

# Listening to Fish

Passive Acoustic Applications in Marine Fisheries



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## Conference Proceedings

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## **Listening to Fish: Proceedings of the International Workshop on the Applications of Passive Acoustics to Fisheries**

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### **Workshop Objectives**

1. Convene an international conference to assess the potential of passive acoustics as a tool with applications in fisheries and marine conservation in estuarine, coastal and oceanic ecosystems.
2. To promote the use of passive acoustics for exploring the oceans, surveying marine biodiversity, and assessing the impact of man's activities upon the oceans.
3. Develop an international research initiative to explore and extend the use of passive acoustics in the marine sciences in both applied and non-applied fields, and to develop potential research theme areas for future funding.

### **Introduction**

On April 8-10, 2002, MIT Sea Grant hosted an international workshop on the application of passive acoustics in fisheries in Dedham, Massachusetts. The 'hands-on' workshop drew over 40 European and North American experts from fisheries, fish biology, acoustics, signal processing, underwater technology and other related fields. The workshop was divided into 4 sessions and 2 working groups with a total of 29 presentations delivered. The first session entitled: "Passive Listening for fishes - what has been done?" reviewed past and current research activities, while the second session "Future developments and applications" examined recommendations for future research and examples where existing programs could be enhanced by passive acoustic technology. The third session "Acoustic technology" reviewed the state of the art and future developments for underwater acoustic and related technologies. A special session included demonstrations of hardware and software. The workshop was capped off by a working group on the biological and ecological aspects of passive acoustic research, moderated by Joe Luczkovich of East Carolina University, and a working group on technology and software issues moderated by David Mann of the University of Southern

Florida in St. Petersburg. A web page was constructed to document the findings of the workshop (<http://web.mit.edu/seagrant/acoustics/index.html>).

The workshop was a great success at bringing together an outstanding group of international researchers to exchange research results, knowledge and ideas related to the application of passive acoustics to fisheries, census of marine life and related issues. The workshop demonstrated the high potential of passive acoustics as a research tool for fisheries and related fields through the presentation of the results of a number of successful research projects. One of the important outcomes of the workshop was the exchange of information about ongoing and past research projects that have successfully used passive acoustics. Previously, many of these scientists had been working in isolation with little interaction with their colleagues working across North America and overseas. The fisheries biologists participating in the workshop also gained valuable insight from exchange of information with scientists with well-established backgrounds in the use of passive acoustics to study marine cetaceans (see Clark, Jarvis and Moretti, herein). Another important result was the exchange of hardware and software technologies among the participants. The workshop has already fostered renewed enthusiasm among the participants for this field of research and has resulted in new domestic and international collaborations. In addition, the workshop brought researchers together with administrators, staff and scientists from several funding agencies and with the media (e.g., NURP, National Geographic, etc.). Finally, extensive discussion of the future research priorities for passive acoustics, and development of both domestic and international collaborations, are expected to go a long way towards promoting the application of passive acoustic technology to fisheries and related fields. Some of the most important research initiatives identified by the workshop participants were: 1) the importance of developing a national database of historic underwater sound archives (see Bradbury and Bloomgarden, herein), 2) the importance of establishing a National/International Reference Library of fish sounds, which would be guided by an international panel of scientists drawn in part from the workshop participants, 3) the importance of establishing an international research and training center for passive acoustics applications to fisheries and marine census (potentially at Grant Gilmore's Laboratory at the Kennedy Space Center), and 4) the importance of active promotion of the technology through publications of the workshop proceedings and related articles. Many more specific research needs in biology and technology were addressed and are presented throughout these proceedings.

## **Background**

Fish are difficult to see and study in the ocean. SCUBA techniques can help in shallow waters and a range of active acoustic and optical techniques can assist in deep water, but we are still largely ignorant of the distribution and behavior of the great majority of marine fish. Possibly one of the greatest challenges to researchers attempting to study the behavioral ecology of fishes is that of finding the fish in the first place. Often a scientist must go to great lengths conducting expensive and time consuming biological surveys simply to determine the locations or habitats where a fish can be found, before any attempt to study its biotic and abiotic interactions can be made. After all, you can't study something you can't find. Any tool that can help scientists to locate fish is therefore

valuable. Fish too face the problem of assessing their environment, navigating through it, and communicating with others of their kind. A surprisingly large number use sound to overcome the problem of living in a visually opaque medium.

Over 800 species of fishes from 109 families worldwide are known to be vocal, though this is likely to be a great underestimate. Of these, over 150 species are found in the northwest Atlantic (Fish and Mowbray 1970<sup>1</sup>). Amongst the vocal fishes are some of the most abundant and important commercial fish species, including cod, haddock and the drum fishes (sciaenidae).

Passive acoustics offers a unique tool to study these fishes, which often live in dark and turbid waters and are difficult to observe by other means. Passive acoustic techniques can be used to locate concentrations of particular species, especially during their vulnerable spawning stage. This in turn allows spawning habitat to be identified, mapped, and protected. It can allow the numbers of fish to be assessed. And it can be used to gain a better understanding of fish behaviour, including fish migrations. Passive acoustics can also be used to simultaneously monitor sources of noise pollution, and to study the impact of man's activities on marine communities. Anthropogenic sources include noise generated by boating activity, seismic surveys, sonars, fish-finders, depth finders, drilling for oil and gas, and military activities. These all have an unknown but potential important impact on marine fauna. We believe that passive acoustic technologies hold special promise and will become important tools in the coming years. However, it has been largely ignored in the northwest Atlantic in the study of fishes important in the marine food chain. It is also a technique that is amenable to cooperative research with commercial fishermen, who can bring their own knowledge to such studies.

### **Applications to Fisheries**

Sounds travel much farther in water than light and underwater sounds, including fish calls, can often be heard over much greater distances than fish can be seen. Listening to fish can contribute a great deal to our knowledge of their abundance, distribution and behavior. Passive acoustics studies using relatively simple techniques have been successful in locating concentrations of important fish species, opening the way for further, more detailed studies of their behavior, distribution and habitat use. As reflected in the various research programs described within this proceedings, already significant strides have been taken in the application of passive acoustics to fisheries:

- \* in an Arctic fjord in northern Norway, workers from the FRS Marine Laboratory, Aberdeen and the University of Tromsø have located a spawning ground of haddock, *Melanogrammus aeglefinus*. Passive listening has revealed that this species, previously thought to spawn offshore in deep water, can also form large spawning concentrations close to shore (see Hawkins).
- \* Norwegian researchers are using passive acoustics to study spawning behavior of Atlantic cod and other gadids (see Nordeide and Finstad, Svellingen et al.).
- \* a number of studies in the estuaries of the eastern United States have helped to localize the spawning areas of drum fishes and *demonstrating* the usefulness of passive acoustics as a tool for identification of essential fish habitat requirements, as well as a tool to provide fisheries

managers with information of sciaenid reproductive biology (see Collins et al., Gilmore, Holt, Luczkovich and Sprague, Roumillat and Brower).

- \* for the first time in the United States passive acoustics are being explored as a tool to census marine fishes on the continental shelf. In one study, a towed hydrophone array is being used to identify spawning sites of red drum in the western Gulf of Mexico (see Holt). In another study, passive acoustics are being used to catalogue soniferous fishes in the Stellwagen Bank National Marine Sanctuary (see Rountree et al., Rountree and Juanes). One goal of the study is to determine the feasibility of using passive acoustics as a supplemental tool in the census of fish diversity and habitat use patterns in the sanctuary.
- \* an ongoing survey of soniferous fishes of Massachusetts has resulted in a significant range extension for the cryptic estuarine and inshore fish, the striped cusk-eel, *Ophidion marginatum* (see Rountree and Juanes). Extensive sampling over many decades with conventional gears in the region had failed to recognize the importance of striped cusk-eel to the fauna, while passive acoustics revealed it to be widespread and abundant. This study demonstrates that even a low-budget, low-tech, approach to passive acoustics can contribute significantly to the census of marine life.

### **New Technology**

Studies described at the workshop have pushed technology to new levels that will allow researchers to expand the frontiers of fisheries science and ocean exploration:

- \* the potential for combining hydrophone arrays with other underwater census technologies is being explored, including ROVs (see Rountree et al., Luczkovich and Sprague), underwater video (see Svellingen et al., Lobel, Barans et al.) and active acoustics (Fudge and Rose). Lobel has pioneered the use of advanced SCUBA technologies for studies of fish vocal behavior.
- \* researchers are beginning to look towards existing acoustic arrays maintained by the Navy and other agencies for applications to fishes (see Jarvis and Moretti).
- \* Advances are being made in the development of modeling tools and software for tracking vocal fish (see Forsythe) and identifying individual fish (see Wood).
- \* New technologies for detecting and recording underwater sounds are rapidly evolving (see Mann).
- \* Historic archives of fish sounds are being assembled and rescued from deterioration and will be made available to researchers and the public through the internet (see Bradbury and Bloomgarden). The establishment of internet access to libraries of fish sounds is an important step to more widespread use of passive acoustics in fisheries science and related fields.

### **The Future of Passive Acoustics**

Although studies described during the workshop reflect the rapid growth of research on passive acoustics applications to fisheries and marine census, there are many areas where technical developments are needed to promote future research:



## Software

- \* the development of sound recognition systems, based on wavelet analysis and other new techniques to enable the automatic discrimination of different species. For a north Atlantic species, the haddock, it has already proved possible to distinguish the voices of individual male fish (see Wood).
- \* automatic event detection/analysis software to quantify temporal patterns of sounds over long time periods.
- \* localization/tracking software (see Forsythe).
- \* software allowing simultaneous analysis of video and audio data in behavior studies (i.e., click on the sound wave of a fish call and view the corresponding video frame in a second window). This capability would allow rapid correlations of individual sounds and sound components with behavior and functional morphology.

The improvement of passive listening technology for systematically detecting and recording sounds at sea, including:

- \* ship based listening systems, with dangling and towed hydrophones.
- \* bottom mounted listening systems based on underwater vehicles and pop-up buoys.
- \* drifting sonobuoy systems, either storing the data, or telemetering data to ships or shore-based listening stations.
- \* large hydrophone arrays, capable of localizing sound sources.
- \* measurement of source levels, and calibration techniques for measuring the distance of sound sources.

Back-yard science: Perhaps of equal importance to passive acoustics systems for use in the open ocean is the development of technology to aid in small scale, low budget studies of marine fishes in estuarine and inshore habitats. We feel that passive acoustics have a great potential as a tool to provide basic information on essential fish habitat use patterns, as it becomes more widely used in classrooms and State and Federal sampling programs. Several studies presented at the workshop demonstrate the usefulness of this type of research to fisheries. A good example of this is the discovery, using passive acoustics, that striped cusk-eels are abundant in Massachusetts estuaries, where despite a long history of conventional sampling in the region, the species was thought to be a very rare straggler. Technologies to aid this type of research include:

- \* archival acoustic recorders - unmanned recorders for use on ships of opportunity in many types of habitats.
- \* homing devices to locate sound sources (see Forsythe, Rountree et al.).
- \* devices that allow simultaneous recording of both audio and video data.
- \* hand-held devices for shore based, or small boat surveys in shallow water.
- \* miniature ROV designed for both video and audio recording of fish behavior from small boats and from shore.

Application of passive acoustics in a wider range of habitats where fish may aggregate to spawn.

For example:

- \* mangrove areas, which are especially difficult to survey by conventional means, but where the diversity of fishes may be especially high.
- \* coral reefs and rocky reefs, where again many species aggregate.
- \* oceanic and inshore banks, where the mass spawning of sound producing species, like cod and haddock, takes place.
- \* the deep sea, where many species like the morids and macrourids are suspected to be vocal from anatomical evidence.
- \* estuaries - the primary spawning grounds for many economically important fishes.

Development of local, regional, national and international networks of “listening posts” especially in estuarine and inshore waters. Incorporation of listening posts into local and regional environmental data networks like GoMOOS and the NOAA/OCRM/NERR’s System Wide Monitoring Program.

#### **The Benefits of Passive Acoustics**

- \* non-invasive, non-destructive census of marine life.
- \* works at night without bias (versus video and other techniques that require lights).
- \* can provide continuous monitoring of fishes.
- \* provides remote census capabilities.
- \* determine the daily and seasonal activity patterns of fishes including determination of discrete daily spawning times.
- \* a better foundation for the management of exploited species by mapping their distribution and pinpointing their spawning grounds.
- \* a better understanding of the habitat preferences of key fish species (e.g., Essential Fish Habitat “EFH” assessment in the US), giving a better focus for their conservation.
- \* establishment of baselines for the abundance and distribution of key fish species, allowing examination of the effects of future environmental change.
- \* obtaining a wider knowledge of the behavior of those fish that cannot readily be studied by any other method.
- \* can be used to monitor environmental noise and determine their sources.
- \* can be used to examine the impact of anthropogenic noise on fish, especially on spawning behaviors.

- \* networks of listening posts can provide synoptic data on the occurrence of fishes and spawning activities on local, regional, national and global scales.

## **Conclusion**

Research presented at this workshop underscores the great strides that have been made in the application of passive acoustics to fisheries and related issues in the last two decades. It is clear from this body of work, that although passive acoustics is currently largely overlooked as a research tool, it is a rapidly “up-and-coming” field of research that holds great promise for the future. It is our hope that publication of this proceeding will stimulate the growth of this field, and will encourage funding agencies to support passive acoustics research.

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# ( ( • **Locating sciaenid spawning aggregations in anticipation of harbor modifications, and reactions of spotted sea trout spawners to acoustic disturbance**

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## **Introduction**

The estuarine-dependent sciaenids are by far the most recreationally (= economically) important fishes in the Savannah River (SC/GA, USA) estuary. Regional populations of the primary species have declined in abundance in recent years amid concerns about reduced spawning stock biomass. Most southern states have responded by tightening harvest regulations.

Plans for major modifications and deepening of the Savannah Harbor and shipping channel have generated special concerns about exacerbating sciaenid spawning stock reductions due to: 1) direct dredging mortality; 2) acoustic disruption of spawning aggregations; or, 3) reducing the acceptability to the fish of any presently utilized spawning sites through alterations to the bathymetry, flow characteristics, etc.

The estuaries of SC, GA, and northern FL differ in a number of ways (e.g., higher tidal amplitudes, no seagrasses) from those to the north and south, and there are reasons to believe that sciaenid spawning behavior may also differ. Studies of sciaenid spawning in this central region have been limited in number, producing for example only three red drum spawning locations: two in SC and one in GA. No studies have been conducted in the Savannah River. Thus, a passive acoustic survey was initiated to define the geographic and temporal distribution of spawning aggregations of the recreationally important sciaenid species, determine site fidelity between years, characterize spawning habitats, and determine effects of dredging activity on aggregations.

## **Methods**

An acoustic survey was conducted during August- November 2000 and February-November 2001 in the Savannah River estuary, with some coverage of the shipping channel offshore. A directional hydrophone, analog receiver, and audio recorder were used to detect and record signals, and specific locations of spawning sites were determined through triangulation. Signal strength (quantified on a 1-5 scale), prominent bathymetric/structural characteristics, light phase, tide stage, current velocity, depth, temperature, salinity, and dissolved oxygen were recorded for each location. Field activities were conducted on average 3 days/week. Emphasis was on the lower estuary where salini-

ties were >15 ppt, but occasional broader surveys were conducted to ensure that no spawning activity was occurring farther upriver.

During June 2001, preliminary dredging operations began in one turning basin in the lower harbor, which had been identified as the location of one of the primary spawning aggregations of spotted seatrout. The reaction of the spawning aggregation to dredging activity was monitored through the end of the spawning season.

## Results

Recreationally/economically important sciaenids encountered included red drum *Sciaenops ocellatus*, spotted sea trout *Cynoscion nebulosus*, black drum *Pogonias cromis*, and weakfish *Cynoscion regalis*. Sporadic drumming of all species occurred in various locations of the lower estuary. However, six primary spawning sites were identified for spotted seatrout, one for weakfish, and one for black drum. All sites were in salinities > 16 ppt, and all were within 12.2 river km of the river mouth.

Time of day of spawning varied somewhat among species, but in general it appeared to be anchored around sunset with peak activity from about 1 hr before through about 3 hr after. This was especially evident with spotted seatrout, which had the longest spawning season. As day length shortened and sunset occurred progressively earlier at the end of the summer, spawning activity began earlier.

Spotted seatrout spawning activity took place during May-September, peaking in July-August. Water temperature apparently was a seasonal spawning cue, as activity ceased abruptly and did not resume when there was a 2°C drop to 24°C over a 2-day period (although spawning in lower temperatures has been previously reported). All six sites located in 2000 were again used in 2001, but activity did not begin at all sites simultaneously. The sites had several characteristics in common: they were in the main river channel rather than side-creeks, they were in or adjacent to deep water (7-10 m), and they were associated with structure of some type. Structure varied among sites, but was generally a large channel marker or a rocky area such as a submerged jetty. Drumming activity appeared strongest when a high or early ebb tide occurred during the appropriate time of day.

Black drum spawned during late March to mid-June at river km 0 (the river mouth) in water temperatures of 14-19°C. Weakfish spawning activity was concentrated just upriver at river km 2 during June to early October at temperatures of 23.9-29.0°C. Weakfish appeared to be less site-specific than black drum or spotted seatrout, with the aggregation sometimes moving temporarily upriver and then returning. Weakfish also tended to aggregate around structure like spotted seatrout, although more weakly, while black drum aggregated in the middle of the channel where no structure could be detected.

No large red drum spawning aggregations were located. A number of times, individuals or very

small groups of drumming males were found. This was most consistently at the mouth of the river and in the shipping channel outside the mouth. All activity noted was during August-September.

The active dredge in the vicinity of a large spotted seatrout aggregation began operations at the upriver end of the turning basin, the opposite end from the aggregation, and moved slowly downriver. No changes in drumming intensity or periodicity relative to the dredge were noted. However, the spawning season ended (as confirmed by checking other known spawning sites) before the dredge actually reached the fish; it was ~100 m away at that point. Large and small vessels transited the area but did not disturb the fish. One acoustic disturbance that was dramatically apparent, however, was a total cessation of drumming when bottlenose dolphin *Tursiops truncatus* (which make a pronounced acoustic signal) passed by. This behavior was also noticed on two occasions with red drum.

### **Discussion**

Passive acoustic mapping of sciaenid spawning sites in preparation for harbor modifications was successful. It confirmed spawning of important sciaenid species within the harbor area, and it defined the spawning temporally and spatially. There was considerable temporal overlap in spawning activity among species, and in the lower 2 river km there appeared to be spatial overlap. However, on a finer scale (hundreds of meters) there was little or no overlap. It is obvious, however, that the lower 2 river km can be considered the most important sciaenid spawning area in the Savannah estuary, as all four species aggregated in that stretch of river. Aggregations of red drum were very small. Comparing this behavior to previous reports from the region is problematic due to the limited number of systems that have been studied; the aggregation in Charleston Harbor, SC was quite large, while the aggregation detected in St. Helena Sound, SC was very small. Thus, it is not known whether red drum typically form large aggregations in this region, or if in some systems they generally spawn in small groups.

Despite the apparent importance of acoustic signals in spawning aggregations for these species, noise from boats, dredges, etc. does not interfere with drumming behavior, even when the source of the noise is close by. Certainly, these fish must be acclimated to vessel passage due to the fact that the Savannah River is a major port. It is unknown whether fish in a less populous habitat would be so impervious to anthropogenic noise. The only response to an acoustic signal was exhibited toward bottlenose dolphin, which prey on these fishes; the cessation of drumming was apparently a predator avoidance behavior.

While spotted seatrout males do not respond to dredging noise, it is unknown what effect a dredge would have as it worked in the midst of the aggregation. Relatively large fishes (e.g., Atlantic sturgeon *Acipenser oxyrinchus*) are reported with some regularity having been sucked up by dredges elsewhere. Further, because two (and possibly three) of these species appear to cue in on structures, removal of these structures, as commonly occurs during deepening and channelization operations, may have a negative impact. Future research plans include statistical analyses of environmental variables as related to drumming activity, and re-examination in 2002 of spotted seatrout spawning behavior in the turning basin that was dredged in 2001.

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# Characterization of sounds and their use in two sciaenid species: weakfish and Atlantic croaker

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## Introduction

Both weakfish *Cynoscion regalis* and Atlantic croaker *Micropogonias undulatus* are members of the family Sciaenidae, a group of fish that have been known to produce sound since the turn of the 20th century. This family of fishes produces sound through the use of highly specialized, extrinsic sonic muscles which lie in close proximity, but are not attached to, the swimbladder (Tower 1908, Tavolga 1964). In weakfish and most sciaenids, sonic muscles are found only in the male; however, in others, including Atlantic croaker, the muscles are found in both males and females (Tower 1908, Fish and Mowbray 1970). Sound production has been linked to reproductive behavior in a number of sciaenid species (Fish and Cummings 1972, Guest and Lasswell 1978, Mok and Gilmore 1983, Saucier and Baltz 1993) and with fright or warning behaviors in a few species, including Atlantic croaker (Fish and Mowbray 1970). The purpose of this paper is to characterize the sounds produced by two species of sciaenid and to discuss the roles of these sounds in the behaviors of these species.

## Methods and Results

### Weakfish experiments

*Field recordings:* Field recordings using a hydrophone (Edmund Scientific) were made near the mouth of the Delaware Bay at three stations along an inshore-offshore transect ranging from 1.24 to 5.64km from shore and varying in depth from 3.5 to 7.8m. One-minute recordings were made at hourly intervals over a 24hr period on eight dates from mid-April through mid-August, encompassing the late spring-early summer spawning season. Recordings of drumming sounds were ranked qualitatively from 0 - 4, with 0 representing no calls and 4 representing continuous calling by a chorus of individuals (Connaughton and Taylor 1995).



Drumming was highly seasonal, increasing dramatically from zero in mid-April to nearly maximal levels in early May. Activity remained at near maximal levels throughout May and June, and decreased gradually in intensity through July and into August. Physiological indicators of reproductive readiness, including plasma androgen levels, male GSI, and the presence of hydrated eggs were all high during the period of maximal drumming activity. Drumming activity also expressed diel trends, reaching maximal levels between 20:00 and 24:00hr (sunset was between 19:50 - 20:40) and declining to a minimum between 05:30 and 10:30hr. Drumming activity, whether seasonal or diel, was most intense inshore, declining in intensity as one moved offshore (Connaughton and Taylor, 1995). The seasonality, evening timing, and inshore location of sound production all coincide with the known reproductive activity of weakfish in this area (Villoso 1989, Taylor and Villoso 1994).

*Captive spawning recordings:* Captive weakfish held in a 1500L tank were induced to spawn with two injections of 1000 IU hCG/kg body weight administered in the early afternoon on two successive days. Fish spawned during the evening of the second day of injections. Spawning activity was documented on standard VHS tape with video (Ikegami CCD camera, ICD 4224) and audio (Edmund Scientific) input (Connaughton and Taylor 1996). Field and captive sounds, staccato bursts of 6-10 individual pulses, were identical (Connaughton and Taylor 1996). It was also determined that dominant frequency and repetition rate vary with temperature and fish size (Connaughton et al. 2000).

During courtship, only pair spawning was observed, though larger groups in larger enclosures might behave differently. Drumming activity was most often initiated after the first spawning event, but based on the timing of sound production and spawning in the field (Taylor and Villoso 1994, Connaughton and Taylor 1995) this observation may be due to a tank effect. The number of drumming bursts per minute varied somewhat between males, but remained relatively constant for a given male for the duration of the evening's sonic activity, i.e. number of bursts per minute did not drop off as time passed after a spawning event. Sound production ceased prior to gamete release, which was apparently synchronized by body contact.

### **Croaker experiments**

*Captive spawning recordings:* As above, field caught Atlantic croaker were maintained in laboratory tanks and induced to spawn following hormone injections, and video/audio recordings (B&W CCD camera, OS-40D, World Precision Instruments; model C21 hydrophone, Cetacean Research Technology) were made. To date, only a single successful trial, involving one male and two females, has been conducted. The courtship behavior of the croaker was similar to that exhibited by the weakfish: drumming began after the first spawning event, was maintained for several hours thereafter, and ceased just prior to gamete release.

Only the male produced courtship sounds, bursts of 1-3 pulses, with a mode of two pulses. Dominant frequency for the single recorded male (33cm total length) was 300Hz and the repetition rate of pulses within a burst was 5.4Hz. Courtship sounds were lower in frequency and repetition rate than fright response sounds (see below). In addition, the number of drumming bursts per

minute decreased steadily following each spawning event, a behavioral characteristic not shared with weakfish (Fig. 1).

*Fright response recordings:* Fright response recordings were made in a rectangular 1250L tank. Sound production was elicited by casting a shadow over the surface of the holding tank, or moving a dip net through the water. Thirteen fish, ranging in total length from 22.5 to 30cm were recorded, and both male and female croaker called readily. The number of pulses per burst for fright response calls varied more widely than in courtship calls, ranging from 1-9, though the mode was still two. In contrast, the repetition rate of pulses within a burst was greater in fright response calls, ranging from 7.87 to 33.56 pulses/sec and expressing a mean of 18.09. Repetition rate was more variable in shorter bursts (2 or 3 pulses per burst) than in longer bursts (Fig. 2). Even given that dominant frequency appears to vary with fish size (650 to 540Hz for 22.5 to 29cm total length fish), courtship sounds appear to have a lower dominant frequency (approximately 100Hz lower for a 33cm fish) (Fig. 3).

## **Discussion**

Sound production in weakfish and croaker may be involved in the formation of spawning aggregations and/or attracting a mate, though because of the small tank size, this could not be determined in our laboratory experiments (Connaughton and Taylor 1996). It may also play a role in female mate selection, since larger individuals of each species produce a sound with a lower dominant frequency (Connaughton et al. 2000). Though weakfish will produce sounds if drawn to the surface when caught hook and line, or when removed from a tank into the air, we have never recorded a fright response call from weakfish like those so easily elicited from Atlantic croaker. In-air 'disturbance' calls elicited from weakfish when they are removed from the water were identical to courtship calls except for having a wider range of pulses in each burst of sound (Connaughton et al. 2000). In contrast, our data suggest that fright response and courtship calls in croaker may be quite distinct in dominant frequency and repetition rate, though more data needs to be collected.

## **Acknowledgements**

This work was supported by the Wallop-Breaux Sport Fishing Act with funds administered through the Delaware Department of Natural Resources and Environmental Control and by in-house funding provided by Washington College.

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## Illustrations and Diagrams

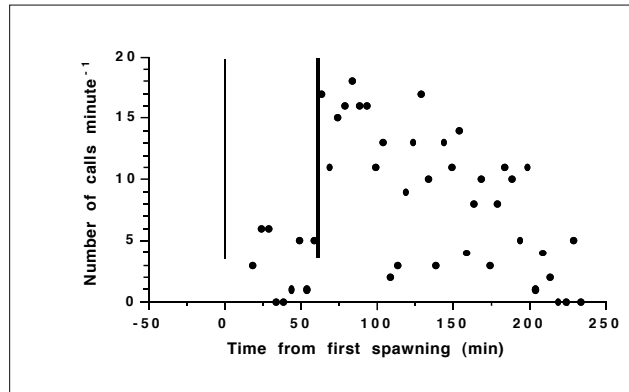


Figure 1. Croaker courtship sound production expressed as number of calls  $\text{min}^{-1}$  across time. Values were determined for one minute out of every five recorded over the course of the evening. The solid vertical line represents the first spawning event (9:29PM) and the double vertical line, the second (10:29PM).

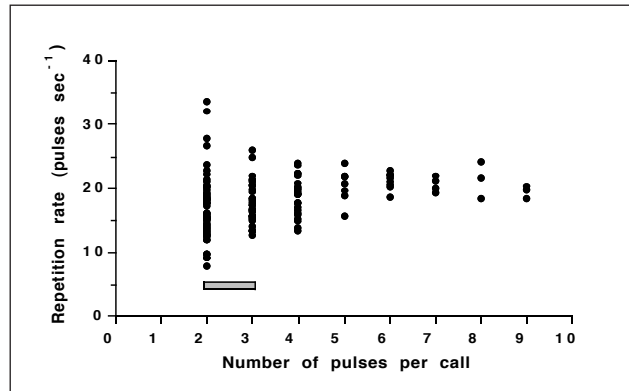


Figure 2. Repetition rate plotted across number of pulses per call from sounds produced by male and female croaker ( $N=13$ ) during fright response behaviors. The shaded block represents the repetition rate and number of pulses observed during courtship sound production.

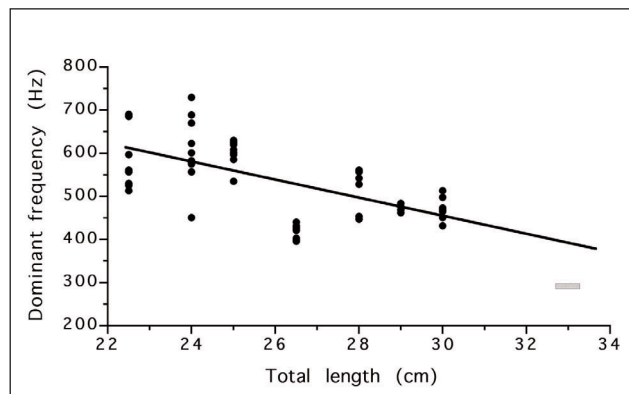


Figure 3. Dominant frequency of individual sound pulses plotted across specimen total length from sounds produced by male and female croaker ( $N=13$ ) during fright response behaviors. The shaded block represents the dominant frequency of calls made by the single male (33 cm) during courtship sound production.

# ( • Detection and characterization of yellowfin and bluefin tuna using passive acoustical techniques

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## Introduction

Underwater sounds generated by *Thunnus albacares* and *Thunnus thynnus* were recorded and studied to explore the possibility of passive-acoustical detection. Tuna vocalizations were recorded at the Monterey Bay Aquarium, Monterey, California, and Maricultura del Norte in Ensensada, Baja California, Mexico. At both locations, the most prevalent sounds associated with tuna were low-frequency pulses varying from 20 to 130 Hz, lasting about 0.1 seconds, and usually single and unanswered (Fig. 1). A behavior similar to coughing was coincident with these sounds: the animal's mouth opened wide with its jaw bones extended and its abdomen expanded, then contracted abruptly. On one occasion in Mexico, this behavior and associated noise were simultaneously recorded (Fig. 2). The center frequencies of these vocalizations may vary as the resonant frequencies of the tuna's swim bladder, suggesting a passive-acoustical proxy for measuring the size of tuna. Matched-filter and phase-difference techniques were explored as means for automating the detection and bearing-estimation processes.

## Conclusion

This study shows that adult bluefin and yellowfin tuna, like many other fish, are capable of generating sound. The acoustical signals are short (~0.1 s), narrow-bandwidth pulses of low frequency (20-130 Hz) and amplitude (~105 dB re 1  $\mu$ Pa @ 1m).

Observations of these fish suggest that a coughing or yawning behavior causes muscular contraction about the swim bladder and an associated short-duration sound pulse of narrow-bandwidth and low-frequency and intensity. If the recorded sounds are generated by swim bladder resonance, then the size of the swim bladder determines the center frequency of the sound pulse. It is unknown whether the tuna vocalizations are generated as a by-product of some biological function such as clearing the gills, or an intentional form of communication.

### **Acknowledgements**

We are thankful to Dr. Rennie Holt, Director of the United States Antarctic Marine Living Resources Program and Dr. John Hunter, Head of the Fisheries Resources Division, SWFSC, for providing the laboratory and equipment resources necessary to complete this study. We would also like to thank Dr. Kenneth Baldwin of the University of New Hampshire Center for Ocean Engineering for allowing S. Allen to conduct his Master's Thesis research at SWFSC. Thanks also to Mr. Ted Dunn, founder of Maricultura Del Norte of Ensenada, Mexico for graciously supporting this effort with access to his fish pens. Thanks finally to Dr. Charles Farwell, the manager of pelagic displays at the Monterey Bay Aquarium in Monterey, California.

## Illustrations and Diagrams

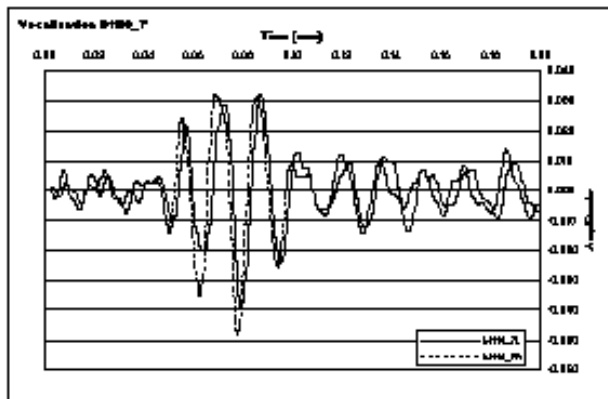


Figure 1. Bluefin vocalization recorded at Maricultura del Norte, 18 November 2000 using two hydrophones (a) and their power spectral densities (b). Signals were low-pass filtered (Order 4 Butterworth,  $f_c=600$  Hz). Estimated sound pressure level is 105 dB re 1 mP.

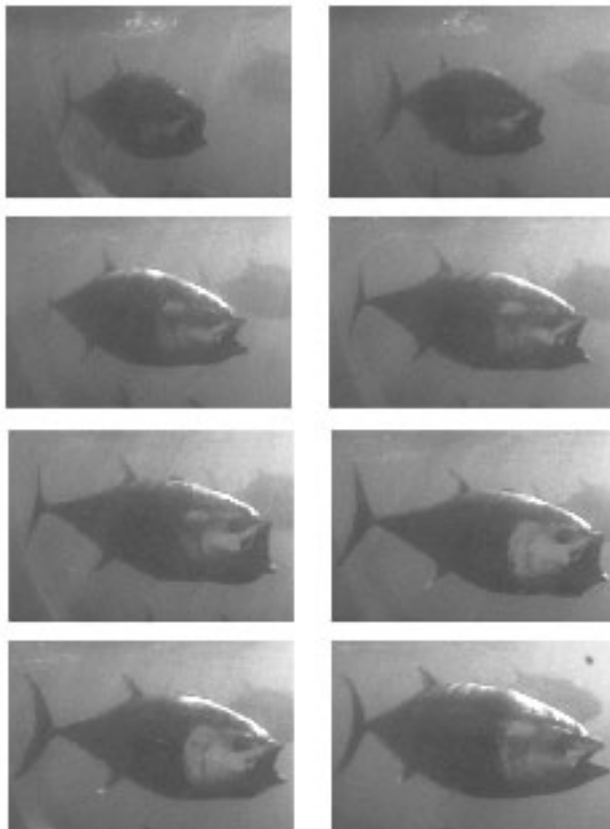


Figure 2. A bluefin tuna vocalizing at Maricultura del Norte Ensenada. During the vocalization, the animal's mouth opened wide with its jaw bones extended and its abdomen expanded, then contracted abruptly

## Acoustic Competition in the Gulf Toadfish *Opsanus beta*: Crepuscular Changes and Acoustic Tagging

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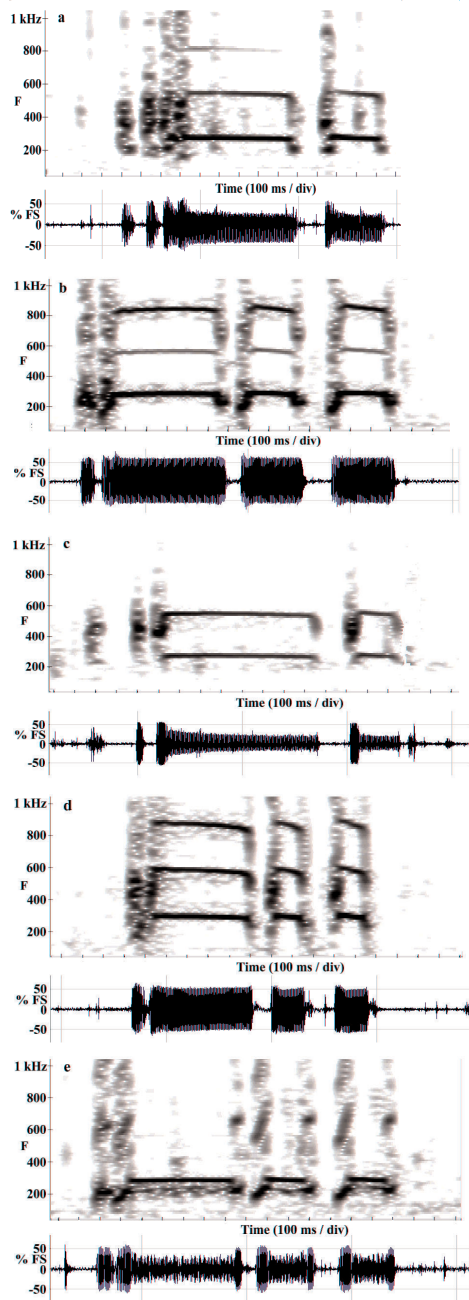
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We quantified crepuscular variation in the emission rate and call properties of the boatwhistle advertisement call of Gulf toadfish *Opsanus beta* from a field recording of a natural population of nesting males in the Florida Keys. Their calls are more variable and complex than previously reported (Fig. 1). A call typically starts with a grunt followed by one to five tonal boop notes (typically two or three) and lasts for over a second. The first boop is considerably longer than later ones, and intervals between boops are relatively constant until the final interval, which approximately doubles in duration. Positions of fish are fixed for long periods, and calls are sufficiently variable that we could discern individual callers in field recordings (Fig. 1). Calling rate increases after sunset when males tend to produce shorter calls with fewer notes (Fig. 2). Analysis by number of notes per call indicates some individuals decrease the number of initial grunts and the duration of the first note, but most of the decrease results from fewer notes. To our knowledge this sort of call plasticity has not been demonstrated before in fishes. We suggest that call shortening lowers the chances of overlapping calls of other males and that the small amount of time actually spent producing sound (total on time) is an adaptation to prevent fatigue in sonic muscles adapted for speed but not endurance.

Anomalous boatwhistles contain a short duration grunt embedded in the tonal portion of the boop or between an introductory grunt and the boop (Fig. 3b, c). Embedded grunts have sound pressure levels and frequency spectra that correspond with those of recognized neighbors, i.e. we are able to identify individuals based on frequency spectrum of their grunts (Fig. 4). We therefore suggest that one fish is grunting during another's call, a phenomenon here termed acoustic tagging. Snaps of nearby pistol shrimp may also be tagged, and chains of tags involving more than two fish occur (Fig. 5). The stimulus to tag is a relatively intense sound with a rapid rise time, and tags are generally produced within 100 ms of a trigger stimulus. Time between the trigger and the tag decreases with increased trigger amplitude. Tagging is distinct from increased calling in response to natural calls or stimulatory playbacks since calls rarely overlap other calls or playbacks. Tagging is not generally reciprocal between fish suggesting parallels to dominance displays.



## Illustrations and Diagrams



*Fig.1. Sonograms and oscillograms from five individual Opsanus beta.*

## Illustrations and Diagrams

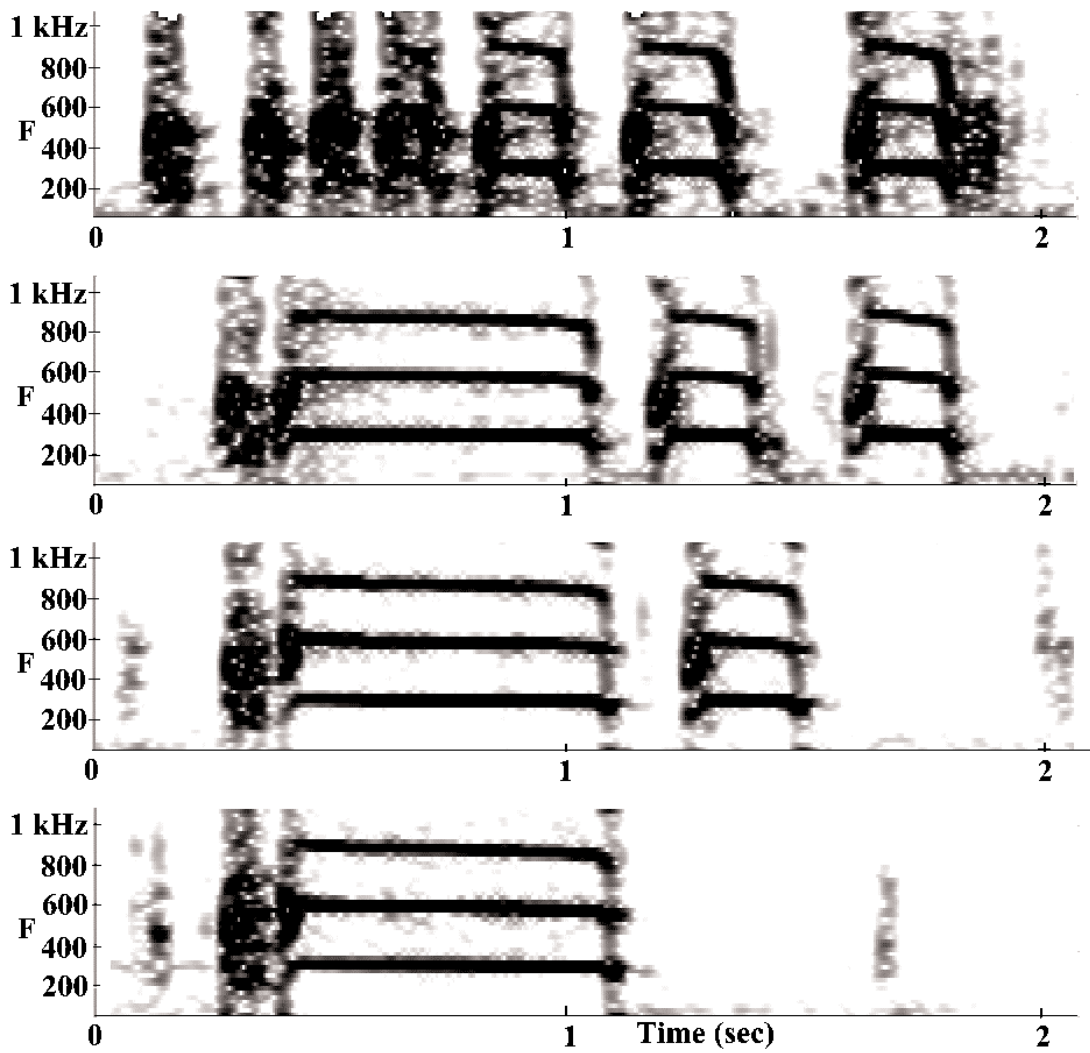


Fig 2. Sonograms from 4-, 3-, 2- and 1-boop calls from an individual *Opsanus beta*.

