and depth from the glider CTD data were used to calculate average sound speed and sound absorption for the 200-kHz transmission. The bottom was delineated using a seafloor picking algorithm by identifying the peak amplitude of the echo representing the seafloor, with a 0.2-m backstep to exclude noise associated with the

seafloor. Fish in contact with or in proximity to the seafloor may be occluded by an acoustic deadzone, a range from the seafloor related to transducer beam angle, pulse length, and roughness of the seabed. Ringdown from the transmit pulse, another property of the transducer frequency, pulse length, and beam angle that makes data close to the transducer unusable was excluded using a forward step of 0.3-m range from the transducer.

Acoustic backscatter in the water column was visible and qualitatively characterized as low-level system noise, plankton layers, and fish. Thresholding was performed on the data to exclude plankton and include fish that were observed in two general patterns of distribution: individual targets and compact schools. Individual point targets were delineated using a single-target detection algorithm with a target strength threshold of -55 dB. Sequential single targets from neighboring pings and likely from a single fish were accumulated into a fish track using a target-tracking algorithm with conservative parameters: requiring a minimum of three pings without gaps, weighted by minimal changes in depth. Each fish track was stored in a database including geographic position of the glider at detection, depth below water surface and target strength (in decibels). When fish form groups, it is not possible to discern individuals. Fish schools were delineated using a school detection algorithm on selected regions of the echogram appearing to be fish schools using a threshold from background of -60 dB. Each school was entered into a database with geographic position, depth, and acoustic backscatter or indicators of density. The regions associated with individual fish and schools were used to mask the

original echogram to eliminate the remaining backscatter from electrical noise from glider operations and non-fish-related backscatter from bubbles or plankton. Resulting backscatter was exported as Nautical Area Scattering Coefficient (NASC) in units of $\text{m}^2 \text{nmi}^{-2}$, accounting for beam spreading and depth (MacLennan et al., 2002; Simmonds & MacLennan, 2005) in 50-m distance bins along transect and mapped along the glider mission transect to visually interpret spatial patterns relative to the other acoustic data streams. The magnitude of backscatter NASC is a proxy for biomass of fish but does not account for fish size in this analysis. Backscatter from the entire water column was logged, but only the bottom 10 m are reported here, representing demersal fish associated with benthic habitats like the pipeline.

Analysis was performed on each mission to identify significant clusters of higher (or lower) acoustic biomass along the glider mission path. The Getis-Ord G_i^* statistic was calculated in ArcMap with Spatial Analyst Extension (ESRI, Version 10.5) using the NASC response variable and Euclidean distance based upon latitude and longitude positions of the glider for each interval bin. The statistic measures the local sum of features and neighbors to compare proportionally to the sum of all features. A z -score record the relative difference between the local and global sums, with magnitude of the z scores displayed as probabilities (p values) according to significant clusters of high (or low) NASC acoustic biomass.

Results

The acoustic data sets collected in 2016 and 2017 include data collected on glider-mounted sensors for all three

acoustic measurements and moored data for passive acoustic telemetry and PAM. A timeline of the data set collection is shown in Figure 1b. Moored data sets include acoustic tag detections over the time the receivers were in place, as well as one continuous passive acoustic recording set analyzed for biological sounds of red groupers. Each glider-based acoustic data set was merged with glider positioning estimates to determine the location of the acoustic data. Glider data sets include acoustic tag detections of fish and receivers, passive acoustic recordings, and water column echosounder backscatter. Gaps for the acoustic data through these missions were limited to the following: M66 contained no passive acoustic recordings due to an instrument failure, M69 did not reach the tagging region and developed a failure with the echosounder transducer, near the end of the deployment and M70 contained no usable echosounder data. M72 contained full data of all three sensors (Table 1).

The first glider deployment was conducted 3 months following the initial fish-tagging effort in the summer of 2016 (M66), with subsequent deployments in the winter (M69), spring (M70), and summer of 2017 (M72) (Figure 1). Three of the four efforts successfully traveled along the pipeline, and two loitered within the tagging region. The first deployment traversed the tagging region on both the offshore and onshore legs, without attempting to control the glider transit relative to the acoustic moorings. The third and fourth deployments loitered around the acoustic moorings for over a day on each of the offshore and onshore transits. In addition, these deployments went well beyond the tagging region and traversed offshore to the shelf break and back as part of

TABLE 1

Glider collected acoustic data sets collected during five glider deployments between summer 2016 and fall 2017.

