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**Integration of Three Acoustic Technologies on Underwater Gliders to Survey Fish**

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**Abstract (150-200 words)**

It is challenging to collect fisheries independent measurements of species distribution and biomass over large areas of the ocean. One tool for making these measurements are underwater gliders that are capable of making large scale surveys.The purpose of this project was to integrate and simultaneously test three complementary acoustic technologies for mapping fish using an underwater glider: active acoustic tags, passive acoustics, and echosounder surveys. We tagged red grouper (*Epinephelus morio*) and red snapper (*Lutjanus campechanus*) with active acoustic tags near the pipeline in the Gulf of Mexico near Tampa Bay, FL. We deployed the glider seasonally and compared detections of fish at moored acoustic receivers and a passive acoustic recorder located in the same region. For the active acoustic tags, the glider detected fewer signals from tags co-located with receivers on the bottom. The glider detected about 70% of the red grouper, while the fixed stations detected 9x%. Red grouper sounds were detected for each glider deployment at the tagging site, as well as at distant sites where red grouper were not tagged. All three technologies identified hot-spots of fish along the pipeline, thus they can be used to identify areas that merit deeper investigation.

**Introduction**

There is significant interest among federal, state, academic and private research scientists in developing new fishery-independent sampling systems to assist resource managers. Fisheries based applications for gliders to date have been exploratory, but are evolving. In recent years, three types of acoustic sensors have been incorporated that can provide data directly applicable to fisheries assessments: passive acoustic recorders, acoustic telemetry receivers, and echosounders. By demonstrating the utility of these data and the cost efficiency of utilizing gliders to obtain them, these sensors can become part of the broader observing infrastructure in the future, potentially at a national level.

Autonomous underwater gliders are robust, proven platforms designed for water column data collection. In typical use, gliders profile from the surface to depth repeatedly using buoyancy and attitude adjustments to propel themselves at horizontal speeds of 0.7 to 1 km/h (Rudnick et al. 2004). They stay deployed for weeks to months at a time, traversing 100s of km, working when and where it 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 efficiently collect water column density data, they are increasingly being incorporated into the national observing system backbone (IOOS 2014, Testor et al, 2009). Sustained glider operations, with nearly continuous coverage in regions such as southern California have by now lasted over a decade (Johnston and Rudnick, 2015).

The purpose of this project was to integrate and simultaneously test three complementary acoustic technologies for mapping fish using an underwater glider. By adding these sensors to gliders fisheries independent data can be collected that complements ongoing research and assessment surveys conducted by federal and regional management agencies. To demonstrate the utility of this approach, we selected a test area, tagged fish, seasonally deployed the glider in the region, and moored acoustic receivers and passive acoustic recorders in the same region for comparison purposes.

In this study we tagged red grouper (*Epinephelus morio*) and American red snapper (*Lutjanus campechanus*). These species were chosen because they support important fisheries in the Gulf of Mexico and because they exhibit high site fidelity (Coleman et al.2010). Red grouper 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; Wall et al. 2014). Red snapper are not known to produce sounds.

Acoustic telemetry is the most widely used technology for tracking in the marine realm (Hussey et al. 2015). Acoustic transmitters emit a signal, which when in range of a receiver, is detected. Tag range varies with habitat, due to signal blockage, ambient noise, and currents, amongst other things. Tracking is most commonly achieved through the deployment of autonomous receivers at known locations (Heupel et al. 2006) but can also be done manually or with mobile platforms such as AUVs (Oliver et. al. 2013), which allow for detections in areas difficult to monitor with fixed stations. Tags are most commonly attached to animals through surgical implantaton 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 tracking have been used to inform a wide range of processes important to fisheries management, including stock structure, invasive species, the efficacy of MPAs, spawning frequency and mortality (Young et al., 2013, Hernandez et al., 2013, Lowerre-Barbieri et al., 2014; Crossin et al. 2017). The use of passive acoustic monitoring (PAM) to monitor soniferous fish has been well demonstrated. Red grouper produce a distinctive species-specific sound throughout the day and night (Nelson et al., 2011, Wall et al., 2014). We have used an array of fixed passive acoustic recorders and recorders on gliders to study the distribution of red grouper sounds produced by other fishes over very large spatial scales (Wall, 2012). These efforts have resulted in spatial and temporal maps of grouper and a number of other fishes. In essence, the sounds produced by red grouper 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 throughout the water column over a continuum of spatial scales (cm to km). Adapting echosounders for use in autonomous platforms like ocean gliders is relatively new (Guihan et al. 2014, Moline et al. 2015, Taylor and Lembke 2017). New small-size, low power echosounders and miniaturized acquisition computers are now deployed on autonomous underwater vehicles 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 fishes. Gliders can also extend ship-based echosounder systems and survey during times of inclement weather. While species identification is not possible with single frequency echosounders alone, surveys of acoustic backscatter can provide indicators of biological hotspots to guide additional research.