## Illustrations and Diagrams

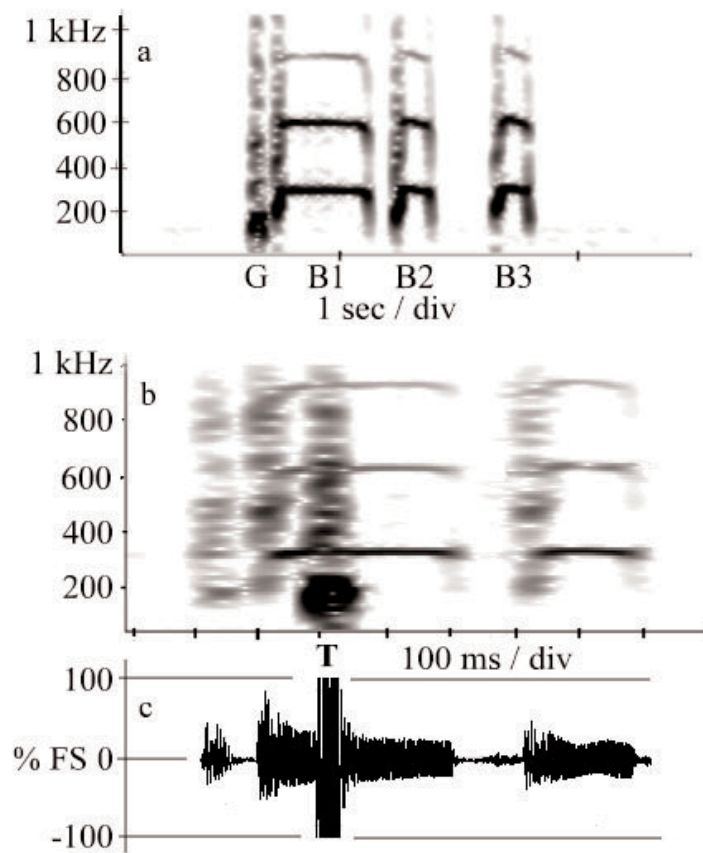


Fig. 3. Sounds of *Opsanus beta* illustrating acoustic tagging. (a) A typical boatwhistle with an initial grunt (G), a long tonal boop B1 and two shorter boops (B2 and B3). (b) Sonagram and (c) oscillogram of a boatwhistle tagged by another fish. The T marks the tag, which has lower frequency energy and greater amplitude than the boatwhistle.

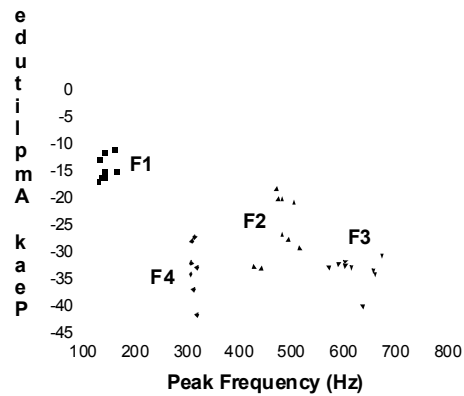


Fig. 4. Plot of peak amplitude in dB against the frequency of peak amplitude from grunt spectra for four toadfish recorded at weekly intervals.

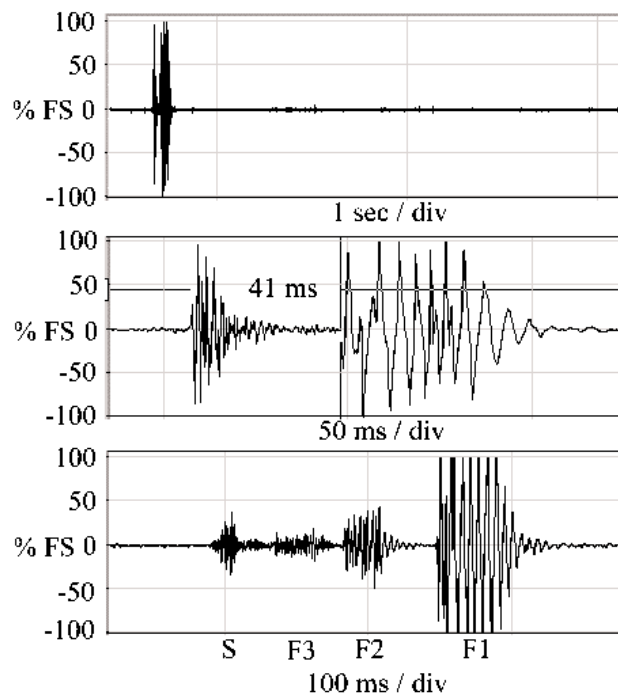


Fig. 5. Tags of shrimp snaps. (a) oscillogram of a pistol shrimp snap tagged by fish 1 with a latency of 41 ms shown in real time. (b) Same selection expanded. (c) Chain of tags initiated by a shrimp snap that is tagged by fish 3. Fish 3's grunt is then tagged by fish 2, who in turn is tagged by fish 1.

# ( • **Passive Acoustic Field Research on Atlantic Cod, *Gadus morhua* L. in Canada**

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## **Introduction**

The Atlantic cod is a very important commercial fish in Newfoundland and Atlantic Canada and has been a part of the culture for centuries. In the past ten years, cod stocks have been drastically depleted. In Newfoundland waters, cod is found from the coast to the continental shelf in water temperatures ranging from approximately -0.5 °C to 8.5 °C. They are broadcast spawners and typically spawn in large aggregations (Robichaud, 2002). The spawning season typically occurs in the spring but varies by area and is influenced by environmental factors, such as temperature (Scott and Scott, 1988). Spawning begins in the north as early as February and ends in the south as late as December. The depth at which spawning occurs varies among stocks; some may spawn in water as shallow as 20m, while others at depths over 300m (Rose, 1993). Differences in spawning behaviours among sub-stocks and among ages and sexes have been reported (Robichaud, 2002). Laboratory studies have shown that cod have elaborate courtship behaviours with males being very territorial and more aggressive males having the most success at spawning. Cod are also known to detect and produce sound and this observation has long been recognized by lab experiments (e.g. Brawn, 1961). This study is the first attempt in Canada to document the sounds made during spawning and to relate them to spawning behaviour in order to link active and passive acoustic research in behavioural field studies.

## **Previous and future research on Atlantic cod behaviour**

Two of the largest spawning components of Atlantic cod in Newfoundland waters have been studied using active acoustics for several years. These include Placentia Bay, located on the south coast of Newfoundland (NAFO regulatory area 3Ps), and Trinity Bay, located on the north east coast (NAFO regulatory area 3L). Annual acoustic surveys using SIMRAD EK 500 echo sounders, along with the analyses of the data using FASIT (Fisheries Assessment and Species Identification Tool) (Lefevre et

al., 2000) have provided insights into stock migrations and spawning behaviours. The echogram in Figure 1 is from April 2000 in Placentia Bay, Newfoundland, showing some of the pelagic behaviour easily observed using an echo sounder. Cod in this area have a peak spawning period between April and June. This spawning aggregation was found in a trench, over 300m deep. The image in the bottom corner is an enlargement of the echogram where single cod targets (white arrow) are resolved.

The use of active acoustics has led to observations of different spawning aggregation structures. Figure 2 is an echogram of spawning columns observed in shallow waters of Placentia Bay in 1997 at a depth of approximately 50m (Rose, 1993). In section A, several columns are shown. Section B is an enlargement of one of these columns, which extends approximately 20m off the ocean floor.

Throughout their range, cod occur in distinct stocks as well as sub-stocks, and spawning behaviour within specific sub-stocks is of interest. Sonar tagging studies have been conducted to investigate the homing ability of Atlantic cod to specific spawning grounds. Long-term sonar transmitting tags (Lotek CAFT16\_3 Acoustic Transmitters) were implanted in female and male cod at a spawning ground in Placentia Bay, Newfoundland in April 1998. Homing of cod back to the spawning ground from which they were taken was observed. Approximately 50% of the tagged cod returned to the same spawning ground (capture site) in subsequent years and 25% of the tagged cod returned 3 years in a row (Robichaud and Rose, 2001). This study provides some of the first direct evidence that cod undertaking long-distance feeding migrations may home to a specific spawning location in consecutive years. Present tagging work that has begun this year also will involve the identification of distinct spawning populations using acoustic surveys; cod have been released within their "home" populations as well as within other groups. Results of this study hope to provide valuable insight into the Atlantic cod's homing properties.

Using active acoustics in surveys and sonar tagging studies, we have learned a great deal about cod spawning aggregations and migratory behaviour. As spawning is the first step towards recruitment and rebuilding cod stocks, there is a continuing interest in the specific behaviour of spawning. Brawn (1961) documented many interesting features of cod spawning behaviour. Cod are known to have specific social behaviours related to spawning. Brawn (1961) observed distinct courtship behaviours performed by males toward females, as well as aggressive behaviour of males toward males. Both sexes in cod have been observed to produce sound, although it is the males whose sound production is thought to play an important role in spawning, such as attracting females and holding territories (Brawn, 1961). In cod, the drumming muscles surrounding the swim bladder are thought to be related to sound production.

Present field studies will observe the acoustic properties of spawning aggregations over two spawning seasons. These studies are interested in both the production and reception of sound by cod, its role in spawning behaviour, and also the influence of ambient noise in the ocean environment on these behaviours. We have chosen two main research areas, which have been studied for the past number of years using active acoustics and sonar tracking. Placentia Bay and Trinity Bay both have relatively large coastal spawning populations. However, Placentia Bay is becoming increasingly industrialized while Trinity Bay is not. With use of a small vessel specially equipped for

the work, cod spawning aggregations will be located using a Biosonics DE 70 kHz echosounder with digital data storage. Once located sounds from the aggregation are detected, they will be recorded using a hydrophone (ITC 8212) with a Stanford Research System pre-amplifier (model SR560). Data will be in the form of WAV files and stored on a hard drive of a lap-top computer and analyzed using Avisoft SASLab Pro software. Video recordings will be made using an underwater video camera (J.W. Fishers MFG. Inc., TOV-1). A parallel study will be conducted on fish from the same stocks kept in the lab at the aquaculture facility at Memorial University of Newfoundland.

## **Summary**

This study is the first of its kind in Canada, and is attempting to document the sounds that cod make during spawning at sea and to relate these to spawning behaviour. The work attempts to link active acoustic research with passive acoustics and to use real-time video to study cod spawning behaviour. From past acoustic research, we have learned much about the state of cod stocks, spawning aggregations, migrations, and homing. With the addition of passive acoustic tools, we hope to learn more about the spawning behaviour of individual cod.

## **Acknowledgments**

Several people were instrumental in past and present studies. We would like to thank Dave Robichaud, Wade Hiscock, Matt Windle, the crews of the CCGS Teleost and CCGS Shamook. Danny Boyce of the Aquaculture Facility at Memorial University and all the participants and sponsors of the International Workshop of Passive Acoustics in Fisheries.

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## Illustrations and Diagrams

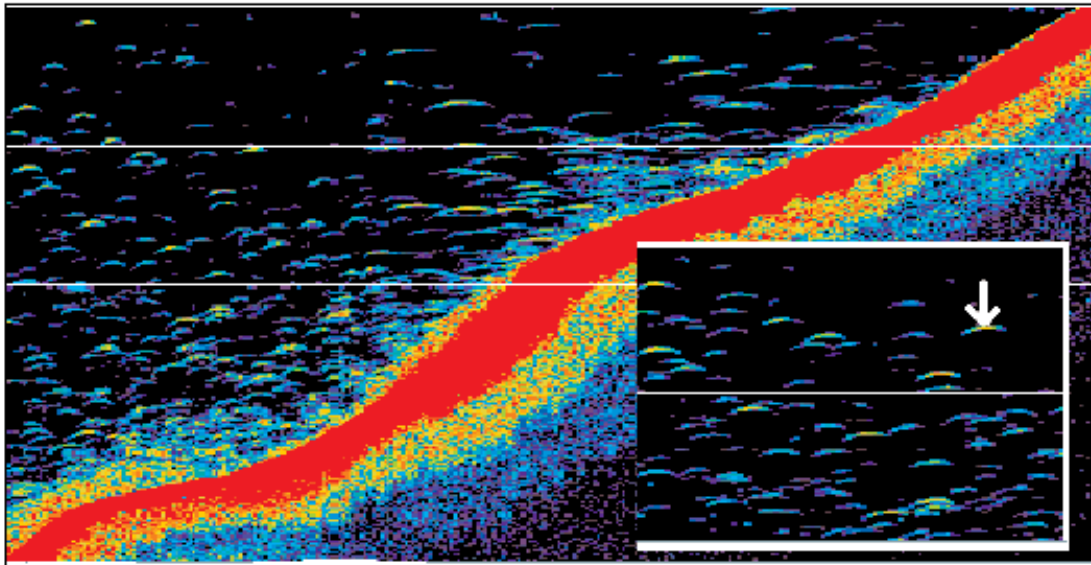


Figure 1: Echogram of a spawning cod aggregation in Placentia Bay, Newfoundland 2001.

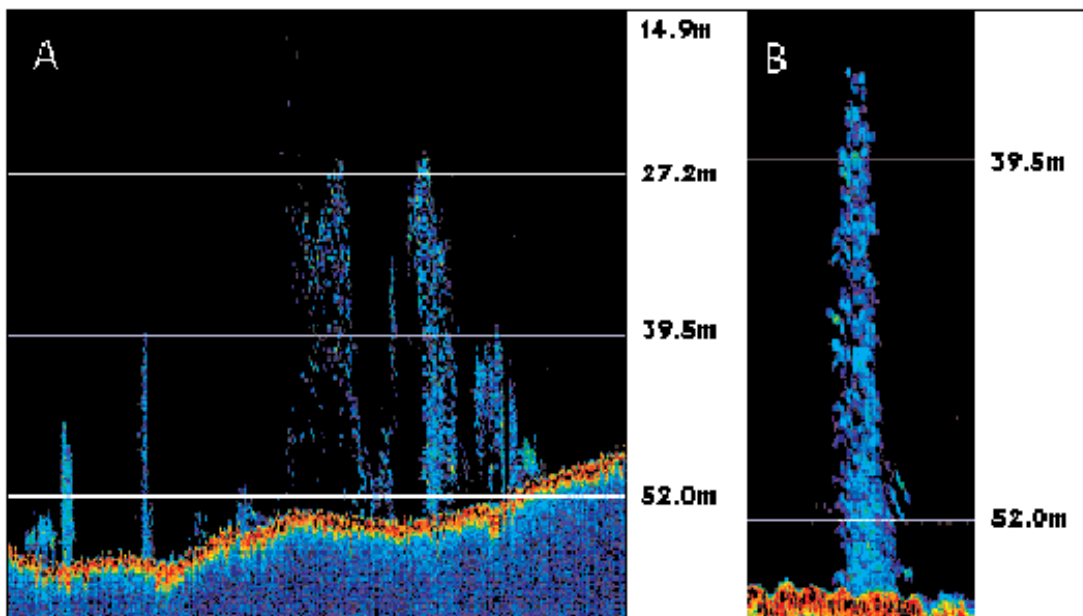


Figure 2: Cod spawning column in Placentia Bay in 1997.

# Passive Acoustic Transects: Mating Calls and Spawning Ecology in East Florida Sciaenids

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## Introduction

*Historical Acoustic Work with Sciaenid Fishes:* Sciaenid fishes have been known to produce sound for centuries (Aristotle, 1910; Dufossé, 1874a,b) and the association of sciaenid sounds with spawning has been known nearly as long (Darwin, 1874; Goode, 1887). For hundreds of years the Chinese have isolated sciaenid spawning sites from their water craft by listening to drumming sounds emanating from the water through the hull of their boats (Han Ling Wu, Shanghai Fisheries Institute, pers. comm.). The isolation of sciaenid spawning sites using underwater technology is recent and dependent on the availability of underwater transducers, hydrophones, and acoustic recorders used to access and study underwater sounds (Fish and Mowbray 1970). Hydrophone tape recordings of vocalizations produced by large sciaenid aggregations during spawning was pioneered by Dobrin (1947), Dijkgraaf (1947, 1949), Knudsen et al. (1948), Protasov and Aronov (1960), Schneider and Hasler (1960), Tavalga (1960, 1981), Fish and Mowbray (1970), Fish and Cummings (1972).

The first isolation and description of soniferous sciaenid aggregations using mobile hydrophones moving along a sound transect at spawning sites was conducted by Takemura et al. (1978), Mok and Gilmore (1983) and Qi et al. (1984). A portable hydrophone and recording system was carried via a boat from one site to another along a measured transect with recordings made along a preset grid or in a linear series (Mok and Gilmore 1983; Gilmore 1994, 1996, 2002). Recordings were made for 30 - 300 seconds at each site depending on transect length. Recorded sounds were verified by recording captured specimens identified to species and documenting specific sound types through sonographic analyses. This technique allowed spatial-temporal isolation and identification of species-specific sounds produced by sciaenid fishes, particularly under conditions of high sound attenuation for large group sounds (low frequency high intensity sounds).

Using detailed sonographic analyses of field recordings made on transects Mok and Gilmore (1983) described the characteristic sounds of black drum, *Pogonias cromis*, spotted sea trout, *Cynoscion nebulosus* and silver perch, *Bairdiella chrysoura*. Subsequent to these observations considerable additional work has been done on sound characterization in these species as well as the weakfish, *C. regalis* and the red drum, *Sciaenops ocellata*. Passive acoustic transect techniques have been used by several investigators to isolate spawning sciaenid groups in the field (Sausier and Baltz, 1992, 1993; Connaughton and Taylor, 1994, 1995; Luczkovich et al., 1999, 2000).

*Proceedings from the International Workshop on the Applications of Passive Acoustics to Fisheries*

*Recent East Florida research 1990-2002:* Over the past twelve years the value of passive acoustic studies in determining spatial and temporal spawning activity in sciaenids has increased. East central Florida studies have been supported by the Florida Fish and Wildlife Conservation Commission, U.S. Geological Survey, National Aeronautics and Space Administration, Canaveral National Seashore and NOAA/National Marine Fisheries Service. The major objectives of these studies have been to develop new techniques and technologies to allow real time continuous monitoring of soniferous aquatic organisms. This included a prototype neural network to identify species specific sounds (Lin 1996), and remotely deployed underwater computer systems (HBOI ALMS; NASA PAMS) with hydrophones and physical sensors for environmental parameters to allow association of physical oceanography with acoustic activity.

*Future acoustic research at the Kennedy Space Center:* The long term objectives of this work at the Kennedy Space Center is to develop an acoustic and sensor array that will allow continuous monitoring of biotic acoustic activity in association with intra and interspecific interactions as well as climatic and oceanographic phenomena. An experimental acoustic arena is being developed in the marine protected areas within the secure zone of the NASA and U.S. Air Force launch complex at Cape Canaveral.

### **Function of Sound Production in Sciaenids**

The most predictable and robust sounds produced by many fishes are those associated with reproduction. As in many soniferous animals, it is the male that must attract a mate and induce her to donate eggs for fertilization, and, therefore, it is often only the male that produces sound. Large choral aggregations of male sciaenid species are formed by spotted seatrout, weakfish, red drum and silver perch specifically to attract females with which to spawn. Since these male choral aggregations contribute no significant resources required by females except the males themselves (no male paternal care, no food, or nest sites) they are appropriately called seatrout "leks", such as those formed by aggregative birds and amphibians strictly for the purpose of reproduction (Höglund and Alatalo 1995). A lek is an arena to which females come and on which most of the mating occurs. An arena is a site on which several males aggregate but does not form the habitat normally used by the species for other activities such as feeding. Sciaenid leks are seasonal and are associated with a wide variety of environmental parameters that are favorable for egg, larval and adult survival. The acoustic properties of lek sites are undoubtedly favorable for mating call transmission and must have specific acoustic properties. Although many sciaenid spawning sites have been isolated to date, their acoustic properties have not been studied in detail (Mok and Gilmore, 1983; Saucier *et al.*, 1992, Saucier and Baltz, 1993; Luczkovich *et al.*, 1999; Gilmore 2002). Aggregative calling only occurs at the appropriate time for spawning, facilitating successful mating, egg fertilization, egg/larval dispersal and survival.

### **Sciaenid Sound Production Mechanisms**

The most robust and energetic sciaenid sounds are produced by sonic muscles indirectly or directly vibrating the membrane of the gas bladder. When a freshly captured, recently calling, male seatrout is dissected, the bright red sonic muscles surrounding the gas bladder can be easily differentiated from the exterior lateral body muscles. The muscle vibratory rate is directly associated with the fundamental frequency of the characteristic seatrout call produced by the gas bladder.

Most of the 1,200 species in this family produce sound using sonic muscles associated with the gas bladder. Using the species specific muscle contraction rates and the gas bladder shape sciaenids produce diagnostic sounds that can be used to identify species within the family (Mok and Gilmore 1983), as has been demonstrated in amphibians and birds. The characteristic shape of the sciaenid gas bladder is so conservative that it has been used as one of the primary characters to classify sciaenids and to determine their phyletic relationships (Chu 1963; Chao 1978, 1986).

### **Classification of Sciaenid Sounds**

Figure 2 illustrate the diagnostic mating calls of sciaenids known to spawn in the Indian River Lagoon system of east central Florida.

### **Sciaenid Acoustic and Spawning Ecology: When and Where do Sciaenids Produce Sound?**

Mok and Gilmore (1983) demonstrated that sciaenid sound production was specifically associated with crepuscular and nocturnal courtship and spawning activities. Pelagic eggs and larvae of the spotted seatrout were collected with plankton nets at spawning sites during vocalization periods (Mok and Gilmore, 1983; Alshuth and Gilmore, 1993, 1994, 1995). These same studies of soniferous spawning aggregations have demonstrated long-term spawning site fidelity, with the principal spawning sites identified by Mok and Gilmore (1983) being used for over twenty years (Gilmore, 1994, 1996, 2002).

As male spotted seatrout could be recognized by distinctive crepuscular calls their presence or absence from specific locations could be determined and the percent occurrence of calls at all acoustic listening sites derived. In addition, the approximate size of the calling group could be estimated based upon sound intensity (dB level, re 1  $\mu$ Pa) and group size estimates using a three part scale: 1 - small group or individual callers; 2 - moderate groups of several tens of callers; and 3 - a large group of what appear to be hundreds of simultaneous callers. Unfortunately, mixed species chorus behaviors were common with *Arius felis* and *Bairdiella chrysoura* joining in with spotted seatrout calls, therefore, elevating site specific sound intensities and masking seatrout numbers based on sound intensity. The percent occurrence of spotted seatrout calls at a site or time period is the most objective data used to define site and period use by seatrout leks. However, Gilmore (1994) found that spatial and temporal distributions of the estimated group size, egg and larval abundance in the water column and percent occurrence of calling trout were highly correlated ( $r =$

0.92 to 0.98 at  $\alpha=0.05$ ). This indicates that group size estimates were a useful, independently derived variable that could be used to verify calling trout distributions and relative use of specific sites or particular times of the year. These two data types have been used to isolate spawning times and locations.

Seasonal mating calls were directly associated with primary spawning activity in east central Florida sciaenids. Figure 4 summarizes their seasonal call pattern at this latitude based on over 300 acoustic transects between 1978 and 2002.

*Spatial distribution of sciaenid spawning calls:* All soniferous spawning populations of sciaenids in the upper Banana River Lagoon, a lagoon associated with the Indian River Lagoon system, within the protected waters of the Kennedy Space Center have been mapped. Spawning sites are utilized only from sunset to midnight during the spawning period with greater call activity on new and full moon phases. Some sites within the Indian River Lagoon system have been known as favored spawning sites with mating calls having been recorded from these sites for over 20 years. Figure 5 represents primary call sites for all sciaenids known to spawn in the upper Banana River Lagoon basin north of the NASA Causeway at the Kennedy Space Center.

### **Future Technology Developments at KSC Relative to Acoustic studies of Sciaenid Fishes**

Once locations and periods of acoustic activity and spawning have been isolated as they have at the Kennedy Space Center, then a number of basic questions and hypotheses can be addressed relative to the evolutionary significance of sound production in sciaenids and other soniferous fishes.

Examples are:

1. Does sciaenid sound production increase the probability of predation mortality?
2. What are the energetic costs of sonifery?
3. How does sciaenid foraging behavior relate to spawning and sound production and are there sexual differences in foraging behavior as a result of differences in mating behavior, acoustic energetics?
4. What are the benefits of sonifery to spawning aggregations?

With the installation of permanent acoustic arrays, portable acoustic systems, roving robotic acoustic platforms and physical sensor arrays we believe it will be possible to address detailed research objectives that will finally unravel the intimate mating, foraging and predatory escape behaviors of regional estuarine sciaenid communities.

### **Acknowledgements**

Sensor Web pod deployments (developed by Kevin Delin, NASA/JPL, Pasadena, CA) and our NASA/KSC PAMS (Portable Acoustic Monitoring System) being deployed by the Clelia submarine during a NOAA OE project August 2001.

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## Illustrations and Diagrams

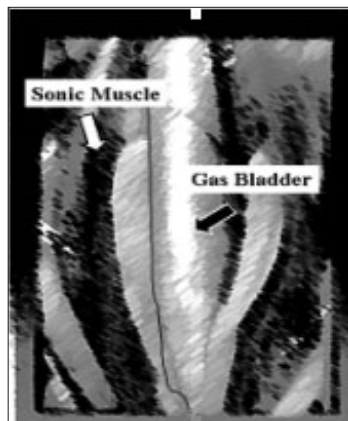
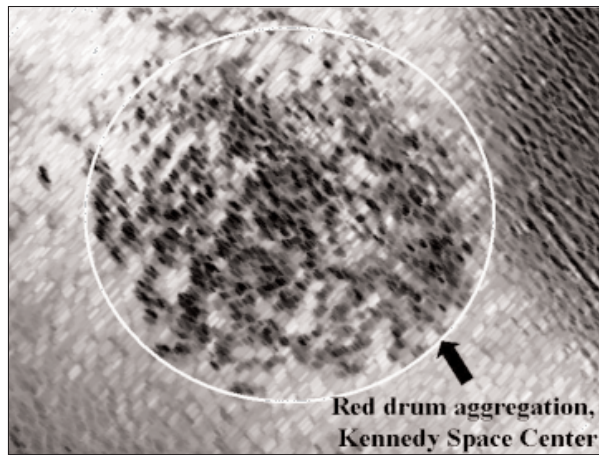


Fig. 1. Representative sciaenid internal anatomy revealing the gas bladder and sonic muscles of a male weakfish, *Cynoscion regalis*.

## Illustrations and Diagrams

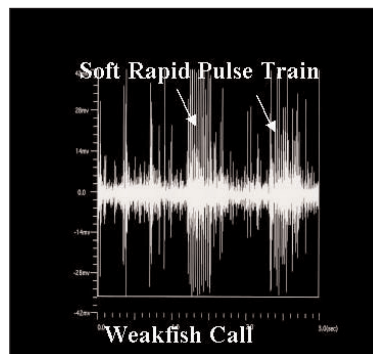
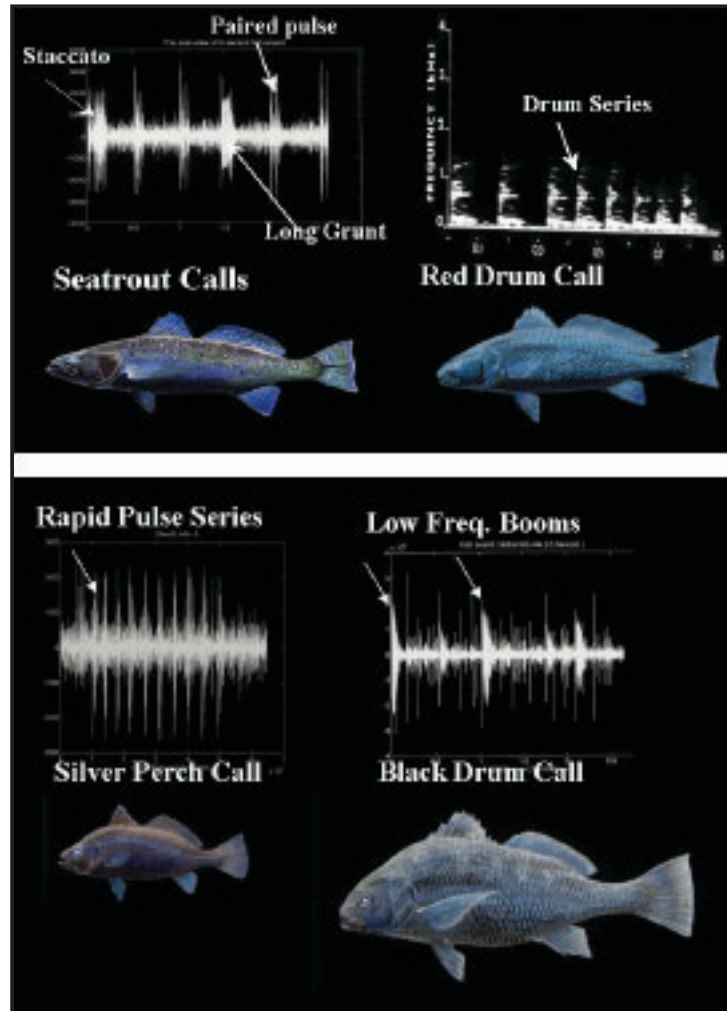


Fig. 2. Energy distribution patterns associated with harmonic frequency bands and fundamental frequencies are species specific and were used to train a neural network to recognize sciaenid calls (Lin 1996).

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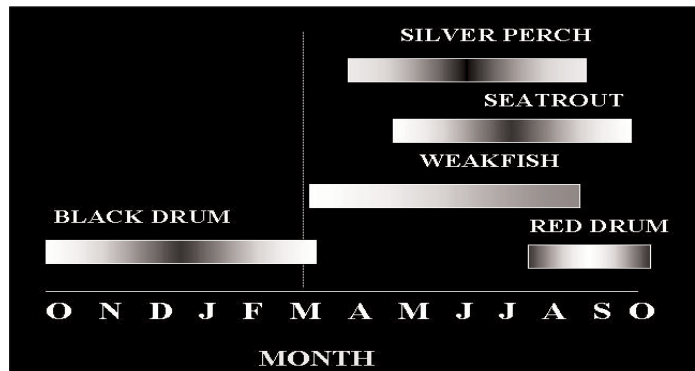


Figure 4. Croaker courtship sound production expressed as number of calls min<sup>-1</sup> across time. Values were determined for one minute out of every five recorded over the course of the evening. The solid vertical line represents the first spawning event (9:29PM) and the double vertical line, the second (10:29PM).

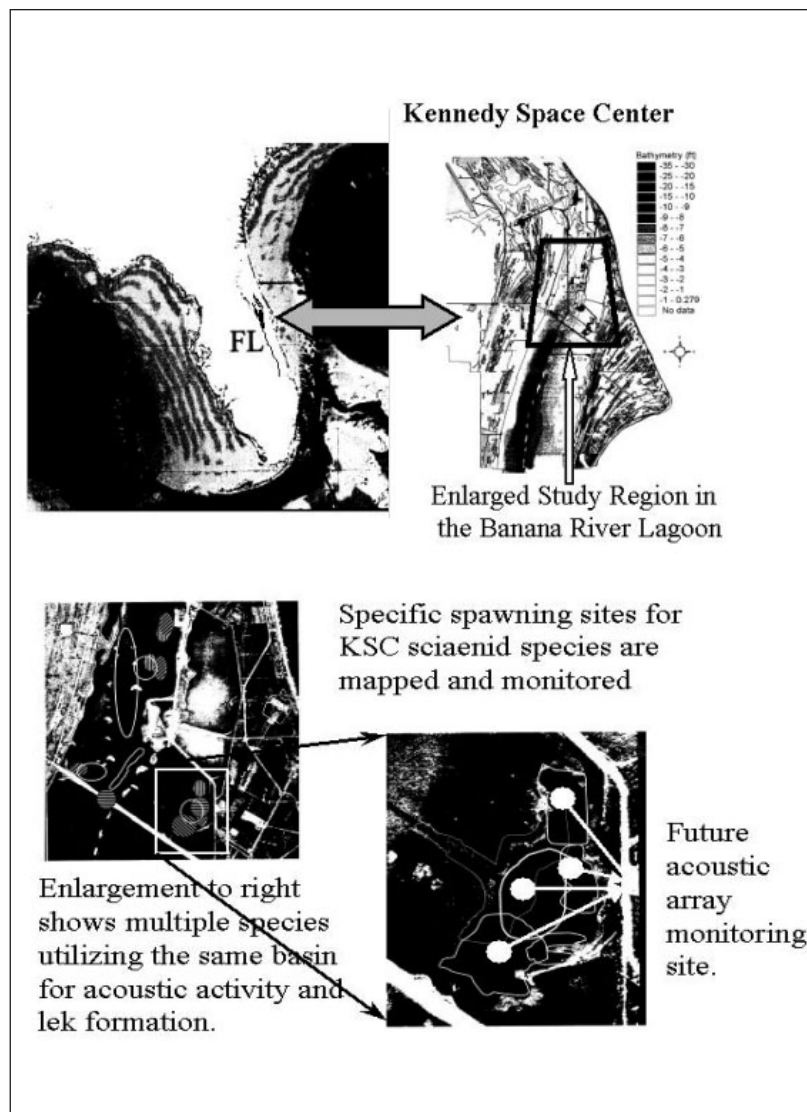


Figure 5

## • **The Use of Passive Acoustics to Identify a Haddock Spawning Area**

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### **Introduction**

The haddock is an important food fish, widely distributed throughout the deeper shelf waters of the North Atlantic. It is very heavily fished and in some areas is considered to be exploited beyond safe biological limits. Fisheries management measures have included the closure of spawning areas (Waiwood & Buzet, 1989). Haddock gather together close to the seabed to spawn (Boudreau, 1992). Fertilization is external and the pelagic eggs hatch near the sea surface. The larvae drift in the upper part of the water column before the young fish move down to the seabed. There is very little detailed information, however, on where haddock spawn. The location of the spawning grounds has to be inferred either from catches of mature fish, or from the distribution of pelagic eggs. Haddock are generally believed to spawn offshore at depths of 200-500m or even deeper (Solemdal et al, 1997), but oral evidence from fishermen suggests that in some areas haddock may spawn inshore (Ames, 1998).

Like other members of the cod family (Gadidae), the haddock is a noisy fish. The male produces a diversity of sounds over the spawning season, with distinctive sounds associated with particular behavioural acts (Hawkins and Amorim, 2000). This behaviour offers the opportunity to detect the presence of spawning fish simply by listening for sounds. A search was therefore carried out in coastal waters by listening for the characteristic sounds of haddock. By this means an aggregation of spawning haddock was located at the upper end of Balsfjord, a sub-arctic fjord in Northern Norway.

### **Aquarium Observations on Spawning Haddock**

Spawning of captive haddock was observed in a 10m diameter annular aquarium tank at the FRS Marine Laboratory Aberdeen. Water depth was 1.5m and the water temperature was maintained at 8°C. The fish were observed from above by means of a low light level TV camera and their behaviour recorded on a time-lapse video tape recorder.

The sounds of the fish were detected with an omni-directional broad-band hydrophone (ITC, 6050C), amplified (Stanford SR560 pre-amplifier, bandwidth 30Hz to 10kHz), sampled at 8 kHz and

recorded directly as WAV files on the hard disk of a lap-top computer by means of Avisoft Recorder. Sound analysis was performed with Avisoft SASLab Pro.

In the aquarium, individual female haddock spawned repeatedly over several weeks. Spawning was accomplished through a close spawning embrace, and preceded by elaborate courtship behaviour. Sounds were recorded in the aquarium from male and female haddock, and from juveniles. However, during the spawning period sounds were predominantly made by the male fish.

Haddock sounds have been described as a series of 'knocks' (Hawkins & Chapman, 1966), repeated regularly at different rates. It has since become apparent that each knock can be subdivided into two short, low-frequency pulses of sound, spaced closely together (Hawkins & Amorim, 2000).

The individual knocks produced by male fish were regularly repeated at a range of different rates, depending on the behaviour of the fish. Short sequences of repeated knocks were emitted during agonistic encounters. At spawning time, male fish produced much longer sequences, lasting from several seconds to several minutes, the knocks being produced at intervals varying from 500 ms to 30 ms. At the very fastest rates, with intervals of less than 50 ms, the sounds were heard as a continuous humming. Different behavioural acts leading up to the spawning embrace were associated with different repetition rates. This rich diversity of sounds produced by the male haddock appears to be characteristic of this species.

Male haddock showed a distinctive solitary display. Dominant males adopted a characteristic pattern of pigmentation, occupied a favoured area and showed a characteristic pattern of movement, moving in tight circles or a figure of eight. During this behaviour the male uttered an almost continuous train of regularly repeated knocks repeated at intervals of between 140 and 60 ms (Figure 1). During the spawning season males spent much of their time in solitary display (9h out of 24, 75% at night), interrupting the display only when other fish entered their territories.

Differences between the sounds of individual male haddock were analysed by measurements on the waveform or through wavelet analysis (see Wood, these proceedings). In most instances the knocks were composed of two pulses separated by intervals of 10-20ms. The two pulses often differed in frequency, the first being higher than the second. Within a given call, or from day to day, there was little variation in the waveform for an individual fish. From month to month, however, there was a significant change in the detail of the waveform, though the double pulse structure was usually retained. There were often striking differences between the sounds of individual males (Figure 2).

The characteristic sounds described from haddock in the aquarium provided clear criteria for the location of spawning male haddock in the sea. The short low frequency sounds (below 1kHz), made up of two pulses separated by intervals of 10 - 20 ms, regularly repeated at intervals of 300 - 30 ms, often for more than several seconds, provided unequivocal evidence of the presence of haddock. Moreover, changes in the repetition rate of the sounds were indicative of different stages in the behaviour of the haddock. The sounds were quite different from those described for other gadoid fish (Hawkins & Rasmussen (1978).

## Observations at Sea

Searching took place in Balsfjord, Tromsø, Northern Norway from a small research vessel (the FF Hvas, Norges Fiskerihøgskole, Tromsø, length 12m). Balsfjord is a subarctic fjord (90 km<sup>2</sup>) with a 30m sill at its entrance, with depths in the inner fjord dropping to 190m. Trawling surveys have shown a preponderance of cod (*Gadus morhua*), but also significant catches of haddock. There is a small local fishery for cod and haddock in the spring, and reports from fishermen suggested that haddock spawned at the head of the fjord.

Sampling took place when individual fish echoes were detected on or close to the seabed on the echo-sounder. The ship was stopped, anchored by the bow, and the hydrophone hung 2m above a weight on the seabed by a cord attached to a small submerged buoy. Sound recordings were made for a minimum of 15 minutes at each station with the main engine and auxiliary generator of the ship shut down. The position of the ship was determined by GPS.

Four surveys were carried out at Balsfjord (17-19 April 2000; 10-12 May 2000; 9-10 December 2000; 3-7 April 2001). The distinctive sounds of haddock were detected at some time during each of the 4 surveys, though not at all stations and with varying incidence. In the first survey, 12 stations were examined. Distinctive haddock sounds were recorded at the majority of stations within the main basin, especially close to the head of the fjord. Slowly repeated knocks, made up of double pulses, were the most common (Figure 3). Some were short (a few seconds), others extended over several minutes. Occasionally, sounds with a faster repetition rate were recorded, suggesting that the haddock were engaging in agonistic and courtship activities. At one station in the main part of the fjord, repeated grunts were recorded which lacked the double pulse structure characteristic of haddock. These were tentatively identified as coming from cod.

Sounds were recorded at all times of the day and night. However, in two areas a continuous low frequency rumbling was detected at night, within which individual haddock knocks could be detected.

During the second survey, sounds were recorded at four of the five stations surveyed. All stations at the head of the fjord yielded haddock sounds, and at three of them, the low frequency rumbling sound was audible at night. At one station it proved possible to record for 10 minute periods every hour over a 24 hour period. This revealed a 10 dB increase in ambient noise level at night, which was attributable to the simultaneous production of sound by many haddock.

The third survey was carried out at the beginning of winter. At three stations long slow knocking sounds were detected, made up of double and occasionally triple pulses, confirming the presence of haddock. The sounds were rare, however, and no low frequency rumbling was detected, suggesting that spawning had not yet begun. The fourth survey investigated 22 stations at the head of Balsfjord during Spring. Many haddock sounds were detected at stations close to the head of the fjord. Low frequency rumbling was detected at night at three stations. No haddock sounds were detected at stations along the eastern edge of the fjord.

## Discussion

By listening, it proved possible to locate concentrations of spawning haddock at the head of Balsfjord during Spring over two successive years, confirming that passive acoustics provide a reliable non-invasive technique for identifying the precise areas where haddock spawn. The method may greatly assist in the search for the spawning areas of commercially important food fishes. Sound production was most intense at night.

## Acknowledgments

These studies were collaborative and depended on the efforts of others. Research at the FRS Marine Laboratory was conducted with Licia Casaretto, Marta Picciullin, & Mark Wood, all of the University of Aberdeen. Studies at sea involved Licia Casaretto, Marta Picciullin and also Kjell Olsen and Captain Eilert Halsnes from the University of Tromsø.

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## Illustrations and Diagrams

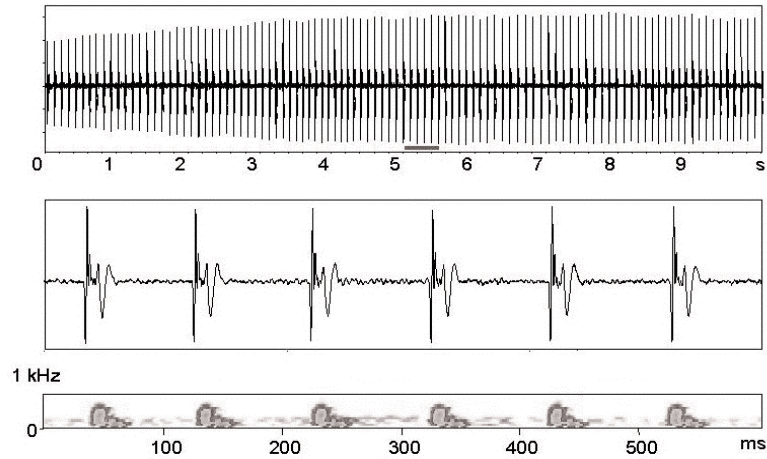


Figure 1. Repetitive knocks from a male haddock during solitary display.

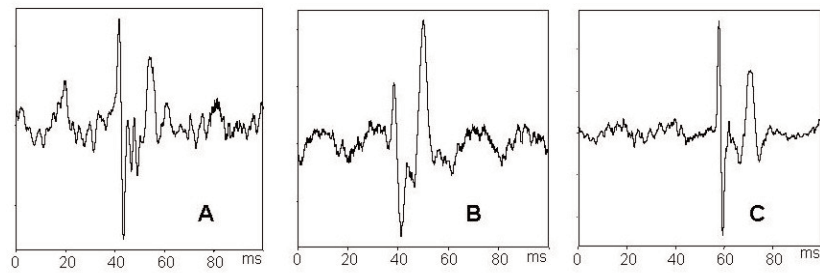


Figure 2. Waveforms of 'knocks' from three individual males (A, B & C).