Mission	Dates	Days Along Pipeline	Hours in Tagging Region	PAM	Tags	WCA
M66	07/29/16 to 08/12/16	14	51	N	Y	Y
M69	01/03/17 to 01/13/17	2	0	Y	Partial	Partial
M70	02/14/17 to 03/09/17	7	89	Y	Y	N
M72	05/16/17 to 06/12/17	15	103	Y	Y	Y

PAM, passive acoustic monitoring by glider; Tags, tag telemetry receptions; WCA, water column acoustical biomass estimations.

the month long deployments. The second deployment was pushed significantly south by strong currents resulting from a frontal system moving through the region after spending just 2 days inshore along the pipeline. Table 1 details the deployment schedule and number of glider days within the vicinity of the test region as well as number of hours within the fish-tagging region.

Acoustic Tag Telemetry

Over the study period, the moored receivers detected 55 of the 56 fish tagged and released on hard-bottom sites with a receiver deployed at the release site (Figures 3 and 4, Table 2). The other five tagged snappers released directly on the pipeline were not detected by the moored receivers at all. The mean number of detections per fish was 56,199 and ranged from 41 to 210,379. The mean number of detections by the glider-mounted receiver per fish, as expected, was significantly lower; 7.6 with a range of 1–29 detections. While at a much lower rate of pings, over the life of the project, the glider detected 68% of all fish tagged, including three of the five fish released on the pipeline without a moored receiver at the release site. As can be seen in Figure 4, although the moored receivers detected almost all the fish, those fish were

not always being detected when the glider actually passed through the tagging region, so it may be possible that some of these fish had moved outside the study region or been removed by the time the glider transited within detection range.

When the glider path was programmed to repeatedly pass through the area with the tagged fish, the number of fish detected increased (Figure 5), and this relationship was significant (linear regression, $n = 11$, $p = 0.0037$). The number of fish detected by the glider increased from

less than 20% when the glider was piloted without loitering to over 50% with loitering in the tag region. The glider detected none of the tagged fish more than a kilometer outside the tagging region, though no significant attempt was made to ascertain migration of the fish by loitering at a distance from the tag and release areas.

Passive Acoustic Monitoring

The passive acoustic recorders on the glider detected red grouper sounds mostly along the pipeline, including in the area of red grouper tagging

FIGURE 3

Predicted locations of glider at telemetry detection timings of red groupers (blue circles), red snappers (red circles), and moored receiver pings (brown triangles, receivers represented by yellow circles) by glider-mounted telemetry receiver at the sites along the pipeline where fish were tagged.