**Methods**

*Test Area*

A test region was chosen within the eastern Gulf of Mexico near Tampa Bay to test all three acoustic technologies where we have a long-standing knowledge base of the region and fish population distributions. We focused on a transect that followed the Gulfstream Natural Gas pipeline (GSNG), because it matches linear glider transects and is known to hold populations of a number of recreationally important bottom fish species (Figure 1). The GSNG originates in the northern Gulf and traverses SE and into Tampa Bay. Its prominence on the bottom varies from being completely covered with sand to sitting up on top of the seabed, with large sections having dredged rock piles lining either side. For our efforts we focused on the regions from the 30 meter to 50 meter isobaths, a length of ~70 km.

*Subsurface Glider*

A Slocum Electric G1 200m 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 and loiter in the tagging region. The biggest challenge to this piloting strategy was occasional currents 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 CTD, WETLabs fluorometer (Chlorophyll, CDOM, bb @ 650nm), Aaderraa dissolved oxygen optode, and three acoustic sensors: one or two passive acoustic recorders, a tag telemetry receiver, and a water-column echosounder (Figure 2). Acoustic data sets could only be analyzed upon retrieval of the glider, with the exception of confirmation that the echosounder was communicating with the glider. Prior to the deployment each sensor was synchronized to UTC time to ensure timestamps across sensors and platforms could be matched. For the majority all deployments, the glider was programmed to surface on three-hour intervals. For positioning, the glider obtained a fresh GPS fix prior to submerging and again when it surfaced prior to transmitting through satellite. Glider positions between surfacing was estimated as linear while subsurface for the three hour segments.

The first deployment was conducted three months following the initial fish tagging effort in the summer of 2016, with subsequent deployments in the winter, spring, and summer of 2017 (Figure 1). Three of the four efforts successfully travelled along the pipeline and 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 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 two 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 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) over the period of April 2016 to April 2017. This included 27 red grouper and 34 red snapper (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). All fish were measured to the nearest mm for total length (TL), and where possible strip-spawned or biopsied to determine sex. Releases were conducted with a seaqualizer to return fish to depth and video-taped to assess the fish’s health and if there was post-release predation. No predation events were observed. Five acoustic release receivers with passive acoustic recorders (to record courtship sound) were deployed throughout the study period (April 2016-June 2017) at sites where fish were released. All fish were released in proximity to a moored receiver with the exception of five fish (tags 57-61) captured, tagged and released in proximity to the pipeline, but out of range of the moored receivers on 4/18/2017.

In the areas of tagging activities, nine anchored acoustic tag receivers (Vemco VR2-AR) equipped with acoustic releases and long-term passive acoustic recorders (Loggerhead Instruments) were deployed so that detections from passive receivers could be compared to those by the glider. Of the nine deployments, five were distributed among tagging sites and the last four were deployed at the two easternmost tagging locations to monitor fine scale movements. On the glider, a Vemco Mobile Transceiver (VMT) was attached externally to the top of the hull using a band clamp and bracket. All tag receivers were set to transmit as well as to record detections to allow for analysis of detection rates of stationary (receiver) as well as moving (fish) targets. All detections are recorded with a timestamp and a transmitted depth of the tag being detected.

*Passive Acoustic Recorders*

Passive acoustic recorders were deployed at fixed locations on the same moorings as the Vemco acoustic tag receivers as well as on the glider. The fixed station recorders consisted of a Soundtrap board (Ocean Instruments NZ) with a 128 GB microSD card that was powered by a rechargeable lithium polymer battery (3.7V 850 mAh) and a primary lithium battery (3.6V SAFT LS or LSH 20Ah). The hydrophone was made from a spherical piezoceramic (-211 dBV/µPa; full-scale system sensitivity: -178 dB re 1uPa). Fixed recorders were set to record on a duty cycle for 1 minute every 20 minutes at a 96 kHz sample rate. The duty cycle was chosen 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.