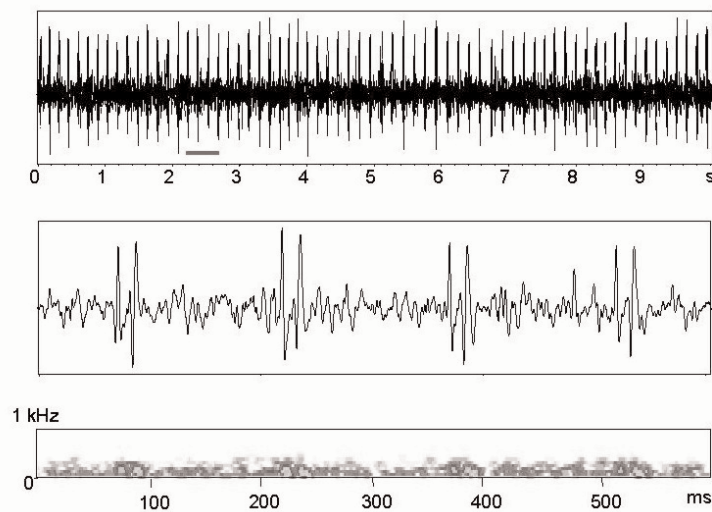


Figure 3. Sounds recorded from Balsfjord, identified as haddock.



## ( · Using a Towed Array to Survey Red Drum Spawning Sites in the Gulf of Mexico

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### Introduction

The red drum (*Sciaenops ocellatus*) is an important recreational and, in some locations, commercial species throughout its range. Juveniles generally live in estuaries and move to nearshore oceanic waters as they reach maturity (Pearson 1929). Adults range widely over the nearshore continental shelf waters throughout the year but apparently move to coastal waters to spawn (Overstreet 1983). Spawning is generally thought to take place in coastal waters near inlets (Jannke 1971, Holt *et al.* 1985) although Lyczkowski-Shultz *et al.* (1988) found eggs and larvae out to 34 km from shore in the eastern Gulf of Mexico. There is also evidence of limited spawning activity within estuaries in Florida (Murphy and Taylor 1990, Johnson and Funicelli 1991) and in North Carolina (Luczkovich *et al.* 1999).

The location of spawning areas has typically been inferred through capture of fish with mature gonads or the distribution of eggs and larvae. Red drum make loud, characteristic sounds during spawning (Guest and Lasswell 1978). Listening for the characteristic sound production has recently been used to locate red drum spawning sites in Indian River Lagoon, Florida (Johnson and Funicelli 1991), and in Plamico Sound, North Carolina (Luczkovich *et al.* 1999), and at tidal inlets in South Carolina (Collins *et al.*, these proceedings). These surveys have been done with both hand-held hydrophones and remotely placed sonobuoys.

Over a four-year period from 1998-2001, a hydrophone mounted on a pier in the Aransas Pass, Texas tidal inlet has been used to record sounds of red drum spawning activity every evening during the September through October spawning period. Recordings were made for 20 s every 15 m from 1700 to 0100 hours and spanned the 4-5 hour evening spawning period of red drum (Holt *et al.* 1985). Red drum produced characteristic spawning sounds from about one hour before sunset to about three hours after sunset with the most intense activity occurring during the two hours following sunset (S. Holt, unpublished data). These data, along with collections of red drum eggs and larvae at the site, confirmed that red drum spawn actively in the vicinity of the tidal inlet. The spatial extent of red drum spawning was still unknown but it was clear that surveying sound production during spawning was an effective means of locating spawning sites.

This paper reports on a survey of potential spawning sites in the nearshore western Gulf of Mexico using a towed hydrophone array.

*Proceedings from the International Workshop on the Applications of Passive Acoustics to Fisheries*

## Study Area and Methods

The survey was conducted in the northwestern Gulf of Mexico along the central portion of the Texas, USA, coast. Preliminary surveys with a hand-held hydrophone in the area revealed that red drum spawning sounds were more commonly observed along the 10 m contour than in either shallow water near the surf zone or farther offshore in deeper water. Hence, for this initial survey, three transects were established roughly parallel to the coastline along the 10 m contour. Transects were sampled on three consecutive nights (one transect per night) in late September 2000. Sampling commenced about 30 - 45 min before sunset, which was about 1925, and ran for about 3.5 hours.

The towed array was composed of eight hydrophones in an 80 meter cable connected to a 200 meter towing cable and was towed at approximately 4.5 kts from a 105 foot stern trawler. The array is spectrally flat (i.e. no peaks in sensitivity) from 6Hz to 18 kHz, with a sensitivity of approximately -191 dB re 1 volt per  $\mu$ Pa at 7.2 kHz. The signals from each of the eight separate hydrophones were saved to an eight-track digital recorder (Tascam DA-88) sampling at 44 kHz. The combination of a temporal window of spawning vocalizations (about 3.5 hours) and optimum towing speed for the array of (4.5 kts) limited each nightly transect to about 20 km.

Red drum produce low frequency sounds described as knocks (Fish and Mowbray 1970) or drumming (Guest and Lasswell 1978). Although Guest and Lasswell (1978) found the "dominant energy" of their recordings from a tank was around 240 Hz - 1000 Hz, I have found the fundamental frequency of red drum calls obtained from unconstrained fish in the field to consistently be around 140 Hz - 160 Hz (Fig. 1). Each call consists of a variable number of pulses, or knocks, that are repeated at a range of pulse repetition rates (Guest and Lasswell 1978, laboratory observations; S Holt unpublished data, field observations). Whether there are specific behaviors associated with specific call types is unknown but the existence of numerous variants in call pattern suggests individual variability. Despite variation in call duration and pulse repetition rate, the consistency in fundamental frequency and general character of the call pattern make recognition by ear relatively easy.

Recorded signals from the array were analyzed by listening to the tapes while observing the real-time power spectra and real-time sonogram on a computer screen (SpectraPro 3.32, Sound Technology Inc.). Two classes of red drum sounds could be distinguished. One was a low frequency rumble with a prominent energy peak in the 150 Hz range. This was presumed to be from large numbers of red drum producing sounds simultaneously but at some distance from the hydrophone. (The sound produced by the ship and the hydrophone itself was determined to have dominant energy in the range of 250 Hz - 300 Hz.) The other class of sounds was clearly distinguishable calls made by an individual or small group of red drum.

The occurrence of background rumble indicates spawning activity in the vicinity of the hydrophone but more work is needed before the spatial scale over which those sounds travel can be meaningfully interpreted. For this paper, I will describe only the distribution of individual or small-group calls. From our observations and the work of Luczkovich *et al.* (1999), it appears that the drumming of an individual red drum can be distinguished over a distance of about 100 m. Thus, we can roughly define the spatial distribution of individual red drum detected by the hydrophones as a 200 m

swath along the transect. The physical location of each observation was determined by comparing the underway data recorded from the ship's SAIL system (which included time and latitude/longitude as well as several physical parameters) and the clock time on the digital recorder which was carefully synchronized with the ship's clock. The data set was initially constructed by recording the hour/minute/second of each identifiable call. The data was then summarized by counting the number of calls heard in each one-minute segment (the ship's location was recorded once per minute so that was our finest scale of spatial resolution). The number of calls/minute was arbitrarily divided into two groups: <16 per minute and 16 or more per minute. This division was set to separate the typically lower occurrence of drumming (5-10 per minute was typical) from the relatively rarer higher rate (we rarely heard more than 20-30 per minute). Finally the drumming rate (i.e. none, low, or high) was plotted on the cruise track.

## Results

Red drum calls were detected along most sections of the three transects (Figs. 2 & 3). Calls were detected both in extensive clusters and in isolated occurrences along the transects. For example, on the San Jose "A" transect (Fig. 3), there are two occurrences of near continuous calling that extend over several kilometers. On the same transect, there are several isolated occurrences of red drum calls and extensive segments (up to 4 km) where there are no calls. Transect segments were dominated by the absence of red drum calls. There was a total of 474 minutes of observations over all transects. Of those, 330 minutes (70%) had no red drum calls, 109 minutes (23%) had low drumming rates (<16 <sup>per min</sup>), and 35 minutes (7%) had high drumming rates (>15 <sup>per min</sup>). High drumming activity was concentrated in two segments along the San Jose "A" transect and in one segment of the Matagorda transect. One segment, on the east end of the transect, spanned 5 minutes of towing time and covered 600 m. The other, farther to the west on that transect, spanned 14 minutes of towing time and covered 2.2 km. Only 4 of the 14 minutes in this segment were low level drumming and none were without drumming.

The most intense drumming activity occurred between 1830 and 2130. Little drumming was heard after 2130 on the Matagorda or San Jose "A" transects (data for the later part of the San Jose "B" transect was lost due to an audio tape malfunction). Low and high drumming rates were distributed throughout this time period without any temporal pattern.

## Discussion

Based on the distribution of sound production, red drum appear to spawn all along the nearshore region of the central Texas coast. This survey was not spatially comprehensive enough to fully delineate the spawning area, but it is clear from this initial survey that spawning activity is widespread. Spawning was not concentrated at inlets as suggested by earlier authors (Simmons and Breuer (1962), Jannke (1971)). Areas of the coastline far removed from the inlets had relatively intense drumming activity and confirms suggestions of Murphy and Taylor (1990) that spawning also occurs over the nearshore continental shelf.

It is still not exactly clear how drumming by male red drum should be interpreted. There are at least three possibilities: 1) the drumming male will engage in spawning at that location on that evening; 2) the drumming male is calling from a potential spawning site but will spawn at that site on that day only if joined (or selected) by a cooperative female; or 3) the drumming male may move to another place before engaging in spawning. Luczkovich *et al.* (1999) observed instances of red drum drumming without finding eggs and Johnson and Funicelli (1991) found red drum eggs without hearing drumming. In both instances, short-term observations were made in shallow water with a hand held hydrophone and the observers may have disturbed the fish or missed part of the spawning process. At this point, it is assumed that drumming roughly equates to spawning but the issue needs more investigation.

The distribution of drumming male red drum suggest that some, if not most, of the spawning takes place among widely distributed individuals as opposed to highly aggregated groups. Only 7% of the one-minute summaries recorded high drumming rates of more than 15 calls per minute. Guest and Lasswell (1978) reported a call rate of about 2-16 calls per minute for captive red drum in courtship. Our subjective impression from listening to the tapes was that many of the low drumming rates were produced by a single fish. There were, however, at least two large aggregations of drumming fish. Both were in the vicinity of Cedar Bayou, a relatively small but historically persistent tidal inlet. One of these aggregations spanned a linear distance of over 2 km and its breath was undetermined. The number of calls per minute (up to 40) indicates that several red drum were calling simultaneously within the roughly 100 meter detection range of the hydrophones and this "density" was consistent over most of the 2 km stretch.

The full extent of the offshore spawning area of red drum is yet to be determined and much remains to be learned about their reproductive strategies, but the use of towed hydrophone arrays offers promise of an efficient means to achieve those goals.

### **Acknowledgments**

I thank John Keller for processing the audio data and Cameron Pratt for preparing the figures. The crew of the R/V Longhorn was instrumental in acquiring the recordings. This work was funded through a grant from the Sid W. Richardson Foundation.

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## Illustrations and Diagrams

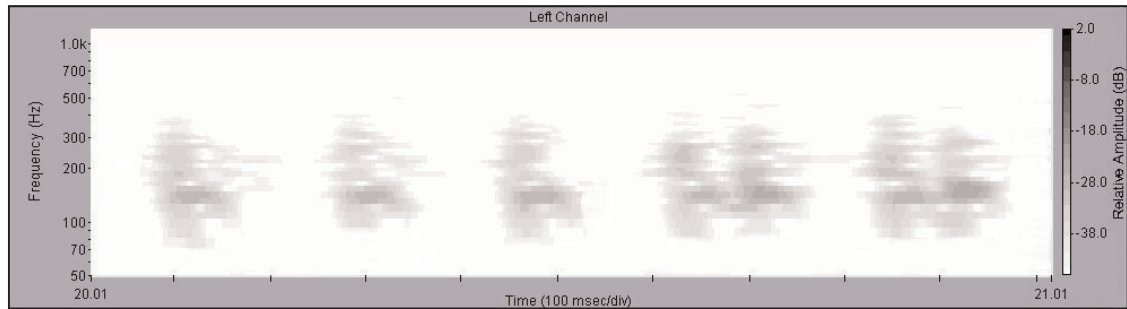


Figure 1. Sonogram of a red drum call from an unconstrained individual in the field. This particular call consists of three widely spaced knocks followed by two pairs of closely spaced knocks.

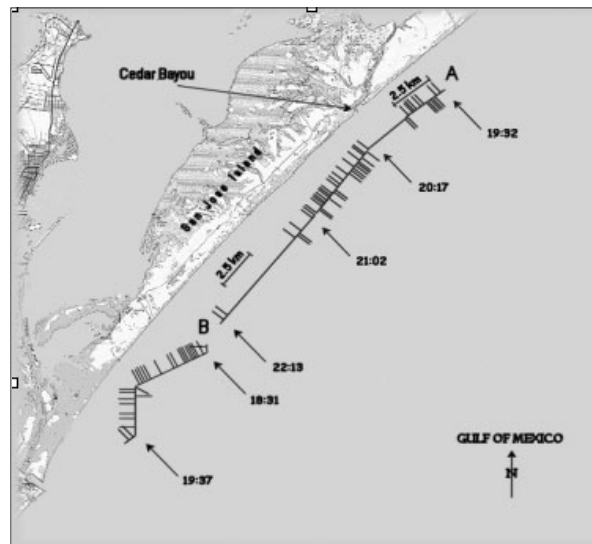


Figure 2. Location San Jose "A" and "B" hydrophone transects. The line indicates the cruise track. Bars above the line indicate low one-minute drumming rates at that location. Bars below the line indicate high one-minute drumming rates. Sampling time is indicated randomly along the track.

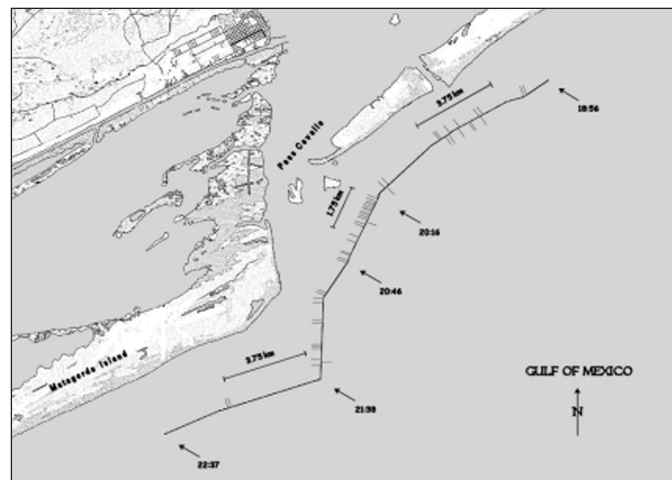


Figure 3. Location of the Matagorda hydrophone transect. See Fig.2 legend for details.

## ( • Reef Fish Courtship and Mating Sounds: unique signals for acoustic monitoring

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The following text is extracted from:

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The table is reprinted from:

Lobel, P.S. (2001) Acoustic behavior of cichlid fishes. *J. Aquaculture & Aquatic Sci.* 9, 167-186.

### **Introduction**

Marine bioacoustics is a multidisciplinary field with practical applications to economically important global fisheries issues. One application of bioacoustics uses passive acoustic technology to record temporal and spatial patterns of fish reproduction by detecting sounds associated with spawning (Mann and Lobel 1995). The applicability of this tool depends upon whether specific species produce reliably identifiable sounds during courtship and spawning (Lobel 2001a). Monitoring courtship and spawning sounds can be used to define important breeding habitats (a priority in planning marine protected areas) and to understand the relationships between fish reproduction and the fate of larvae in ocean currents. Mating is the crucial biological event to monitor in order to understand the life history tactics of fishes, especially coastal marine species with a pelagic larval phase. Mating is also a critical endpoint measurement in pollution impact studies. Measuring a decrease in reproduction may be an early indication of subtle adverse effects of pollution. It is well known that many fishes produce sounds associated with courtship. However, which fishes produce specific sounds during spawning is not as well known.

A strong case for the value of bioacoustic monitoring is made by the discoveries that two of the world's most valuable fishes, cod and haddock, produce distinct courtship and spawning sounds (Nordeide and Kjellsby 1999, Hawkins and Amorim 2000). This paper documents the spawning sounds of four coral reef fishes and illustrates different types of acoustic patterns.

## Examples of Spawning Sounds

Methods are reported by Lobel (2001a) and spawning behaviors with sounds are described in references cited below for each species.

*Ostracion meleagris* (Family Ostraciidae) produces a clear tonal sound with one harmonic (Figure 1a, Lobel 1996).

*Dascyllus albisella* (Family Pomacentridae) produces a spawning sound composed of a simple series of one to four pulses (Figure 1b). This spawning sound differs from its courtship sound only by having fewer pulses (Lobel and Mann 1995). A spawning sound was not found in another pomacentrid (*Abudefduf sordidus*) or in related freshwater cichlids (Lobel 1998, 2001b, Lobel and Kerr 1999), even though these other fishes produce courtship sounds similar to *D. albisella*.

*Hypoplectrus nigricans* (Family Serranidae) produces a distinct two-part spawning sound (Figure 1c). A short downward frequency sweep is followed by a short silence and then followed by a broad-band sound, which is made as the fish disperse gametes (Lobel 1992). This sound may be a combination of swimbladder sound and hydrodynamic noise from rapid fin fluttering.

*Scarus iserti* (Family Scaridae) spawns in aggregations of about 20 to 40 individuals. These fish gather in groups over the reef surface and then suddenly and with great speed, rush upwards a few meters, turn rapidly while releasing gametes and dart back to the reef shelter (Lobel 1992). This spawning sound is hydrodynamic noise produced by the fish's swimming movements (Figure 1d).

## Discussion

Why do some fishes make spawning sounds? By the time mating has started, mate selection has already taken place. Such sounds may have originated as a mere by-product of movements associated with swimming and gamete extrusion. Furthermore, these sounds are in the low frequency range that has been shown to be highly attractive to predators, e.g. sharks (Myrberg et al. 1972). Spawning fishes may be less responsive to predatory threats once they are completely preoccupied with mating (Lobel and Neudecker 1985, Sancho et al. 2000). The possibility that spawning sounds may be an attracting signal to predators on adults or newly spawned embryos is a significant potential cost in terms of natural selection. This implies that spawning sounds must also provide some evolutionary advantage as well. Spawning sounds may have evolved to behaviorally synchronize gamete release in order to maximize external fertilization.



**Table 1. (reprinted from Lobel 2001b)**

Possible information transmitted by sound patterns (in order of increasing complexity of signal interpretation)

<b>Message</b>	<b>Acoustic clue</b>
Mate location	sound occurrence
Readiness to spawn	sound occurrence synchronization of gamete release (= mating or spawning sound)
Vigor / aggressiveness	duration of call &/ call repetition rate
Individual size	dominant frequency
Species identity	variation in pulse repetition rate in a call, number of pulses in a call, variation in pulse amplitude, call duration , plus color patterns & behavior
Individual identity	combination of all above clues, plus other features of behavior

### **Acknowledgement**

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## Illustrations and Diagrams

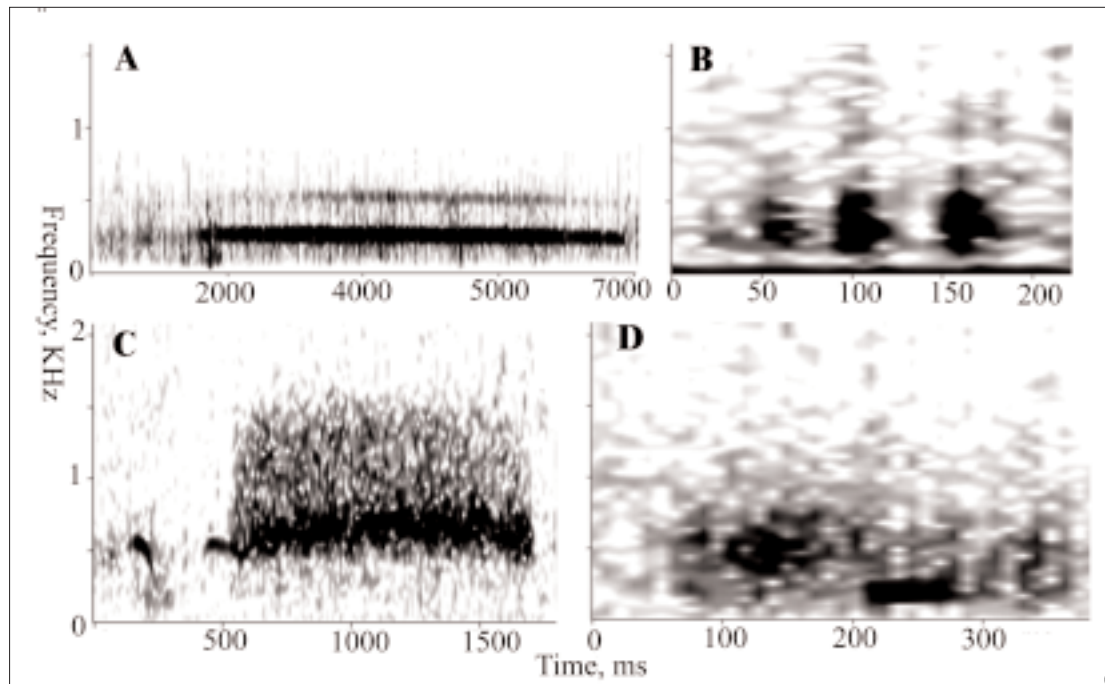


Figure 1. Sonograms produced using the hamming window function and an FFT size of 2048 points (Canary software). Frequency scale is the same in all graphs, but time scale differs in each. a) *Ostracion meleagris*, duration 6213 ms, dominant frequency, DF 258 Hz, b) *Dascyllus albisella*, 3 pulses, duration 130 ms, DF 328 Hz, c) *Hypoplectrus nigricans*, duration 1581 ms, DF 656 Hz, d) *Scarus iserti*, duration 329 ms, DF (two peaks) 492 & 211 Hz. Size range of these fishes is about 10 – 20 cm SL. (reprinted from Lobel 2002).

# Using Passive Acoustics to Monitor Spawning of Fishes in the Drum Family (Sciaenidae)

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## Introduction

Drum fish (Family Sciaenidae) are known for their sound production during mating, from which the family derives its name (Fish and Mowbray 1970). Members of the drum family are dominant species in the large and valuable commercial and recreational fisheries in North Carolina and the Southeastern USA. Recently, concerns have been raised about the decline in the population and spawning stock of some sciaenids, especially the red drum, *Sciaenops ocellatus* (Ross et al. 1995). One management option that has been suggested is to create spawning reserves, but spawning areas must be surveyed first in order to protect them. Sciaenid fishes held in captivity produce species-specific sounds associated with spawning behavior (Guest & Laswell 1978; Connaughton and Taylor 1996, Sprague et al. 2000) and recently spawned eggs and sounds co-occur in field samples (Mok and Gilmore 1983, Luczkovich et al. 1999). Spectral analysis of these sounds allows us to identify each sciaenid species based on their sound production, even when they co-occur in the same area (see Sprague et al 2000, Sprague and Luczkovich these proceedings). Because sounds are produced by male fishes in the Sciaenidae in communication during courtship and spawning, we are able to use these sounds as an indicator of spawning areas. Here we report on how we used passive acoustic survey techniques for mapping spawning areas of red drum, weakfish (*Cynoscion regalis*), spotted seatrout (*C. nebulosus*) and silver perch (*Bairdiella chrysoura*) in Pamlico Sound, NC.

## Methods

Sounds of sciaenid fishes were recorded in two ways: 1) a hydrophone and recording system deployed from a small boat that was able to move from station to station; and 2) a hydrophone array system on a remotely operated vehicle (ROV) with low-light video capabilities. From May through September during 1997 and 1998, we used an InterOcean (902) Calibrated Acoustic Listening System [consisting of a gain-adjustable pre-amp, a hydrophone, and an overall sound pressure level meter] and a Sony (TCD-D8) Digital Audio Tape recorder to record from a small boat at fixed stations in Pamlico Sound for up to 5 min per station after sunset on monthly intervals. The

hydrophone was suspended over the side of the boat at a depth of 1 m. In order to confirm that the sites where we recorded sounds were spawning areas, we conducted ichthyoplankton surveys at the hydrophone stations immediately after each sound recording ended. A 28-cm diameter bongo net with 500  $\mu\text{m}$  mesh was towed at the surface for 5 min to capture the buoyant eggs. In May of 2001, we used a Phantom S2 ROV with low-light video and a calibrated International Transducer Corporation (ITC-4066) hydrophone array to record the sound production of a silver perch *in situ*. The hydrophone array was mounted on the ROV on a 1.5 m long boom. The pre-amplified signal from the hydrophone array was sent up the 900-foot ROV umbilical cord to an audio and video recorder on board the boat. Although we used a four-hydrophone array, which was originally intended to help localize fish sounds, only one hydrophone (hydrophone number 4 located on the far right side of the boom as viewed from the point of view of the video camera) was selected for recording in this study. All sound recordings were resampled at 24 kHz from the original tapes using a National Instruments A/D board. We used 1024-point Fast-Fourier-Transforms (FFTs) to obtain spectrograms and estimates of overall sound pressure levels. To generate the spectrograms, we used Virtual Instruments written for use with LabView data acquisition software and Mathematica for creating plots. Statistical analysis was done using Systat 10 (Sprague et al. 2000).

## Results

We detected the spawning aggregations of silver perch, weakfish, spotted seatrout, and red drum in Pamlico Sound during both 1997 and 1998. Male silver perch were detected on both the eastern and western side of Pamlico Sound, but were loudest at the inlet stations during May and June of both years (Figure 1a). The male weakfish were detected making their characteristic “purring” sounds only at stations on the eastern side of Pamlico Sound, near Ocracoke and Hatteras Inlets in May through August of both years, but the peak calling was in May and June (Figure 1b). Spotted seatrout were found producing their grunts at stations on both sides of the sound from June through September, but were more regularly recorded near the Bay River on the western side of Pamlico Sound in July of both years (Figure 1c). Red drum were heard both at the inlets and on the western side of the sound in August through September both years, but they were loudest in September near the mouth of the Bay River in the western side of the sound (Figure 1d). The overall picture is one of a seasonally shifting use of specific areas near river mouths and inlets by the four species, with distinct peak spawning times for each species. To demonstrate that these sounds are associated with spawning activity, we collected sciaenid type eggs in the areas where we had recorded fish sounds. The overall sound pressure level (in dB re 1  $\mu\text{Pa}$ ) at each station was directly correlated with the  $\log_{10}$  transformed sciaenid type egg density (Figure 2,  $r = 0.61$ ). This suggests that the sounds (produced by male fish) and the recently spawned sciaenid eggs (produced by female fish) are associated in space and time, an indication that the sounds are associated with spawning.

The low-light capabilities of the video camera of the Phantom S2 ROV allowed us to see fish as they made their sounds. Thus, we were able to measure the sound production by silver perch when they were a known distance from the hydrophone. In this way, we were able to determine the sound

source level for an individual fish *in situ*, which is a necessary first step for modeling sound production and propagation. In May 2001, we had the opportunity to capture a single silver perch on video while it passed in front of the ROV and the hydrophone, producing some of the loudest sounds that we had recorded during our surveys. The ROV was deployed in Wallace Channel, near Ocracoke Inlet, at a depth of 28 feet, in an area where we had previously recorded loud vocalizations of both silver perch and weakfish. Poor water clarity and strong currents at this site limited the camera's ability to see and the mobility of the ROV, which was deployed with a down-weight rig to hold near to the bottom during the tidal current shifts. On May 5, 2001 at 21:18:05, we recorded a calling male silver perch and measured the sound pressure level at hydrophone #4 when the fish was swimming through (from left to right) the viewing field of the low-light video (Figure 3). At this point, the sound pressure level was 126 dB re 1  $\mu$ Pa. At 21:18:15, after the fish swam across the video field of view, and closer to hydrophone # 4, which was on the boom to the right, the sound pressure level was measured at 129 dB re 1  $\mu$ Pa. Thus, the overall sound pressure level increased as the fish (sound source) got closer to the hydrophone.

## Discussion

The passive acoustic approach we have described is limited to soniferous fishes, but almost all sciaenids fall into this category. Soniferous sciaenid fishes produced sounds during spawning in Pamlico Sound, and these general areas have been mapped. Weakfish and silver perch call commonly near Hatteras and Ocracoke inlets, peaking in May and June, whereas spotted seatrout were commonly detected calling throughout the summer in both eastern and western Pamlico Sound, peaking in July. Red drum were less commonly detected by passive acoustics than the other species of sciaenids, perhaps due to their declining spawning stocks; they were only detected at the inlets and in western Pamlico Sound in August and September, with the greatest sound production at the mouth of the Bay River in September. Sciaenid-type egg abundance was correlated to overall sound pressure level (loudness) of sciaenid drumming in field surveys, suggesting that egg production could be estimated from sound production. This passive acoustic approach to estimating spawning stock relative abundance would be useful to fishery biologists attempting to verify the variations in spawning stock sizes from year to year. No estimates of absolute fish abundance can be made at the present time; but biomass estimation may be possible in the future if active acoustics were also used.

From the ROV hydrophone measurement of sound source levels, we can now estimate the distance over which fish sounds can be detected. For an individual silver perch calling 1 m from the hydrophone at 129 dB re 1  $\mu$ Pa, (assuming a cylindrical spreading model, where  $r_{\max}$  is the radius of the cylinder, see Luczkovich et al. 1999), we can now estimate  $r_{\max} = 10^{(SPL_{\text{source}} - SPL_{\text{background}})/10} = 79$  m. However, this cylindrical spreading model assumes that sound waves will propagate through water with constant temperature and salinity and a uniform depth, conditions that are unlikely to occur at the inlets. Consequently, we may be over-estimating the distance which we can detect sounds. It is also possible that sound may be channeled further than this due to particular bathymetric and water stratification conditions peculiar to Pamlico Sound and the inlets.

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## Illustrations and Diagrams

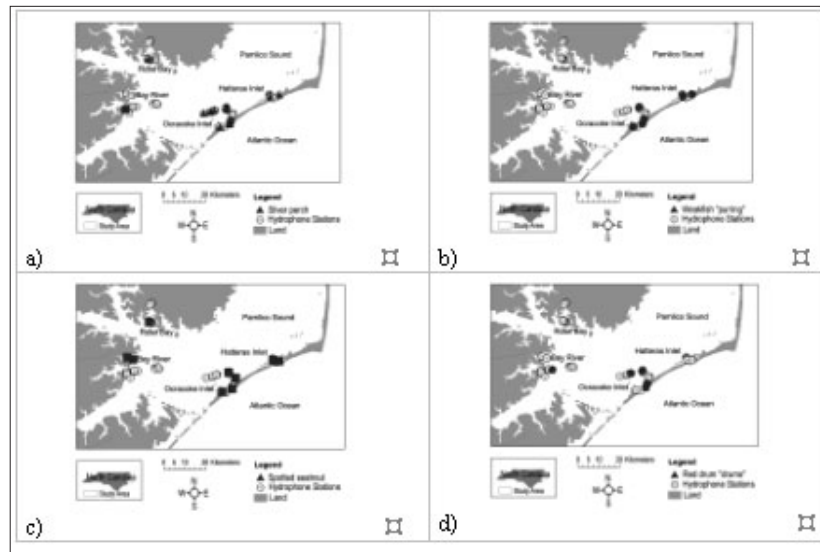


Figure 1 Maps of Pamlico Sound sciaenid species' spawning areas and times as determined by hydrophone surveys: a) silver perch (triangles), peaking in May and June; b) weakfish (circles) peaking in May and June; c) spotted seatrout (squares) peaking in July; and red drum (pentagons) peaking in September.

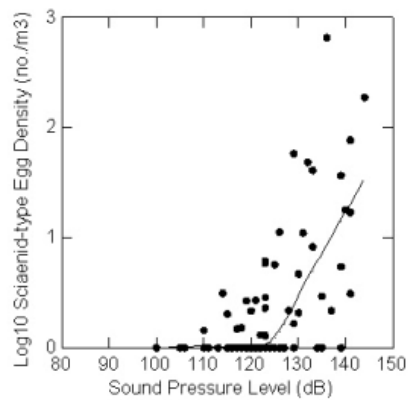


Figure 2 Log 10 transformed sciaenid-type egg production plotted versus sound pressure level (db re 1  $\mu$ Pa). Line fitted with a locally weighted regression (LOWESS).

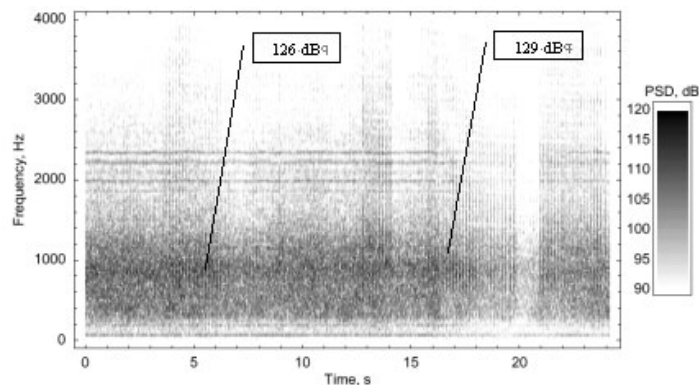


Figure 3. Spectrogram of 24-s segment of the ROV audio track from hydrophone #4, recorded 5 May 2001, beginning at 21:18:00. The sound source levels (in sound pressure in dB re 1  $\mu$ Pa) are shown for two times at which the silver perch first appears in the ROV video camera field of view (at 5-6 s) and just after it passed out of view of the camera, when it was the loudest (at 16-17 s)





## Is acoustic calls a premating reproductive barrier between two northeast Atlantic cod (*Gadus morhua*) groups—a review

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### Summary

This paper reviews the first attempts to test the hypothesis that spawning calls of male migratory “Arctic” and a stationary “Coastal” cod group, which are sympatric during the spawning season, is a premating behavioural reproductive barrier. As predicted from the hypothesis, a hushed hubbub of sound with a transient character, band-width and harmonic spacing typical of cod calls, was revealed at a major spawning ground during the spawning period but not six months later. Moreover, individual calls from male cod kept in tanks varied a lot both in harmonic spacing and duration, from 42 to 79 Hz and 0.11 to 1.25 s, respectively. Such individual variation in calls is expected if females choose mate on the basis of their calls. However, the results so far has failed to support the third prediction, since no differences have been found between the calls of the two groups, neither in harmonic spacing, duration, or temporal structure of the calls.

### Introduction

Northeast Atlantic cod consist of two stocks, the Northeast Arctic, or “Arctic” cod, and the Norwegian coastal cod, or “Coastal” cod (Rollefson 1934). Arctic cod migrate from the feeding areas in the Barents Sea to the spawning areas along the Norwegian coast and the most important spawning area is off the Lofoten Islands where the main spawning occurs in March and April (Bergstad & al. 1987). Coastal cod inhabit coastal areas and fjords, migrate short distances and spawns in a large number of fjords along the Norwegian coast (Rollefson 1954), including off the Lofoten Islands (Hyllen 1964). Both cod groups spawn in March and April and mature specimens are sympatric during spawning at the major spawning grounds off the Lofoten Islands (Nordeide 1998). A controversial topic during decades has been whether or not the two cod groups interbreed, and a majority of studies conclude that they rarely do (see references in Nordeide & Pettersen 1998). If so, active partner choice is required, and lekking has recently been suggested to best describe the cod’s mating system (Hutchings & al. 1999; Nordeide & Folstad 2000).

Møller (1968) suggested that active partner choice based on acoustic calls may be an behavioural mechanism which prevents interbreeding between the two cod groups. The aim of this paper is to

summarize the first attempts to test predictions derived from Møller's hypothesis. The predictions are that (i) recordings from major cod spawning grounds should reveal sound with characteristics typical of cod whereas much less sound should be revealed outside the spawning season, (ii) calls from individual cod should show considerable variation, and (iii) calls from Arctic and Coastal cod should differ.

## **Material and methods**

To study sound at a major spawning ground, recordings were carried out during the night at five stations off the Lofoten Islands at 68°13.0'N 14°38.7'E in Northern Norway, during the spawning season 8 and 9 April 1997, and half a year later on 4 September 1997 (Nordeide & Kjellsby 1999). The measuring hydrophone with a 32 dB gain built-in preamplifier had a total sensitivity of -152 dB re 1 V/ $\mu$ Pa within the frequency range of 16 Hz to 2 kHz. In order to emphasize the transient character of the sound the digital recordings were analysed with Short-time Fourier Techniques (STFT), at the Norwegian Defence Research Establishment (Nordeide & Kjellsby 1999).

To compare the calls from the two groups, recordings were carried out in land-based tanks in 1998 to 2001 (Finstad, 2002.). Specimens of the Arctic and Coastal cod were caught by trawl and transferred to tanks where recordings were carried out during the spawning period in 1998 - 2001. The smallest male used was 53 cm and the largest male was 94 cm long, whereas the smallest and largest females were 51 cm and 104 cm long, respectively. The average length of the five cod groups varied from 74.2 cm to 84.0 cm for males, and from 68.8 cm to 90.5 cm for females. Most recordings were from three 6 m diameter fibreglass tanks, but a 3 m diameter fibreglass tank was also used. Water level was 1.4 - 1.5 m in all tanks. Recording equipment was a 1 inch piezoceramic spherical hydrophone with a sensitivity of -198 dB ref 1V 1 $\mu$ Pa, a Levell preamplifier type TA 601 with 60 dB gain, and a Sony TCD-D100 digital tape recorder. In 1998, the recordings were carried out with 12 specimens (six Coastal males) in the experimental tank, whereas seven Arctic cod (5 males) were present in 1999. After the first years of experience we had identified two major problems: (i) we were not able to identify which cod produced the calls, and (ii) relatively few grunts had been recorded. In 2000 and 2001 we therefore chose to first record grunts with all cod in each group kept together, to increase the number of grunts. Thereafter, we split the groups of fish into a total of 10 smaller sub-groups to increase the minimum number of individual cod which could possibly produce the grunts. The groups in 2000 and 2001 consisted of 8 (3 males), 25 (19 males) and 22 (7 males) cod, respectively. The sub-groups consisted of from 4 (2 males) to 16 (11 males) cod. Towards the end of the spawning season the fish were killed. Examination of their otoliths by the Institute of Marine Research in Bergen, revealed that the recordings were carried out with groups and sub-groups consisting of (i) only male Coastal cod with or without the presence of Arctic females, (ii) only male Arctic cod with or without the presence of Coastal females, and (iii) a mixture of Coastal and Arctic males and females. These three alternative combinations are referred to as "Coastal-vocal", "Arctic-vocal" and "Mix-vocal" groups respectively, since only males produce sound during the spawning period (Brawn 1961c, Hawkins & Rasmussen 1978, see also Templeman & Hodder 1958, Engen & Folstad 1999). The number of individual cod (statistical "N") which could have produced the

recorded grunts were minimum 3 and maximum 12 in the “Coastal-vocal” group, minimum 2 and maximum 7 in the “Arctic-vocal”; and minimum 4 and maximum 22 in the “Mix-vocal” groups. Analysis by Avisoft-SASLabPro v. 3.74 provided estimates of harmonic spacing and duration of the grunts. Temporal structure of 78 recorded high quality grunts were analysed from oscillograms. Parameters included were number of downward peaks, time-intervals between peaks, and duration of the grunt. These parameters were analysed by Principal Component Analysis by the software “The Unscrambler” v. 7.5.

## Results and Discussion

Field recordings provide support for the hypothesis that acoustic communication is important during cod spawning. Sound recordings at the major spawning ground off the Lofoten Islands revealed a hushed hubbub of sound, at approximately 40 - 500 Hz during the spawning period (Fig. 1a). Much less sound was revealed in September (Fig. 1b) when no cod spawn and migratory cod had emigrated to the Barents Sea. Nordeide & Kjellsby (1999) argues that this sound most likely is made by spawning cod since (1) The sound activity is highest in the frequency range where it has been suggested cod communicate (Chapman & Hawkins 1973; Hawkins & Rasmussen 1978). (2) The sound above 50 Hz had a transient character as expected for cod grunts. (3) More than ca. 50 million male cod spawned off the Lofoten Islands in April 1997, and recordings were made where the Institute of Marine Research in Bergen located the highest densities of spawning cod. (4) Cod totally dominated, by constituting more than 98 % by wet weight, the experimental and commercial catches in the area the seven days before, during and after the recordings (Nordeide & Kjellsby 1999).

Variation in calls between individual cod kept in tanks is as expected under the hypothesis that acoustic communication is important during female mate choice. Grunts from cod kept in tanks vary in harmonic spacing from 42 Hz to 79 Hz, and in duration from 0.11 s to 1.25 (Table 1). The two grunts with the lowest and highest harmonic spacing came from two different individuals, since they were recorded from two different sub-groups. The shortest and longest calls were also produced by two different individuals. This shows that different cod individuals may grunt at different frequencies and durations, but we cannot tell anything about each individual cod’s possibility to vary their calls.

	Frequency (Hz)				Duration (s)			
	<b>N</b>	<b>Mean</b>	<b>Min</b>	<b>Max</b>	<b>N</b>	<b>Mean</b>	<b>Min</b>	<b>Max</b>
CC-vocal <sup>1</sup>	18	53.4	47	60	11	0.33	0.13	0.94
NAC-vocal <sup>2</sup>	11	55.7	50	60	11	0.31	0.11	0.74
MIX-vocal <sup>3</sup>	126	51.5	42	79	95	0.22	0.13	1.25
All grunts	155	52.1	42	79	116	0.24	0.11	1.25

Table 1 (above). Mean, minimum and maximum values of frequency and duration of grunts from CC-vocal<sup>1</sup>, NAC-vocal<sup>2</sup> and the MIX-vocal<sup>3</sup> group. Number of grunts (N) of frequency measurements and duration measurements differ because some of the duration measurements were difficult to perform due to background noise. The table is from Finstad (2002.).

- <sup>1</sup> Grunts from groups and sub-groups consisting of CC males and CC and NAC females, based on otolith analyses
- <sup>2</sup> Grunts from groups and sub-groups consisting of only NAC individuals, based on otolith analyses
- <sup>3</sup> Grunts from groups and sub-groups consisting of both CC and NAC, both males and females, based on otolith analyses

The average harmonic spacing of grunts from the Coastal-vocal groups and Arctic-vocal groups were 53.4 Hz and 55.7 Hz, respectively, and the calls from the two cod groups lasted on average 0.33 s and 0.31 s, respectively (Table 1). The difference of 2.3 Hz in harmonic spacing and 0.02 s in duration between the two groups, is probably negligible. The difference cannot be tested statistically because the grunts are not independent events, since we were not able to tell which cod produced each call. Moreover, the calls from the Mix-vocal groups show no bimodal distribution in harmonic spacing or duration, as is expected if Coastal and Arctic cod call at two separate frequencies or durations. In the multivariate analysis of the temporal structure of the grunts, the first and second principal component explained 45 and 20%, respectively, of the total variation. However, the analysis did not cluster the grunts from Arctic-vocal and Coastal-vocal cod into two separate groups, as should be expected if the temporal structure of the two cod-groups differed (Finstad, 2002.). The hypothesis thus failed to pass the third test, since we have not been able to separate the calls from the two cod groups. However, analysis of temporal structure will continue with less rough analytical tools.

