NOAA FISHERIES

Best Practices for Implementing Acoustic Technologies to Improve Reef Fish Ecosystem Surveys

Report from the 2017 GCFI Workshop

NOAA Technical Memorandum NMFS-F/SPO-192
April 2019

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U.S. Department Of Commerce

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The steering committee comprised of internationally recognized experts (Tonny Algrøy, Kevin Boswell, Jeff Condiotty, David Demer, Toby Jarvis, Frank Reier Knudsen, William Michaels, Patrick Sullivan, Chris Taylor, Charles Thompson) are recognized for developing the framework of this symposium and workshop. Alejandro Acosta and Robert Glazer were key organizers for the 70th annual GCFI Conference that provided the international forum for this concurrent acoustic symposium and workshop held in Merida, Mexico during November 4-10, 2017. Experts from Kongsberg Simrad (Tonny Algrøy, Jeff Condiotty, Lars Nonboe Anderson, and Leonardo Jose Figueroa Argueta) provided logistical support with acoustic instrumentation, and Luis Rodriquez organized the boat charter for the acoustic training. Emilia Cortes Gomez and Leonardo Jose Figueroa Argueta helped with English-Spanish translations for the workshop. Most importantly, the combined efforts of the instructors, support staff, and participants contributed to the overall success of the workshop that we hope will result in long-lasting collaborative expertise to improve the sustainability and health of reef-fish ecosystems in the region.

RECONOCIMIENTO

Este simposio, el taller y el informe final han sido posibles gracias a la contribución e iniciativa estratégica de Innovación Oceánica del Instituto de Pesquerías del Golfo y el Caribe (GCFI) patrocinada por la Administración Nacional de la Atmósfera Oceánica (NOAA). Hacemos un reconocimiento a Robert Glazer (Director Ejecutivo de GCFI) por la presentación del proyecto, con el objetivo de enriquecer la información científica utilizando tecnologías innovadoras para la sostenibilidad de los recursos marinos vivos en las regiones del Golfo de México y el Caribe. Este Proyecto fué patrocinado por la Oficina de Ciencia y Tecnología de Pesquerías de NOAA. Además de la asociación GCFI-NOAA, estamos agradecidos con Kongsberg Simrad y Echoview Pty Ltda, por el apoyo financiero y técnico que fueron fundamentales para el éxito de éste taller de capacitación acústica.

El comité directivo compuesto por expertos reconocidos internacionalmente (Tonny Algrøy, Kevin Boswell, Jeff Condiotty, David Demer, Toby Jarvis, Frank Reier Knudsen, William Michaels, Patrick Sullivan, Chris Taylor, Charles Thompson) son reconocidos por desarrollar el marco de este simposio y taller. Alejandro Acosta y Robert Glazer quienes fueron los organizadores clave de la 70 Conferencia anual de GCFI que proporcionó el foro internacional para éste simposio y el taller de acústica simultáneo celebrado en Mérida, México, del 4 al 10 de noviembre de 2017. A la experiencia de Kongsberg Simrad (Tonny Algrøy, Jeff Condiotty, Lars Nonboe Anderson, y Leonardo José Figueroa Argueta) quienes proporcionaron apoyo logístico con instrumentación acústica, y a Luis Rodríguez por facilitar el barco utilizado durante el entrenamiento acústico. A Emilia Cortes Gómez y Leonardo José Figueroa Argueta quienes brindaron asistencia en la traducción del inglés al español en el material de capacitación y durante el taller. Lo más importante es que los esfuerzos combinados de los instructores, el personal de apoyo y los participantes contribuyeron al éxito general del taller y al informe final que tendrán un impacto perdurable en la construcción conjunta de conocimiento y experiencia que permitan mejorar los ecosistemas de peces de arrecife en la región.

Best Practices for Implementing Acoustic Technologies to Improve Reef Fish Ecosystem Surveys: Report from the 2017 GCFI Acoustics Workshop.