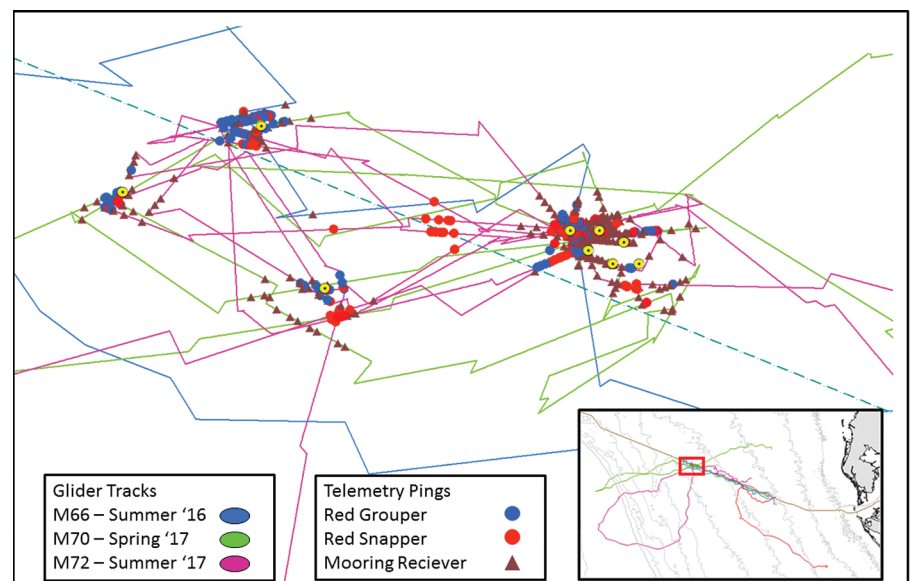
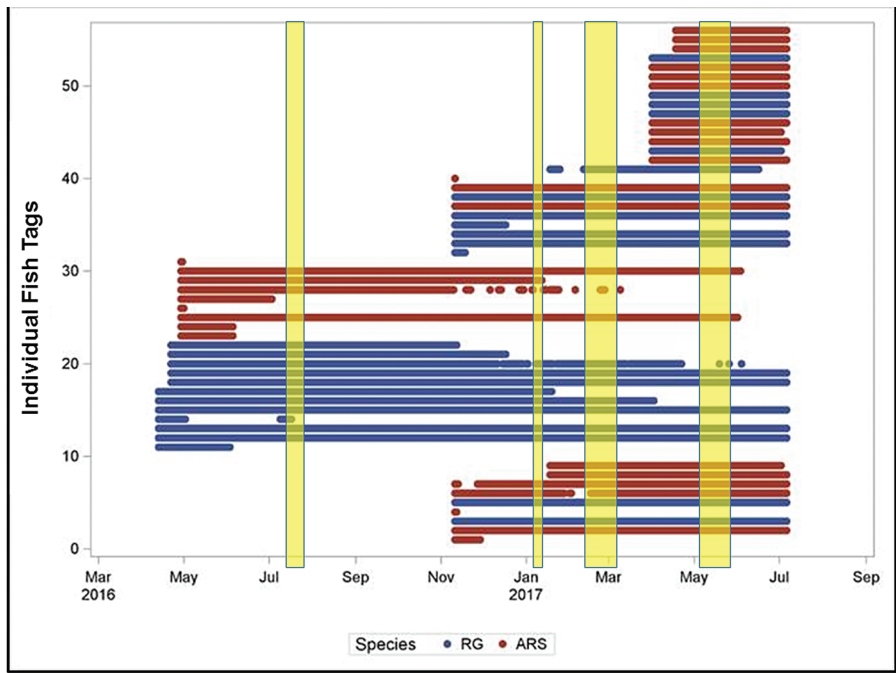


FIGURE 4

Detections of tagged red groupers (blue) and red snappers (red) by any of the moored telemetry recorders over the duration of the effort demonstrating the presence of these fish within the tagging region through the test period including glider deployments. Yellow overlay represents times glider was deployed, though actual time within the tagging region is a fraction of those periods.



(Figure 6). Two glider missions had both an externally mounted acoustic recorder and an internal recorder with a hydrophone in the aft tail section. Detections from these recordings showed that the aft recorder picked up more red grouper sounds (M69:

aft recorder estimated 1,275 total, hull-mounted recorder estimated 540; M70: aft recorder estimated 2,300 total, hull-mounted recorder estimated 850). It should be noted that the external and internal recorders were not synchronized in their recording schedule.

TABLE 2

Summary of fish-tagging efforts.

Date	Red Snapper	Red Grouper	Total
4/13/2016	–	7	7
4/22/2016	–	5	5
4/29/2016	9	–	9
11/11/2016	8	8	16
1/18/2017	2	2	4
4/1/2017	7	5	12
4/18/2017	7	–	7
4/18/2107	1	–	1
Total	34	27	61

The moored passive acoustic recorder located with the acoustic tag receivers showed that red groupers produced sounds throughout the year (Figure 7a). There was up to a six-fold variability in average daily sound production, but with no obvious seasonal variability. Calls were detected every day. There was a diel periodicity in the average number of calls per hour, with a peak at 1700 h ET (Figure 7b).