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## Illustrations and Diagrams

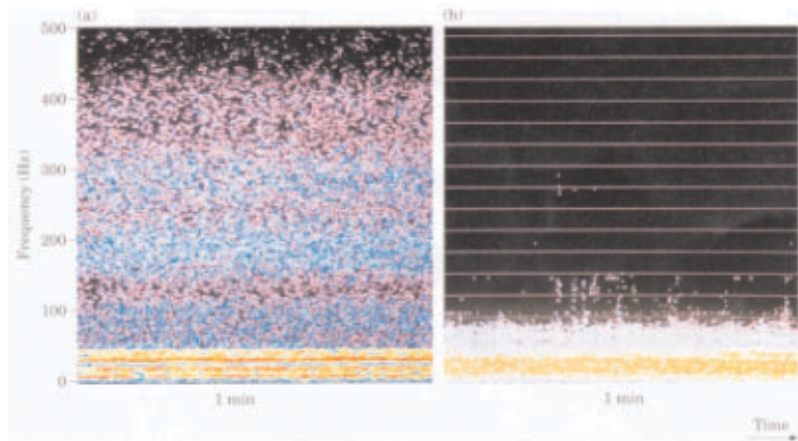


Figure 1. Recordings from a major spawning ground off the Lofoten Islands, (a) during the spawning period in April and (b) in September when no cod spawn. Reprinted from *ICES Journal of Marine Science*, Vol. 56, Nordeide, J.T. & E. Kjellsby, Sound from spawning cod at their spawning grounds, 326-332, 1999, by permission of the publisher Academic Press.

## • Applications of underwater acoustics data in fisheries management for spotted seatrout, *Cynoscion nebulosus*, in estuaries of South Carolina

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### Introduction

The spotted seatrout, *Cynoscion nebulosus*, is an estuarine-dependent member of the family Sciaenidae. Spotted seatrout are year-round residents of estuaries along the South Atlantic coast and spawning takes place inshore and in coastal areas (McMichael and Peters, 1989; Luczkovich *et al.*, 1999). During summer months, male spotted seatrout produce “drumming” sounds, this resulting from the contraction of the swimbladder by specialized muscles which are seasonally hypertrophied from the abdominal hypaxialis muscle mass (Fish and Mowbray, 1970; Mok and Gilmore, 1983). Direct involvement of sound production with spawning has been shown for this and other sciaenids (Mok and Gilmore, 1983; Saucier *et al.*, 1992; Saucier and Baltz, 1993; Luczkovich *et al.*, 1999). By listening to these sounds during evening hours (Holt *et al.* 1985) using hydrophone equipment we determined the locations, seasonality and diurnal periodicity of spawning aggregations in Charleston Harbor (Saucier *et al.*, 1992; Riekerk *et al.*, unpublished data).

Spotted seatrout are group-synchronous spawners with indeterminate fecundity. As such, they release gametes in several batches over a protracted spawning season and total fecundity is not fixed prior to the onset of spawning (Wallace and Selman, 1981). The spawning season extends from April through September along the South Atlantic and Gulf of Mexico coasts (Overstreet, 1983; Brown-Peterson *et al.*, 1988; McMichael and Peters, 1989; Wenner *et al.*, 1990; Saucier and Baltz, 1993). As in other indeterminate spawning fish, annual fecundity in this species is dictated by the number of oocytes released during each spawning event (batch fecundity, BF) and the number of such spawning events during the course of the season (spawning frequency, SF). Estimation of annual fecundity (AF) is intuitively necessary to determine the contribution of an entire spawning season, and is made even more useful for fisheries management purposes if separated by size class or age cohort within a population (Prager *et al.*, 1987; Zhao and Wenner, 1995).

Behavior patterns based on acoustic data enabled us to target females in imminent spawning condition, then carry out oocyte counts for batch fecundity estimation. Additional random sampling in other estuarine areas of the SC coast provided the data necessary to estimate spawning frequency

for each of the three dominant age classes (ages 1-3) in our waters. Ultimately, our annual fecundity estimates for each age class will facilitate management of this species in South Carolina.

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### **Estimation of batch fecundity**

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We conducted sampling for batch fecundity studies during two consecutive afternoons fortnightly from the middle of April through the first week of September 1998, 1999 and 2000. We deployed a trammel net from a shallow water boat at pre-selected sites in Charleston Harbor. Sites were chosen based on proximity to known spawning locales established through hydrophone work. Water depth at the sampling sites ranged from 0.3 to 1.5 meters and sampling was conducted during the afternoon (1400-1800h) high tide. Male spotted seatrout, identified by their drumming sounds, were measured and released on site. Females were brought back to the laboratory for processing. We recorded standard life-history parameters for each specimen, preserved sagittal otoliths for aging and removed sections of the posterior portion of each ovary for histological work. In addition, whole ovaries that evidenced oocyte maturation were fixed in 10% buffered seawater formalin for enumeration of hydrated oocytes (Hunter and Macewicz, 1985).

~~One hundred and thirty-five ovaries were used to estimate batch fecundity of spotted seatrout aged 1-3.~~ We re-weighed preserved ovaries to the nearest 0.01 g and randomly extracted 130-150 mg aliquots from three of eight possible regions in the ovary (four per lobe). We counted hydrated oocytes and used their mean number per subsample to estimate the total number of oocytes in the ovary. To investigate the relationships between batch fecundity and length, somatic weight (ovary-free body weight), and age we used linear regression on log-transformed data. We used ANOVA on ranked data for comparisons of mean batch fecundity among ages, months and years.

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As expected, we found a significant difference in mean batch fecundity among age classes (Kruskal-Wallis test,  $P < 0.05$ ). Age 1 spotted seatrout, produced an average of 145,452 oocytes per spawn. Fish aged 2 and 3 spawned an average of 291,123 and 529,976 oocytes per batch, respectively. Therefore, mean batch fecundity was compared among months and years for each age class separately. There were no significant inter-annual or monthly variations in mean batch fecundity for any of the three age classes.

Pooling data across years, total length explained 69% of the variability in spotted seatrout batch fecundity. Batch fecundity showed a similarly strong relationship to female somatic (ovary-free) weight but did not relate quite as strongly to age. The equations below describe these relationships:

$\text{Log BF} = 3.134(\text{Log TL}) - 2.653$	$(r^2 = 0.686)$	$P < 0.05$
$\text{Log BF} = 1.011(\text{Log OFWT}) + 2.709$	$(r^2 = 0.675)$	$P < 0.05$
$\text{Log BF} = 0.288(\text{Age}) + 4.844$	$(r^2 = 0.586)$	$P < 0.05$

### **Calculation of spawning frequency**



We obtained samples for spawning frequency determination during the course of stratified random trammel net sampling in several estuaries along the SC coast. Each stratum was sampled once a month throughout the year during ebbing tide. However, we only used spotted seatrout samples obtained during summer months (1 May through 31 August) for this study.

We calculated monthly spawning frequencies for age classes 1-3 using the postovulatory follicle method of Hunter and Macewicz (1985) where spawning frequency is the inverse of the proportion of ovaries with postovulatory follicles (POF) < 24 h old among mature and developing females.

Over a decade of sampling the Charleston Harbor estuarine system we have observed that, among females captured in shallow water during the spawning season, oocyte maturation begins at about 1200h. From mid to late afternoon these females leave the marsh edge for deeper water to spawn. Our hydrophone surveys have indicated that spawning typically begins around 1800h and ceases around 2200h. Females then return to feeding grounds near the marsh where they are available to our sampling gear. Knowledge of this reproductive behavior enabled us to target spotted seatrout in the mid-late afternoon specifically to capture fish with late-maturing oocytes for batch fecundity estimation. Females that were back in the shallows after having spawned the previous evening were available for capture during daytime sampling. In addition, we carried out round-the clock sampling on two occasions during the 2000-spawning season. Samples from this effort allowed for the calibration of criteria used to age POFs.

A total of 941 female spotted seatrout, captured during the spawning seasons of 1998, 1999 and 2000 was examined to determine spawning frequency. Females used to determine SF ranged in length from 240 mm to 542 mm (mean 340 mm) and in age from 1 to 5. However, 97% of the specimens belonged to age classes 1-3. Thus, reproductive parameters are presented only for these age classes.

Small sample sizes prevented calculation of monthly spawning frequencies for each age class by year. Thus, data for all three years were pooled to obtain a single monthly spawning frequency estimate by age class (Table 1). Overall, spotted seatrout ages 1-3 in South Carolina spawned every 4.4 days or roughly 28 times during the reproductive season.

### **Estimation of annual fecundity**

We calculated monthly egg production (MEP) by multiplying the monthly spawning frequency by the mean monthly batch fecundity for each specimen. Because not all age-1 female trout were mature at the beginning of the spawning season, the fraction of mature age-1 females obtained from a previous study (Wenner, unpublished data) was used to refine the MEP estimate. MEP estimates were then summed to arrive at an annual fecundity estimate for each age class (Table 1). We used linear regression on log-transformed data to investigate the relationship between annual fecundity and age and thus predict annual fecundity for spotted seatrout aged 4 and 5. Age explained 98% of the variability in annual fecundity for age classes 1-3. From this relationship, the predicted annual fecundities for age classes 4 and 5 were 43,752,211 and 101,157,945, respectively.

Age	Month	Mean BF	SF	% mature	Mean MEP
1	May	117,760 (12)	4.18 (89)	78.6	386,897
	June	135,403 (16)	9.40 (166)	94.0	1,196,418
	July	141,237 (16)	6.54 (185)	97.0	895,978
	August	176,594 (18)	4.57 (129)	100	807,035

Annual fecundity = 3,286,328

2	May	280,724 (34)	6.80 (114)	100	1,908,926
	June	307,322 (10)	7.60 (79)	100	2,335,650
	July	370,170 (1)	9.04 (48)	100	3,346,337
	August	307,195 (7)	6.34 (44)	100	1,947,620

Annual fecundity = 9,538,533

3	May	487,475 (13)	7.42 (46)	100	3,617,061
	June	519,630 (4)	9.12 (23)	100	4,739,027
	July	765,911 (2)	3.1 (10)	100	2,374,325
	August	590,994 (2)	11.61 (8)	100	6,861,439

Annual fecundity = 17,591,852

*Table 1. Fecundity parameters for C. nebulosus ages 1 - 3 from South Carolina estuaries. BF= batch fecundity in numbers of oocytes; SF= spawning frequency expressed as the number of spawns per month; MEP= monthly egg production= (BF\*SF)%mature. Annual fecundity is the sum of mean monthly MEP values for each year class and represents the total number of oocytes produced by any given female from 1 May to 31 August. Numbers in parentheses indicate sample size.*

We expanded annual fecundities relative to the abundance of each age class in our samples for the three years of the study. We estimated that the overall average contribution from age 1 fish to the reproductive output for the season was approximately 25% whereas fish aged 2 and 3 contributed 34% and 19% of oocytes, respectively. Ages 4-5, which comprised less than 3% of specimens sampled, each contributed about 11% based on predicted annual fecundity values.

## Discussion

Attempts at estimating the spawning potential of a species have rarely incorporated spawning behavior into the methodology used in capturing the animals primarily due to limitations of the sampling gear. Moreover, estimates of fecundity (batch numbers and spawning frequencies) have relied on the assumption that the collection of a reasonable size range of adult females during established spawning periods should be sufficient to cover all phases of reproductive activities (DeMartini and Fountain, 1981; Lisovenko and Adrianov, 1991). Our choice not to use the relative

occurrence of hydrated oocytes to estimate spawning frequencies was based on our knowledge of the spawning behavior of this species. Previous work conducted in the study area (Riekerk *et al.*, unpublished data) established the location and timing of spawning activities allowing us to focus our sampling efforts in shallow waters near known spawning locations to collect females with late maturing oocytes. This constant loss of late maturing females from the fish available to our nets in shallow water would have decreased the relative abundance of this maturity stage in our samples. Therefore, using the relative number of late maturing oocytes for spawning frequency calculations would have resulted in an underestimate of spotted seatrout reproductive potential.

Because obtaining representative numbers of animals with late-maturing oocytes is not often feasible, researchers have relied on the relative abundance of postovulatory follicles to calculate spawning frequencies (i.e. Hunter and Goldberg, 1980; Hunter *et al.*, 1986; Brown-Peterson *et al.*, 1988; Fitzhugh *et al.*, 1993; Taylor *et al.*, 1998; Macchi and Acha, 2000; Brown-Peterson and Warren, 2001; Nieland *et al.*, 2002). This method has depended on the ability to time the disappearance of these structures. Our diurnal sampling of reproductively active spotted seatrout during warm water conditions allowed us to establish criteria to accurately estimate the age of POFs throughout the spawning season. Furthermore, we were able to verify our assessments by sampling around the clock on two occasions to collect fish over the time period immediately following a spawn. This would not have been possible had we failed to establish and verify the location of spawning aggregations with the use of passive acoustics.

The main impetus behind this study was to establish realistic annual fecundity estimates by age class that could be used in predictive modeling of the spotted seatrout population in coastal South Carolina. Herein, we present equations relating fecundity to length and age that can be used to estimate the reproductive potential for each age class of spotted seatrout along the South Carolina coast. The average season-long oocyte output of age 1 fish was one-third that of age 2 (~3.28 M vs. 9.5 M). When analyzed in relation to the abundance of the other age classes, age 2 fish were predicted to contribute more overall fertilizable oocytes to the environment. Even though the average age 3 fish produced almost twice as many oocytes (17.5 M) than the average age 2, the abundance of age 3 trout in our estuarine samples was low enough to make their overall contribution to a season's spawning effort only half that of 2 year-olds. This exemplifies the potential for error in estimating reproductive output based on the abundance of year classes, especially that of younger fish.

### **Acknowledgements**

We thank members of the Inshore Fisheries Section of the South Carolina Department of Natural Resources for assisting in field data collection throughout this study (Dr. C. Wenner, J. Archambault, H. von Kolnitz, W. Hegler, E. Levesque, L. Goss, C. McDonough, C. Johnson, A. Palmer). Dr. C. Wenner, H. von Kolnitz and E. Levesque conducted age assessments. Histological processing was provided by C. McDonough, R. Evitt, A. Palmer and W. Hegler. C. McDonough, T. Piper, K. Maynard and R. Evitt assisted with oocyte counts. J. Archambault coordinated data management and Dr. C. Wenner and E. Levesque provided helpful suggestions on the manuscript. Funding for this study was provided by the National Marine Fisheries Service under MARFIN grant #NA77FF0550.

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# Soniferous Fishes of Massachusetts

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## Introduction

Since the seminal work of Fish and Mowbray (1970), little advancement has been made towards the study of soniferous fishes from the marine waters of the Northeastern United States. A review of the literature suggests at least 51 fishes are vocal in New England waters (Table 1), although many of these species are uncommon stragglers to these waters. Spontaneous sound production is known from only about half of these species. However, laboratory studies are often hampered by the difficulty of maintaining healthy specimens, and the difficulty of inducing natural behaviors such as spawning under confinement. This is further complicated by the fact that many fish are primarily vocal during the spawning season, and may not vocalize until maturity, and because vocal behavior is usually limited to males (e.g., haddock and weakfish). The objectives of this study were to conduct a pilot field survey of soniferous fishes in Massachusetts's waters to determine what species are vocal and examine temporal patterns in vocal behavior. However, because of the unexpected finding of widespread calls of the striped cusk-eel on Cape Cod, this paper will focus on this enigmatic species.

*Table 1 (below). Partial list of species known to be capable of sound production based on field and/or laboratory studies, and which occur at least seasonally in New England (Long Island to Maine) estuarine and shelf waters (Fish et al. 1952, Fish and Mowbray 1970, Hawkins and Rasmussen 1978, Tavalga 1980, Mann et al. 1997). \*Sound production capability assumed based on the presence of anatomical structures usually associated with vocalization. (All species were not necessarily subjected to both mechanical and electrical stimulation in the Fish et al. 1952 and Fish and Mowbray 1970 studies).*

Scientific name	Common name	Sounds produced spontaneously (S) or under either mechanical (M) or electrical (E) stimulation
Anguillidae	American eel	Weak: M,E and S

Anguilla rostrata	American eel	Weak: M,E and S
Clupeidae	American eel	Weak: M,E and S
Brevoortia tyrannus	Atlantic menhaden	Weak: M
Clupea harengus	Atlantic herring	Weak: M, E
Opisthonema oglinum	Atlantic thread herring	Weak: M,E
Gadidae		
*Brosme brosme	Cusk	?
Gadus morhua	Atlantic cod	Strong: M, S
Melanogrammus aeglefinus	Haddock	Strong: S
Merluccius bilinearis	Silver hake	Weak: M
Pollachius virens	Pollock	Weak: M
Urophycis chuss	Red hake	Weak: E
Urophycis regia	Spotted hake	Weak: E
Ophidiidae		
*Lepophidium profundorum	Fawn cusk-eel	?
Ophidion marginatum	Striped cusk-eel	Strong: S
Batrachoididae		
Opsanus tau	Oyster toadfish	Strong: S
Dactylopteridae		
Dactylopterus volitans	Flying gurnard	Strong: M
Triglidae		
Prionotus carolinus	Northern searobin	Strong: M, S
Prionotus evolans	Striped searobin	Strong: S
Cottidae		
Myoxocephalus aeneus	Grubby	Weak: M,E
Myoxocephalus octodecemspinosus	Longhorn sculpin	Strong: M,S
Percichthyidae		
Morone saxatilis	Striped bass	Moderate: M,E
Serranidae		
Centropristis striata	Black sea bass	Weak: M,E
Pomatomidae		
Pomatomus saltatrix	Bluefish	Weak: M,E
Carangidae		
Alectis ciliaris	African pompano	Strong: M
Caranx crysos	Blue runner	Moderate: M,S
Caranx hippos	Crevalle jack	Strong: M,S
Caranx latus	Horse-eye jack	Strong: M,E,S
Caranx ruber	Bar jack	Strong: M,S
Chloroscombrus chrysurus	Atlantic bumper	Moderate: M,E
Selene setapinnis	Atlantic moonfish	Strong: M
Selene vomer	Lookdown	Strong: M
Seriola dumerili	Greater amberjack	Moderate: S
Lutjanidae		
Ocyurus chrysurus	Yellowtail snapper	Weak: M,E,S
Lutjanus griseus	Gray snapper	Weak M,E
Haemulidae		
Orthopristis chrysoptera	Pigfish	Strong: M,S
Sparidae		
Stenotomus chrysops	Scup	Weak: M
Sciaenidae		

Bairdiella chrysoura	Silver perch	Strong: M,S
Cynoscion nebulosus	Spotted seatrout	?
Cynoscion regalis	Weakfish	Strong: M,S
Leiostomus xanthurus	Spot	Moderate: M,E,S
Menticirrhus saxatilis	Northern kingfish	Weak: M
Micropogon undulatus	Atlantic croaker	Strong: M,S
Pogonias cromis	Black drum	Strong: M,S
Labridae		
Tautoga onitis	Tautog	Moderate: E,S
Tautoglabrus adspersus	Cunner	Weak: E
Balistidae		
Aluterus schoepfi	Orange filefish	Moderate: M,E,S
Balistes capricus	Gray triggerfish	Moderate: M,E,S
Monacanthus hispidus	Planehead filefish	Moderate: M,E
Ostraciidae		
Lactophrys quadricornis	Scrawled cowfish	Moderate: M
Tetraodontidae		
Chilomycterus schoepfi	Striped burrfish	Moderate: M,E
Sphoeroides maculatus	Northern puffer	Moderate: M
Molidae		
Mola mola	Ocean sunfish	Strong: M

## Methods

Recordings of fish sounds were made at 12 different sites across Cape Cod at least once between June and October 2001. However, the primary sampling location was the Cotuit town landing which was sampled on 18 different dates, including 5 dates on which monitoring was conducted over the diel cycle. Except for the diel studies, most sampling was conducted around sunset, usually beginning 1 to 2 hours before sunset and continuing for 2 to 3 hours after sunset. To obtain information on the daily pattern of fish calls, diel studies were conducted on five different dates at Cotuit town landing. For these studies, sounds were recorded approximately from 1300-1400, 1900-2300, 0100-0200, and 0400-0600, corresponding to afternoon, sunset, night, and sunrise periods, respectively. Low cost hydrophones (Arretec, PB 3098 Bletchley, Milton Keynes MK2 2AD, United Kingdom) were deployed from docks, piers, jetties and small boats and recorded to a hi-fi VCR. Occasionally, recordings were made to a Sony hand-held tape recorder (model TCM-929). In addition, whenever possible, video recordings were made simultaneously to the VCR using a hand-deployed underwater video camera equipped with infrared lights (models made by Vista Cam, 9911 Goodhue St. NE, Blaine MN 55449, and Aqua vu, Nature Vision Inc., 213 NW 4th St., Brainerd, MN 56401). Sounds were captured to a PC while playing back from a VCR using Cool Edit 2000 (made by Syntrillium Software Corporation). Some spectral analyses were also conducted using Signal for Windows (Engineering Design, 43 Newton St, Belmont, MA 02478). To quantify call frequency, 1-4 hour sound samples were divided into 10-minute segments and a randomly selected 2 minute sound clip was obtained from each. Calls for toadfish, striped cusk-eel and searobins were identified and counted. Reference sound clips of unknown calls were made and used to make counts of unknown sounds by type (e.g., "grunt-A" etc.).



## Results

Over 53 VHS and 12 cassette tapes comprising over 160 hours of recordings were collected. Calls of striped cusk-eels, *Ophidion marginatum*, oyster toadfish, *Opsanus tau*, and striped searobin, *Prionotus evolans*, dominated the observations. Several unidentified calls were also common. We are continuing our efforts to identify these calls. In addition, various sources of natural and man-made noise were also recorded including: outboard boats, barges, jet-skies, dock noises, fishing noises, depth-finders, and gas release from sediments. Based on the occurrence of vocal choruses, we found sunset spawning aggregations of the striped cusk-eels at eight of 12 locations sampled across the length of Cape Cod, including two sites (Barnstable Harbor and Provincetown Harbor) on the north shore. Cusk-eels were recorded from the first sampling date (June 11) through the end of August, but abruptly stopped by early September. Oyster toadfish were also already calling at the start of the field season, but sunset choruses had ceased by mid-July. Striped searobin calls were not associated with sunset, but occurred throughout the night. Searobin calls were most frequent in August and September but were still present in October. The cusk-eel sounds recorded in MA are nearly identical to striped cusk-eel sounds recorded by the first author under laboratory conditions in New Jersey (Mann *et al.* 1997), and more recent sounds recorded in the field and attributed to stripe cusk-eels in Narragansett Bay (Perkins 2002) and North Carolina (Sprague and Luczkovich 2001). Our attribution of these sounds to the striped cusk-eel is further validated by the capture of a 170 mm TL specimen while recording sounds in Cotuit, MA in July 2001, and by subsequent sightings of a larger individual later that same month. Cusk-eels can sometimes be observed in the shallows at night with the aid of a spot light (Rountree, pers. Observ.). In Figure 1, chatters vary in relative amplitude and range from 8 to 16 pulses and call times of 275 msec to 730 msec. The dominant frequency was 1098-1866 Hz (compared to the toadfish call at the beginning of the sequence at 171-585 Hz). A sample call recorded from Provincetown, MA on August 23, 2001 is shown in Figure 2. This call is considerably longer (31 pulses, 1,715 msec) than those in Figure 1, but is still well within the range characteristic of the species (Mann *et al.* 1997, Sprague and Luczkovich 2001). A single representative pulse has most energy between 914 and 1524 Hz (Fig. 2).

Striped cusk-eel calls can be heard sporadically throughout the day, but calls clearly become more frequent at sunset (Fig. 3). Peak number of calls occurred between 20 to 60 minutes after sunset, and declined to near zero within two hours. In contrast, the oyster toadfish calls more frequently during the day, but also exhibits a strong increase in activity associated with sunset (Figure 4). Although data are more limited, peak activity occur 1-2 hours after sunset, with more gradual declines through the night compared to the striped cusk-eel.

## Discussion

It is significant that the striped cusk-eel was the most frequently heard and widely distributed species encountered during this study as it has previously been thought to occur from Block Island south to Florida, with only rare stragglers occurring as far north as Cape Cod (Collette and Klein-MacPhee 2002), despite extensive faunal surveys in the region over several decades. This finding nicely demonstrates the usefulness of passive acoustics as a supplement to traditional survey methods, particularly for species difficult to sample in other ways. The seasonal and daily pattern of striped cusk-eel vocal activity agrees with published laboratory findings (Mann *et al.* 1997, Sprague and Luczkovich 2001). Striped cusk-eels were already chorusing by mid-June when sampling began, but had stopped by mid-September in good agreement with previous studies. Call frequency increases rapidly at sunset developing into a loud chorus that lasts from 1 to 2 hours (Fig. 3). Captive cusk-eels have been observed to chorus after sunset as part of courtship and spawning behavior (Mann *et al.* 1997, Rountree and Bowers-Altman 2002). We believe that our observations suggest widespread spawning of striped cusk-eels within estuaries of both the north and south shores of Cape Cod. The species' cryptic nocturnal behavior, and habit of remaining burrowed during the day likely account for the failure of previous researchers using conventional sampling gears (i.e., trawls and seine sampling mostly limited to daylight hours) to recognize its importance to the region. At this time the northern range of the striped cusk-eel must be reconsidered. How much farther up the coast the species extends is unknown. It is notable that Geoghegan *et al.* (1998) recorded a single adult striped cusk-eel at Seabrook, New Hampshire and argued that it might represent a small local population. Therefore, we suspect that reproducing populations of this species may occur at least to New Hampshire waters. However, the scarcity of ophidiid eggs in ichthyoplankton surveys of the region is puzzling (e.g., Fahay 1992) and future studies on the distribution and ecology of this cryptic species are needed. Boat sounds were problematic during the day, sometimes occurring during 50-99% of the sound sample clips. During these times, sounds of fishes could not be heard above the boat's noise. Boat noise was rare during the evening hours. The impact of boat-associated noise on the behavior of fishes is poorly known, but it had a strong impact on our ability to record day-time fish sounds. It is hoped that the newly available archive of fish sounds originally published by Fish and Mowbray (1970) and recently repackaged by the University of Rhode Island (Rountree *et al.* 2002) will aid in the identification of the unknown calls recorded on Cape Cod. In summary this study has demonstrated the usefulness of even low-cost passive acoustics technology as a tool to survey estuarine and marine fishes. Information on the temporal and spatial patterns of fish vocal behavior can be used to gain insight into temporal and spatial patterns in habitat use patterns by vocal species. In particular, identification of spawning habitats through passive acoustics surveys is promising.

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## Illustrations and Diagrams

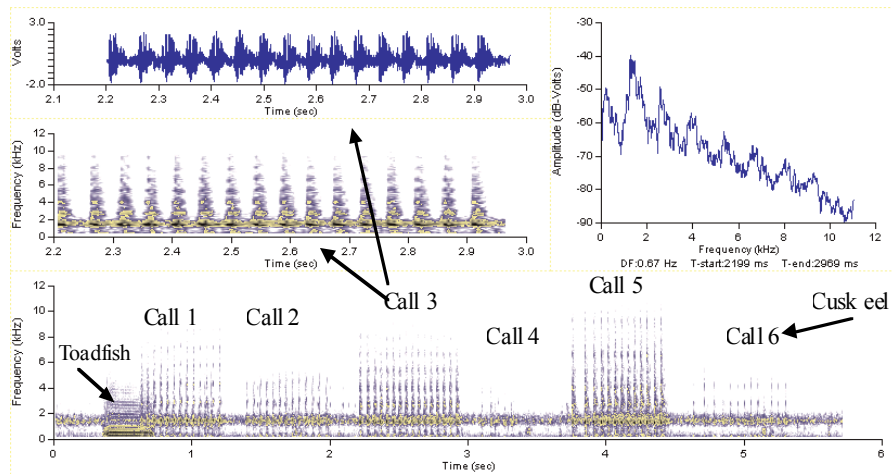


Figure 1. Representative sample of cusk-eel calls recorded in Cotuit, MA on June 20th 2001. The lower panel shows a string of six separate cusk-eel calls, likely from six different individuals. The first call overlaps with that of a toadfish. The upper left figures show the waveform and spectrogram for call 3. The power spectrum of call 3 is shown in the upper right panel.

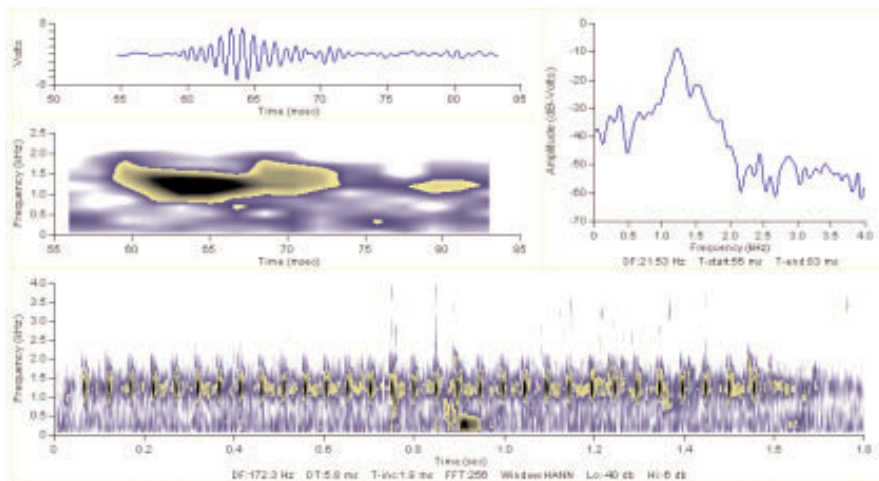


Figure 2. Single chatter attributed to the striped cusk-eel, *Ophidion marginatum*, recorded from Provincetown, MA on 23 August 2001. The lower panel shows the energy spectrum for the entire call, while the upper panels show the waveform, energy spectrum and power spectrum of a single pulse.

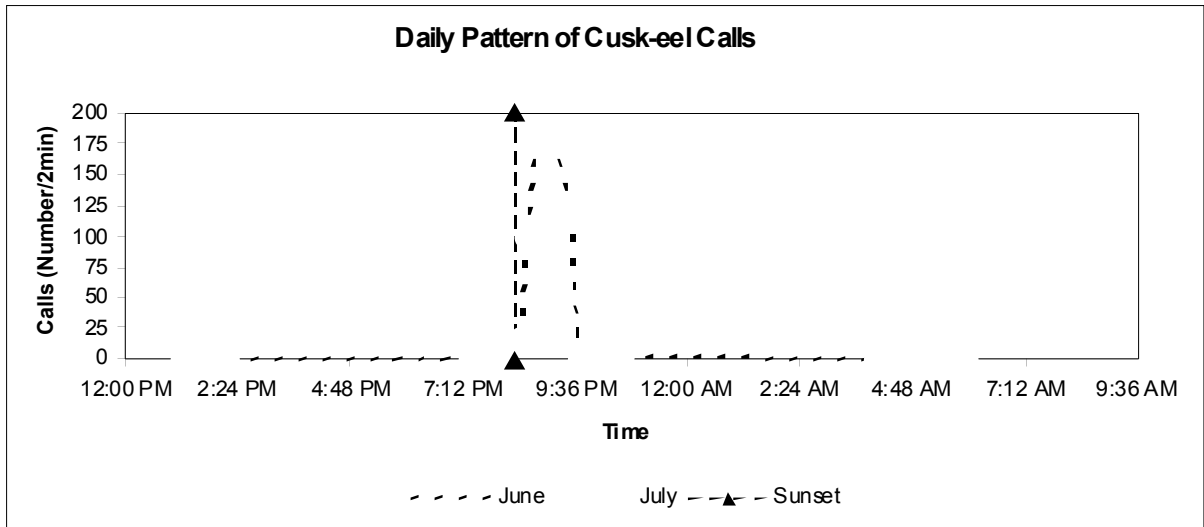


Figure 3. Daily pattern of striped cusk-eel, *Ophidion marginatum*, calls collected on two dates (20-21 June and 2-3 July, 2001). All calls heard within 2 minutes sound clips were counted. Sample clips were taken randomly from within 10-minute sample bins. The vertical arrow marks the time of sunset as obtained from a hand-held GPS.

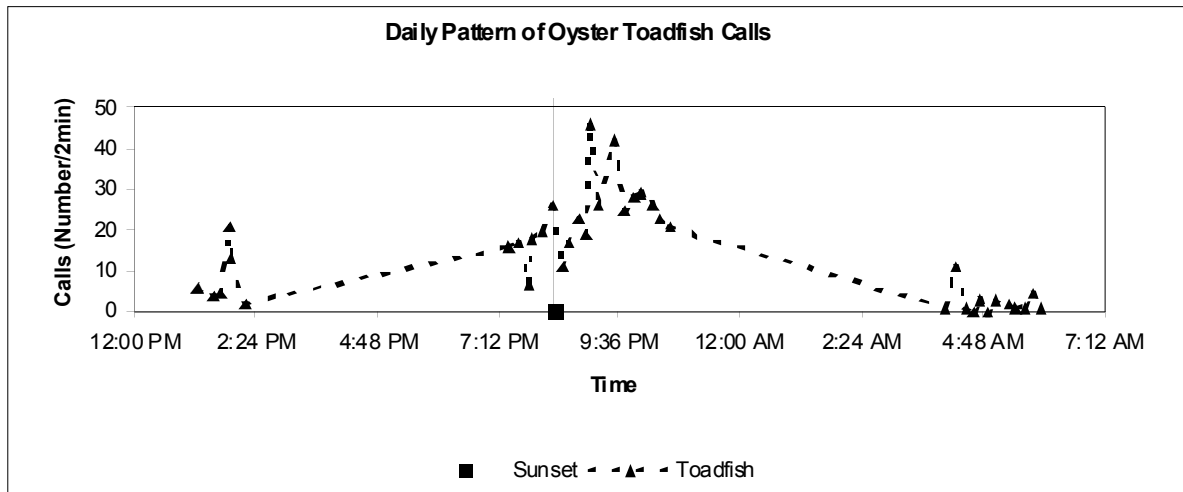


Figure 4. Daily pattern of oyster toadfish, *Opsanus tau*, call on June 20-21, 2001.

## The mating behaviour of Atlantic cod (*Gadus morhua*).

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### Introduction

Atlantic cod (*Gadus morhua*) is a marine demersal fish that inhabits cool-temperate to subarctic waters from inshore regions to the edge of the continental shelf on both sides of the North Atlantic (Scott and Scott 1988). Atlantic cod has been harvested throughout its range for hundreds of years and yet despite being of theoretical interest and practical importance, very little has been learned about its reproductive behaviour during this period.

Throughout the Atlantic, there are many recognized cod stocks, each of which has its own set of characteristics. Age at maturity varies between 2 and 7 years (Myers *et al.* 1997) and Atlantic cod typically spawn over a period of less than 3 months (Brander 1994; Chambers and Waiwood 1996; Kjesbu *et al.* 1996) in water depth ranging from tens (Smedbol and Wroblewski 1997) to hundreds of metres (Brander 1994; Morgan *et al.* 1997). Individuals are assumed to breed annually and Atlantic cod are considered to be batch spawners as only 5-25% of a female's egg complement is released at any time during her 3- to 6-week spawning period (Chambers and Waiwood 1996; Kjesbu *et al.* 1996). Individual females release hundreds of thousands, often millions, of tiny eggs (1.2-1.6 mm in diameter), for which no parental care is provided, directly into oceanic waters (Scott and Scott 1988).

The limited information available on Atlantic cod spawning behaviour suggests complex mating patterns, the occurrence of behavioural and acoustic displays by males, mate choice by females, and alternative reproductive strategies among males (Brawn 1961a; Hutchings *et al.* 1999). However, there is no information on the selective causes and consequences of these behaviours, nor the structure of the mating system (Nordeide and Folstad 2000).

Our research employs a quantitative approach to understand causes and consequences of variation in the mating system of Atlantic cod at the individual and population levels. We are incorporating both detailed experimental studies in the laboratory and observations of cod in the wild. Our research involves several components including the following: (i) mating system structure and identification of behavioural and phenotypic correlates of reproductive success, (ii) intra- and inter-population variation in sound production during spawning, and (iii) patterns of variation in drumming muscle mass.

### **Laboratory observations of spawning Atlantic cod**

The laboratory component of our research involves cod from two spatially distinct areas in the Northwest Atlantic: Southwest Scotian Shelf and Southern Gulf of St. Lawrence, identified by the Northwest Atlantic Fishery Organization (NAFO) Divisions as 4X and 4T, respectively. Mature adults from each stock were collected and taken to a 680 m<sup>3</sup> aquarium at Dalhousie where spawning occurred. Groups of fish representing each stock were examined separately during their temporally distinct spawning periods. Cod were maintained at densities similar to those in nature (approximately 0.1 fish per m<sup>3</sup>; Rose 1993; Morgan *et al.* 1997) and spawning behaviour of individually tagged fish was recorded by videotape and visual observation. A hydrophone was placed in the centre of the tank and sounds were recorded continuously during the spawning season. A random sample of fertilized eggs was collected daily and pedigree analysis is being undertaken using microsatellite DNA. In addition to providing information on individual male and female reproductive success, the DNA analyses, coupled with behavioural observations, will allow us to determine phenotypic and behavioural correlates of reproductive success.

Observations to date suggest that strong differences in spawning behaviour exist between and within Atlantic cod populations. A strong dominance hierarchy, territoriality, and high levels of aggression characterized males from 4T but this wasn't the case for males from 4X among which very little aggressive behaviour occurred and no fish held territories for prolonged periods. However, preliminary examination of the sound recordings have suggested that 4X fish are more vocal than 4T fish. Similarly, we found that for both females and males, 4X fish had heavier drumming muscles relative to their body weight (drumming muscle somatic index) than those from 4T (Figure 1).

We also observed intra-population differences in behaviour, particularly for fish from 4T. We found that the aquarium was dominated by 3-4 males that fiercely defended territories during the spawning season and frequently engaged in courtship activity. Other males were much more passive and it seems that some specialized as sneakers in spawning events and even might have been imitating females to gain access to male territories. Initial observations suggest that fish which were dominant and engaged in most courtship activity were ones with the largest drumming muscle somatic index (and were not necessarily the largest in length). We are waiting for results of the pedigree analysis to determine the way in which these behaviours might have influenced reproductive success.

### **Field observations of variation in Atlantic cod drumming muscle mass**

Sound production by males is hypothesized to be important to successful mating in cod (Brawn 1961a, b; Engen and Folstad 1999; Hutchings *et al.* 1999) and we wanted to examine patterns of variation in the size of their sound-producing "drumming" muscles in more detail. Brawn (1961b) found that Atlantic cod produced sound most frequently during the spawning period and although both sexes were capable of producing sounds throughout the year, only males seemed to do so during the spawning season, typically during aggressive defense of territories and courtship display.

During March 2001 - February 2002, we sampled approximately 100 cod/month from NAFO Division 4X to quantify seasonal and individual variation in body condition and drumming muscle mass. We found that drumming muscle mass tended to increase with fish size. Furthermore, when we controlled for fish size, we found that spawning males had larger drumming muscles than non-spawning males (Figure 2) but there was no such relationship for females. In addition, males had larger drumming muscles than females both during spawning and non-spawning seasons.

Interestingly, we also observed a weak, but significant relationship between drumming muscle somatic index and body condition for males in spawning condition (Figure 3). This suggests that male drumming ability could convey reliable information to females about mate quality.

### **Conclusions**

We will continue our research on Atlantic cod by combining pedigree data with phenotypic and behavioural observations of fish in our aquarium to assess correlates of reproductive success. Also, we will study sound production by cod in more detail by examining the types and characteristics of sounds produced, the behavioural contexts in which sounds occur, and temporal patterns of sound production.

In recent years, stock collapses have caused many Atlantic cod fisheries to be reduced and others even closed. Knowledge of Atlantic cod spawning behaviour will likely contribute to better understanding of population dynamics and improved ability to predict the effects of fishing on cod populations.

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## Illustrations and Diagrams

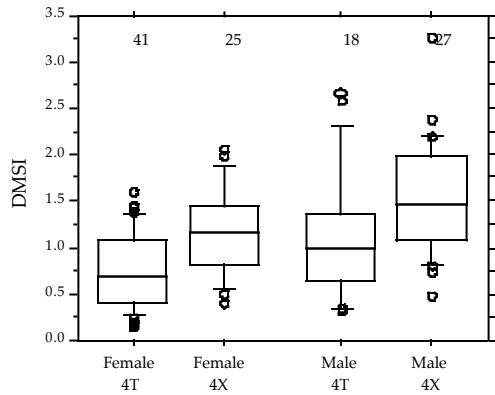


Figure 1. Drumming muscle somatic index (DMSI) for female and male Atlantic cod from Northwest Atlantic Fishery Organization (NAFO) Divisions 4T and 4X. Box plots indicate outliers (points) and 10th, 25th, 50th, 75th, and 90th percentiles. Sample sizes given above estimates.

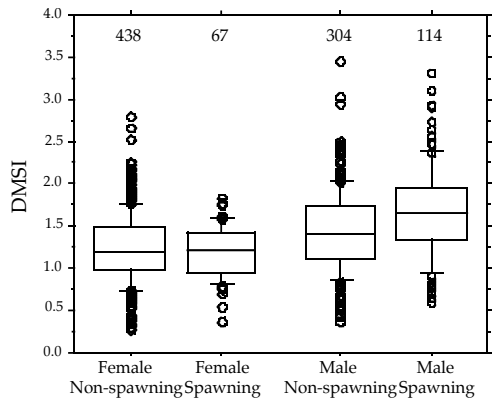


Figure 2. Drumming muscle somatic index (DMSI) for non-spawning and spawning female and male Atlantic cod from Northwest Atlantic Fishery Organization (NAFO) Division 4X. Box plots indicate outliers (points) and 10th, 25th, 50th, 75th, and 90th percentiles. Sample sizes given above estimates.