EXECUTIVE SUMMARY

Approximately 330 participants from 30 countries attended the 70th Gulf and Caribbean Fisheries Institute (GCFI) conference held in Merida, Mexico during 4-10 November 2017. The conference featured a symposium on Acoustic Technologies to Improve Reef Fish Ecosystem Surveys, which provided presentations on the various acoustic technologies used to monitor reef fish ecosystems. An acoustic workshop was also held to build scientific capacity and foster collaborative acoustic expertise, in order to enhance research and survey operations in reef-fish ecosystems. Recognizing the connectivity of marine populations across the geopolitical jurisdictions of the wider Caribbean region, National Oceanic and Atmospheric Administration (NOAA) supported the GCFI Ocean Innovation Strategic Initiative grant to build scientific capacity in the region for the sustainability of living marine resources.

The acoustic workshop was conducted over three days with collaboration between GCFI, NOAA, Kongsberg-Simrad, Echoview and the South East Acoustic Consortium (SEAC). On the first day (November 4th), 33 participants and instructors from 10 countries departed from city of Progreso aboard the boat *Isla Mujeres* for training on the use of three versions of the Simrad EK80 wideband echosounder: EK80 WBTs (designed for ships), EK80 WBAT (designed for autonomous platforms), and portable EK80 EcoSounder. Acoustic data was collected on a reef site approximately 18 miles offshore. During the second day (November 5th), participants received an overview of echosounder data processing and analytical methods using Echoview software, with a focus on reef environments. Participants learned how to load, calibrate and clean their acoustic data, how to detect, track and classify reef fish, and how to quantify their distribution and abundance. The third day of the acoustic workshop (November 9th) brought together the diverse perspectives of 57 participants from 13 countries to address the operational challenges of conducting acoustic surveys of reef-fish ecosystems. Case studies were presented by experts on various topics relevant to conducting acoustic operations in reef-fish habitats, such as statistical survey design, sensor selection and configuration, and interpreting acoustic data. Participants worked to prioritize management and operational objectives that can feasibly be achieved with acoustic technologies in the region, and developed the framework for the technical report.

This report provides guidance on the best practices for active- and passive-acoustic operations to enhance the understanding of reef-fish ecosystems. The acoustic workshop forged collaborative partnerships and provided direction for future training workshops on the integration of acoustic and optical technologies. These collaborative efforts are critical for building the next generation of experts, whose role will be to optimize survey operations with technologies for improving the sustainability of living-marine-resources in reef-fish ecosystems with connectivity across the geopolitical jurisdictions of the region.

Buenas Prácticas para la Implentacíon de Technologías Acústicas para el Mejoramiento de Análisis en los Ecosistemas de Peces de Arrecife: Informe del Taller de Acústica de GCFI 2017.

RESÚMEN EJECUTIVO

Aproximadamente 330 participantes provenientes de 30 paises asistieron a la 70 Conferencia del Instituto Pesquero del Golfo y el Caribe (GCFI) celebrada en Mérida, México, del 4 al 10 de noviembre de 2017. En esta conferencia GCFI, presentó el simposio sobre Tecnologías Acústicas para el mejoramiento de estimaciones de ecosistemas de peces de arrecife, realizando 12 presentaciones sobre las diversas tecnologías acústicas utilizadas para monitorear los ecosistemas de peces de arrecife. También se realizó un taller de acústica para mejorar la capacidad científica y de las operaciones de investigación y levantamiento en ecosistemas de peces de arrecife.