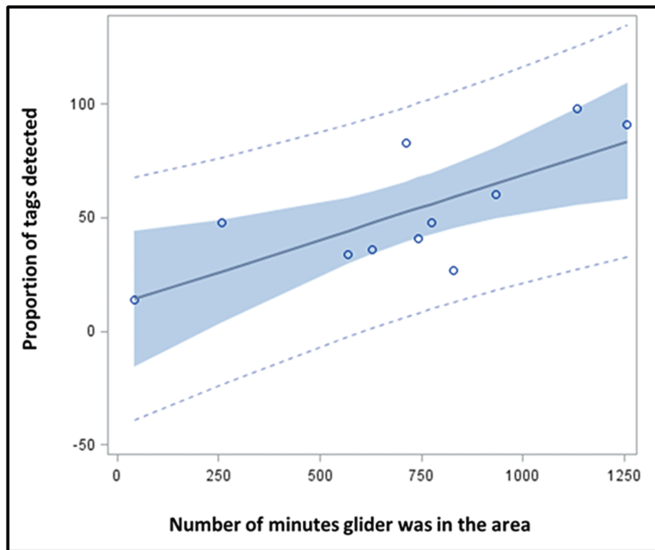
Echosounder

Only data from M66, M69, and M72 were used for analysis, M70 data were not useful due to a transducer failure. Acoustic backscatter in the water column comprised mid-depth scattering layers likely representing plankton, along with individual fish and fish schools near the seafloor. Inspection of echograms from each mission showed varying levels of background noise caused by glider mechanical or electrical systems (Figure 8). The glider system noise may mask some low-level backscatter from small plankton, but backscatter from the individual fish and fish schools appeared well above the signal to noise minimum for detection at 100-m range limit for this study. There were no problems with the echosounder ping interfering with the passive acoustic recordings or acoustic telemetry receivers, because the echosounder signal is at a much higher frequency than the red grouper sounds or telemetry tags utilized.

Fish schools were sparsely distributed along the glider path during M66 (Figure 9a). Analysis detected several clusters of high acoustic biomass. Two such clusters were detected within 20 m on an outgoing and returning path in proximity to the pipeline, 6 days apart. Other areas if high biomass were almost 3 km away

FIGURE 5

Comparison of fixed receiver and glider-mounted receiver for fish detections. The glider consistently detected fewer receivers and fish than the moored receivers, but performance improved with piloting the glider to loiter in the tagging region for longer periods of time.

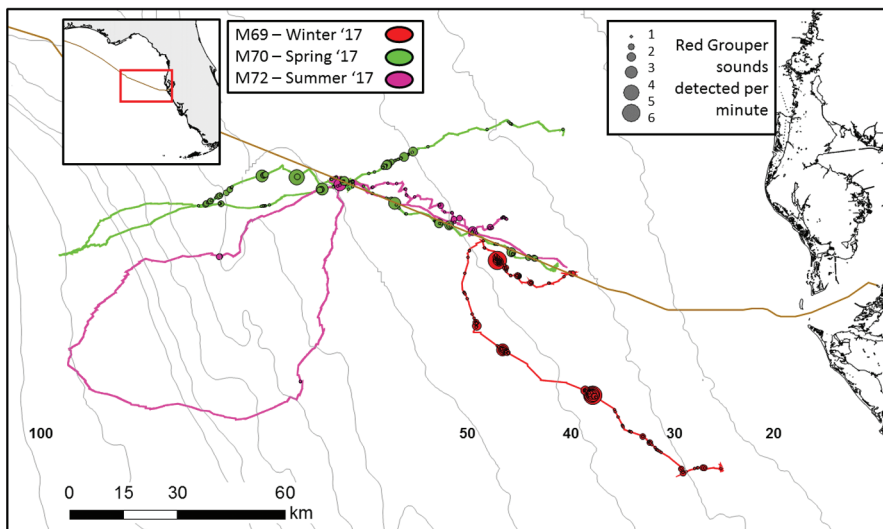


from the pipeline. M69 did not traverse the full extent of the pipeline focus area (Figure 9b). Overall, very low acoustic densities were observed during this entire mission. This mission also occurred during the winter and may represent a relatively low

occupation rate by fish in the region. This mission was not analyzed further. M72 had a low level of density along much of the mission. But analysis identified areas of high biomass that were in proximity to the pipeline. The pattern of distribution in these

FIGURE 6

Passive acoustic monitoring results from glider. All missions for entire tracks and area corresponding to location where fish were tagged for telemetry (inset); larger bubbles indicate more grouper calls recorded.



areas was clearly delineated fish schools close to the seafloor and extending for 10 s of meters in length (Figure 9c). Closer inspection of the areas of clusters also revealed large schools of fish close to the seafloor.