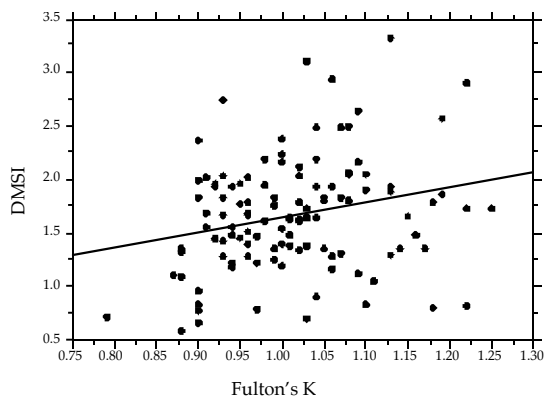


Figure 3. The relationship between drumming muscle somatic index (DMSI) and body condition (as indicated by Fulton's K condition factor) for spawning male Atlantic cod from Northwest Atlantic Fishery Organization (NAFO) Division 4X.

## Spotted Seatrout Spawning Requirements and Essential Fish Habitat: A Microhabitat Approach Using Hydrophones

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### Summary

Hydrophones can be used in conjunction with a microhabitat approach to yield a fish's eye view of its habitat requirements. At the finest scale, the microhabitat of an individual is the site it occupies at a given point in time. Sites are presumably selected to optimize an individual's net energy gain while avoiding predators (i.e., tradeoffs of growth vs mortality). Since similarly sized individuals of a species select similar microhabitats, many careful measurements of individuals and associated physical, chemical, and biological variables should define the population's responses to environmental gradients. As defined here, the microhabitat is an occupied site, not a little bitty habitat type. Fine-scale measurements of environmental conditions at a site occupied by one or more individuals constitute an observation, and many independent observations characterize the population's response to complex gradients.

Habitat is a loosely used ecological term that can be applied at the individual, population, and community levels and is often entangled with so many other ecological concepts that it can mean everything and therefore nothing. The term 'habitat' has almost been relegated to the status of a pseudocognate (*sensu* Salt 1979, Ecology) in that it is a term in common use and each individual who uses it feels that all others share his own intuitive definition. Nevertheless, it is used and can be useful. We can use habitat as the range of environmental conditions in which a species/population/life-history stage can live. It is a general term that broadly defines where a species lives without specifying patterns of resource use (*sensu* Hurlbert 1981, realized niche = resources used: energy, materials, and sites (Evolutionary Theory 5:177-184)). There are several points of view. From a fish's point of view, its distribution over environmental gradients describes its habitat. From a biologist's point of view, strata in the environment can be arbitrarily described as habitats, but more properly as "habitat types". At the community level, the environments dominated by a single species (e.g., *Spartina alterniflora*) may be characterized as *Spartina* habitat, but more properly as a "*Spartina* community".

The concept of Essential Fish Habitat (EFH) is based on 1996 federal legislation and is aimed at enhancing the sustainability of our fisheries. The legislation established four levels of data quality in

defining EFH: I. Presence/absence, II. Density patterns (e.g., population responses to gradients, suitability), III. Condition/health (e.g., growth, parasite loads, pollution loads, RNA/DNA ratios), and IV. Production (e.g., secondary production, reproductive output). What is EFH? Essential is a qualifier that carries a notion of quality. We are not just asking where a species lives (Level I), but where it lives well (Levels II-IV). Where are its resource needs best met? Now we are concerned with patterns of resource use (*sensu* Hurlbert 1981, realized niche = resources used: energy, materials, and sites (Evolutionary Theory 5:177-184)).

How can we use a fish's eye view to define EFH? We can seek answers to three questions. How are species and life history stages distributed in the environment? What intervals along environmental gradients are selected or avoided? What is most important to the fish in terms of growth and/or survival?

*Level I data: Presence/Absence data:* Most risk averse approach to protecting habitat (based on the precautionary principle); however, reliance on Level I data overprotects less valuable habitat and essentially equates water with EFH. High quality habitat is given the same level of protection as Low quality habitat and scientists/managers lose credibility.

*Level II data: Density data:* Uses fish population's responses (density patterns) to environmental gradients. Level II assessments can be improved by relating population's response in terms of resource use to resource availability (e.g., habitat suitability), and high quality can be distinguished from low quality habitat. Habitat Suitability [ $S = \text{Suitability} = P(E | F) / P(E)$ ] is an index of habitat quality based on a quotient of Resource Use and Resource Availability (Bovee, K. D. & T. Cochnauer, 1977, U.S. Fish & Wildlife Service Biological Services Program FWS/OBS-77/63). Resource use is a probability statement, given the presence of fish, and resource availability is a probability statement, regardless of the presence of fish. Suitability is an index of use divided by availability that ranges from zero (intolerable) to one (optimal) after standardization.

*Level III data: Growth data:* I have not been able to relate this level to hydrophone work on spotted seatrout, but others may find an application for other soniferous species that make sounds for non-reproductive functions (e.g., foraging parrotfishes). What environmental conditions foster growth of early juvenile spotted seatrout? Nursery microhabitat selection is presumably controlled by some combination of physiological constraints, prey distributions, foraging success, competitor densities, and predation pressure, all of which may influence growth and/or survival. Linkages between microhabitat, diet, & conspecific density may predict recent daily growth which in turn reveals the recruitment potential of preferred nursery characteristics (Baltz *et al.* 1998, *Env Biol Fish* 53: 89-103).

*Level IV: Production data:* This is the best kind of information and the best example is from a study of oyster seed production (Chatry, Dugas, and Easley 1983, *Cont. Mar. Sci.* 26: 81-94). Oyster seed set and growth are best at 20-22 ppt (Level III data), but oyster predators (drills, etc) seriously deplete populations in high salinity water (> 15 ppt). Oyster seed production is highest for seed set at 12-16 ppt the previous summer, and therefore EFH for oyster seed production is highest in a narrow summer salinity range of 12-16 ppt.

I will argue that suitability indices for reproduction (Saucier & Baltz, 1993, *Env Biol Fish* 36: 257-272) are high-level EFH data and qualify at Level IV. Moreover, this kind of data can be acquired easily with hydrophones. Saucier and Baltz (1993) used a microhabitat approach to identify selected and avoided points along salinity, depth, substrate, and velocity gradients used for spawning by spotted seatrout. Relatively deep, moving waters with a salinity of 14-23 and a temperature of 29-33 °C were selected. Conflicting literature from earlier studies in the northern Gulf of Mexico suggested that spawning occurred more or less exclusively in bays, passes or the open gulf. We found that spotted seatrout spawn across a wide variety of habitat types (bays, channels, passes, and open gulf) where environmental conditions are right. We found that spawning locations shifted along a salinity gradient up to 30 km on a north-south axis, and concluded that environmental conditions were more important than places.

### **Spawning temperatures for Louisiana spotted seatrout**

#### **Spawning salinity for Louisiana spotted seatrout**

There are several pitfalls to avoid. Non-linear effects along environmental gradients should be expected. Non-representativeness in sampling design may lead to biased results, especially sampling bias that focuses on particular habitat types may generate misinformation. Noisy crews, boats and traffic may make it difficult to locate spawning aggregations. Misidentification of drumming species can be avoided by careful comparisons with known recordings, and verification of actual spawning by the collection and rearing of eggs from drumming sites to identifiable larvae is important. A stratified water column may present contrasting environmental variables in a vertical profile (We want to know what's going on at the fish's nose).

*Hydrophone Techniques & Assumptions:* Aggregation size: Sound Intensity may be used to estimate Source Level (SL) if distance to source is known. Source Level is calculated by adding a one-way spherical spreading loss (i.e., a  $20 \log [\text{depth in meters} - 1]$ ) for a correction (absorption is ignored). It is a continuous variable that estimates group size for statistical modeling:  $SL = \text{microhabitat variables} + \text{temporal variables} + \epsilon$ . A recorded Sound Intensity (my standard settings were 132 db re 1  $\mu$  pascal) of +5 db yields a Source Level of 139.6 db for an aggregation on the bottom in 15 m of water [e.g.,  $132 + 5 + (20 \log 14) = 139.6$  db]. A cylindrical correction or no correction may be more appropriate under given circumstances.

*Future Applications:* My wish list is topped by a fixed or moveable listening array with overlapping directional capabilities to generate position fixes, computer programs to process fix data, and real-time transmission capabilities to allow a small boat to move to aggregation sites and random sites for measurements of resource use and availability.

*Recommendations for EFH:* Quality research and wise management related to fish habitat depend on how clearly we can define habitat and EFH and that we are all discussing the same concepts. We should try to take a fish's point of view and let them describe what is essential along environmental gradients. By comparing resource use with environmental availability, we gain insights into patterns

of selection and avoidance. We can identify biological endpoints that reflect the health and well being of individuals and communities of fishes. Use of the best data and research designs available will help avoid management errors in describing EFH. Management errors that result in over- or under-protecting EFH can be viewed as having positive and negative outcomes:

**Over-protection**

- Species & habitats are better protected (+)
- Scientists & managers may lose credibility (-)
- Costs the regulated group its profits (-)
- Enforcement is more expensive (-)

**Under-protection**

- Species & habitats at greater risk (-)
- Scientists & managers may lose credibility (-)
- Regulated group is happy (+)
- Enforcement is less costly (+)

Clearly, we can use hydrophones and a microhabitat approach to credibly describe EFH for some soniferous spawning fishes, like spotted seatrout.

**Acknowledgments**

I am grateful to Grant Gilmore and Mike Mok for an acoustical primer and other assistance, Scott Holt for showing us how to rear larvae, Louisiana Sea Grant for funding, and Rodney Rountree, Tony Hawkins, & Cliff Goudey for putting together the workshop.

## Creating a Web-based Library of Underwater Biological Sounds

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### **Introduction**

Establishing an archive of fish and other underwater biological sounds will meet many of the long-standing challenges faced by marine acousticians - the ability to catalogue their sounds and data in a way that fosters comparative studies, easy access to the sounds for analysis and identification, and the capacity to search through passive recordings for sounds of particular interest. The Macaulay Library of Natural Sounds (MLNS), with a long history of working toward these goals in ornithology and animal behavior, recently launched a new Internet-accessible archive of underwater sounds with the help of over sixty individual recordists and institutions worldwide. Researchers will be able to annotate their sounds with detailed and extensive data through an online database application, summarize search results in exportable tables and maps, and download copies of recordings for research, teaching, and conservation. MLNS is committed to dual goals of maintaining open access to allow other researchers to listen and help identify sounds, while protecting recordists' copyrights and restricting access during the publication process. Detailed and extensive metadata are needed, however, to create the functionality such an archive requires.

### **Acquisition of Source Material**

A recent survey of suitable original recordings resulted in commitments by more than 60 researchers or institutions to supply original tapes and metadata for archival at MLNS. These consist of over 8000 hours of audio tape and 800 hours of video and include recordings of 95 species of marine mammals and more than 200 species of fish (representing 36 families) and marine invertebrates. Upon request, MLNS staff will visit participating institutions to help organize and pack original tapes, collect the metadata and any information required to import it, and then carefully track the status and location of all contributed material through the shipping and archival processes.

### **Restoration**

Many older recordings exist on deteriorating tape stocks. These must be treated before copying. MLNS has extensive experience and an excellent track record in tape restoration. Many of these tapes can be restored in-house using controlled baking and vacuum treatments. A few may be so

deteriorated that they must be out-sourced to specialists who examine the molecular structure with electron microscopes before undertaking situation-specific restoration procedures.

### **Ingestion**

Most analog sound tapes are digitized once at high resolution (96 kHz/24 bits). Although the high sampling and bit rates are not necessary for all recordings (given ambient noise levels and frequency composition of the sounds), these high-resolution settings greatly accelerate the archival process by freeing technicians from detailed monitoring of signal levels and inadvertent aliasing. They also preserve any high frequency sounds that are unnoticed or in the background but that may later prove of interest. Proper digitization of Odontocete sonar signals will require a combination of replay at reduced speeds and even higher digitization rates. Digital recordings are copied at their original rates. Analog video will be converted to digital tape replicas. All digitized materials will be stored on local hard disks until transferred to hard media.

### **Extraction**

Whereas terrestrial recordists can limit recording time by watching their subjects, marine researchers often record blindly for long periods, and their recordings therefore often have a much smaller fraction of useful content than do terrestrial ones. At least a third of the contributed audio material consists of such unedited continuous recordings. Once digitized, these must be examined in real-time and the relevant sounds extracted. We will work with developers to adapt prototype detector software for real-time extraction of appropriate marine sound tapes. This tool will be essential for reducing raw audio streams to separate sound files.

### **Formatting & Storage**

All high-resolution digital copies of extracted sounds and videos will be preserved in a deep archive. Sounds will be stored as AIFF files on DVD-ROM discs in a computer-controlled jukebox array. Video will be encoded as MPEG-2 files and stored in a near-line digital AIT (Advanced Intelligent Tape) library. Copies of each sound and video will be created in a variety of down-sampled popular formats (compact disc quality, RealAudio, QuickTime, Windows Media, and perhaps MP3) and stored on CLO's new EMC Symmetrix hard drive system. These latter copies will be the ones available over the Web. High-resolution copies can be obtained by special order. Automatic routines will randomly monitor the integrity of the DVD-ROM copies and the EMC system copies. Damaged files can be robotically regenerated from backup high-resolution copies.

### **Identification and Annotation**

Remote experts will be able to examine copies of extracted sounds or annotate copies of longer



behavioral sequences (both audio and video). Given our ability to create a lower resolution copy of any sound or video clip, it will be easy to download these to the consultant over the Web along with software for recording identifications or annotations that would then be uploaded to our database. Our software will be specifically designed to accept annotation data created remotely and synchronize it with all subsequent copies of the files. These tools will thus create a much larger pool of participating consultants.

### **Importing of Metadata**

CLO has adopted one of the industry standards for its database, Oracle's relational system, and is designing a data architecture that conforms with the Dublin Core (<http://www.dublincore.org>) protocols. These define a set of metadata and XML tags that allow our databases to be accessible and compatible with other libraries and museums worldwide. Lower levels in this architecture allow for taxon-specific data for behavioral repertoires or habitat use, sophisticated GIS links using ESRI routines, complex and high level data mining protocols, and within-file (e.g. annotation and extracted parametric data) searches. CLO is developing general tools for data importation and searching through a wide variety of database formats. All data, whether entered by hand or ported, will be checked for accuracy and veracity before being published online.

### **Client Services**

CLO's sound and video libraries have a wide diversity of users. These include private individuals, scientific researchers, conservationists, wildlife managers, education programs at all levels, website owners, military and government agencies, the media and film industries, and various commercial companies. Our major goal in the recent acquisition of an EMC enterprise storage and Web delivery system was the provision of rapid, direct, and reliable access to the CLO archives through the Internet. This requires JAVA and HTML/XML programs for the Web pages and underlying engines for a variety of online services including a) powerful searches of our metadata and within-file annotations; b) provision of search results as data tables with hot links or maps including links to a variety of online GIS tools; c) the ability to hear any selected cut online; d) the ability to collect a series of multimedia selections onto a worktable for comparison, sequencing, or editing; e) creation of a shopping cart with secure credit-card payment protocols; and f) tracked delivery of requested resources through streaming, Web downloads, or shipment of hard copies (CD, DVD). Some of these features are being developed CLO-wide, but others will require specific adaptations for the marine animal sound collections.

### **Analytical Tools**

In addition to search, selection, and retrieval, CLO intends to provide various sound analysis tools online. These may include the abilities to a) see a playable spectrogram or waveform (or both time-

aligned) of any sound in the archive; b) select and play any part of a visible spectrogram or waveform; c) select a large number of sounds in the archive and submit a batch job to compare each sound with every other sound using any of several alternative tools (spectrographic cross-correlation, temporal cross-correlation, multiple measurement and PCA, etc.); and d) submit an unknown sound and associated metadata and receive a likely identification (or list of alternative suspects).

### **Acknowledgements**

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# • Potential for coupling of underwater TV monitoring with passive acoustics

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## Introduction

The temporally and spatially fluid nature of fish associations often confuses interpretations of their underwater sounds. Ideally, visual confirmation of the sound producers and any behaviors associated with sound making should accompany acoustic data. Investigators have long been expanding their inventory of specific sounds that represent, conclusively or potentially, specific underwater sources. These are the acoustic “standards” by which to compare unknown sounds for recognition/identification purposes. Unfortunately, these standards are often not available for acoustic research on fishes. Although some sonic signatures have been corroborated with visual observations, many more are needed to assist in interpretations of sonic data from hydrophones placed in complex habitats with many interacting species of vertebrates and invertebrates. The underwater television (UWTV) is ideal for direct correlations between specific sounds and their causes, if the water visibility is acceptable.

Underwater video devices can provide a wealth of information to scientists and fishery managers including seasonal movements of fishes, the potential for development of indices of abundance for some migrating and resident populations, and any seasonal behaviors associated with the formation of pre-spawning aggregations along a migration route. An UWTV system offshore allows the study of fishes on the bottom throughout the year without the costly trips to a research site in inclement weather. The present visual capability of UWTV should be integrated with acoustic information to enhance fisheries biologists’ understanding of fish behavior and movements within the region. This paper describes recent results from a permanent installation of an UWTV at an artificial reef offshore.

## The Underwater Television System

The research site was established in 25-28 m of water about 72 Km off central Georgia on May 11, 1999 with the deployment of several large fish attraction units (Artificial Reefs, Inc.). On August 24, 1999, the underwater TV cameras, cable and computer were installed and images were transmitted

via microwaves to shore. Artificial reef structures are arranged in a circle around the camera system to maintain a resident aggregation of reef fishes, to attract transient species and to focus local fish activities within the view of the cameras.

The video system consists of two main parts. A pressure housing, located on the sea floor and a video capture engine, located remotely. Six monochrome video cameras are housed with a micro-controller and a few basic sensors. The micro-controller provides the means to multiplex the 6 analog video signals to one coaxial cable running between the pressure housing and the video capture engine. The video capture engine is a computer running under the Windows NT operating system. A console application controls a video frame grabber, which takes the analog video signal and converts it to digital images. The system has the ability to capture multi-frame or single frame images based on parameters set by the user. The micro-controller in the pressure housing receives commands from the video capture engine for camera selection, tilting data, and system status updating. The embedded computer also acts as a web server through which the video system is controlled. File transfer and system parameter updates are made possible by an interface between the web server and the console application controlling the video system using pcANYWHERE.

Small black and white security cameras (Supercircuits PC-23C) with low light capabilities (to 0.04 lux) and relatively low resolution (460 lines) were used. Camera lenses of 8 mm allowed a 12 degree angle of view, and the seabed was in view at about 13.7 m from the camera. Daily observations (~65) were conducted between 1200 and 2130 GMT (Greenwich Mean Time). Still images ~15 Kb (jpg) were recorded and logged at 10 minute intervals for 10 sec. Video clips ~400 Kb (avi) were recorded on the hour from camera No. 5, since only camera No. 5 was directed at reef structure with any reef fish activity. Images were downloaded from the remote computer to the laboratory computer for fish counts and long-term data storage.

### **Observations using UWTV**

We have learned how to deploy and maintain the UWTV system and remote operations systems. We have temporally documented species presence and activity. The seasonal dates of the first appearance of various fish species are especially important for identification of any prespawning migration to the south by adult grouper, one of our main target species. Seasonal changes in the makeup of the fish assemblage at the UWTV site appear much greater than previously believed. We are documenting the annual cycle of juvenile recruitment in spring and summer followed by intense predation by transient species later in the year.

Large schools of bait fish have been present in most seasons accompanied by schools of predatory greater amberjacks (*Seriola dumerili*). The subjects of interest to us, snapper and grouper species, however, have yet to establish resident populations at the site. Year-round resident species included Atlantic spadefish (*Chaetodipetus faber*), gray triggerfish (*Balistes capricus*), and the predators black seabass (*Centropristis striata*), and great barracuda (*Shyraena barracuda*). Other resident species may

not have been observed due to decreased visibility and/or increased cryptic behavior during winter.

The visibility near the bottom was relatively poor throughout May, at some times in late summer and often after winter Northeaster storms and hurricanes. Swarms of juvenile round scad (*Decapterus punctatus*) appeared in mid-May and were occasionally accompanied by snapper and grouper species. Transient species in May included loggerhead seaturtle (*Caretta caretta*), sand tiger shark (*Odontaspis taurus*), rock hind (*Epinephelus adscensionis*), nurse shark (*Ginglymostoma cirratum*), and cobia (*Rachycentrum canadum*). The settlement and recruitment to an area by juvenile baitfish may attract many temporary predatory species. In 2000, we first sighted small baitfish in April, although periodic clouds of very small juveniles could not be identified to species.

During 1999, tomtate (*Haemulon aruolineatum*), especially juveniles, were one of the most abundant and conspicuous members of the fish assemblage in close proximity with the structural reef units. Large schools of round scad often swam in and out of view near the tops of reef units. Immediately above any fish structure and well up into the water column were loose aggregations of adult greater amberjack. Other jacks occasionally passed through the site, including black bar jack (*Caranx ruber*).

Although resident predators must significantly reduce recruitment of many species, large stochastic predation events appear to have a formidable influence on mortality and survival of small and juvenile reef fishes. Two important large-scale predation events observed in 1999-2000 were the arrival of migrating loons (*Caranx ruber*) and the mid-winter appearance of large populations of ctenophores (believed to be *Leucothea milticornus*) near the bottom. We observed the loons to visually select fish prey in and near the structural reef units within a meter of the bottom. Also, the large numbers of ctenophores and/or jellyfish in winter corresponded to the temporary residence of an ocean sunfish (*Mola mola*) and a relatively large population of adult Atlantic spadefish. Both species are known to feed on jellyfish. The importance of predator-prey relationships was confirmed by inference from general observations of the relatively simultaneous arrival of baitfish and some of the higher level predators in the early spring. The infrequent appearance of high level piscivores at the small artificial reef site suggests large feeding ranges of many species, which appear to be "passing through" looking for feeding opportunities. Species that may move back and forth between other habitats within their hunting range and were observed at the site include large adults of loggerhead turtles, sand bar sharks, red snapper (*Lutjanus campechanus*), gag (*Mycteroperca microlepis*) and scamp (*M. phenax*).

## Discussion

Observations from the artificial reef research site can contribute significantly to the understanding of the short-term and long-term temporal changes in an offshore reef fish assemblage. Permanent installations of UWTV systems have the advantage of non-obtrusive observations of fish interactions. The sorts of behaviors that are of most interest to biologists, such as feeding or spawning, are rarely observed in the wild. Documenting such rare events often requires constant, long-term obser-

vation that is difficult under natural conditions because the ocean is always changing. Observations by divers are severely limited during seasons of high seas, often including both winter and spring, when migration and/or spawning activities among reef fishes most often occur.

Although the lack of mobility of our UWTV is a spatial limitation, a semi-permanent setting allows temporal investigations. Similar visual studies could develop sound catalogs of transient species and more detailed behavior-related sound patterns of resident species for potential management applications. For instance, estimates of population size of coral-nibbling parrot fish might be made after correlations between the mean rate of munching done per fish, with visual verification of the feeding behavior/sound relationship.

Synergistic information would come from the simultaneous combination of visual and sonic information. The addition of less expensive, passive acoustic data gathering devices could compensate for the lack of spatial coverage by more expensive UWTV systems. It could also provide more complete coverage of the events taking place in the vicinity of the cameras, but beyond their field of view.

Imagine, if you will, the interesting array of sounds that might have accompanied the feeding of loons on cigar minnows near the bottom, Atlantic spadefish biting a chunk off a passing jellyfish or a school of tuna passing through the artificial reef structures. Each of these complex sound series may be far more interpretable with TV documentation during the first several encounters. Behavioral observations correlated with acoustics and environmental conditions and validated over time would contribute to the interpretations of results from other sampling areas for which only acoustic data are available.

Integration of a relatively permanent TV and passive hydrophone offshore to refine the acoustic "dictionary" seems to be nearing reality. The UWTV systems exist associated with Fish Watch, Africam, Aquarius and specific public aquariums throughout the US. The bandwidth necessary to add simultaneous passive acoustic data should be minimal and be waiting only for the enthusiasm to make it happen.

The primary scientific objective of the UWTV system established off Georgia was to document and quantify prespawning aggregations of gag grouper as they move south along the continental shelf. If an associated sound recognition pattern were associated with such fish aggregations and movements, multiple listening stations could be established at key locations across the shelf and along the potential migration path at a cost for monitoring much less than that using other methods. The visual findings of the present UWTV study expand our understanding of the importance of large scale stochastic predation events on relatively localized reef fish aggregations, especially of juveniles and bait species. The sounds generated by the assemblage interactions would have filled chapters of a catalog on reef fish sounds. The scientific community anxiously awaits the development and application of tools that will allow simultaneous visual and sonic investigations of fish associations and behaviors.

## **Acknowledgments**

Any marine research requires a team effort with many experts and professionals involved to accomplish even a small task offshore. In the case of remote transmissions from an underwater TV system, the numbers of support electronics/computer, divers, vessel operators and agencies willing to loan facilities and/or manpower to get the job done can be staggering. We thank all those multi-agency staff and, in particular, the staff that always can be depended on to accomplish multiple tasks to keep the system functioning: Trent Moore, Cheryl Burden Ross and Travis McKissick. We thank many staff of the following institutions/ agencies/ groups for their undying support, including: the Skidaway Institute of Oceanography, the Gray's Reef National Marine Sanctuary, the SC Marine Resources Div, Artificial Reef Section and MARMAP program, the Georgia Coastal Resources Division and the USN Explosive Ordnance Disposal Mobile Unit #12. We are grateful for funding from the US Navy through the Office of Naval Research, National Oceanographic Partnership Program, Grant No. N00014-98-1-0808.



## Application of Passive Acoustic Methods for Detection, Location and Tracking of Whales

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### Introduction

Baleen whales produce species specific sounds. At least five species produce long, patterned, hierarchically organized sequences of sounds referred to as songs. Baleen whale distribution and relative abundance estimates are traditionally based on visual surveys from vessels and/or airplanes. This approach is limited by visibility conditions and access to observation platforms. Acoustic monitoring using either single or multiple sensors offers a significant improvement by increasing spatial and temporal sampling. Throughout the last 20 years, acoustic hardware and software tools have been developed and applied to survey whale species and gain insights into natural behaviors. This includes the use of Navy SOSUS arrays to detect and estimate numbers of vocal animals throughout an ocean basin, autonomous seafloor sensors to detect, locate and track species of interest in regions, and sparse or towed hydrophone arrays to detect, locate and track selected species in specific study areas. For at least four species, SOSUS data reveal annual seasonal and large geographic fluctuations reflecting migration, feeding and breeding patterns. For bowheads combined visual-acoustic efforts have lead to calculation of a robust population assessment and trend over a 20-year period, as well as understandings of acoustic functions. For blue and fin whales, integrated approaches combining passive acoustic methods with visual, biopsy, photo-ID and prey field surveys are beginning to reveal critical details of behavioral ecology and significant insights into vocal functions.

### Background

The Cornell Bioacoustics Research Program specializes in the development and application of advanced techniques to investigate the mechanisms and evolutionary bases of animal acoustic behaviors. Techniques successfully developed for the study of one organism or taxonomic group are often applied to another group. Part of the motivation for including the topic of whales in this symposium was to provide an opportunity to exchange information with researchers primarily interested in fishes. Clearly many of the tools developed for studies on whales are applicable to fish. Species in both taxa produce rich assortments of sounds in the low-frequency band (<1000Hz). Most sounds are species specific and can be used as indicators of species presence and relative abundance. Males



are known to produce acoustic displays associated with breeding. Similar sound propagation models can be applied to quantify probabilities of detection. An integrated approach in which acoustic techniques are combined with other methods (e.g., visual, molecular, oceanographic) can yield tremendous advancements in our collective understandings of marine biology.

### **Whale bioacoustics**

All 11 species of baleen whales produce sounds. Representations of sound repertoires are complete for the five coastal species, bowhead, gray, humpback and the southern and northern right whales. There are good representations for two pelagic species, blue and fin whales. Whale source levels (RMS power in dB re 1  $\mu$ Pa @ 1 m) have been reported as high as 188 dB (tabulated in Richardson *et al.* 1995). Under certain conditions (e.g., water depth that is not well matched to the signal's frequency band of lowest transmission loss, or highly reverberant environments), there is little or no advantage to increased source level, and selection should favor changes in other acoustic features to optimize communication effectiveness and range.

In the marine environment, assuming a selective advantage for long-range communication, the influences of physical acoustics should have imposed strong selective pressures on the acoustic features of communication sounds. There is evidence in support of this general hypothesis on sound function when considering the physical acoustic properties of the ocean environment in combination with the acoustic features of sounds produced by mysticete whales. Two primary acoustic properties that strongly influence communication range are transmission loss (TL) and ambient noise. In a shallow water habitat (< 200-300m) sounds in the 100-800Hz band experience the lowest TL and there is often a window of low ambient noise in this frequency range. Along a shelf break or in deep ocean environments (> 1000m), sounds below 100Hz experience the lowest TL and between 10-50Hz there is a plateau of low ambient noise. The acoustic features for species which breed and forage in predominantly coastal habitats are very different from those from a pelagic environment, as illustrated in Figure 1.

Ambient noise levels are different for these two environments, and the dominant frequency band of a species' song is generally matched to the frequency band of low ambient noise as shown in Figure 2 (Clark and Ellison in press).

Traditional visual survey methods are inadequate for documenting species presence/absence, distribution or relative abundance. The spatial and temporal sampling scales required are prohibitive for ship or aerial surveys, but passive acoustic sampling can offer an effective solution. Over the last ten years the acoustic activity of four species have been monitored on an ocean-scale basis in the north Pacific and North Atlantic using the Navy's SOSUS network (Watkins *et al.* 2000, Charif *et al.* 2001). Results provide large scale patterns of vocal activity throughout the year in areas where animals (e.g., humpbacks) are known to breed. Surprisingly, however, for pelagic species with no known breeding or calving grounds, singing occurs throughout most of the year even during the feeding season in high latitude areas (Figure 3).

For regional-scale sampling, autonomous seafloor recorders have been used in conjunction with visual surveys (aircraft or vessels) to estimate species densities and with active acoustic surveys to study the relationship between whales and the physical and biological oceanographic conditions. The results from such integrated efforts are immensely more informative than any one survey method alone. The number of cases in which acoustics detected species first and more often than visual survey is increasing, even for species that are plentiful and highly visible.

In cases where a highly focused effort is required, for example, when conducting a visual-acoustic census or testing specific hypotheses regarding sound function, a variety of hydrophone systems can be used. This includes sparse arrays of hydrophones, distributed networks of autonomous seafloor recorders or a towed beamforming arrays (Clark *et al.* 1996; Clark and Fristrup 1997; Croll *et al.* 2002). Such techniques provide mechanisms to continuously describe the number, locations and movements of individual animals in great detail. When combined with data from other focused field methods such as photo-id and biopsy sampling, one can relate age, sex, breeding status and behavior of individuals within a population to their acoustic behaviors (e.g., Croll *et al.* 2002). Integrated approaches offer tremendous opportunities for expanding critical knowledge in such diverse areas as marine vertebrate mating strategies and human impacts on the marine environment.

### **Acknowledgements**

The basis for this synthesis comes from several decades of research sponsored by the National Geographic Society, New York Zoological Society, National Science Foundation, Naval Research Lab, North Slope Borough Department of Wildlife Management, and the Office of Naval Research. Jack Bradbury, Donald Croll, William Ellison, Leila Hatch and Roger Payne provided stimulating discussions. I am indebted to all the staff in the Bioacoustics Research Program for assistance with data collection, analysis, and interpretation.

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## Illustrations and Diagrams

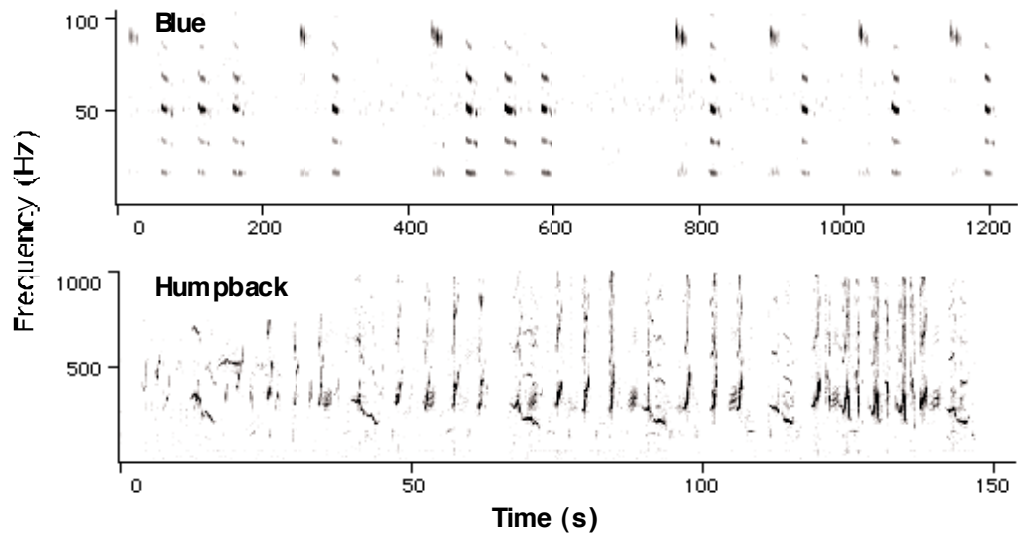


Figure 1. Spectrograms of blue and humpback songs to illustrate differences in acoustic characteristics for species predominantly from pelagic (blue) and coastal (humpback) habitats.

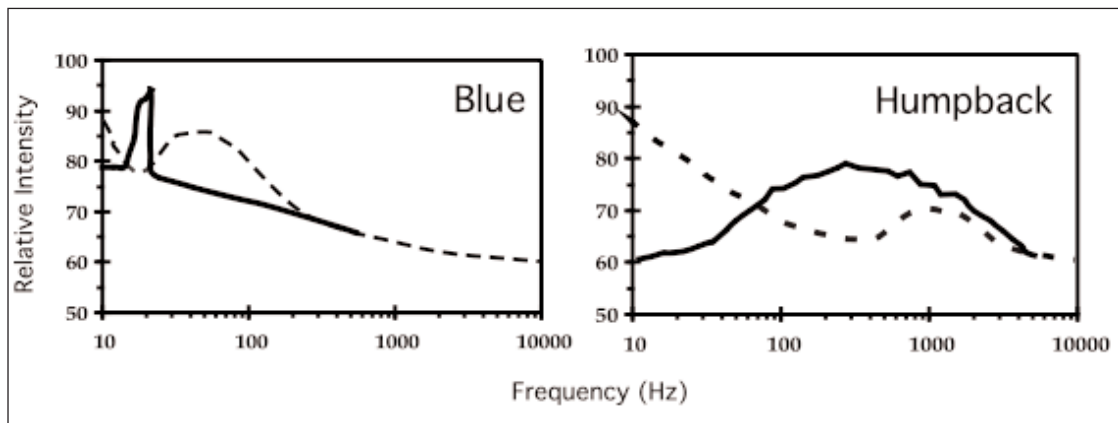


Figure 2. Spectra (solid lines) for pelagic (blue) and coastal (humpback) species overlaid on ambient noise spectra (dashed lines) for the two different habitats.

## Illustrations and Diagrams

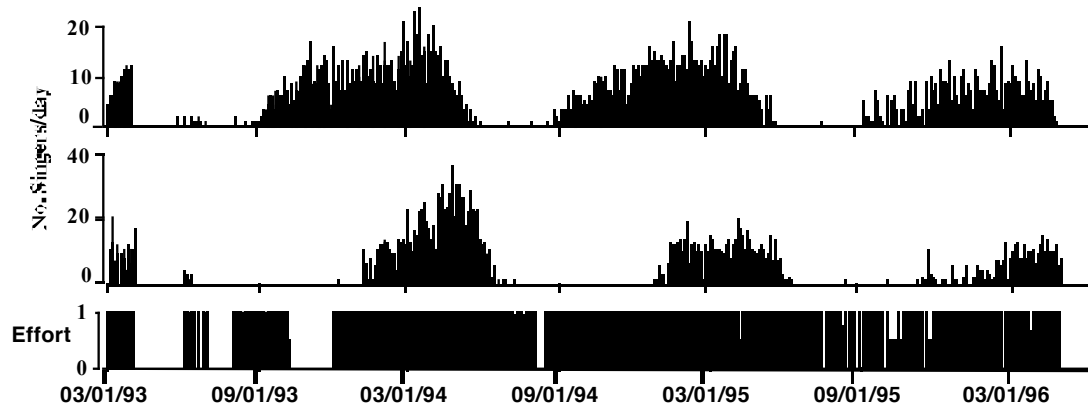


Figure 3. Daily counts of blue (top panel) and humpback (bottom panel) singers detected on SOSUS arrays in the western North Atlantic over a three year period.

# Passive Detection and Localization of Transient Signals from Marine Mammals using Widely Spaced Bottom Mounted Hydrophones in Open Ocean Environments

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## Abstract

One objective of the Marine Mammal Monitoring on Navy Ranges project is to use existing Navy undersea range infrastructure to develop a toolset for passive detection and localization of marine mammals. The Office of Naval Research funded the M3R project as part of the Navy's effort to determine the effects of acoustic emissions on marine mammals and threatened/ endangered species. A necessary first step in this effort is the creation of a baseline of behavior which requires long-term monitoring of marine mammals. Such monitoring, in turn, requires the ability to detect and localize the animals. This paper will present algorithms for passive detection and localization of transient signals developed as part of the M3R toolset. It will also present results of the application of these tools to detection and tracking of various toothed whales at the Atlantic Undersea Test and Evaluation Center (AUTEK), Andros Island, Bahamas.

## Introduction

Navy undersea ranges such as the Atlantic Undersea Test and Evaluation Center (AUTEK) use arrays of widely spaced bottom mounted hydrophones to acoustically track undersea and surface vehicles. Traditionally, the vehicles are equipped with acoustic pingers that emit known identification signals at known repetition rates. Increasingly, range instrumentation infrastructure (Figure 1) is being applied to non-traditional tracking problems. The Marine Mammal Monitoring on Navy Undersea Ranges (M3R) program has developed a set of signal processing tools to detect and track marine mammals using Navy range facilities [1]. Under the M3R program, algorithms were developed to automatically detect and track two classes of whale vocalizations — clicks and whistles. Both of these classes of signals are transient in nature. The tool set was recently tested at AUTEK over a two-week period. Over five hundred square nautical miles of ocean were simultaneously monitored via 68 broad-band hydrophones. Several species of toothed whales were automatically detected and tracked in real-time. The positional accuracy of the M3R tracking tools was confirmed by visual sightings by a surface craft and by manual analysis of the hydrophone data.

## Discussion

Visual sightings [2] and aural analysis of hydrophone recordings [3] indicate that many species of toothed whales are present at AUTECH. The most commonly seen and heard are sperm whales, dolphins and short finned pilot whales, all of which are present nearly year round. Consequently, the M3R tools were developed to detect and track these common species. For purposes of algorithm development, the vocalizations produced by the whales were characterized as clicks and whistles. Clicks are, in general, any impulsive, broad-band signal. However, sperm whale clicks were of particular interest. Sperm whale clicks are very distinct, have high source level, and occur in regular patterns [4] or “click trains” (Figure 2). Whistles were more broadly defined as any narrowband event that sweeps in frequency over time (Figure 3).

There are three distinct parts to the whale localization problem. First the vocalizations or whale calls must be automatically detected. In order to determine the position of the animal in three dimensions, a given call must be detected on a minimum of four hydrophones. The second part of the problem is the association of the detections received on various hydrophones with each other. That is, one must be able to determine that the call received on hydrophone A at time  $t_A$  is the same signal that was received by hydrophone B at time  $t_B$ . Finally, associated sets of arrival times are input into a multilateration algorithm to solve for position. A three-dimensional hyperbolic positioning model [5] is used to determine the vocalizing animal’s location in X, Y, and Z as well as the time of emission of the call.

M3R employs a real-time frequency domain energy detector for whale call detection. A spectrogram of the incoming acoustic data from each of the hydrophones is formed using 512-point fast Fourier transforms (FFT) with a rectangular window and fifty percent overlap. The resultant spectrogram has a frequency resolution of approximately 51 Hz and a time resolution of approximately 9.8 ms. Each time-frequency bin of the spectrogram is compared to a time varying threshold,  $D(f,t)$ . The threshold is set to be  $m$  dB above the (time) average power within frequency bin  $f$ . The output of the detector,  $Q_i(f,t)$ , for each hydrophone, is a binary valued “detection spectrogram” which contains a 1 in each time-frequency bin that exceeded  $D(f,t)$  and a 0 everywhere else (Figure 4). The detection spectrogram indicates, in real-time, the presence of whale vocalizations as well as providing information on their frequency content. As evident in Figures 2 and 3, the signal structure of (sperm whale) clicks is very different from the signal structure of whistles. Therefore, separate detection association algorithms were developed for each signal type.

A series of clicks from a single sperm whale exhibits nearly the same inter-click interval on all receiving hydrophones. Calls from each additional animal exhibit their own unique pattern. In fact, inter-click interval patterns were found to be an effective means of both differentiating between individual whales and associating patterns of detections among hydrophones [6]. In the first step of the M3R click association algorithm the time-frequency detection spectra from all hydrophones were reduced to binary “click maps”. Click maps contain a 1 for time indices where broad band events occurred in the detection spectrum and 0 for all other times (Figure 5). Conceptually, the next step is to cross correlate the click maps from several hydrophones with a master hydrophone to find the difference in time of arrival between each hydrophone and the master. However, care must be

taken in implementing the cross correlation in order to properly associate each click detection among the hydrophones. Figure 6a shows an example of a click map from a single hydrophone containing clicks from two individuals. Figure 6b shows the click map from a second hydrophone over the same time period. The question is which clicks in figure 6b belong to which individual?

The M3R click association algorithm uses the notion of a “scanning sieve” [7] to match detection patterns between hydrophones. The sequence of click detections (i.e. click map) within the scanning sieve on the master channel is compared to the clicks maps from surrounding hydrophones (“scanned” signals). The scanning sieve time window always starts on a click detection, and is moved across the scanned signal one click detection at a time. That is, the resultant correlation value at any time delay represents the number of matches between the master channel pattern starting a specific click and the scanned channel pattern starting at a specific click. The delay of the maximum correlation value represents the difference in time of arrival where the first clicks in the scanning sieve and the scanned signal were best aligned. The output of the scanning sieve process are sets of time difference of arrival (TDOA) for each click detection received on the master channel (Figure 7). The TDOA data from each hydrophone are then histogrammed to estimate the number of separable sources (Figure 8). Only detections associated with significant populations are used (Figure 9). These associated TDOA sets are then sent to the AUTECH multilateration tracking algorithm which calculates 3D position.