Two different recorders were used on the gliders: a DSG recorder (Loggerhead Instruments) which had been previously integrated into the glider (Wall et. al., 2012), and an externally mounted Remora recorder (Figure 2). The DSG board was housed internally and powered by the glider batteries and the hydrophone (HTI-96-min -170dBV/µPa) was integrated into the flooded aft cowling. The DSG recorded with a duty cycle of 1 minute every 5 minutes 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 the same Soundtrap board as used in the fixed recorders (Remora, Loggerhead Instruments). The Remora was powered by an internal lithium polymer battery (3.7V, 2500 mAh). The Remora was set to record for 1 minute every 5 minutes 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 (Figure 2).

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 grouper 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 1.42 times greater than the reference band for between 0.6-2.5 seconds. 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. The glider provided power, acquisition parameters, and clock synchronization, while the AZFP returned status and cumulative number of transmitted pings. AZFP echosounder operated at a single frequency of 200 kHz using a single beam 7-degree 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 ECOPuck opening in the glider science bay and pitched forward 22.5-degrees so that it would transmit downward and vertically when the glider was descending. The AZFP transmitted short pulses (pulse length = 150 us) 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. The glider must be recovered to download data for processing and interpretation.

Data from missions M66, M69 and M72 were analyzed. The transducer failed during 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) georeferenced acoustic backscatter, 2) correct for glider depth and vertical position of targets and seafloor depth, 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 of transducer was not vertical. Salinity, temperature and depth from the glider CTD data was 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 0.2m backstep to exclude noise associated with the seafloor. Ringdown from the transmit pulse was excluded using a forward step of 0.3 m range from the transducer.

Detecting acoustic backscatter likely associated with fish involved two procedures. 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 dB). 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 enters 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 fish area backscattering coefficients was exported as Nautical Area Scattering Coefficient (NASC) in 50 m distance bins along transect and mapped along the glider mission transect to visual interpret spatial patterns relative to the other acoustic data streams. Backscatter from the entire water column was logged, but only the bottom 10m are reported here, likely representing demersal fish associated with benthic habitats like the pipeline.

A hotspot analysis was performed on each mission to identify significant clusters of higher (or lower) acoustic biomass along the glider mission path. The Getis-Or Gi\* statistic was calculated in ArcMap with Spatial Analyst (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 records 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.

*Data Analysis*

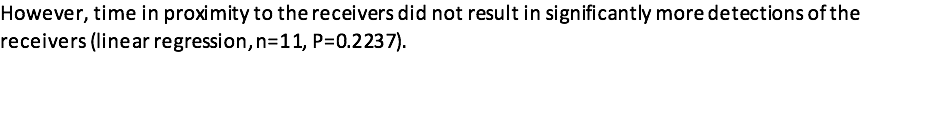
For the tag telemetry and PAM we were able to compare glider detections with detections using traditionally deployed bottom receivers. For acoustic tag telemetry we compared detection rates for tagged red grouper and red snapper using traditional fixed receivers and the glider mounted VMT when the glider was within 400m of the bottom-mounted receiver. For passive acoustic recordings we compared detection rates for glider mounted receivers (one mounted in the aft cowling, and one mounted on top of the glider) with a fixed passive acoustic receiver. For all three technologies, we compared how detections of fish varied over the entire glider paths. We did not have a comparable moored echosounder with which to compare to the glider, thus comparative analyses were limited to comparisons between red grouper detected with PAM and biomass measured by the echosounder along the transect. Each glider-based acoustic data set was merged with glider positioning estimations to determine the location of the acoustic data.

**Results**

The acoustic data sets collected in 2016 and 2017 include both moored and glider collected data. A timeline of the data set collection is shown in Figure 1. Moored data sets include acoustic tag detections over the time period the receivers were in place, as well as one continuous passive acoustic recording set analyzed for biological sounds of red grouper. 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: M66 contained no passive acoustic recordings due to an instrument failure; M69 did not reach the tagging region and developed a problem with the echosounder transducer reducing the quality of the data; M70 contained no usable echosounder data. M72 contained full data.