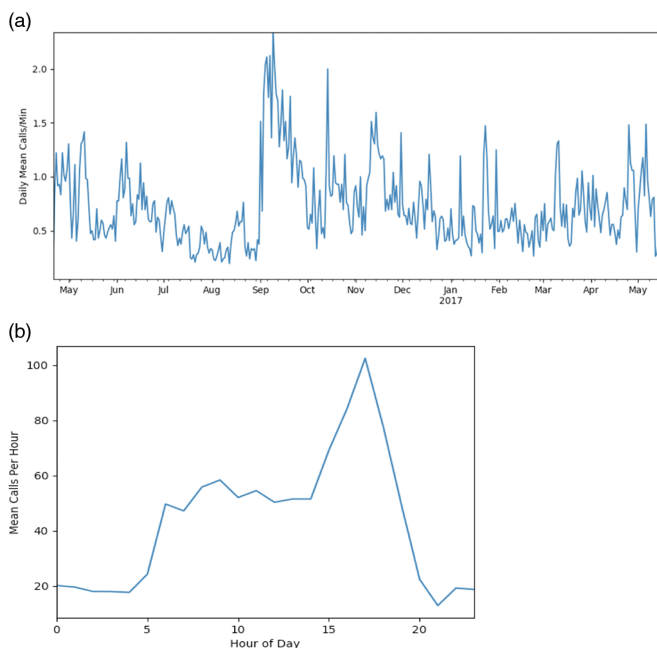
Discussion

This project showed it was possible to integrate three complementary acoustic technologies to map fish distributions, acoustic telemetry, PAM, and calibrated echosounder biomass. All three glider-mounted technologies identified congregations of fish along the pipeline region and the combination of the specific data sets provided additional context; for instance, increased grouper sounds and water column biomass were both seen within the regions where fish were tagged and repeatedly detected. Additionally, the PAM and echosounder backscatter provided areas with red grouper detections and biomass congregations throughout the deployments, including areas away from known structure.

Challenges that led to partial data sets from each of the individual data sets from the glider were resolved by the last deployment, specifically the failures of the PAM during one mission resulted in using two recorders for the remainder of the deployments and the transducer failure of the echosounder was resolved by replacement from the manufacturer. Glider piloting was adjusted during the project to increase coverage and time spent within the tagging region, which resulted in a larger percentage of the tagged fish being detected and more comprehensive passive acoustic and echosounder data sets. This versatility in designing the glider deployments may be beneficial to some studies. Continued research with each of these technologies and

FIGURE 7

Variability in red grouper sound production at a fixed receiver located along the pipeline. (a) Time series of the daily average of calls per hour at one location. (b) Mean daily calls per hour shows that calls are most commonly produced at dusk (Eastern Time).



combinations with other sensors that can be achieved on gliders should be encouraged.

This project provides some comparisons between moored and mobile platforms. A single moving platform like a glider has an advantage over an array of moored receivers or recorders due to its ability to traverse large distances, allowing greater context about where fish may move and the water column dynamics that may impact such movement. Yet moored systems have a significant advantage when researching daily trends or processes needing continuous monitoring. Even though a glider could be piloted to loiter for weeks to months at a time in a specific region to mimic a mooring, the cost effectiveness would need to be considered and may compromise some of the advantages of larger scale surveys that a glider is capable of. Additionally, the moored equipment had better detection capabilities than

the equipment on the glider, likely due to glider noise and sensor placement.

Some comparisons can also be drawn to shipboard operations with these acoustic technologies compared with gliders. With biomass echosounders, shipboard methods present obvious advantages of additional frequencies and more powerful equipment with better capabilities. Yet the cost of ship time, at-sea duration limits, and potential foul weather hindrances may balance this in some applications where the glider is more cost effective and the data collected can achieve research objectives. As glider use has evolved, studies of their effectiveness at ascertaining large- to moderate-scale patterns has been demonstrated to often be as effective as using manned ships for some data sets, such as repeated CTD profiling transects (Rudnick & Cole, 2011). It is likely that similar transecting on a repeated and systematic basis while

collecting these acoustic data sets will provide valuable information about congregations and patterns of movement at a cost well below the utilization of ships.