Whistle vocalizations do not typically follow known repetition patterns. An individual can emit a single short whistle or groups of sweeps that last several seconds or both. However, the time-frequency characteristics of the calls in whatever sequence they may occur remain the same on all receiving hydrophones. To determine the TDOA of signals among the hydrophones, the detection spectrograms  $Q(f,t)$  of the available hydrophones are cross-correlated against a master channel,  $M$  [8]. The cross correlation  $C_i(t, \tau)$  between the  $i$ -th channel and the master channel is calculated over a time window of approximately 6 to 10 seconds. That time window is then advanced by one half its duration and  $C_i(t, \tau)$  is updated.

$$C_i(t, \tau) = \sum \sum Q_M(f, t) Q_i(f, t + \tau)$$

The time delay associated with the peak of the correlation functions indicates the TDOA for a signal relative to the master hydrophone (Figure 10a). If whistles from multiple whales are present within a cross correlation time window, multiple correlation peaks will be evident (Figure 10b). Note that if both clicks and whistles are present at the same time, sperm whale clicks will dominate the detection spectra. Correlation peaks due to whistle signals will be obscured. Therefore, for practical purposes, broad-band click events should be removed from the detection spectra prior to cross correlation.

While cross correlation of detection spectra indicates times of signal arrival and the presence of multiple whales, it does not associate the time delays of the correlation peaks with an individual across the hydrophone channels. However, as mentioned early, the sequence of whistles from an individual is the same on all receiving hydrophones. Figure 11 shows the time differences of arrival relative to a master hydrophone of the correlation peaks for five hydrophones. Notice that there are



two distinct patterns of detections versus time along specific time delays. Matching these patterns along time delays associates the TDOA's among the hydrophones with an individual whale.

Associated sets of TDOA can then be sent to the multilateration tracking algorithm which calculates 3D position.

## Recent Results

The M3R toolset was demonstrated at AUTEK as part of a joint experiment with researchers from Woods Hole Oceanographic Institution (WHOI). The WHOI team was testing a new whale tagging system [9]. The M3R algorithms were used with sixty-eight of the AUTEK hydrophones to monitor over 500 sq. NMI. When marine mammals were localized, their positions were relayed to the tagging vessel, which then endeavored to maneuver close enough to place a tag.

The detection, association and tracking algorithms described in Section 2.0 were implemented to run in real-time for arrays of five to seven hydrophones. Given that there were 68 hydrophones to monitor, other display tools were used to broadly locate whales before applying the high resolution positioning algorithm. The Circle display is a Matlab program that shows the number of detections on each hydrophone by drawing a circle around the respective hydrophone. The number of detections per minute is mapped to the color of the circle. Figure 12 shows an example of the Circle display while two groups of whales were on the range. The bright circles around Hydrophone 85 were caused by a single clicking sperm whale. The bright circles around Hydrophone 53 were caused by a group of pilot whales just off the range (hydrophones 47, 48, 54 and 55 were not monitored). The WHOI team successfully tagged two of the pilot whales shortly after this picture was taken.

The strip chart program displays the detection spectrogram from a particular hydrophone in real-time. The program reads the detection data from a server process allowing the user to run multiple charts on multiple computers simultaneously. During the AUTEK tests this display was quite handy for monitoring phones over a wide area. At various times, both broad sperm whales clicks, and pilot whale clicks and whistles were evident (Figure 13).

Both the click association and whistle association algorithms worked well during the exercise. Vocalizing whales were heard on range almost everyday. At different times, individuals and/or groups of sperm whales, short finned pilot whales, roughed toothed dolphins, melon headed whales and even a beaked whale were all detected and tracked by the M3R algorithms. The track positions produced by M3R were confirmed by GPS readings and visual observations from the tagging vessel, as well as by manual monitoring of the hydrophones. Figures 14a-b show an example of real-time X-Y position and depth plots for a group of two or three sperm whales. The depth plot indicates that these whales were likely performing deep feeding dives. On some dives monitored during the test, sperm whales were tracked at depths of 1000 to 1200 m. Figure 14c shows the depth track for a single sperm whale that was performing shallow, near-surface dives. Figure 15 shows the real-time X-Y position plot for a group of whistlers, which were later identified by WHOI team members as roughed toothed dolphins and melon headed whales.

## Summary

The M3R project has developed algorithms for the passive detection and tracking of marine mammals using widely spaced, bottom-mounted hydrophones characteristic of Navy undersea tracking ranges. While these algorithms have been implemented and tested for deployment at the AUTEK, they are applicable to any fixed or portable range that uses multilateration tracking algorithms. Potential ranges with the hardware to support the M3R system include the Pacific Missile Range Facility, the Southern California Offshore Acoustic Range, and any of the Navy's various portable systems.

The M3R algorithms have been designed to work in a highly channelized multi-processor hardware environment, and the software architecture has been developed to be fully network compatible. Signal detection, and detection-association algorithms for two primary types of whale calls, whistles and clicks, have been developed. These algorithms are specifically designed to be used with widely spaced sensors, and assume that the marine mammals vocalize repetitively with sufficient source levels to be detected on multiple hydrophones.

The M3R algorithms, for both clicks and whistles, have been successfully demonstrated resulting in real time 3D tracking of several species of toothed whales including sperm whales, rough toothed dolphins, melon headed whales and pilot whales. The M3R tool set allows automated collection of data previously unavailable for the long-term monitoring of marine mammal bioacoustics within their natural environment. This opportunity has been created with minimal investment in infrastructure by providing Navy ranges as a dual-use asset. Research applications of the M3R system include the ability to remotely estimate marine mammal abundance, assessment of bioacoustic behavioral baselines, and evaluation of the impact of anthropogenic noise compared to those baselines.

## Acknowledgements

We would like to acknowledge our sponsor, Dr. Robert Gisiner, at the Office of Naval Research, for funding this project. We would also like to thank the AUTEK personnel, especially Thomas Szlyk, for access to their considerable infrastructure and ongoing support. In addition, we would like to thank the NUWC Division Newport ILIR program manager, Richard Philips, for supporting the initiative to create a baseline sperm whale bioacoustic characterization in the Tongue of the Ocean (TOTO).

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## Illustrations and Diagrams

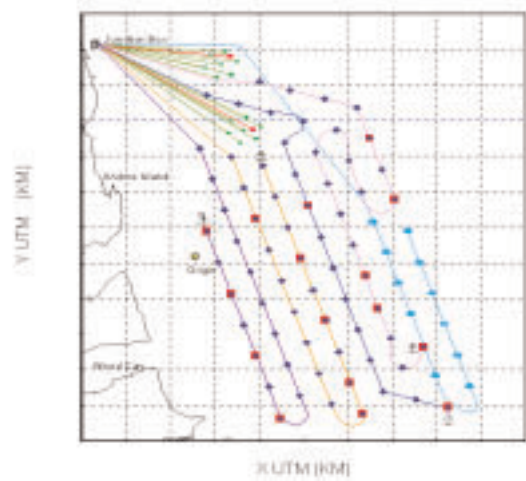


Figure 1: AUTEC has sixty eight, broad-band bottom mounted hydrophones with a 2 NMi baseline.

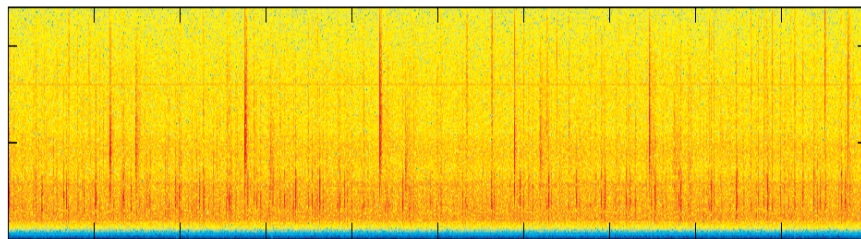


Figure 2: Spectrogram showing sperm whale clicks from several individuals.

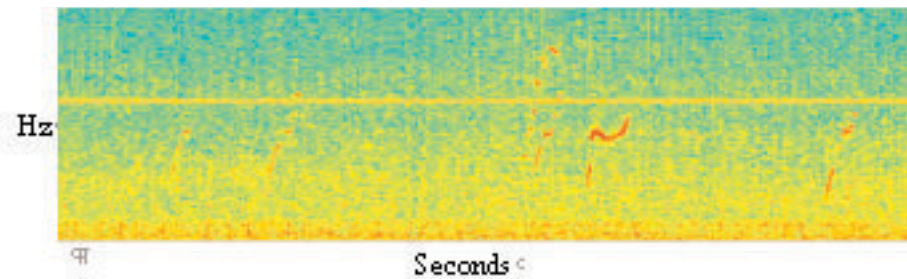


Figure 3: Spectrogram showing a sequence of whistles probably from a short finned pilot whale.

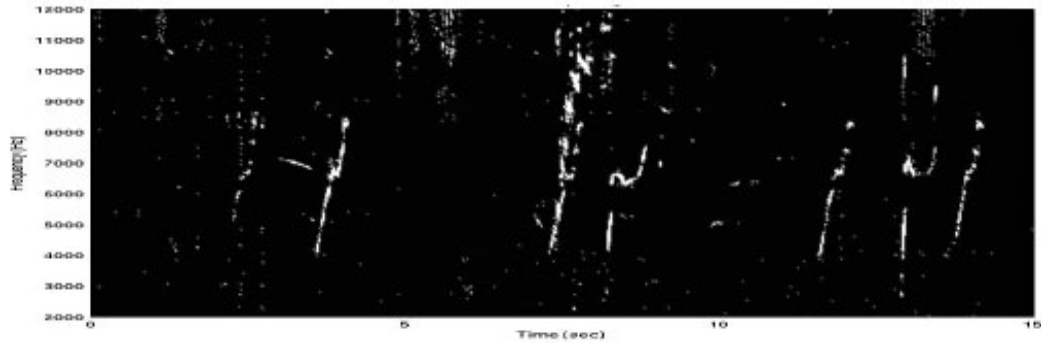


Figure 4: Detection spectro-gram,  $Q(f,t)$ , of whistles. Threshold was set 6-dB above the average spectral power.

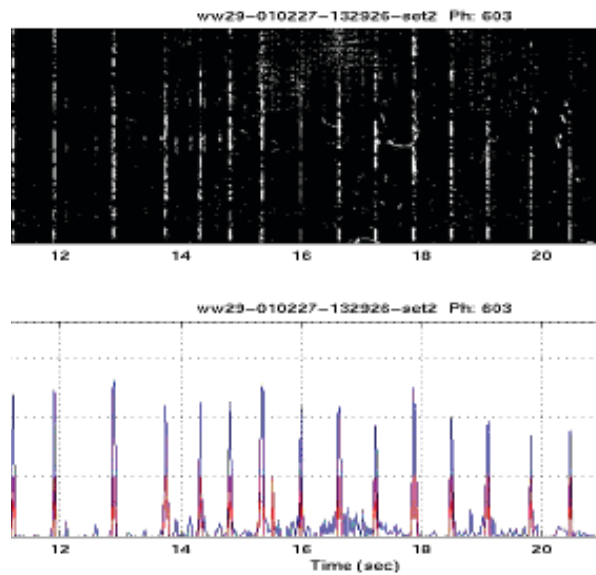


Figure 5: Click maps are formed by summing the detection spectrum (above) along frequency then thresholding the sums. The red curve indicates the click map for this data.

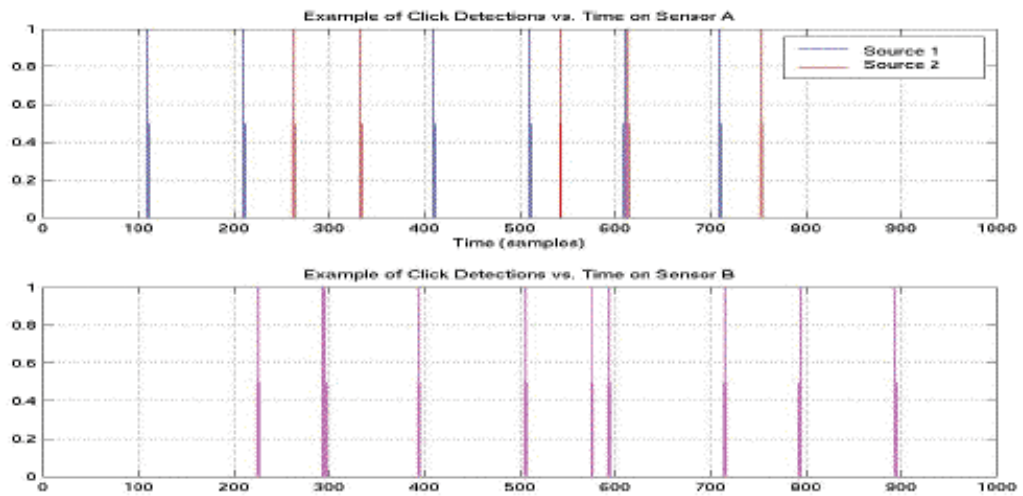


Figure 6: Click maps for two hydrophones containing clicks from two individuals. It is not evident which clicks received by hydrophone B are associated with Source 1 or Source 2.

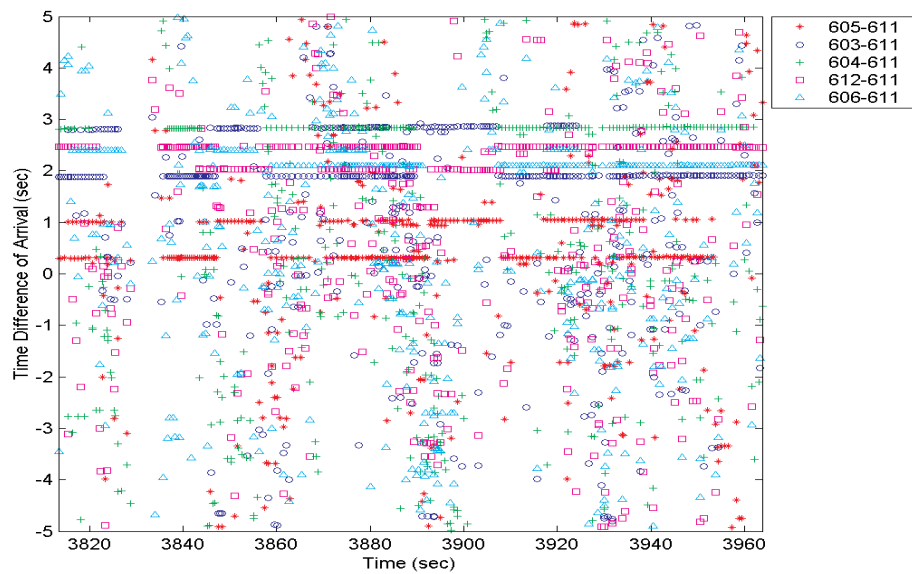


Figure 7: Preliminary output of the M3R click association algorithm showing the estimated TDOA between the scanning sieve, hydrophone 611, and five additional hydrophones

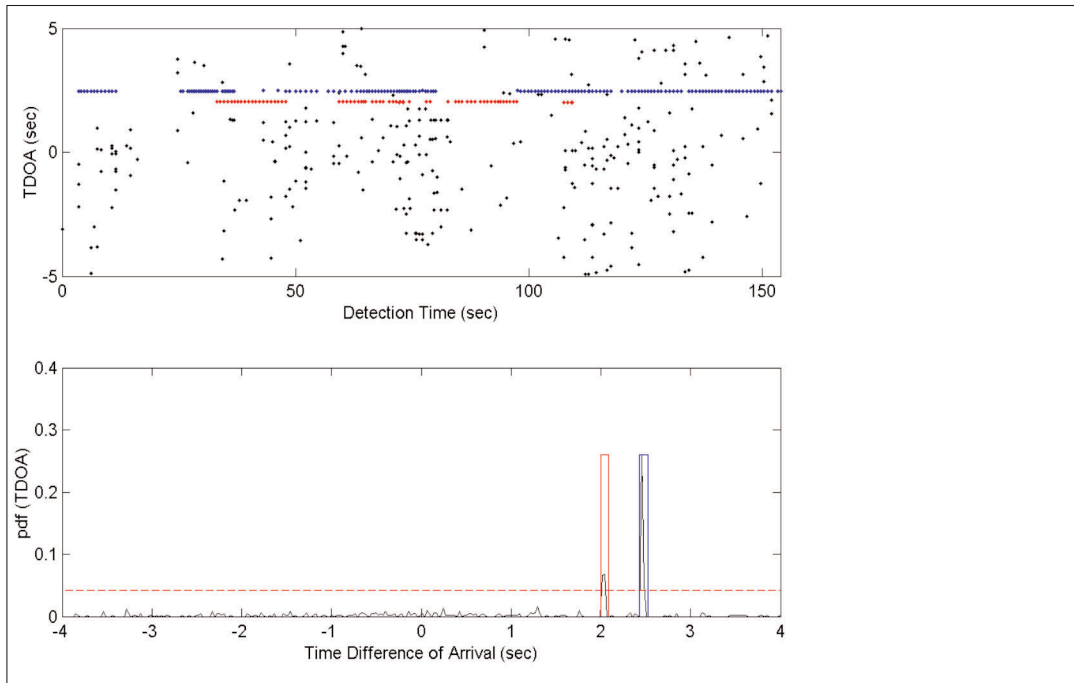


Figure 8: Above is the output of the click association algorithm for hydrophone 612 (indicated in purple in figure 7). Two separate times of arrival are evident indicating the presence of 2 whales. A histogram of the TDOA data shows two significant populations.

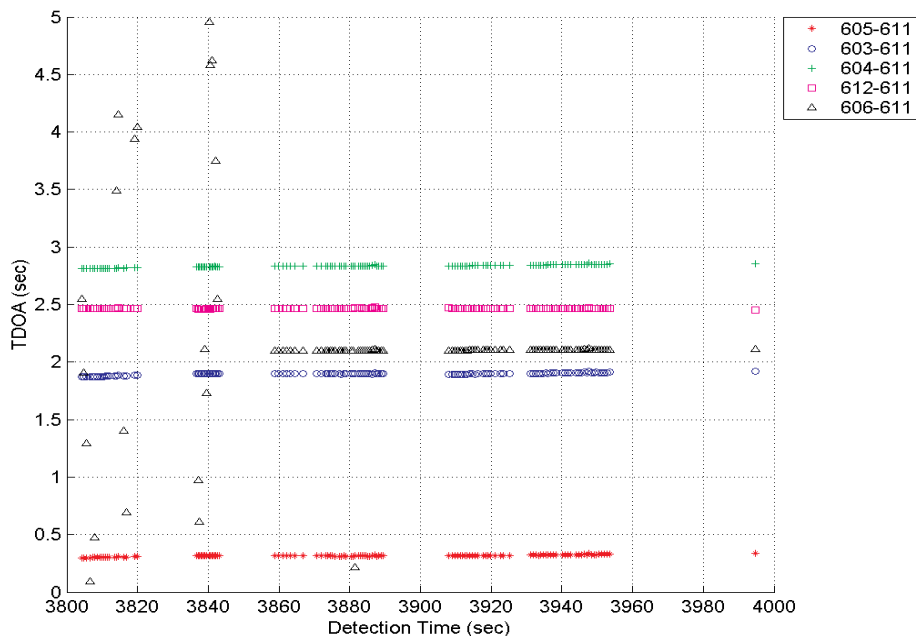


Figure 9: Final output of the click association algorithm for calls from a single sperm whale. The points indicate the TDOA at which the algorithm found the best matches between the scanning sieve and the clicks maps of hydrophones 605, 603, 604, 612 and 606 relative to master hydrophone, 611. Notice the minimal scatter of the TDOA points.

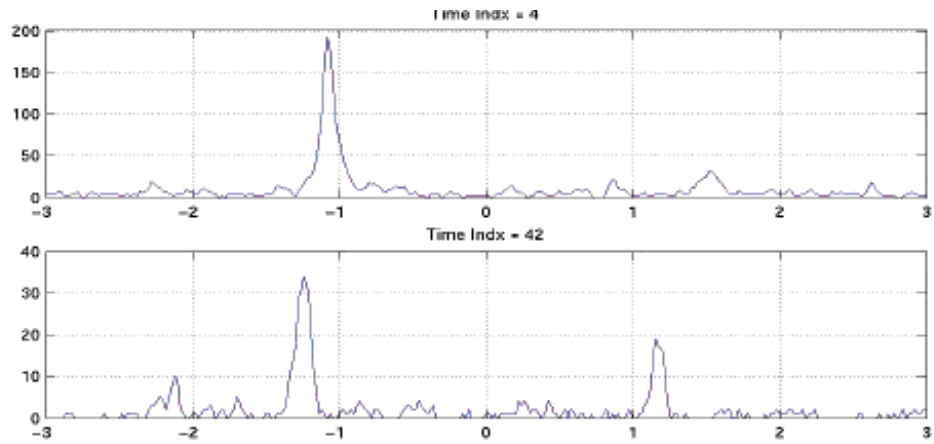


Figure 10:

- a) Results of cross correlation indicating the TDOA of the signal from one whale.
- b) Cross correlation results indicating the TDOA's of signals from two whales.

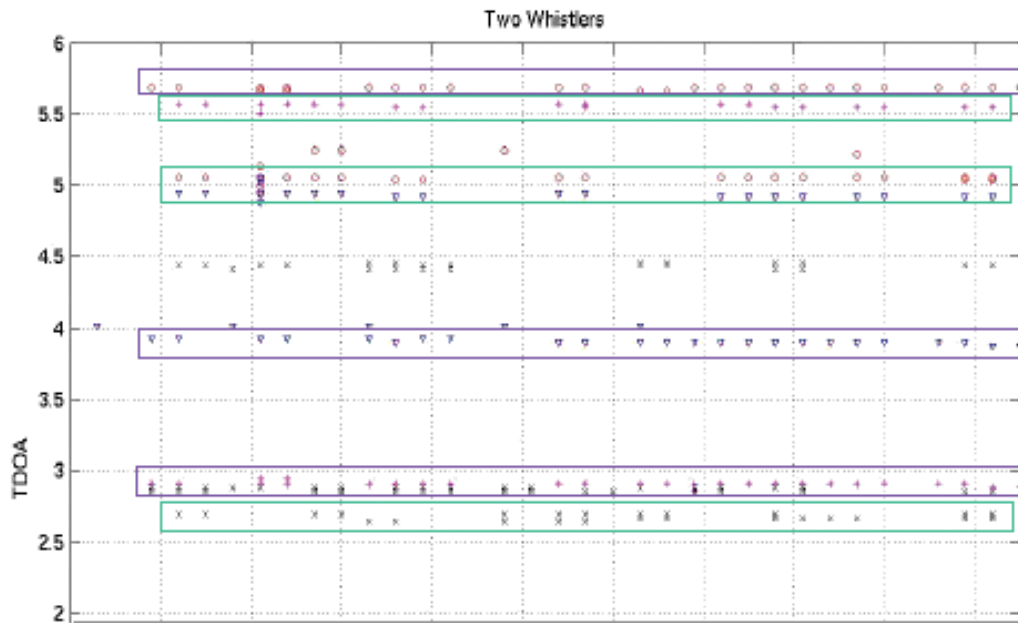


Figure 11: TDOA data resulting from cross correlations of five hydrophones against a master hydrophone. Two individual whales show two distinct patterns (indicated by purple and green boxes) of detections versus time along specific TDOA's.



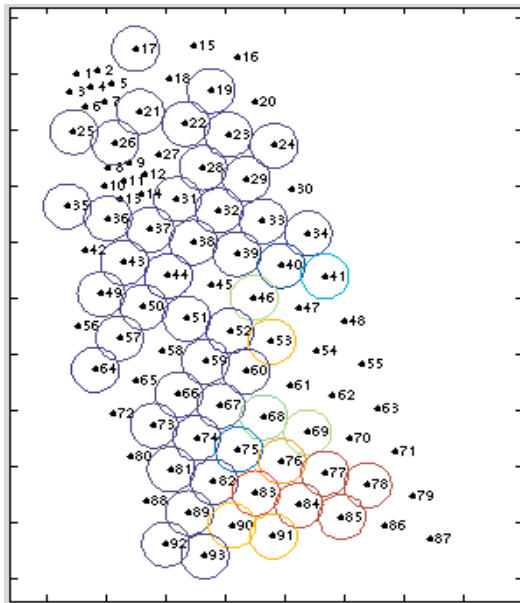


Figure 12: Circle detection count display. Maps color of the circle around a hydrophone to the number of detection per minute.

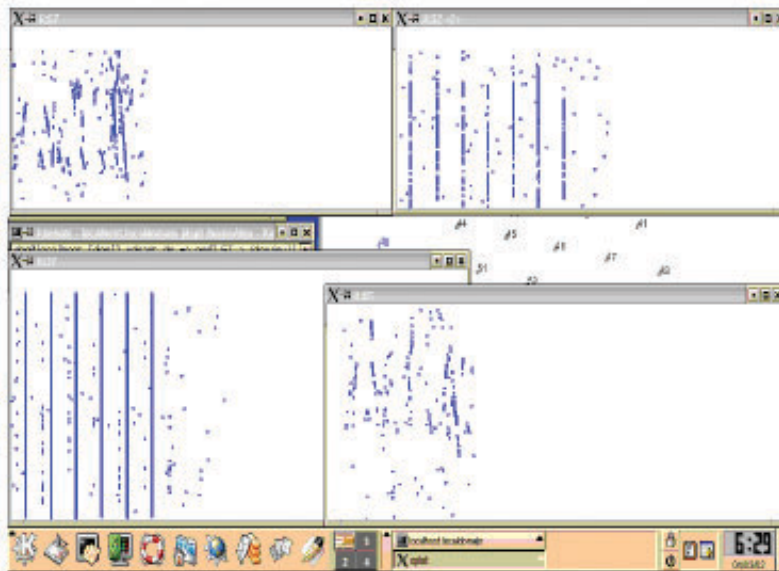


Figure 13: Strip chart displays scroll horizontally to display detection spectra for a given hydrophone in real-time. The top right and lower left charts show sperm whale clicks while the top left and lower right show whistles.

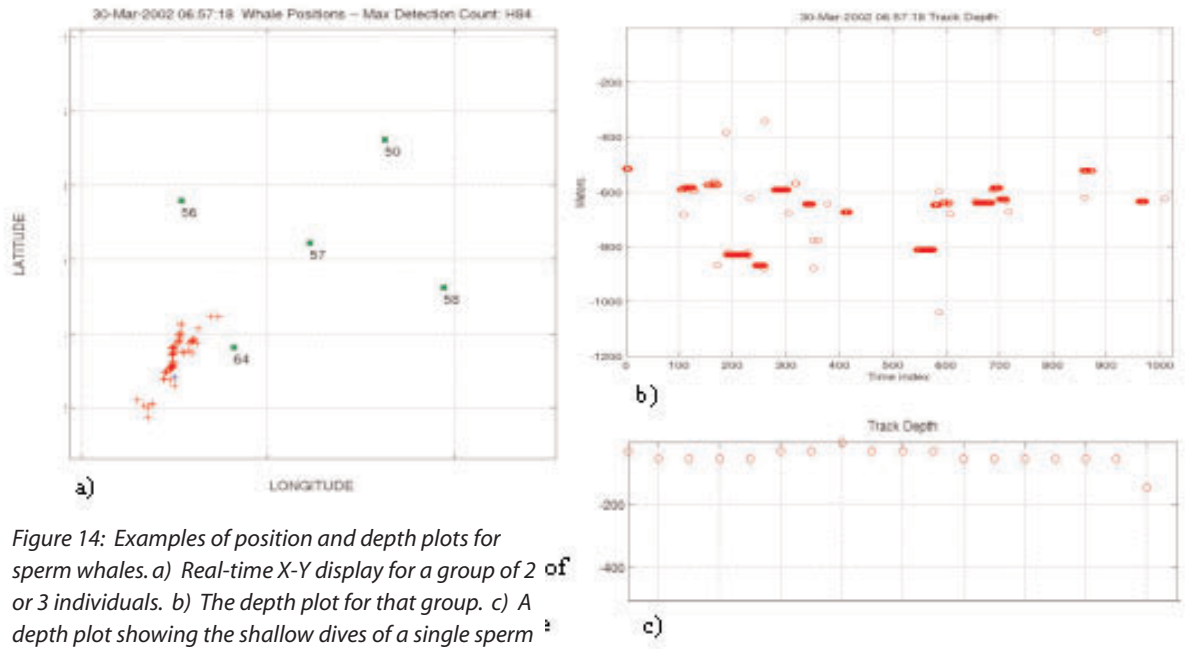


Figure 14: Examples of position and depth plots for sperm whales. a) Real-time X-Y display for a group of 2 or 3 individuals. b) The depth plot for that group. c) A depth plot showing the shallow dives of a single sperm whale.

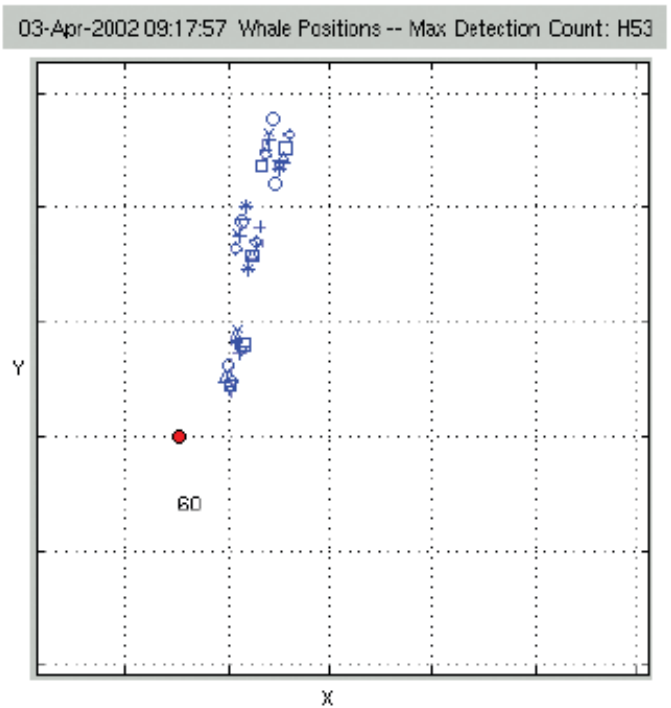


Figure 15: A real-time X-Y position plot for multiple whistlers. The icon shapes indicate the individuals that the M3R tools were able to identify. This group was observed by researchers aboard the WHOI whale tagging vessel. The group consisted of more than twenty roughed toothed dolphins and melon headed whales.



## **Multihydrophone localization of low frequency broadband sources**

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### **Introduction**

To localize high areas of fish activity and adequately characterize fish behavior, it is useful to localize individual fish by their emitted sounds over a range of 10s-100s of meters. In theory, one can use multiple hydrophones distributed in space to localize a source position/direction: using time-of-flight differences among the hydrophones, generate multiple hyperboloids then solve for the surfaces' intersection to give a unique position for the source, perhaps in the least-squares sense. In practice, this is difficult for low frequency signals generated by fish (thumps, etc.) because the onsets of the signals are not well defined. By using cross correlations among the received signals as a "fuzzy" measure of time difference it is possible to do the equivalent of the intersecting hyperboloids calculation with an uncertain measure of time differences, giving the equivalent of a probability density of source location over a predetermined space of a priori possible locations.

The proposed method of tracking should be flexible, easily deployed, and self-calibrating. A useful side benefit of this kind of computerized fish tracking is to provide a record of vocalizations for later processing.

### **Prior art: conventional beamforming approach**

A conventional beamformer coherently adds the outputs of several hydrophones using time delays per hydrophone to emphasize energy arriving from a particular direction (and to suppress energy arriving from other directions). In general, the spacing among hydrophones must be several times the wavelength of the detected sound to form an accurate estimate of direction; in addition, conventional arrays of hydrophones have ambiguity in locating a sound source (e.g., the angular ambiguity around a line array).

### **Alternative: Position estimates from time differences among hydrophone pairs**

An alternative to beamforming is to use a "loose" array of hydrophones with an irregular geometry to perform the localization. In this method, hydrophones are used in pairs. For each pair, correlated pulses of sound arriving with a time difference ( $t$  between hydrophones correspond to a single

source whose position lies on a hyperboloid with the hydrophone pair at the foci. Using several pairs of hydrophones reduces the problem of location to finding the intersection (possibly in the least squares sense) of several hyperboloids. The problem with this method is that uncertainty in the required  $t$  produces an uncertain estimate of the hyperboloids' intersections. This uncertainty is relatively small for high frequency clicks, but is greater at low frequencies or for narrowband signals like thumps and whistles.

To overcome the effects of uncertainty, it is useful to keep the estimates of  $t$  "fuzzy" by replacing the number (by a probability distribution around the most likely  $t$ ). The use of statistics derived from the cross correlation functions between pairs of hydrophones does exactly this. Data from multiple hydrophone pairs can be fused into a single coherent picture by combining statistics from several hydrophone pairs in a manner to multiplying probabilities of independent events to obtain the probability of all events occurring simultaneously.

### **Position estimation experiment**

To test the effectiveness of the localization technique, 5 hydrophones were deployed in a lake. The hydrophones were arranged as vertices of an inverted square pyramid 1 meter on a side with the apex 1 meter below the base.

Figure 1 below shows the "fuzzy" surface (mapped as a Mercator projection using elevation from the horizontal plane and "longitude" around the equator) formed from the magnitude of the cross correlation function of a cusk-eel sound as measured by a pair of hydrophones in the array. The dark red areas are the most likely positions of the source as measured by the magnitude of the cross correlation of the two hydrophones' signals. Figure 2 represents the product of the first two cross correlation magnitudes.

The improvement using just two pairs is dramatic. Finally, figure 3 below shows the results of including all hydrophone pairs in the product.

### **Discussion**

The technique described above performs well in a low-noise environment. By simulation, several potential sources of error were modeled using the acoustic data gathered in the original experiment. The error sources considered were

1. Uncertainty in hydrophone positions (contaminates all measurements);
2. Uncertainty in signal arrival times;
3. Signals at hydrophones not exact copies of source (directivity of source);
4. Reverberation (images of the signal from boundaries);
5. Ambient noise;

6. Overlapping signals from multiple sources.

Of the 6 sources of error, the most damaging were numbers 4 and 6. Because the estimation process used has a nonlinear component (product of magnitudes), multiple signals received simultaneously from the same type of fish generate multiple cross correlation peaks. These in turn generate spurious product terms when multiplied together to form the final estimate. The minimization of this effect is the subject of future research.

## Illustrations and Diagrams

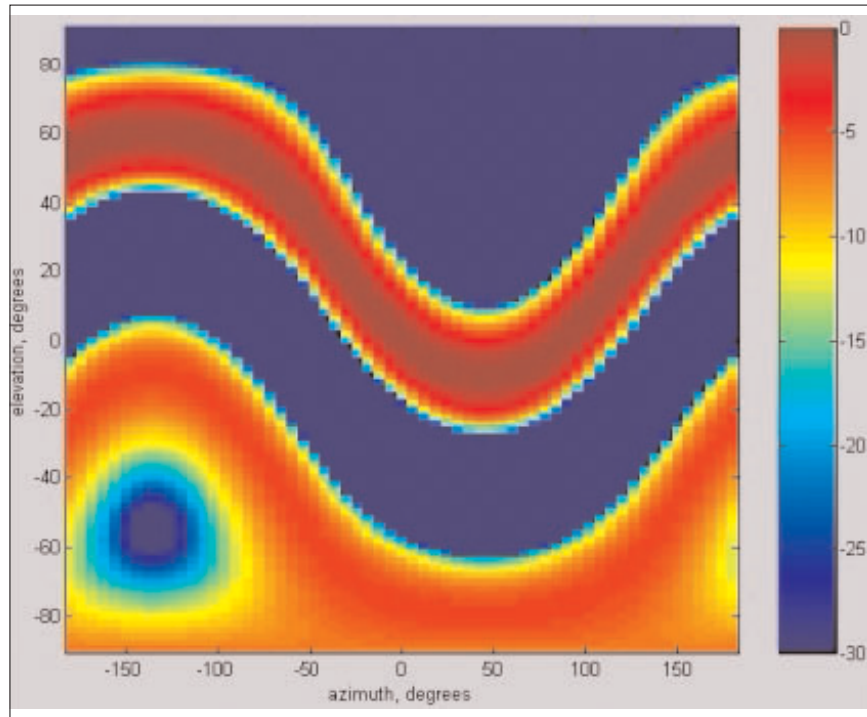


Figure 1. Magnitude of the broadband cross correlation (dB relative to max) for 2 hydrophones (apex and 1 base).

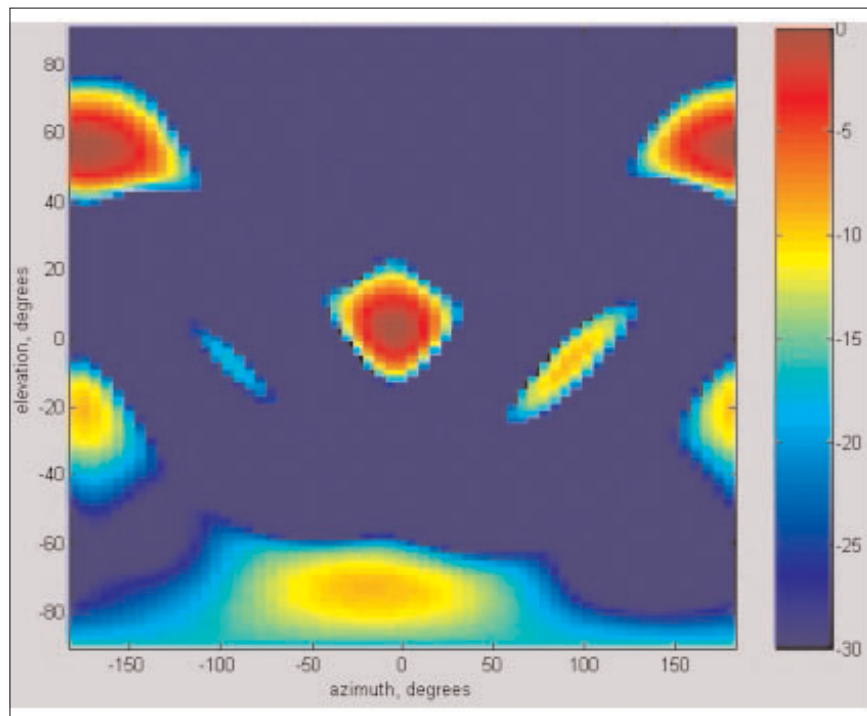


Figure 2. product of correlation magnitudes for the first 2 hydrophone pairs.

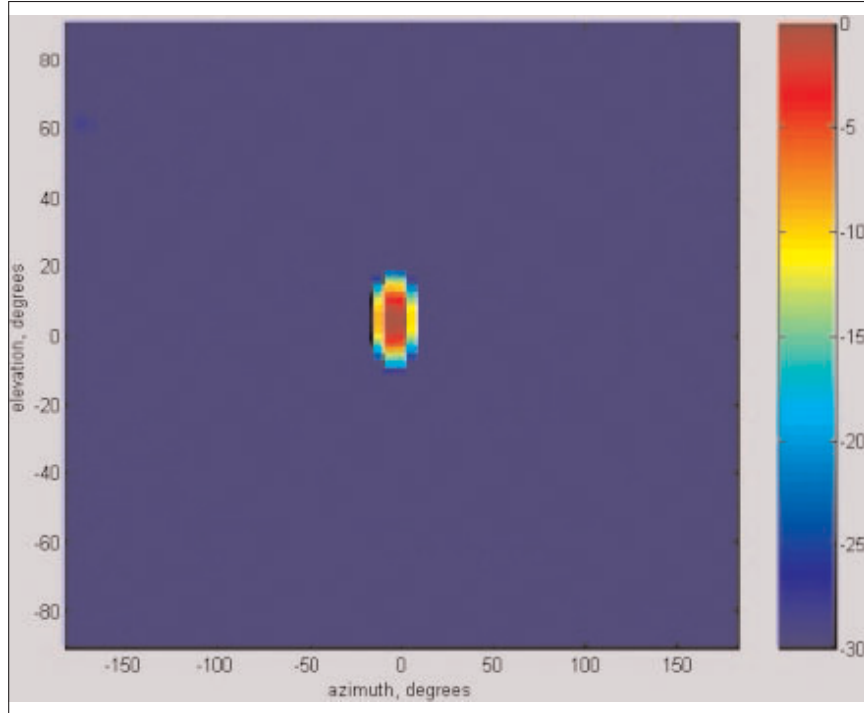


Figure 3. product of magnitudes of all hydrophone pairs.

## Synchronized underwater audio-video recording

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Extracted from: Lobel P. S. 2001 Fish bioacoustics and behavior: passive acoustic detection and the application of a closed-circuit rebreather for field study. *Marine Technology Society Journal*, 35:19-28

### **Introduction**

One advanced technique used in undersea research to study fish acoustic behavior is simply the interdisciplinary application of established acoustic technology combined with new mini-video cameras and hydrophones while diving with a UBA rebreather. Rebreathers and hydrophones have been around for more than 40 years but it has been only in the last decade that video cameras and hydrophones have become miniaturized. Most importantly, these video cameras are equipped with audio input enabling synchronous audio-video recording. Acoustic signal analysis is also greatly simplified by direct connections to advanced portable computers and new sound analysis software. Even so, the basic situation is the same now as when Steinberg and Koczy (1964) stated, "the principle accomplishment of the techniques for underwater observation is that of extending man's senses of sight and hearing underwater".

Being able to observe and record the sonic behavior of marine animals was recognized as an important scientific approach to understanding fish behavior ever since it was first revealed that sounds were integral to behavior in many species (Fish 1954, Griffin 1955, Moulton 1958, Tavolga 1960). The approach that I use in recording bioacoustics was pioneered in the 1960's at the Lerner Marine Laboratory in Bimini, Bahamas and during missions of the underwater habitat, TEKTITE. In 1963, a television and hydrophone system was deployed in about 20m depth and linked by cable to the Lerner lab with a room full of electronic equipment for recording (see figures in Kronengold et al. 1964). This system recorded a variety of sounds but the fixed camera did not usually catch the identity of the sound producer (Kumpf 1964). This early system did, however, clearly document several temporal patterns of distinctive sound production by marine animals (Cummings et al. 1964). This system was also used for the playback of sounds to determine the effectiveness of pulsed low frequency sounds for attracting sharks and other fishes (Richard 1968, Myrberg et al. 1969). During the TEKTITE missions of 1969, divers used rebreathers from an underwater habitat to record fish sounds using a 8mm film movie camera and a tape-recorder with hydrophone operated independently but simultaneously (Bright 1972). Bright clearly noted the benefit of the noiseless rebreather when



recording fish behavior. The two major advances today are 1) advanced video and hydrophone technology enabling truly synchronous audio recording (in a much smaller package) and 2) the increased reliability of electronic rebreather systems.

### **Bubble Noise**

Bubbles not only produce noisy sounds but also near-field vibrations in the water (Fig. 1, 2). This water disturbance is probably similar to the hydrodynamic disturbances produced by fast moving predators to which most fish are especially sensitive by means of their lateral line and sensory pore system. The common range of reef fish hearing is roughly between 20 and 1000 Hz although some hearing specialist species can hear in ranges up to 10 KHz. One herring species can hear at 180 KHz (Hawkins 1981, Mann et al. 1997, Popper and Fay 1998). However, it is fair to note that some fish apparently habituate to boat and scuba noise, as is seen at some marine protected areas or other sites with high diver activities. For example, I recently recorded a situation where scuba and excessive boat noise did not affect the mating activity of the damselfish, *Dascyllus reticulatus* in a lagoon (Lobel pers. obs., Saipan, July 2000).