**Acoustic Tag Telemetry**

Data from the moored receivers, as well as the VMT on the glider were filtered for times when the glider was within 400 m range of the receiver, as this is a conservative estimate of range (Lowerre-Barbieri et al. 2016) (Figure 3). The time that the glider was within range of any given receiver differed with date/mission, ranging from a total of 50 minutes on 20 May 2017 to 4,070 minutes on 5 June 2017.



However, the advantage of a moving platform is that it can cover greater space than moored receivers, and the glider did detect three of the five fish released near the pipeline but not near a receiver. These fish were not detected on the moored receivers.

**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 5). Still there were isolated locations with relatively high red grouper sounds detected. 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 1275 total, hull-mounted recorder estimated 540; M70: aft recorder estimated 2300 total, hull-mounted recorder estimated 850). It should be noted that the external and internal recorders were not synchronized in their recording schedule.

The moored passive acoustic recorder located with the acoustic tag receivers showed that red grouper produced sounds throughout the year (Figure 6). 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 hours ET.

**Echosounder**

Only data from M66, M69 and M72 were used for analysis. 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 7). 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.

Fish schools were sparsely distributed along the glider path during mission 66. Hotspot analysis detected several significant clusters of high acoustic biomass. Several clusters were in close proximity to the pipeline (Figure 8A). Two significant hotspots were detected within 20 m on an outgoing and returning path, 6 days apart. Other hotspots were almost 3 km away from the pipeline (Figure 8A). M69 did not traverse the full extent of the pipeline focus area. Overall, very low acoustic densities were observed during this entire mission. It should be noted that 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 a hotspot analysis identified significant hotspots that were in close proximity to the pipeline. The pattern of distribution in the hotspots were clearly delineated fish schools close to the seafloor, and extending for 10s of meters in length (Figure 8B). Closer inspection of the areas of hotspots revealed large schools of fish close to the seafloor (Figure 8B).

**Discussion**

This project showed it was possible to integrate three complementary acoustic technologies to map fish distributions. Challenges that led to partial datasets from the glider were resolved by the last deployment.

The glider detected fewer fish with the acoustic telemetry than the bottom-moored receivers. This could be due to several factors. First, the red grouper and red snapper tend to be associated with the bottom where the fixed acoustic receivers were located, while the glider is in the water column. The reflections of the acoustic signal from the water surface could impact tag detectability. The VMT receiver was mounted on the top of the glider, so ultrasonic tag signals from directly below the glider might be shadowed by glider body. This could be tested in the future by comparing detections of top-mounted and bottom-mounted receivers.

It is not feasible to put fixed receivers over the same scale that the glider is able to traverse, so fixed receivers and glider-mounted receivers are complementary. This was seen where the glider detected three of five fish that were tagged along the pipeline in an area where there were no fixed receivers.

The passive acoustic monitoring showed higher red grouper sound detections in the flooded aft cowling versus on top of the glider. This could be due to acoustic shadowing by the glider, or differences in mechanical noise received by the two hydrophones.

The echosounder provided indicators of biological biomass throughout the water column along the mission. The most common patterns of backscatter were from midwater plankton layers that may be related to oceanographic features, though not analyzed here. Fish schools were observed along several glider tracks, with some notable hotspots coincident with the glider passing over the pipeline. Integrating an echosounder on the glider enables surveying large areas on longer missions than typically covered by ship, though at a slower speed. While the tag telemetry and passive acoustic hydrophones receive 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.

All three technologies identified hot-spots of fish along the pipeline. Additional areas with red grouper were detected with passive acoustics where tagged fish were not detected, likely due to limited dispersal of red grouper. Some of these locations also had higher echosounder biomass. The main changes we would test in future missions, would be to mount both the tag telemetry receiver and passive acoustic recorders on the bottom of the glider, where there may be less acoustic shadowing. We would also add larger battery packs to the passive acoustic monitoring for longer recording times. Because fish sound production can be variable, it is possible to miss sound production by recording on a short duty cycle.

**Tables**

Table 1. Glider collected acoustic data sets collected during five glider deployments between summer 2016 and fall 2017. PAM = Passive acoustic monitoring by glider, Tags = Tag telemetry receptions, WCA = Water column acoustical biomass estimations.

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

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** |

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