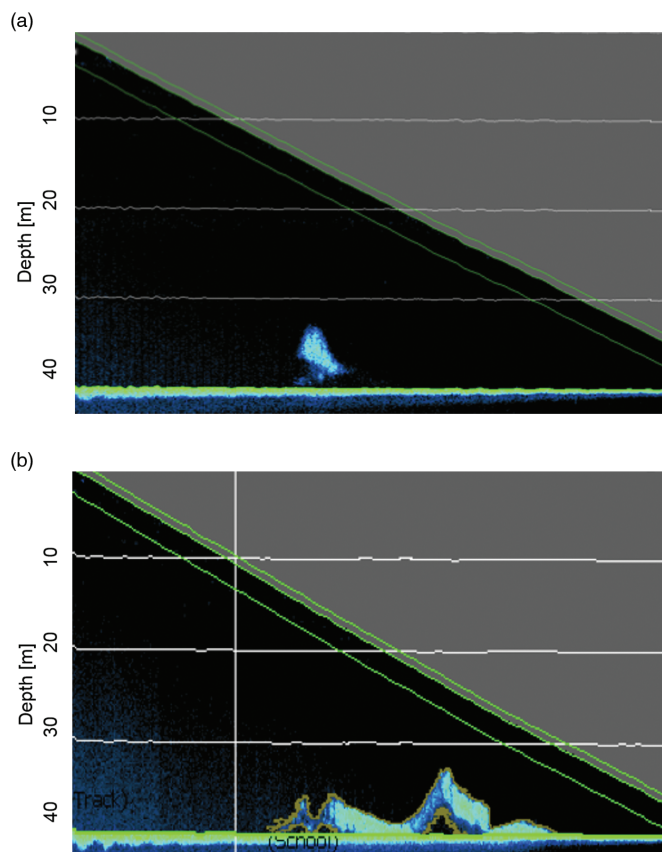
Overall, the acoustic telemetry detections by the glider of other receivers and fish were fewer than the bottom-moored receivers. This could be due to several factors. Red groupers and red snappers tend to be associated with the bottom where the fixed acoustic receivers were located, while the glider is in the water column, sometimes at the surface 45-m away or more. Surface and bottom reflection characteristics and the mounting of the VMT to the glider respective to shadowing of the tags could be significant. And it is known that there can be a reduced range of the VMT in noisy conditions; even just the flow of water past the transducer at 0.25 m/s may contribute to reduced effectiveness (per vendor communication). However, it is not likely cost effective to put fixed receivers over the same scale that the glider is able to traverse, so fixed receivers and glider-mounted receivers are complementary.

The PAM showed higher red grouper sound detections in the flooded aft cowling versus on top of the glider. This is likely due to acoustic shadowing by the glider or differences in mechanical or environmental noise (again water flow) received by the two hydrophones. In comparing glider detections to moored receiver detections, no discernable link to any seasonal or diurnal patterns indicate that the deployment schedule impacted the glider results in a significant way. However, with a sample size of only four deployments, this may eventually become more noteworthy as more data are collected.

Although the tag telemetry and passive acoustic hydrophones receive

FIGURE 8

Example echograms show fish schools close to the seafloor along a glider dive. Both also show faint and easily discernable background noise from glider mechanical or electrical systems in the lower left of the echogram.



signals from a sphere around the glider, the echosounder uses a narrow beam to transmit and receive echoes, which gives a much smaller search volume for biological sources. The echosounder provided indicators of biological biomass throughout the water column along the mission. Fish schools were observed along several glider tracks, with some notable increases with the glider passing over the pipeline, as well as some off the pipeline, possibly representing structured reef habitats. Integrating an echosounder on the glider enables surveying large areas on longer missions than typically covered by ship, though at a slower speed. Echosounder-integrated gliders have been used to survey biomass of large

swarms and patches of Antarctic krill (Guihen et al., 2014). The narrow beam of the echosounder transducer (nominally 7°) samples a very narrow swath of the water column, showing a limitation of the sensor in detecting fish biomass for sparsely distributed individuals or schools. However, in this study, we demonstrated the ability to detect both individuals and schools in the water column.

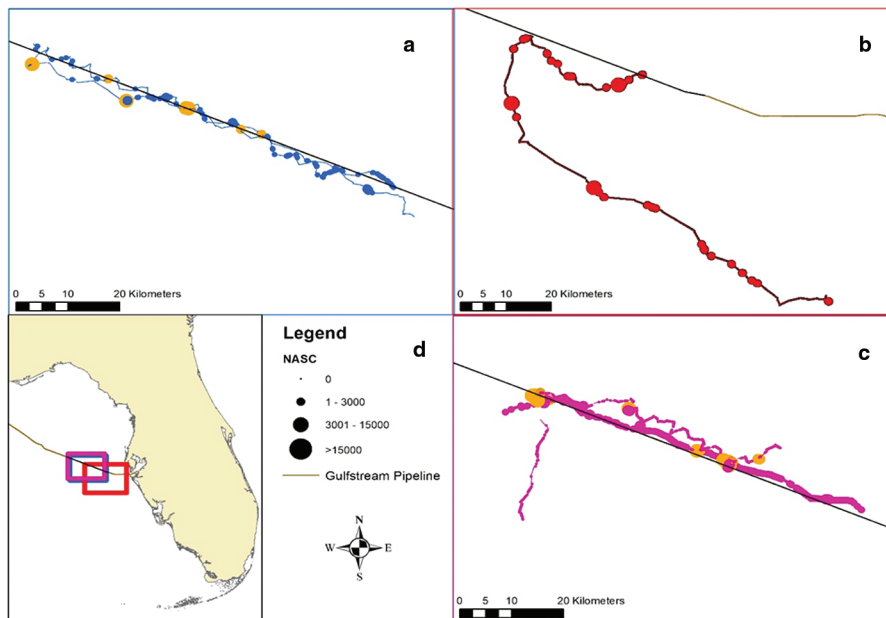
One other significant advantage of the glider is the other environmental variables being simultaneously collected, providing better context into circulation patterns, water column structure, and possibly even environmental health of regions. For instance, persistent monitoring as