I started recording the acoustic behavior of free ranging fishes in 1988 using open circuit scuba and first generation 8mm camcorders connected to a hydrophone (Lobel 1992). Because of the scuba bubbles, I had to spend many hours per day in the water to allow the subject fish to habituate to my presence. This required remaining motionless on the bottom for long periods and carefully controlling my breathing so that only a trickle of tiny bubbles was slowly exhaled (Figure 3). This somewhat avoided the louder noise caused by a big burst of bubbles from a single exhalation. In order to obtain quality acoustic recordings without scuba bubble noise interference, acoustic measurements were edited in the lab from those portions of the video made between breaths. Thus, divers needed to be very disciplined in their respiratory pace and activity while recording.

We started using a rebreather three years ago and, without a doubt, it is the most successful method for obtaining fish behavioral and bioacoustic data (Lobel and Kerr, pers. obs). Beginning with my first field experience with the rebreather (after 31 years of scuba), I was greatly impressed with how differently fish behaved when there were no bubbles. The great advantage of the rebreather is to allow us to approach animals more closely. But this is also a bit more risky for the same reason. I have found that eels and grey reef sharks are more inquisitive and approach much closer without noisy bubbles. On the other hand, the only time I experienced a school of juvenile parrotfish actually swim toward and over me, as if I was just a rock, was when using a rebreather. This aspect of using rebreathers will have its most significant impact on the practice of conducting

underwater transects for species census and abundance surveys. We have found that we see more individuals and a greater diversity, especially large fishes, while diving with the rebreather (Lobel and Kerr pers. obs.). Taking this one step further, we have recently acquired camouflage pattern wetsuits that are made to blend in with reef habitat. Thus, divers not only make no noise, but their silhouettes are less conspicuous and make the diver appear less like a large predator. Underwater photographers were among the first to use rebreathers routinely for the same reasons (e.g. Cranston 1993). Any type of observational data that marine biologists collect will clearly benefit from using the rebreather. Examples include: 1) conducting transects to determine species diversity and abundance, 2) quantifying fish feeding habits by observation, and 3) defining species habitat usage and behavior. Such field projects require a tool that provides the greatest degree of scientific accuracy possible and confidence in the results. The advantage of the rebreather is that it allows for: 1) noiseless operations, 2) the long bottom time necessary to allow fish to acclimate to the observer's presence (overall, the use of a rebreather greatly reduces the time needed to habituate fishes compared to open circuit), and 3) sufficient dive time to record entire courtship and spawning activities. The unit only releases a limited amount of bubbles when ascending due to expansion and overflow of gases in the scrubber assembly.

### **Acknowledgement**

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### **References**

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Lobel P.S. 2001 Fish bioacoustics and behavior: passive acoustic detection and the application of a closed-circuit rebreather for field study. *Marine Technology Society Journal*, 35:19-28

## Illustrations and Diagrams



*Figure 1. Recording fishes underwater using a video camera and hydrophone. Photo by Lisa Kerr Lobel.*

## ( • **New technologies for passive acoustic detection of fish sound production**

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### **Introduction**

Passive acoustic detection of fish sounds relies heavily on advances in recording and data processing technology. The recent explosion in fast, inexpensive personal computers and electronics has created tremendous growth potential in the field. This paper describes early efforts in developing passive acoustic detection systems for fishes and more recent efforts utilizing digital systems. The goals of each of these systems were to automatically detect and quantify sounds of interest in real-time, minimize false detections, and minimize the amount of data that needs to be stored to determine calling rates continuously over long periods of time.

### **First Generation Passive Acoustic Detection System**

Most fish sounds are either simple pulsed broad-band sounds or tonal type sounds, where the pulse rates or dominant frequency are species-specific (e.g. Lobel and Mann, 1995; Mann and Lobel, 1998; reviewed in Zelick *et al.*, 1999). Fish sounds do not typically exhibit complex frequency modulations seen in many marine mammal vocalizations. This makes it possible to describe most fish sounds with a few metrics, such as sound duration, peak frequency, and bandwidth. Timing between pulses can be recorded by storing the time of onset of each pulse. By recording these simple metrics, a system can be developed to automatically detect and process sounds of interest and greatly reduce the amount of data that would be acquired by simply recording continuously.

Early attempts at passive acoustic detection involved developing a largely analog system that would detect sounds that were above some background level and store the time of occurrence and sound duration (actual sound data were not stored) (Mann and Lobel, 1995) (Fig. 1). From these data, the rate of sound production of different species' sounds could be determined. This system was employed to measure sound production rates of individual damselfish over periods of months, and revealed a striking dawn chorus in sound production and a tight link between sound production and spawning cycles (Mann and Lobel, 1995).

### **Real-Time Digital Signal Processing Systems**

While the analog system was a robust detector, continued increases in data storage capacities and the emergence of inexpensive digital signal processing chips and the flexibility that these provide, prompted the development of a programmable digital system. This system is commercially produced by Tucker-Davis Technologies (Gainesville, FL) and consists of a battery-powered datalogger with two channels of A/D, 32 MB of RAM, and a graphical programming interface. The flexibility of the datalogger is that it can be used to process the signal in real-time including a wide array of filtering (FIR, IIR) techniques and adaptive thresholding. The datalogger can be programmed to store whatever data is desired by the researcher. To demonstrate its flexibility, a device was programmed to detect the sounds produced by the toadfish *Opsanus beta*, store the time of occurrence of the sound and record a 1000-point sound sample (Fig 2).

### **The Future of Fisheries Bioacoustics**

The primary tools for the fish bioacoustician will remain the PC and continuous digital recording systems for some time. To promote the emergence of fisheries bioacoustics requires more research into the sounds made by different fish species and the development of new technologies that utilize these data.

Ultimately fisheries bioacoustics should move the way of fisheries acoustics where the signal output is not the actual sound data, but the locations and intensity of fish spawning.

A useful analogy is the development of SONAR systems for fish quantification. These systems do not deliver raw sound data to the researcher. They return processed data on fish location and abundance. One can envision the day when real-time fisheries bioacoustics systems will produce maps of the locations of sound-producing fishes that can provide managers with data on the temporal and spatial extent of spawning.

### **Acknowledgments**

My introduction and passion for the field of passive acoustic detection was driven by my Ph.D. advisor Phillip Lobel. Support for the development of the digital datalogger was provided to TDT by an NIH grant to the author.

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Mann, D.A., and P.S. Lobel. 1998. Acoustic behavior of the damselfish *Dascyllus albisella*: behavioral and geographic variation. *Environ. Biol. Fish.* 51: 421-428.

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# Illustrations and Diagrams

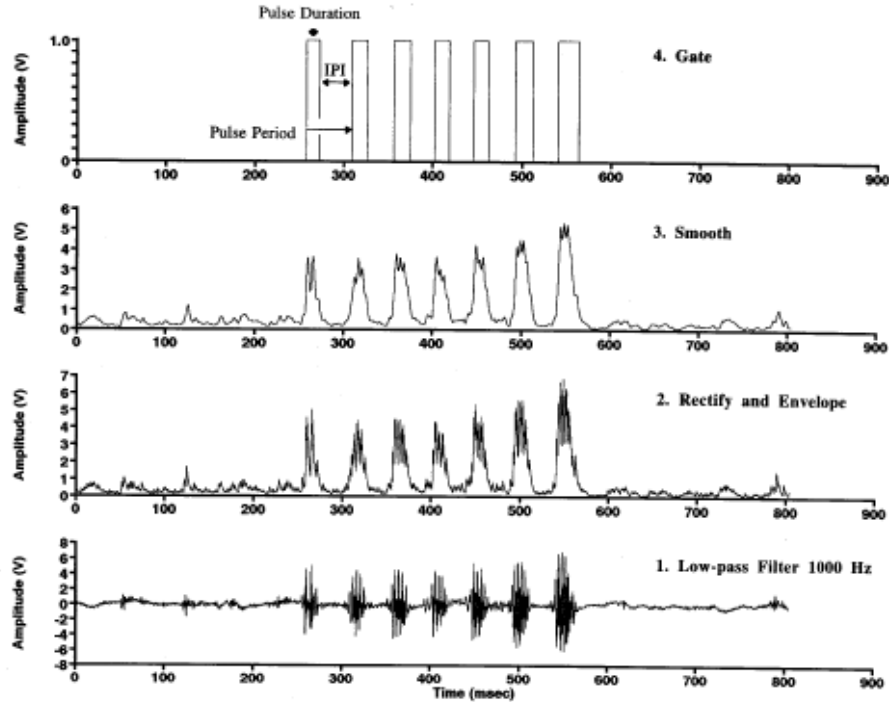


Figure 1. Signal processing scheme for the detection of damselfish (*Dascyllus albisella*) calls.

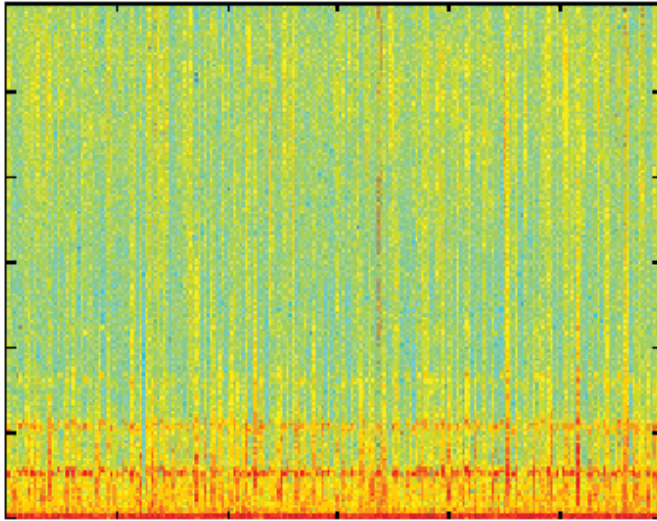


Figure 2. Spectrogram of a series of automatically-detected toadfish (*Opsanus beta*) calls plotted one after another. The dominant frequency of these calls is approximately 250 Hz.



## **A remote-controlled instrument platform for fish behaviour studies and sound monitoring**

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This paper was originally presented as a poster at a symposium titled "Fish Bioacoustics." The symposium was held in Chicago, USA May 30-June 2, 2001. The paper will also be published in the journal "Bioacoustics".

### **Introduction**

A new remote-controlled instrument platform for in situ recording of behaviour-specific fish sound and synchronous video observations has been developed. Such studies have normally been carried out using a cable connection between the hydrophone and the observing vessel, which must be positioned relatively close to the hydrophone itself and generate noise. Vessel generated noise will not only affect the recorded sound pattern, but may also have an impact on the behaviour of the fish studied.

The new remote-controlled platform allows operation at distances up to 10 nautical miles and has therefore been developed to omit such problems during behaviour studies of wild fish in their natural environments.

### **Description of the system**

The instrument platform consists of two main units (fig 1); a surface buoy and an underwater electronic bottle capable of operating at depths down to 500m. The surface buoy contains a high-speed, full duplex, 115 kbps, data telemetry radio and a video link transmitter. It is connected to an underwater bottle via a 12 lead Kevlar cable. The underwater bottle is made of an anodized aluminum cylinder mounted on a stainless steel frame and houses a full feature single-board computer in order to control various instruments, and to log data from different sensors. Two rechargeable batteries provide power, 24 VDC, to the electronics. All electronic parts have been chosen to minimize power consumption, making it possible to run the system continuously for approximately 20 hours before recharging.



For sound recording a hydrophone is used and connected to the amplifier in the electronic bottle via a sub-sea connector on the end lid. All amplifier settings are fully remote controlled from the observing vessel via the radio telemetry link, and its output is connected to the PC sound card. The digitized signal is temporarily stored on a flash memory in order to avoid mechanical noise from a hard disk drive which might disturb the received signal. The recording program allows automatic frequency, level- and pre triggering facilities, which makes it suitable for a selective sound recording.

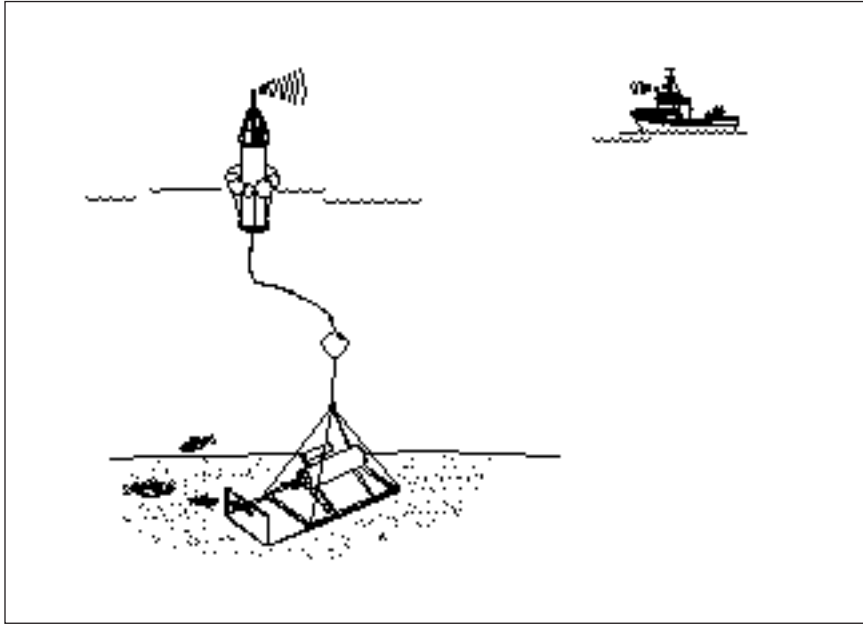
A low light video camera placed on the top of the bottle is used for simultaneous video observations. Both sound- and video signals are transmitted to the observing vessel and monitored in real time.

A number of sub-sea connectors on the electronic bottle allow connection of different sensors and equipment like pan/tilt unit, artificial light, echo sounder etc., making the system suitable for a variety of tasks. Modification of the underwater unit can easily be done to support different instrumentation needed for a wide range of studies.

The video transmitter and the data link enable the instrument platform to be operated from an observing vessel at a distance of up to 1 nautical miles for video transfer, and up to 10 nautical miles with data link only.

The remote controlled instrument platform has so far been successfully used to record fish sounds with synchronous video observations from cod, haddock, saithe, and tusk. The advantages of a remote-controlled instrument platform over a system with long cables have been clearly demonstrated in these studies.

## Illustrations and Diagrams



*Fig. 1. Fish behavior and sound production can be monitored from a distance with the remote-controlled instrument platform, using radio link.*

## **Potential for the use of Remotely Operated Vehicles (ROVs) as a platform for passive acoustics.**

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### **Introduction**

We are still largely ignorant of the distribution and behavior of the great majority of marine fish. Possibly one of the greatest challenges to researchers attempting to study the behavioral ecology of fishes is that of finding the fish in the first place. Since some fish are soniferous, acoustic detection and tracking may offer methods of population assessment for management decisions. Passive acoustic techniques can be a valuable tool for the identification of essential fish habitats (EFH) for soniferous species. These techniques can allow for non-destructive surveys of large areas to pinpoint habitats frequented by soniferous species, particularly during spawning events when vocal activity tends to be greatest. Studies of fish sounds can provide a wealth of data on temporal and spatial distribution patterns, habitat use, and spawning, feeding, and predator avoidance behaviors. Currently most investigators use simple omnidirectional hydrophones and can usually only locate the general area of a spawning aggregation, but have often been forced to use circumstantial evidence of the identity and behavior of the calling species (e.g. Saucer and Baltz 1993, Luczkovich *et al.* 1999a,b). Attempts to use passive acoustics as a tool to identify EFH based on spatial patterns in sound production is also critically hampered by the lack of sufficient data describing the sound characteristics of individual species and behaviors under field conditions. We propose that acoustic technologies utilizing hydrophone arrays to home in on sound sources can greatly improve the study of soniferous fishes and their habitat requirements. First, homing in on sound sources will provide a valuable new tool to validate the identity of sound producers, especially when coupled with underwater photography or video devices. Second, the ability to home in on vocal fishes would enhance our ability to correlate fish sound production with specific locations and habitats. In this paper, we describe our preliminary attempts to develop a Soniferous Fish Locator (SFL) for use with a remotely operated vehicle (ROV) to home in on fish sound sources and make recommendations for future efforts.

## Tracking and Homing Basics

The use of passive acoustics for homing was developed for naval warfare during and before WW II. A passive acoustics homing system was implemented on torpedoes for destruction of ships and submarines. The technique of homing was extended to detection and tracking of submarines by sonobuoys during World II. These systems were developed before the advent of small, fast computers and were implemented with electronics that are now known as operational amplifiers. Adequate Signal-to-Noise ratios were required for implementing these techniques. Homing on ships and submarines by torpedoes requires only 2 directional hydrophones because the torpedo body blocks out sound from behind it. The available aperture is small so frequencies such that there are several wavelengths across the directional hydrophones are used for the lowest frequency in the tracking bandwidth. The torpedo determines the bearing from acoustic signature (signal) of the ship or submarine by cross-correlating the signatures from the 2 hydrophones. The cross-correlation function is:

$$C_{12}(\tau) = \frac{1}{T} \int_{t-T/2}^{t+T/2} [s_1(t)s_2(t+\tau)] dt \quad \text{as} \quad T \rightarrow \infty \quad (1)$$

where  $s_1(t)$  and  $s_2(t)$  are the noise-free time signals from the 2 hydrophones,  $\tau$  is the time delay between the arrivals of the signals at their respective hydrophones and  $T$  is the period over which the cross-correlation is estimated. The longer  $T$  is, the better the cross-correlation estimate  $E[C_{12}(\tau)]$ . For this function, there are 2 bearings or values of  $\tau$  that can arise for the maximum value of  $E[C_{12}(\tau)]$ . One represents the back direction that we know is wrong because the body of the torpedo blocks out that back direction. The other bearing then has to be the correct one. Hydrophone separation,  $x$ , in homing torpedoes is small but a relatively broad segment of the noise spectra is available to provide sufficient bearing accuracy for tracking.

The cross-correlation function of Equation (1) cannot be realized in practice but only estimated. Accuracy of the estimate depends primarily on 1) signal-to-noise ratio (SNR), 2) bandwidth of the signal and 3) separation of the hydrophones. Obviously for wider separations, bearing accuracy is better. The choice of hydrophone separation is a compromise imposed by the operational requirements arising when one wishes to place hydrophones on an ROV. Loss of coherence depends on environmental conditions and their effect on propagation of sound. Loss of coherence is more severe at the higher frequencies, but it is not an important factor for arrays that will fit on an ROV. For large signal bandwidths, the peak of the cross-correlation function is narrow. When estimating the cross-correlation function, the time gate  $T$  imposes a  $(\sin \pi f)/\pi f$  type function upon the estimate that, along with SNR, determines how accurately one can track a fish. When the bandwidth is large and SNR high, one can choose a small time window and/or a small hydrophone separation and get good homing results.

## Methods

The SFL was designed to work based on the well-understood principle of null steering on an acoustic source with two cardioid hydrophones (Fig. 1). Specifically, the SFL consists of three hydrophones configured to form two orthogonal cardioids shown by the solid and dotted lines (Fig. 1). The two cardioids are 180 degrees out of phase with each other in this configuration. Electronic summing of the two cardioids results in a null along the x-axis (Fig. 1). A bearing to a sound source is obtained by rotating the SFL until the sound direction is coincident with the null. To enable an operator to determine bearing, output from the SFL will be sent to both earphones and a recording device. The null is found by listening to the summed output of the two cardioids in one ear while simultaneously listening to the sound intensity with the other ear. Feeding output from cardioid 1 prior to summation with cardioid 2 to the second earphone channel eliminates noise from behind the SFL (sound from behind the SFL is nulled out by the cardioid, Fig. 1). Hence, the operator listens only to the intensity of sounds coming from in front of the SFL. This is an important property of the SFL that reduces interference due to ROV noise and/or boat noise when operating in shallow water. The distances,  $d$ , separating the hydrophones can be changed to increase or decrease the sensitivity of the dipole and allow the operator to tune the maximum sensitivity toward the predominant frequency band of the type of soniferous fish species for which he/she is searching.

Initial tests of the feasibility of deploying an array of hydrophones on a Phantom III model ROV as part of the SFL were conducted in test tanks located at the Northeast-Great Lakes Center for the National Under Sea Research Program at Avery Pt. Connecticut in October 2001. Tests were conducted on the array configuration, attachment methods and ROV noise production. The ROV was not able to support a hydrophone array in the required configuration (Fig. 1) because of ballast problems. We therefore had to modify the configuration so that the hydrophone array could be supported by the ROV frame (Fig. 2). Unfortunately, this configuration does not allow for the cancellation of ROV noise (the array must be forward of the noise source as in Fig. 1). With this configuration, noise levels under various operating conditions were tested: 1) with all thrusters off and the ROV sitting on the bottom, 2) with top thrusters on, 3) with rear thrusters on, and 4) with all thrusters on.

Field testing was conducted within the Stellwagen Bank National Marine Sanctuary on board the R/V Connecticut from October 17-24, 2001. Ten ROV dives were conducted in sand, gravel and boulder habitats within the sanctuary. Operations were conducted in depths of up to 70 m under sometimes harsh environmental conditions and strong tidal currents. To reduce ship noise, ROV dives were conducted while the ship was at anchor and running off of its generators. The array was composed of three TH608-40 model hydrophones made by Engineering Acoustics, Inc (933 Lewis Drive, Suite C, Winter Park, FL 32789). The hydrophones had a nominal sensitivity at the preamplifier output of -160.5 dB. The 3-channel audio data from the array was captured to a laptop PC with a 4-channel I/O board and NIDisk software supplied by Engineering Design (43 Newton St., Belmont, MA 02478). Sound signal processing was conducted using Signal 4.0 (Engineering Design). A 1 kHz sine wave was played through a portable CD player into the system and the input voltage recorded at the beginning of each ROV dive. This allowed calibration of the system gain, in addition to the hydrophone. A single channel of audio data was simultaneously recorded to video (both Hi-8 and

VHS) for backup. The calibration signal was also recorded to the videotape so that calibrated audio data can be obtained directly from the tapes to obtain signal source levels.

## Results

Tank tests revealed a very high level of noise, even with the thrusters turned off and the ROV sitting motionless on the bottom of the tank (Fig. 3). Although noise levels were highly variable, we estimated levels of >130 dBV with thruster off and >160 dBV with all thrusters on. The high level of noise precluded the operation of the SFL with a “flying” ROV, with the current array configuration. We therefore decided to modify the operation of the ROV while in the field in order to increase the signal to noise ratio enough to obtain bearing information. We required the ROV to remain stationary with its thrusters turned off long enough to acquire the bearing to the sound source.

With all thrusters on, the ROV produced high levels of sound at both high and low frequencies (Fig. 4). Dominant frequencies were centered on 7-8 kHz. While the stationary ROV was significantly quieter, it still generated substantial noise centered on 8 kHz (Fig. 5). The low frequency noise in Fig. 5 is an artifact resulting from mechanical banging, rubbing and tapping on the tank sides by technicians testing sound reception.

Recording fish sounds in the field with an array attached to the ROV proved to be very difficult in practice. Strong currents limited our ability to remain stationary on the bottom. The ROV was rarely able to maintain its position on the bottom for more than a few minutes before the operator was forced to turn on its thrusters to stabilize the vehicle. This also required the operator to turn on the ROV lights, thus further disturbing the fishes. Fish sounds were recorded on only one occasion when we were able to maintain the ROV on the bottom with its thrusters and lights off (Fig. 6). A prolonged series of low thumps and growls from a single fish were recorded over a 20 minute period when the ROV was sitting stationary with its lights off. During this time a large cusk, *Brosme brosme*, was frequently observed hanging around the ROV. It is highly likely that the cusk is the source of the recorded sounds. We estimated the ambient noise (ROV + ship + seas) level at around 134 dBV and the cusk call at around 140 dBV. At other times when the lights and thrusters were on, cusk were only observed in a highly agitated state, and appeared to strongly avoid the ROV.

## Discussion

Based on preliminary analysis of these data we feel that the concept of a Soniferous Locator Device is viable. However, current ROV designs preclude optimal configuration of the hydrophone array, requiring the SFL to be operated in a stationary mode. We propose that a vehicle specifically designed for low noise production and capable of carrying an SFL with a 2-3 m base line in its nose would provide an exciting new passive acoustic tool for soniferous fish surveys. The low calling rate of the fish recorded in this study demonstrates that it would be difficult to track fish using the manual null steering method proposed. Faster digital tracking using this same principal would correct

this problem and should be implemented in future efforts. However, it is important to point out that data collected during this cruise demonstrates that an ROV can serve as an adequate vehicle for the collection of underwater acoustic data even without the SFL. The ROV with a hydrophone attached would be used to locate an optimum location and then would be set down on the bottom to record sounds. In this way, a roving survey could be conducted.

Although cusk have long been considered to be soniferous because of the presence of a sonic muscle, they had never been recorded until Norwegian scientists recently recorded their spawning sounds (Aud Vold Soldal, Institute of Marine Research, Norway, pers. Comm.). The calls apparently resemble haddock spawning calls and are very different from those we recorded during this study. Our recordings were conducted well outside of the spawning season for cusk, so the sounds were likely associated with other behavior (feeding or territorial display). Observations made subsequent to this study revealed that cusk vigorously guard the chum bag attached to the ROV and frequently chase away other fishes, suggesting the species is highly aggressive and territorial. Because so little is known of the cusk's behavior, ecology and habitat requirements, and because it appears to respond well to a stationary ROV with its lights turned off, it makes a promising field study animal for passive acoustics.

A secondary outcome of the cruise was that we obtained sufficient video data to suggest that the behavior of some species is strongly influenced by the ROV and/or the ROV lights. Adult cunner, *Tautoglabrus adspersus*, redfish, *Sebastes fasciatus*, and pollock, *Pollachius virens*, obviously avoided the ROV during the day, but pollock were strongly attracted to the ROV at night due to our use of chum and bright lights. The chum attracted swarms of amphipods that in turn attracted a large aggregation of pollock as well as haddock, cod and skates. Cusk were only observed in boulder habitat and avoided the mobile ROV both during the day and night when the lights were on. When only infrared lights were used, the cusk was clearly attracted to the chum bag on the ROV and showed no avoidance of a stationary ROV. Contrastingly, species such as cunner, redfish and silver hake appear to avoid the ROV regardless of whether its lights are on or off, or whether it is moving or stationary. The response of the cusk to the mobile ROV with its lights turned on suggest the species strongly avoids the ROV. It could not be determined whether the lights or the ROV noise caused this avoidance, however subsequent observations of cusk behavior indicate no avoidance of stationary cameras with white lights. We suggest then, that the noise generated by the ROV can be a significant source of bias in studies using ROVs for fish census.

### **Acknowledgements**

We thank Meghan Hendry-Brogan for diligent work in both the field and laboratory to collect and process fish sound data. Rebecca Jordan and David Howe assisted in the field. This project received major funding from the Northeast and Great Lakes National Undersea Research Center, which also provided extensive logistical support. The Woods Hole Sea Grant College Program also provided supporting funds. The Sounds Conservancy, Quebec-Labrador Foundation/Atlantic Center for the Environment provided a stipend for Megan's fieldwork.

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## Illustrations and Diagrams

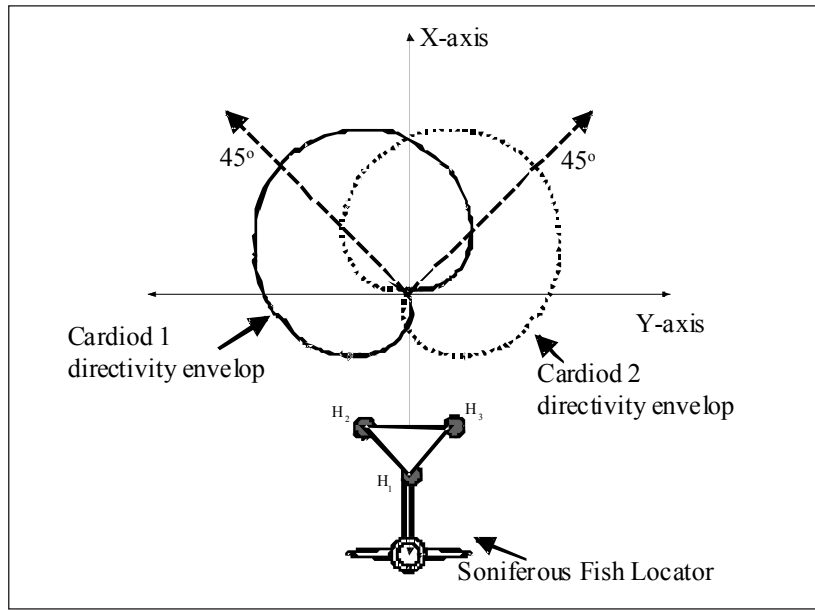


Figure 1. Illustration of the principle of null steering on an acoustic source with two cardioid hydrophones. The Soniferous Fish Locator consists of three hydrophones (H1-H3) configured to form two orthogonal cardioids shown by the solid and dotted lines. The two cardioids are 180 degrees out of phase with each other. Summing the two results in a null along the x-axis. A bearing to a sound source is obtained by rotating the SFL until the source direction is coincident with the null.

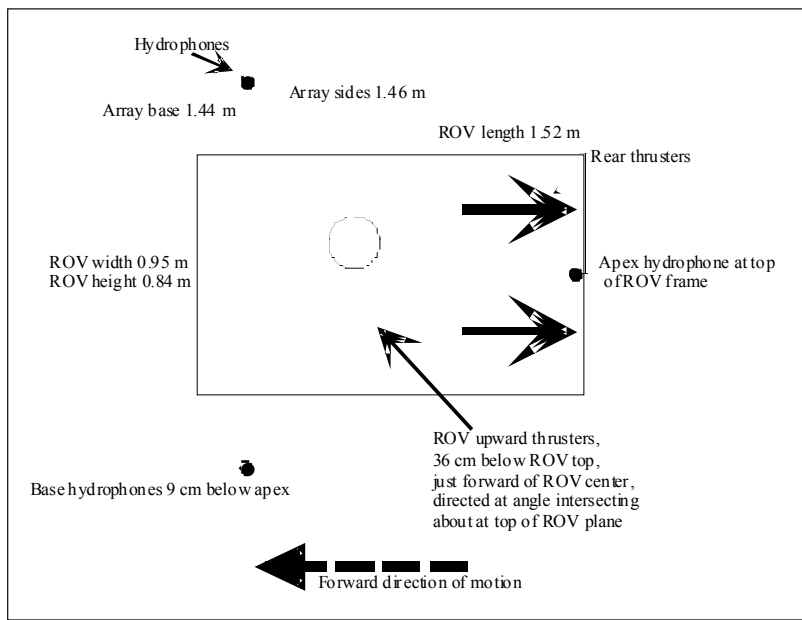


Figure 2. Schematic illustration of the hydrophone array configuration and attachment to the Phantom III ROV.

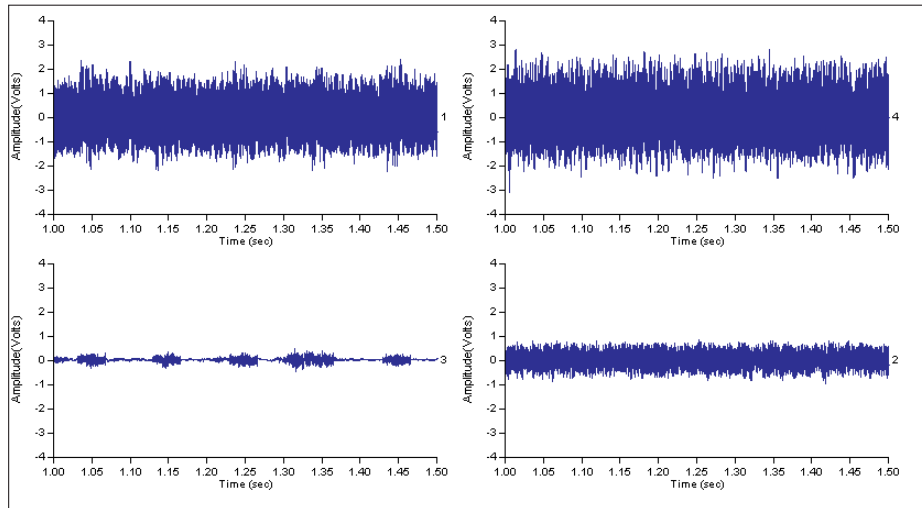


Figure 3. Tank test of noise generation by the ROV with all thrusters off (lower left), top thrusters on (lower right), back thrusters on (upper left) and all thrusters on (upper right). Digitized at 20 kHz.

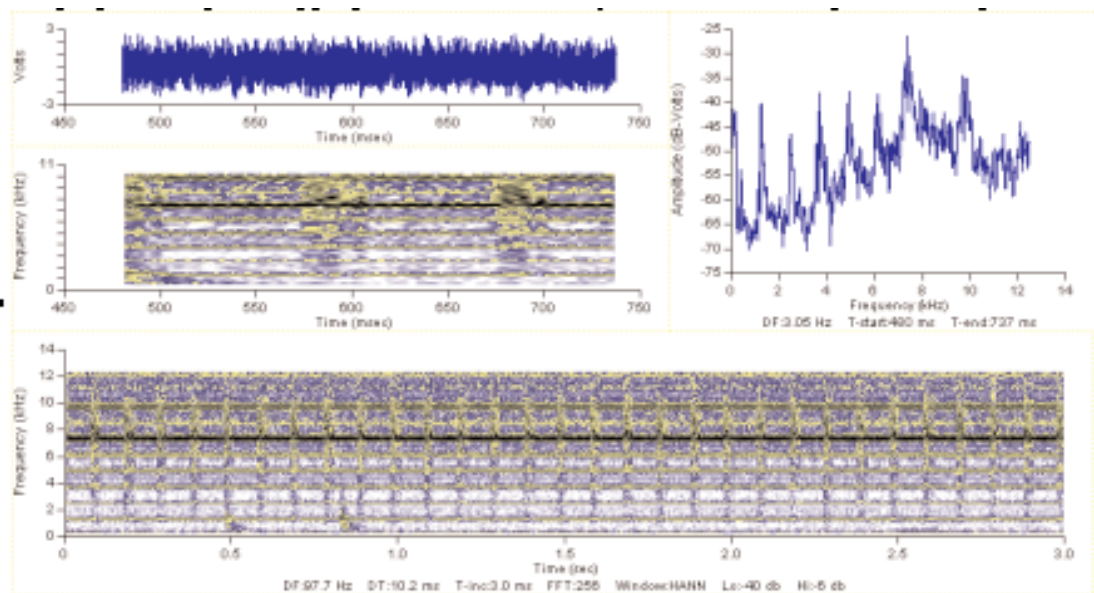


Figure 4. Noise generation from the ROV with all thrusters on. Recorded at 20 kHz.

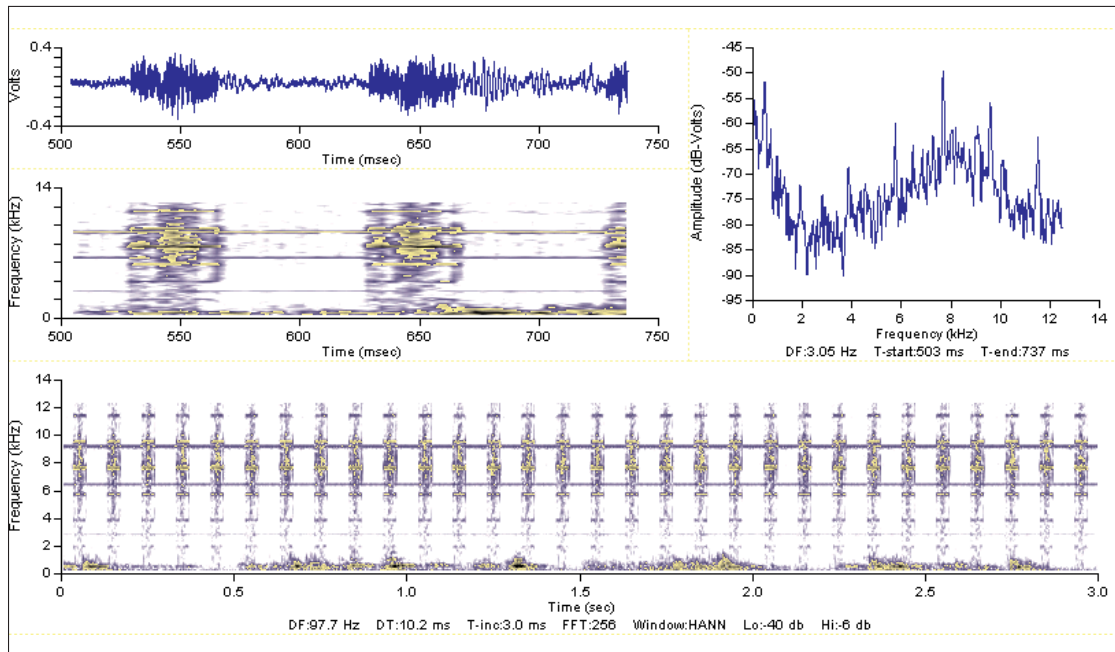


Figure 5. Noise generated by the ROV while sitting on the tank bottom with all thrusters off.

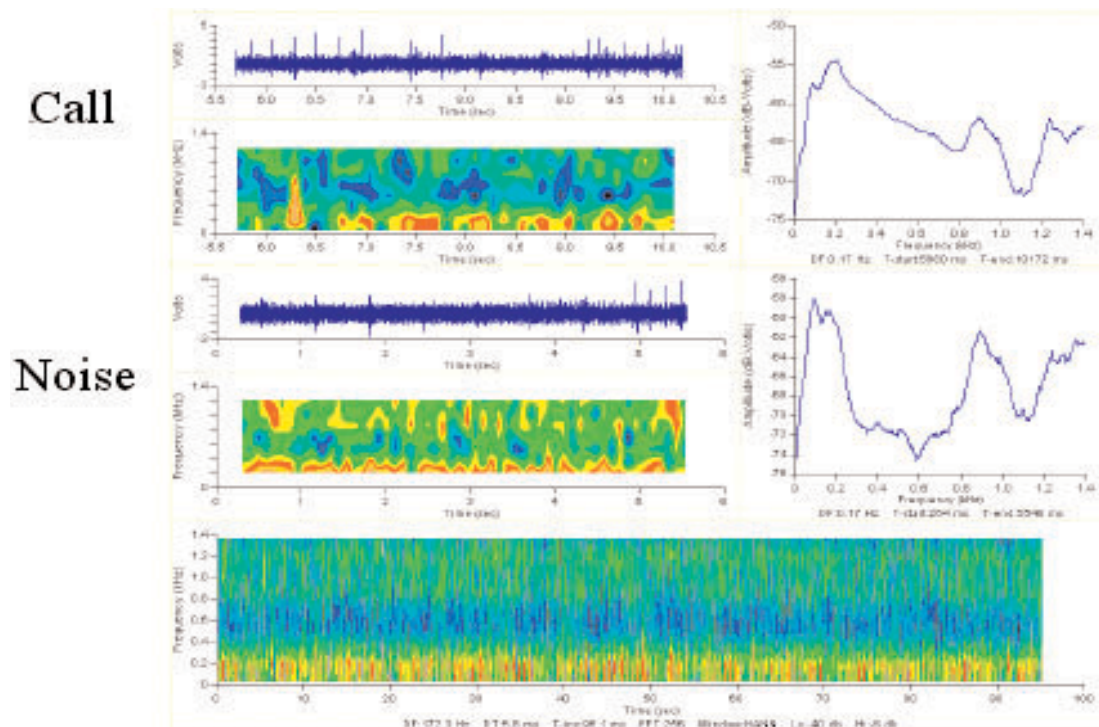


Figure 6. Recording of ROV/Ship and ambient noise (bottom panel) together with the call of the cusk, *Brosme brosme*. The spectrum of a 95 second sequence of multiple fish calls of a single fish is shown in the bottom panel. The middle panels contain relative amplitude waveform, spectra and power spectra for a 5 second sequence containing only noise, while the upper panels contain a single fish call (sampled at 20 kHz and filtered above 1400 Hz).

# Quantifying Species-Specific Contributions to the Overall Sound Level

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## Introduction

Many fishes are soniferous (sound-producing) and produce species-specific sounds (Fish and Mowbray 1970, Sprague *et al.* 2000). The sound production of an individual fish or group of fishes can be used to determine their presence in an area and as an indication of courtship and spawning behavior. Often, we would like to quantify the sound production of a particular individual or species, but how do we separate that sound from other sounds that are simultaneously produced by biological sources, wave noise, and anthropogenic sources such as boats and ships? A short answer to this question is to use a portion of the sound in which the desired source dominates over all others. This portion could be a time segment in which the desired source is much louder than the background (i.e., all other sounds), a portion of the frequency spectrum in which the desired source is much louder than the background, or a combination of these techniques.

## Separating and Combining Sounds

Parseval's Theorem tells us that the squared-pressure of each frequency component contributes additively to the time-averaged overall squared-pressure  $P^2$

$$P^2_{av} = \sum P^2(f_n) \quad (1)$$

In other words, each frequency component in a power spectrum or sonogram makes an additive contribution to the total sound power because sound power is proportional to the squared-pressure. Also, when sounds are mutually incoherent (i.e., originating from sources not correlated in time), their time-averaged squared-pressures,  $(P_1^2)_{av}$  and  $(P_2^2)_{av}$  add to give the squared-pressure of the combined sound,

$$P_{av}^2 = (P_1^2)_{av} + (P_2^2)_{av} \quad (2)$$

Equation (2) applies to most fish and background sounds because most naturally-occurring sounds are incoherent.

The total sound pressure level (SPL) is also calculated from  $P_{av}^2$  using the relationship

$$SPL = 10 \log \frac{P^2}{P_0^2}, \quad (3)$$

where  $P_0$  is the reference pressure (1  $\mu$ Pa for underwater acoustics). To combine two mutually incoherent sounds with SPLs  $SPL_1$  and  $SPL_2$ , we must convert each SPL to a squared-pressure using the inverse of Equation (3) before adding them. The combined SPL is

$$SPL = 10 \log_{10} \left( 10^{\frac{SPL_1}{10}} + 10^{\frac{SPL_2}{10}} \right). \quad (4)$$

Equation (4) can be used to combine or separate the SPLs of various sources, including fish sounds and the background.