done in this study could prove highly valuable in analyzing fish response to the effect of an event such as an oil spill, red tide bloom, hypoxia event, tropical storm passage, etc. It is envisioned that performing these types of deployments could develop a time series capable of observing seasonal and yearly trends, which could provide the baseline understanding needed to understand the effect of certain events. During these deployments, CTD, fluorometer, and dissolved oxygen variables were collected but not presented here.

Several adjustments to the equipment and operational scope may prove beneficial to increase detection rates of glider attached instrumentation. For instance, mounting locations for both the acoustic telemetry receiver and passive acoustic recorders could be adjusted to attempt to improve their effectiveness. Larger battery packs for the PAM for longer recording times should increase detections missed due to duty cycling. Optimization of glider path, especially in and around tagging areas, proved very effective with limited experience, but further optimizations along the entire transects could provide better context to fish distributions and movements for certain applications or species, especially if seafloor habitat or other environmental conditions enable justification for such. For instance, with minimal effort and glider time spent, a survey of the region surrounding the tagging region may have provided context for fish that may have migrated locally. Lastly, this effort makes no attempt to quantify fish response to glider presence. This could be a source of bias worthy of future study, but in the authors' opinion, the glider is an unlikely disruptor of natural fish behavior due to the slow speed, low noise, and generally passive environmental interaction.

FIGURE 9

Acoustic density values along path of glider for M66 (a), M69 (b), and M72 (c). Insets in map (d) show location of bounding boxes for each mission. Acoustic density (in NASC, a proxy for fish biomass) is represented by dots of varying size proportional to the NASC value at each interval. Significant clusters of high density are colored orange-red.



In summary, even at the current state of the technologies, useful data sets have been collected on an operational level that can benefit greatly from sustained and repeated glider deployments with fisheries-specific acoustic packages. The advantages of autonomous systems like gliders that can enable cost effective, systematic, water column observations that directly and indirectly are related to fish populations, regardless of the weather, sea states, and environmental conditions, make the platform worthy of future consideration and refinement. Building on studies like these, we foresee gliders playing an increasingly important role in providing fishery independent data important to management.

Acknowledgments

The authors thank Steven Murawski, Alex Silverman, Steven Butcher,

Heather Broadbent, Gerardo Toro-Farmer, Edmund Hughes, Sarah Grasty, Robert Weisberg, Yonggang Liu, Chuanmin Hu, Joel Bickford, Sarah Walters Burnsed, Hayden Staley, Jordie Bergman, Matt Garrett, Kathleen Hubbard, Michael Hall, Todd Kellison, Matt Howard, Robert Currier, Matthew Campbell, Captain Edward Walker, Captain Jon West, Captain Branden Baumeister and the Crew of the *R/V Weatherbird*, Chris DeCollibus, Ben Allsup and all of Teledyne Webb Research, Jan Buermans and all of ASL Environmental, Denise King and all of Vemco, and Mote Marine Laboratory for their technical and operational assistance, scientific guidance, and institutional support.

We also thank the reviewers for their time to generate feedback which helped the manuscript's presentation.

Funding for the effort was provided by the Florida RESTORE Act Center

of Excellence Program (FLRACEP) Grant RCEGR020002-01-00 and the NOAA Fisheries Advanced Sampling Technology Working Group Grant NAI4OAR4320260. Institutional support was provided through FWRI and Grant F-59 from the U.S. Fish and Wildlife Service Sport Fish Restoration program and the State of Florida to the University of South Florida.

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