### Background Correction Function $C_{bg}$

Pierce (1989) developed a background correction function  $C_{bg}$ , based on Equation (4), to determine the sound pressure level of a source  $SPL_1$  when background noise is present:

$$SPL_1 = SPL_{tot} - C_{bg}(\Delta SPL). \quad (5)$$

In Equation (5),  $\Delta SPL$  is the difference between the source and background SPLs and  $SPL_{tot}$  is the total sound pressure level. The  $C_{bg}$  technique is inaccurate when  $\Delta SPL < 3$  dB because small inaccuracies in the measurement of  $SPL_{tot}$  lead to large inaccuracies in  $SPL_1$ . Figure 1 shows a plot of  $C_{bg}$  vs.  $\Delta SPL$ . When a sound is 10 dB or more above the background, the total SPL is the same as the SPL of the sound (i.e.,  $\Delta SPL$  is zero).

In order to determine the source SPL using  $C_{bg}$ , the total SPL and the background SPL must be measured.

### **Using the Background Correction Factor to Determine Silver Perch SPL**

We recorded an individual silver perch *Bairdiella chrysoura* in Wallace Channel, NC, USA using a hydrophone and video camera attached to a remote operated vehicle (ROV) placed on the sea floor in 10 m of water. The video confirmed that the fish made sound as it swam close to the hydrophone. A spectrogram of the recording is shown in Luczkovich and Sprague (these proceedings). We estimated the background SPL by measuring the sound levels between the pulses in the silver perch call and determined the silver perch SPL by subtracting  $C_{bg}$  from the total SPL during the pulses. The sound was sampled at 24 kHz, and we computed SPLs from the time-averaged squared-pressure in 1024-point Hanning windows. Each consecutive window overlapped the previous window by 512 sample points to insure that each sample point occurred near the center of at least one sample window. The peaks of the background SPL were interpolated to give an upper estimate of the background SPL, and the valleys were interpolated to give a lower estimate. Figure 2 shows an interpolated plot of the total and the maximum and minimum background SPL as well as the silver perch SPL. The maximum silver perch SPL was 129 dB (using either the maximum or minimum background SPL).

### **Spectral Analysis of Sounds and Sciaenid Egg Identification**

We have established a correlation between sound levels produced by Sciaenid fishes and the presence of fertilized sciaenid-type eggs in Pamlico Sound (Luczkovich *et al.* 1999, Luczkovich and Sprague these proceedings). We conducted planktonic egg surveys at suspected weakfish *Cynoscion regalis* and silver perch spawning sites using 28-cm diameter bongo net with 500  $\mu$ m mesh towed at the surface for 5 min to capture the buoyant eggs. We recorded the drumming sounds at the same location before and after the tow and compared the species-specific power spectral density (PSD) in a 10-s average power spectrum to the measured egg density. The weakfish PSD was taken as the sum of the PSDs in the power spectrum from 304-375 Hz and the silver perch PSD the sum the PSDs from 984-1078 Hz (Sprague *et al.* 2000). We assumed, based on our mtDNA RFLP analysis of sciaenid-type eggs and the results of Daniel and Graves (1993), that eggs less than 0.8 mm were those of silver perch and those greater than 0.85 mm were those of weakfish. The regression relationships of egg density vs. species-specific PSD, after log-transforming, are nearly linear in both cases with an  $R^2$  of 0.38 for weakfish and 0.44 for silver perch. The large variations in the data could be the result of errors associated with the egg sampling technique. We believe that in many cases our egg sample nets did not capture nearby eggs due to variations in currents, patchiness in the egg distribution, and perhaps in the buoyancy of the eggs (due to salinity fluctuations). Despite the variations, these data are significant and provide the basis for predicting the egg production for each of these species from sound levels in the future.

### **Silver Perch Acoustic Avoidance of Bottlenose Dolphins**

During our study of sciaenid spawning areas, we noticed that silver perch aggregations would sud-

denly become quiet when we heard bottlenose dolphin *Tursiops truncatus* signature whistles. To verify our observations, we played a recording of bottlenose dolphin signature whistles (with frequency content 4-8 kHz) at similar source levels to those produced by bottlenose dolphins near a silver perch aggregation and found that the signature whistles significantly quieted the silver perch vocalizations (Luczkovich *et al.* 2000). We also played a 700-Hz tone at the same source level with no significant effect on the silver perch.

We determined the silver perch PSD by summing the PSDs in the power spectrum for frequency components from 950-1200Hz, the frequency range where silver perch are dominant, for consecutive 10-s average power spectra (see Figure 3). To determine the silver perch reaction to the playback, we took the difference between the measured silver perch PSD immediately before playback and during the interval between 20-30 s after playback. Using an analysis of covariance (ANCOVA), we compared the decrease in silver perch PSD after playback of bottlenose dolphin whistles to changes in silver perch PSD after the 700-Hz tones and also to spontaneous PSD changes before and 20-30 s after an ad-hoc selected time in a 120-s recording of silver perch with no sound playback. The bottlenose dolphin whistle produced a significant 9-dB decrease in silver perch SPL [ANCOVA, (among playback treatment adjusted means), (among slopes of the regression lines for each treatment),,]. The silver perch responded to bottlenose dolphin signature whistles by reducing their sound production.

## Conclusions

Several techniques have been demonstrated for determining the sound level of an individual or species in the presence of other sound sources. Each technique isolates a portion of the sound in which the desired source dominates over the others. The sound portion could be a time interval in which the desired source is much louder than the others or it could be a portion of the frequency spectrum in which the desired source dominates. In some situations, techniques that combine time intervals and characteristic frequency bands must be used to separate the contributions of the desired source.

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## Illustrations and Diagrams

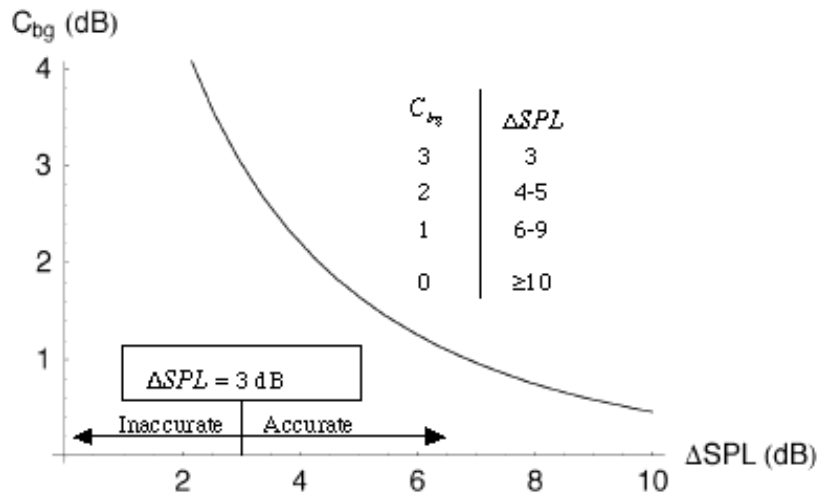


Figure 1. The background correction function vs. the difference between the source and background sound pressure levels. The inset table gives  $C_{bg}$ -values to the nearest decibel. The background correction function is inaccurate for  $\Delta SPL < 3$  dB (Pierce, 1989)

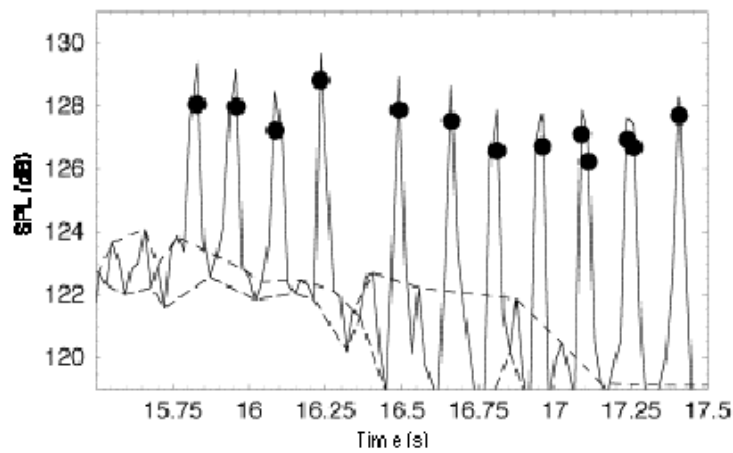


Figure 2. Sound pressure levels (SPLs) in a silver perch sound recording at Wallace Channel, NC, USA. The solid line is the total SPL, the upper dashed line the maximum background SPL, the lower dashed line the minimum background SPL, and the dots the silver perch SPL calculated using the background correction factor.

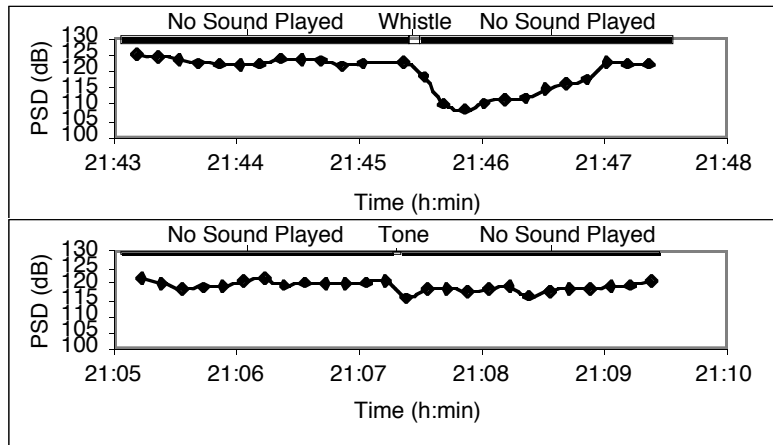


Figure 3. Examples of silver perch species-specific PSD fluctuations upon playback of a bottlenose dolphin signature whistle (above) and a 700-Hz tone (below) at the same source level.

## ( ( • **Classifying Fish Sounds Using Wavelets**

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### **Introduction**

Many species of marine fish emit low frequency sounds composed of sequences of nearly identical transient units. The production of these sounds is often coupled with displays of aggression and/or courtship. In order to associate sound production with fish behaviour we need to be able to distinguish between the sounds of different species and between individual fish to be able to identify which fish is emitting sound at any given time.

Wavelets have been used to produce features of the waveforms which are then used to discriminate between the sounds from different fish. We consider the performance of this method for discriminating between individual haddock, *Melanogrammus aeglefinus*, and for discriminating between sounds from three fish species, the haddock, cod *Gadus morhua*, and pollack *Pollachius pollachius*.

### **Data**

Recordings of the haddock were made at the FRS Marine Laboratory, Aberdeen in a semi-annular tank (90m<sup>3</sup>) containing 3 male and 5 female fish. The sounds were detected by a broad-band hydrophone, amplified and sampled at a frequency of 8 kHz. The haddock were maintained under controlled conditions, and recordings were made over two spawning seasons (February-April, 1999 and 2000). Haddock sounds consisted of long trains of regularly repeated 'knocks'.

Figure 1 shows a typical recording consisting of a series of regularly spaced low frequency sound units, or knocks. Figure 2 shows the different waveforms of the 3 male haddock. The haddock varied their sound by repeating these knocks at different rates.

The cod sounds were recorded in the aquarium of the FRS Marine Laboratory and consisted of long grunts, produced singly or in groups of up to 5. The pollack sounds were recorded in the sea at a depth of 15m in Loch Torridon, Wester Ross, from a cage of fish, and consisted of short repeated grunts. The sounds of all three species are described by Hawkins and Rasmussen (1978).

## Wavelets

Wavelets are special mathematical functions, designed to overcome the shortfalls of the well known Fourier Transform. Wavelets are produced by scaling (compressing or expanding) and shifting a single 'mother' wavelet along the time axis. These wavelets are usually designed to form an orthonormal basis, in which any sound signal may be represented as a series of the scaled and shifted wavelets. The 'amount' of each wavelet present in the decomposition determines the dominant frequency components and their location in the signal. For this reason we say that the wavelet transform has good time and frequency localization.

Background material on wavelet analysis may be found in Jawerth and Sweldens (1994), Bruce and Gao (1996) and Abramovich *et al.* (2000). A more mathematical treatment is given by Chui (1992a,b) and Daubechies (1992).

## Recognition of Individual Haddock

Wavelets were used to extract features from the sound units which would enable individual haddock or different species to be automatically recognised. The procedure consisted of 4 steps.

1. The smoothing property of wavelets was used to automatically isolate individual sound units in the recordings. By setting certain smaller wavelet coefficients to zero and then applying the inverse wavelet transform we were able to extract individual haddock knocks, or cod and pollack grunts from the background. These were extracted in 32ms windows (containing 256 data points) and were standardised so that their amplitude was of unit variance.
2. Due to the way in which the knocks were extracted in (1), and the fact that the wavelet transform is sensitive to shifts along the time scale, the non-decimated (or stationary) wavelet transform was used to decompose the knocks. A member of the Coiflet family of wavelets was found to give the best results.
3. Plots of the non-decimated wavelet coefficients in descending order of absolute value in each level are very similar for sounds from the same fish, but clearly different for sounds from different fish. These plots suggest suitable features for discriminating between the knocks of individual male haddock and between different fish species. For haddock, a plot of the scores on the first two canonical variates (Krazanowski (1996)) showed three well separated clusters.
4. Certain features from (3) were selected and used in a discriminant analysis to allocate unclassified knocks to one of the three male haddock or to each of the three species, or to a spurious sound. The method of extracting pulses in (1) meant that sounds were picked up which were not produced by any of the male haddock, cod or pollack. These spurious sounds, caused by splashes for example, could not be eliminated and so were allocated to a fourth group.

## Results and Conclusions

In a test data set of the haddock sounds, 175 knocks were detected as having come from fish A, 336 from B, 194 from C and 142 were spurious sounds. The classification rates are shown in table 1. The overall success rate was 89%. It was shown that using the fact that knocks occurred in long repetitive series increased the success rate to 95%.

For the allocation of sounds to different species, 5 sounds were detected as having come from cod, 609 from haddock, 151 from pollack and 94 of the sounds were spurious. The classification rates are shown in table 2. The overall success rate achieved was 83%.

Table 1 - Classification rates of individual haddock knocks

		% of knocks allocated to				
		<b>A</b>	<b>B</b>	<b>C</b>	<b>Spur.</b>	<b>number</b>
True sound source	A	96.6	0.0	2.9	0.6	175
	B	0.0	94.3	1.2	4.5	336
	C	0.0	4.1	89.7	6.2	194
	Spur.	9.2	12.7	9.9	68.3	142

Table 2 – Classification rates of cod/haddock/pollack sounds

		% of sounds allocated to				
		Cod	Haddock	Pollack	Spurious	number
True sound source	Cod	100	0.0	0.0	0.0	5
	Haddock	3.0	91.6	0.5	4.9	609
	Pollack	2.0	0.0	72.8	25.2	151
	Spurious	0.0	25.5	31.9	42.6	94

Wavelets provide a useful method of automatic sound recognition. The methods described above can count and assign a large number of sounds far more quickly than can be done by eye. This technique has the potential to separate fish sounds from ambient noise in the sea, and may provide a non-invasive method for locating spawning fish.

### Acknowledgements

We thank Professors I.T. Jolliffe and A.D. Hawkins, University of Aberdeen, and Dr G. Horgan, Biomathematics and Statistics Scotland, for their supervision and input. We thank Licia Casaretto, FRS Marine Laboratory, for recording the haddock sounds, and Professor A.D. Hawkins for supplying the cod and pollack recordings.

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## Illustrations and Diagrams

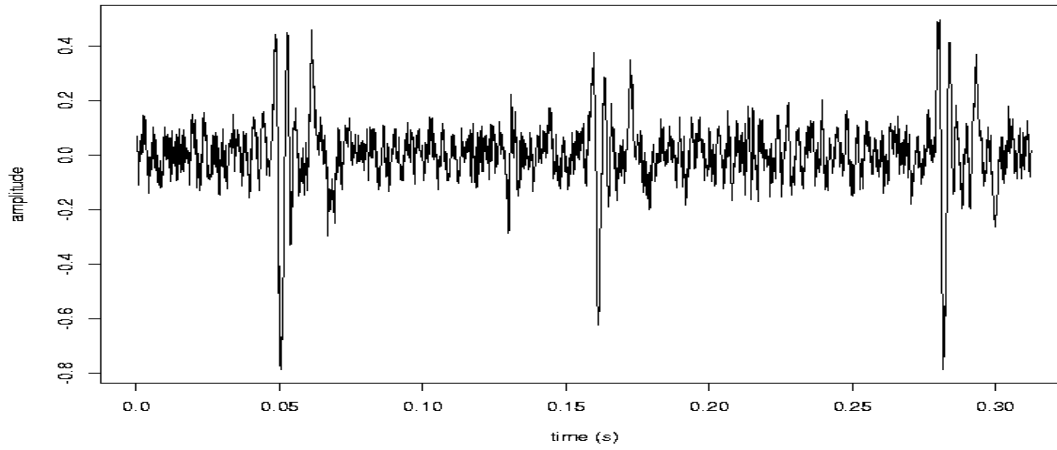


Figure 1 - Sound recording of a single haddock made in the tank

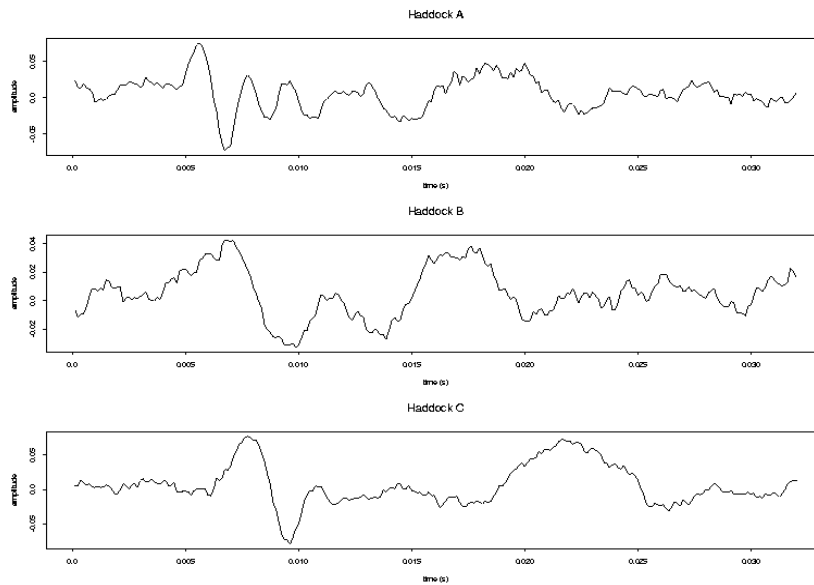


Figure 2 - The waveform produced by the haddock.

( • **A summary report on the Biology Session and Biology Working Group from the International Workshop on the Application of Passive Acoustics in Fisheries.**

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### **Summary**

Fishes are known sound-producers in the sea. Sound production is associated with mating, aggression, and feeding in fishes. The sounds are species-specific in many cases, but the identification of fishes based on sound production alone has led to mis-identifications in the past. Sound-truthing, or the identification of species' sounds has been accomplished by use of recording of individuals in aquaria and in situ using underwater video and audio. A library of known fish sounds is being assembled and will be archived at Cornell Library of Natural Sounds. Data rescue of existing recordings that are in danger of being lost due to age and inadequate storage is underway, but needs are great in this area. Sounds can be detected over fairly long distances (1 km), so after sound-truthing and archiving of sounds, detection of the fish in an area by means of passive acoustics alone becomes possible, even if the fish has not been captured and observed.

### **Introduction**

Listen to the fish? When I suggest that they do this, most people respond that they were not aware that fish produce sounds. Yet, Aristotle reported this phenomenon (*Historia Animalium*, IV, 9), and Native Americans may have listened for underwater sounds to locate groups of fish while hunting them. Passive acoustics has been used for over 50 years in fish biology and fisheries surveys (see Fish *et al.* 1952 and Fish and Mowbray 1970 for a summary of early work) and is being used routinely today to determine habitat use, delineate and monitor spawning areas, and study the behavior of fishes (various papers presented in these proceedings). Fishes produce sounds to communicate with one another while they are feeding, mating, or being aggressive and also make noises associated with feeding and swimming. Over 700 species of fishes have been identified as sound producers (soniferous fishes) (Kaatz 2002). The purpose of this report is to summarize the findings of the Biology Working Group that was held on the third day of the workshop. The Biology Working Group was tasked with reviewing papers presented during the workshop, and information from the literature, and to summarize our state-of-knowledge on passive acoustics applications to fisheries and the census of marine life. Specifically, the group sought to identify areas of that have been well



studied, as well as those in need of further research, and to set forth a list of research areas that the workshop participants deemed of highest priority.

### **What have we learned in the workshop on the biology of fishery organisms and fish from studying passive acoustics?**

Using hydrophones, marine ecologists and fishery biologists have been able to listen to the sounds fishes produce and identify species-specific signatures using signal processing and spectral analysis computer algorithms. Often these sounds are very loud and dominate the acoustic environment where they occur, as in the drum family *Sciaenidae*, so much so that they interfere with military and petroleum prospecting operations that involve acoustic monitoring. In other situations, such as damselfishes on coral reefs, the sounds are not loud and require specialized techniques to detect them (Mann and Lobel 1995, Lobel and Mann 1995).

The main problem that has been overcome in the past by biologists using the passive acoustic approach is to identify the species producing a sound: one first must do “sound-truthing” to discover which sound has been produced by an individual fish. There are two main ways this has been accomplished: (1) captive fish recordings and (2) *in situ* recordings. Most identifications of fish sounds in the past have been done using captive fishes that produced sounds under conditions that are far from natural. Fishes held in aquaria often do not exhibit natural behavior and sound production is adversely affected. Although some fishes produce sounds naturally after capture in aquarium environments that mimic the environment *in situ*, most do not. Investigators have resorted to mechanical or some other kind of stimulation (including electrical shock!) to produce a disturbance call, which may or may not represent the sounds produced by fishes in nature. As was discussed at length, aquaria present their own series of technical difficulties, including tank echoes and background produced by air bubbles, pumps and motors. Yong Han and Joe Blue provided insight as to how these difficulties might be overcome to some degree by proper design of the aquarium. Verification *in situ* of the location of the sound source, sound source levels, and identity of the species involved is frequently difficult. One example of the difficulty in correct identification was reported by Sprague and Luczkovich (2001), who corrected a long-standing error in identification of the “chatter” sound, originally attributed to weakfish by Fish and Mowbray (1970), but now known to be produced by striped cusk eel (Mann *et al.* 1997). The problem of matching sounds to species and behaviors occurs because of the limited ability of biologists to observe fish producing sounds *in situ*. Although some observations have been made recently using underwater video in clear tropical reef waters (Mann and Lobel 1998, Lobel 2001, and Lobel these proceedings) and even in temperate environments with turbid waters (Luczkovich and Sprague 2002; Rountree *et al.*, these proceedings), many attempts to record fishes have failed because of mechanical sounds produced by the platform with the videocamera (bubbles from SCUBA divers, motors and propellers of ROVs and subs) to which fishes are extremely sensitive and which inhibit or mask fish sound production. Lobel (2001) has developed underwater videography techniques that use calibrated hydrophones and videocameras operated by divers using a rebreather apparatus, which produces no bubbles. Underwater autonomous recording devices such as timer-operated sonobuoys have also been used

to detect the sounds produced by fishes and the acoustic avoidance response produced when their bottlenose dolphin predators also are detected on the recording (Luczkovich *et al.* 2000). Because there is no observer near the autonomous recording device, disturbances are minimized and natural behavior can be recorded. A future goal for identification of species sounds should be to develop combined acoustic and videotape recorders that are triggered when sounds or water movements of a specific level and type are detected.

Knowledge of sound source levels is important for calculating the detection limits (in terms of area sampled) of hydrophones and sonobuoys. Sound in water is measured as a Sound Pressure level (SPL) in dB re 1  $\mu$ Pa, which can be measured with calibrated hydrophones and recording devices. Luczkovich and Sprague (2002) reported that the sound source level for an individual silver perch *Bairdiella chrysoura* 1 m from the hydrophone was 129 dB. Lobel and Mann (1995) measured the sound source levels of the domino damselfish *Dascyllus albisella* and modeled the propagation of the sound (Mann and Lobel 1997). More precise measurement of sound source levels in the future will require that one know both the location of the fish and the hydrophone, so that proper assumptions can be applied to the calculation of sound transmission loss and the determination of acoustic sampling areas (Mann and Lobel 1997). Calibrated hydrophones and recording devices that are easy to use are needed for such studies (see Mann *et al.*, these proceedings, for a discussion of the recording technology available).

Another problem discussed related to species identification of fish sounds is the nomenclature used to describe these sounds. Numerous investigators have used terms such as “grunts,” “knocks,” “snaps,” “pops,” “staccato,” “drumming,” “humming,” “rumbles,” “percolating,” “purring,” etc. to describe the sounds heard; these names are often onomatopoeic. There was general agreement at the workshop that such names be used in the future in the published literature to describe a sound, but that there was a need to standardize our names for fish sounds. This standardization will allow rapid communication between biologists and other observers while listening to unfamiliar sounds. Some biologists have given different names to the same sounds; others have given the same name to a similar but different sounds produced by two species, even though the sounds differ between species when examined spectrographically (see below). This can lead to confusion, and so as much as possible unique names can be given an individual sound (“long-spine squirrelfish grunt” versus “silver perch long aggregated grunt”). Standardization of names should give priority to previously published names whenever possible. Kaatz (2002) suggested a possible approach using a plot of sound duration vs. frequency, which allows a clustering of similar sound types, so that we can name them accordingly. Thus a “hum” has a long duration at a particular low frequency, whereas a “grunt” has a short duration at a low frequency.

One way to more precisely report a sound produced by a fish in captivity or *in situ* is to make a spectrograph or “voice print” of the sound recording. Sound spectral analysis software has been used to great advantage in fish passive acoustics surveys and archives. Fishery biologists should be aware of the established methods and pitfalls for doing such spectral analysis of sounds. A primer

on bioacoustics may be needed for the biologist new to the field of passive acoustics; this is available in Canary for Macintosh sound-analysis software package available at ([www.cornell.edu/lms](http://www.cornell.edu/lms)) and soon to be released in a PC WINDOWS version called RAVEN. Another primer is also available at the Acoustical Society of America website ([www.asa.org](http://www.asa.org)). In the past, species' sounds have been characterized in terms of their spectral properties, pulse repetition rates, dominant frequencies, and power spectra using Fast Fourier Transforms (FFTs), which are available in most sound analysis software programs (SpectroGram, CoolEdit, Canary, LabView, Avisoft, Spectraplus, Signal, Igor, etc. - see Mann *et al.*, these proceedings, for a discussion about sound recording and analysis technology).

Spectral analysis has proved very useful identifying species and in separating the contribution of individual species to the overall sound levels. The sound and egg production of the sciaenids silver perch, *Bairdiella chrysoura*, and weakfish, *Cynoscion regalis*, are correlated (Luczkovich *et al.* 1999). It was known from captive fish recordings that *B. chrysoura* and *C. regalis* have different dominant frequencies (Sprague *et al.* 2000). Using spectral analysis and Parcival's Theorem, Sprague and Luczkovich (these proceedings) have shown how the sound contribution of each species of sciaenid can be separated in a recording that contains more than one species. This frequency-specific SPL can be correlated with egg production from each species. A different form of spectral analysis called wavelet analysis has been used to identify species and individual fish within a species (Wood *et al.* 2002). If we can recognize individual fish on the basis of their wavelet "voice prints", then this would allow soniferous fish individuals to be tagged and recaptured without humans having to capture them in nets. Such approaches may revolutionize fishery biology for soniferous species. We can also "clean up" noisy recordings using wavelets. Wavelet analysis shows great promise in future studies to segregate the sounds of multiple individuals in large aquaria and *in situ*.

Biologists have been able to link the aggressive and spawning behavior of fishes to their sound production using *in situ* and tank studies. For example, Myrberg (1972) and Myrberg *et al.* (1986) has described the behavioral ecology of the bicolor damselfish *Stegastes partitus*, which uses sounds both in mating and in defense of its territories. A similar pattern of sound production "popping" has been recorded by Lobel and Mann (1995) and Mann and Lobel (1998) for the domino damselfish *Dascyllus albisella* in the Pacific. The domino damselfish produces a visual "signal jump" display in conjunction with the sound production during courtship. The sound production and spawning frequency can thus be monitored remotely over time using a hydrophone wired to a land-based microcomputer, a system that has been termed a "spawn-o-meter" (Mann and Lobel 1995). Mok and Gilmore (1983) established that spotted seatrout *Cynoscion nebulosus* (Sciaenidae) sounds are associated with spawning by using both tank recordings of mature ripe seatrout and passive acoustic hydrophone surveys combined with ichthyoplankton surveys. This approach has also been extended to the weakfish *C. regalis* by Luczkovich *et al.* (1999). Some work describing the sounds produced in association with spawning in haddock *Melanogrammus aeglefinus* has been described by Hawkins and Amorim (2000), Hawkins *et al.* (2002), and Casaretto and Hawkins (2002). These authors described the complete mating and courtship behavior of the haddock, with a detailed analysis of the sound production at each step in the mating sequence. This sort of basic behavioral biology is still lacking for most fishes detected in passive acoustic surveys. Without this type of behavioral study, we may know that a fish is present in an area, but not what it is doing there. So, improve-

ments in our ability to simultaneously observe fish and listen to them are needed, including better research aquaria and underwater video techniques.

Passive acoustics approach provides a rapid way of establishing the spawning component of essential fish habitat (EFH). Delineation of spawning areas has been done (Mok and Gilmore 1983, Saucier and Baltz, Luczkovich *et al.* 1999, Roumillat *et al.*, Collins *et al.*, Holt *et al.*, these proceedings). But how far away are the fish? Need to set standards for the different levels of EFH data. Baltz (these proceedings) described the different levels of EFH data and suggested that passive acoustics can be used to establish Level 1 data (presence or absence in an area).

### **What do we need to do in the future that will help fishery managers and fish biologists to learn more about fishes and their sound production?**

Sound propagation in the marine environment, especially in shallow water, is a very complex problem. Some of the workshop participants gave some hints of what may be done by researchers in the area of passive acoustics and fisheries in the future. Susan Jarvis explained how sound propagation was studied by Navy scientists following sperm whales in the Bahamas swimming through the large hydrophone array set in place there for submarine sonar studies; although these whales make sounds with higher source sound pressure levels, similar approaches could be used with fishes swimming through fixed hydrophone arrays. Scott Holt described the use of towed arrays to locate spawning areas of red drum along the Texas coast. By monitoring the sound levels of a very loud and close by individual red drum, the multiple hydrophone elements on the towed array was useful in localizing the individual sound-producing fish. Some new approaches to making captive and *in situ* recordings came out of the workshop. Joe Blue suggested using “butterfly” shaped tanks in captive fish recordings, because they reduce tank echoes. Tony Hawkins warned against the use of thin-walled fiberglass tanks surrounded by air, which can increase the echo effect. Hawkins then described his combination approach of using an enclosure in the field to record haddock sounds, which provided a more natural acoustic environment without tank noise and echo problems. But, recorded sounds must be assumed to come from the fish, as one cannot screen out ambient sounds in the marine environment. Blue suggested putting the fish and the hydrophone in a narrow diameter pipe that is less than the wavelength of the sound that you are interested in recording. It may be difficult to get the fish to produce sounds in such an unnatural situation, however. Workshop participants described new acoustic devices for monitoring fish sounds, including the NURC ROVs fitted with hydrophones, ECU and Navy Sonobuoys, and the NOAA/NMFS remote underwater device acoustic recording (RUDAR), and various AUVs. One such AUV was a “glider”, which produces very little sound itself because it uses a motor only to get to the surface, then glides to the bottom.

Because aquatic environments cover huge areas and great depths, acoustics holds great promise in locating fish that cannot be easily seen using ROVs, submarines, SCUBA or underwater video. Because light is attenuated more rapidly in water than sound, and sound waves in water travels 5 times the speed of sound waves in air, the detection of a fish species in an area where habitat surveys are conducted is far more likely than detection with nets and visual means.

All workshop participants agreed that there was a great need to conduct studies of fishes using passive acoustics in the future. Some areas of future research needs were suggested at the workshop, including:

- 1). Quantification of fish aggregations size by use of passive and active acoustics used together.
- 2). Linking the passive acoustical work to behavioral work (with more video and audio recordings made together where visibility allows).
- 3). Modelling sound propagation of fish sounds in different environments.
- 4). Correlation of sounds from specific habitats with overall environmental quality
- 5). Development of directional arrays and beam-forming technologies to precisely locate the sound sources at dark or in turbid waters.
- 6). Determination of the sizes of fishes making sounds and if both males and females make sounds (in some species).
- 7). The need to establish what proportion of the fish are calling at a given time.
- 8). The need to determine and model how sound pressure levels (SPLs) vary with shoal size and distance from sound source.
- 9). Modelling of chorusing behavior. Are individual fishes calling together, i.e., are the choruses synchronized?
- 10). The need to secure funding for establishment of long-term remote listening stations at established sites so that spatial and temporal (diurnal and seasonal) variations in sound are characterized.
- 11). The need to establish a national center in the US for the study of bioacoustics of fishes.
- 12). The need to do conduct these studies in ways that will allow testing of specific scientific hypotheses in collaborations with physical, chemical, and biological oceanographers.

This partial list of future research directions will be undertaken by individuals at the workshop and their colleagues from traditional grant funding sources (the National Science Foundation, Sea Grant Program, NOAA).

Some obstacles must be overcome in the future: cases of mistaken identity have occurred in the past (e.g. the striped cusk-eel chatter sound was long confused with weakfish, Sprague and Luczkovich 2001) and unknown sounds exist. Thus, there is an urgent need to have an archive of known sounds that can be reliably associated with fish species and particular behaviors. Such an archive has been funded by ONR and is being assembled by bioacousticians from the Library of Natural Sounds at Cornell University from thousands of hours of underwater recordings of fishes and the aquatic environments made by scientists (Bloomgarden and Bradbury 2002). There is a need to establish a set of standards for voucher sounds, which should be separated in the archive in terms of the species taxonomic affiliations, environmental conditions, and recording environment. For example, in the archive we should differentiate between:

- (1) Captive/tank recordings - these are routinely done for "sound truthing". When there is only one species in the tank, there is no question as to which species produced the sounds. But, what standards should be used for aquarium design, reduction of tank echoes and noises?

- (2) *In situ* recordings - these can be done with modern video and audio technology. But how do we avoid the problem with location of the sound source, so as not to confuse fishes making the sounds with the ones that just happen to be in the area (the cusk-eel weakfish problem).

Even when all the fish are of the same species in a tank or *in situ*, we are often interested in which individual fish produced a given sound. This allows us to relate the size or behavior of the fish to the sound and gives an understanding of what the social environment was in which it produced the sound (mating behavior, foraging, aggression etc.).

One area of great importance in the future is determining the impact of noise pollution in the marine environment. If fishes rely on sound for communication, are the noises produced by human activities interfering with the fishes ability to mate, fight, and locate food or predators? We need to do more research on the impact of fishing gear, boats, pipelines, dredging, petroleum exploration seismic surveys, and military operations on soniferous fishes. Should these be noises regulated? At what levels? Can the fish hear these sounds? Do they respond to the sounds? McCauley *et al.* (2002) have shown that a fish's ability to hear is affected by prolonged exposure to the sounds produced by air guns used in seismic surveys by geologists. American shad are affected by echo-sounders using high frequency sounds, which they can hear (Mann *et al.* 1997, Mann *et al.* 1998) apparently because bottlenose dolphins, a shad predator, also use these frequencies for echo location. Is spawning interrupted? Bottlenose dolphin disrupt the spawning of silver perch (Luczkovich *et al.* 2000), but we know little of how echo sounders and fishing vessel noises affect this species and its relatives in the Sciaenidae. Are migration routes blocked? For example, American shad migrate upstream to spawn, but turn away at places where underwater gas pipelines cross the estuary or river, due to the acoustic environment produced by the rushing fluids and gasses in the pipe (Art Popper pers comm.).

The passive acoustics approach can provide fish biologists and fishery scientists with a non-destructive sampling tool that can provide a unique perspective of the biology and ecology of soniferous species of fishes.

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## Working Group on Technology Issues

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### **Introduction**

The purpose of this report is to summarize the findings of the Technology Working Group that was held on the third day of the workshop. The Technology Working Group was tasked with reviewing papers presented during the workshop, and information from the literature, and to summarize our state-of-knowledge on passive acoustics applications to fisheries and the census of marine life. In addition, the group was tasked with providing recommendations on areas of technology development that were deemed by the participants to be of highest priority and most likely to facilitate advances in the application passive acoustics to fisheries issues.

The success and development of fish bioacoustics depends on high quality recording systems and analysis software. It is important that the technology is matched to the questions being asked. This document provides an overview of existing technologies with the purpose of identifying technologies that can be applied to specific fish bioacoustics questions. It is not meant as an exhaustive survey of existing academic and commercial products. The main conclusion is that for most questions the needed technology exists for advancing fish bioacoustics. The main impediments are the level of education on the use of technology within the field and a general awareness by funding agencies of the great potential that studies of fish bioacoustics can provide to research studies on fish and fisheries. This workshop has been a first step to removing both of these impediments, and for identifying ways to break them down further.

### **Hydrophones**

Hydrophones are the most basic element of any recording system. They are underwater microphones that typically convert sound pressure into an electrical signal that can be recorded by a data acquisition system. There are many commercial suppliers of hydrophones that are appropriate for fish sound recordings.

### **Simple Systems**

Perhaps the most important technology area identified by participants are simple systems to record

and analyze sounds. Simple recording and analysis systems are useful for recording fish sounds to identify the sounds produced by different species and for performing surveys of locations of sound-producing fishes. A simple system consists of a hydrophone with a data acquisition device. Data acquisition systems include audio and digital tape recorders, audio-video recorders (Lobel), and computers with sound cards. Digital systems provide obvious advantages over analog systems in terms of greater frequency bandwidth and dynamic range, and will be the most commonly used systems in the future. Which system is chosen will depend on the recording situation. Computer systems that may be practical for recordings made in the laboratory, may not be practical in a field situation, because of power and portability issues. One important development is the use of remotely operated vehicles (ROVs) and permanent underwater listening stations for monitoring sound producing fishes (Blue and Rountree; Luczkovich and Sprague; Brower and Barans). These systems will be important in characterizing which species produce which sounds, especially for species that will be difficult to maintain in a laboratory tank. They will also prove useful for documenting behavior of fish aggregations when multiple fish call simultaneously.

Several caveats of recording systems were brought up that one needs to be aware of including:

1. **Data compression:** Some recorders (such as mini-disc and MP3) use data compression techniques that alter the recorded sound frequency and level. These would not be appropriate for use in cataloguing known fish sounds, but could be very useful for ecological surveys of sound-producing fishes.
2. **Automatic Gain Control (AGC):** Many systems (especially many audio tape recorders and video cameras) use automatic gain control to keep the recorded volume within the same range. If a system uses AGC, it will not be possible to determine the received sound level.
3. **Bit resolution:** Systems that record with a higher bit-resolution will have a larger dynamic range (the range of the quietest and loudest sounds that can be recorded).

One issue that many participants have encountered are problems with boat-induced noise on recording systems, either through electrical noise on the boat, or the physical movement of the boat causing the hydrophone to move. Bungee cords have been successfully used to decouple boat movement and hydrophone movement, and acceleration canceling hydrophones are commercially available. One other technique is to use telemetry buoys from the ship (see below).

### **Dataloggers**

Audio dataloggers are useful for recording over long periods of time in many locations simultaneously. Dataloggers provide a way to gather information on the distributions of sound-producing fish that would not be possible otherwise without considerable investment of human resources. A good example of this are the pop-ups recorders (Clark).

Computers are the best option for recording as an audio datalogger where continuous power is available, such as from shore or on a boat. Commercial software (such as Avisoft) exists for recording on a given duty cycle. However, continuous power is rarely available in field situations where

one would like to make recordings. In these situations low-power battery-operated dataloggers are required.

To date all audio dataloggers that have been used for fish bioacoustics have been engineered by individual laboratories to perform this task. These include analog tape recorders that have been modified to record on a particular duty cycle (Luczkovich), and digital dataloggers that have been programmed to record as desired (Clark; Mann). There is no commercially available datalogger that can be purchased and used directly without either engineering or software programming (usually both). This lack of an off-the-shelf product has greatly limited their use in fish bioacoustics.

### **Telemetry**

Telemetry systems broadcast a hydrophone signal to a boat or shore-based receiver. They perform the same function as dataloggers in allowing recordings over a large area for long periods of time. Several types of telemetry systems are available including sonobuoys (VHF), cell phone systems, and short range microwave systems. All of these systems require line-of-sight between the transmitter and receiver, and a relatively high-level of engineering to setup and maintain. Telemetry is also capable of delivering video to document behavior during sound production (Øvredal).

Satellite systems generally do not support the bandwidth needed for transmitting acoustic data. At this point, some amount of preprocessing would be required, so that limited data on sound characteristics (e.g. RMS level, frequency spectra) could be transmitted.

### **Hydrophone Arrays**

Hydrophone arrays could be used for localizing sound producing fishes and for producing a directional receiver to improve the signal to noise ratio (Forsythe). They have been used for determining the locations of vocalizing whales in many different situations, but have not yet been applied to fishes (Jarvis). They require a high-level of sophistication for setting up, operating, and analyzing the data. Hydrophone arrays hold promise in answering questions about fish distributions that could not be otherwise obtained with single hydrophone recordings. Most participants recognized the potential benefits of hydrophone arrays, and they were one area where further training and descriptions of existing systems would be useful.

### **Speakers**

Underwater speakers are useful in conducting playback experiments to determine the reaction of fish to different types of sounds. The US Navy rents low-frequency projects (e.g. J-9, J-11) to research projects, and there are also commercially available speakers for swimming pools that can be used in research situations (although these usually do not produce good low-frequency responses below 100 or 200 Hz). All of these speakers require processing of the signals to be played to produce an

accurate reproduction of a fish sound (Hawkins). That is they do not have a flat frequency response. So, one can not merely play back a recorded sound and hope to get a perfect reproduction of it.

### **Signal Processing Software**

There are many commercially available packages for data acquisition and signal processing. Some such as MATLAB (Mathworks, Inc.) have a great deal of flexibility and power, but require a high level of knowledge of signal processing. Others are targeted specifically at bioacousticians including Signal (Engineering Design), Canary (Cornell University), and Avisoft. The manuals to these software programs are often the clearest source of information for learning signal processing techniques and their applications.

One area that was identified as an important area of research and development are tools for automatic identification of species and for analyzing long data sets. Such tools would depend on the development of a library of fish sounds (Bloomberg). They would have great value in making passive acoustics accessible to all fisheries researchers.

### **Education**

Most fish bioacousticians are biologists first and engineers second. This is because we have arrived at fish bioacoustics as a powerful way to study fishes that no other approach can provide. This means that we have to pick up engineering and signal processing principles as we go along. Unfortunately, there is no one good source of information about recording and signal processing that is accessible and practical for the fish bioacoustician. This gap can be bridged both by producing these targeted materials and conducting training workshops, and by attracting engineers with a biological interest to the field.

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