Con el reconocimiento de la conectividad de las poblaciones marinas en las jurisdicciones geopolíticas de la región del Gran Caribe, la Administración Nacional Oceánica y Atmosférica (NOAA) patrocinó el proyecto e iniciativa estratégica de Innovación Oceánica del Instituto Pesquero del Golfo y el Caribe (GCFI) para incrementar la capacidad científica y sostenibilidad de los recursos marinos vivos en la región. Este taller de acústica se realizó durante tres días con esfuerzos conjuntos de GCFI, NOAA, Kongsberg-Simrad, Echoview y SouthEast Acoustic Consortium (SEAC). El primer día 4 de noviembre, 33 participantes e instructores de 10 países salieron de la ciudad de Progreso a bordo del bote Isla Mujeres para recibir capacitación sobre el uso de tres versiones de la ecosonda de banda ancha Simrad EK80: EK80 WBTs (diseñada para plataformas autónomas) y el EK80 EcoSounder portátil. Se recolectó información acústica en un arrecife ubicado aproximadamente a 18 millas de la costa. Durante el segundo día, 5 de noviembre, los participantes recibieron una descripción general del procesamiento de datos acústicos y métodos análiticos, usando el software Echoview para procesar y analizar los datos recopilados de las ecosondas científicas del sitio de estudio y otros estudios en el ambiente de arrecife. Los participantes aprendieron las características del software Echoview para producir estimaciones de la abundancia de peces de arrecife y la descripción de su hábitat. El tercer día del taller celebrado el 9 de noviembre reunió las diversas perspectivas de 57 participantes de 13 países para abordar los desafíos operacionales de la realización de estudios de ecosistemas de peces de arrecifes. Los expertos presentaron diversos casos de estudio sobre diferentes temas relevantes para la ejecución de operaciones acústicas en hábitats de peces de arrecife, tales como el diseño de la muestra estadística, la selección y configuración de los sensores y la interpretación de los datos acústicos. Los participantes trabajaron para priorizar los objetivos operativos y de gestión que fueran alcanzables con las tecnologías acústicas en la región, y poder desarrollar el marco para el informe técnico.

Los resultados y recomendaciones de éste taller se presentan aquí como una guía sobre las mejores prácticas para realizar investigaciones y operaciones de análisis en ecosistemas de peces de arrecife. Las recomendaciones también proporcionan orientación para futuros talleres de capacitación sobre la integración de tecnologías acústicas y ópticas para mejorar las operaciones de recolección de información que permita apoyar decisiones de gestión administrativa sobre la sostenibilidad de los recursos de peces de arrecife en la región. La conclusión general de esfuerzos tales como éste taller son críticos para construir la futura generación de expertos, quienes de manera conjunta optimizarán las operaciones de recolección de información con tecnologías que permitan mejorar la sostenibilidad de los recursos marinos vivos que tienen conectividad en las jurisdicciones geopolíticas de la región.

1 INTRODUCTION (W.L. MICHAELS)

1.1 BACKGROUND

Marine conservation requires collaborative efforts to assess the connectivity of living marine resources across geopolitical jurisdictions.

The Gulf and Caribbean Fisheries Institute (GCFI) founded about seven decades ago promotes the exchange of information for the conservation and management of marine resources in the Gulf of Mexico and Caribbean region. The GCFI provides an annual conference as an international forum for scientists, managers, students and stakeholders from various sectors and countries to ensure balance representation and perspectives on current issues relevant to the use and sustainability of marine resources in the region. Fisheries resources and supporting reef habitats have significant socioeconomic importance for the coastal communities in this region, but the stock assessments of commercially and recreationally important species are challenged by the complexity of life history and habitat use patterns, along with the difficulty of sampling reef habitats. The wider Caribbean region is comprised of 42 geopolitical jurisdictions; therefore, it is recognized that marine conservation requires collaborative efforts to assess the connectivity of living marine resources across geopolitical jurisdictions.

For this reason, GCFI partnered with the National Oceanic and Atmospheric Administration (NOAA) to address data-limited stock assessments in the region. The GCFI-NOAA Data-limited Assessment Strategic Initiative recently completed a series of workshops that provided advice on data-limited assessment methods (Cummings et al., 2014), strategies for improving fishery-independent sampling (Cummings et al., 2015), and recommendations on optimizing between fishery-dependent and fishery-independent sampling in the region (Cummings et al., 2017). The partnerships developed from these workshops emphasized that collaborative science is critical for resource management.

The next generation of experts in the application of ocean technology will enhance integrated ecosystem surveys to improve transboundary stock assessments.

These workshops provided the framework for the existing GCFI-NOAA Ocean Innovation Strategic Initiative to develop innovative approaches to improve survey efficiencies, analytical tools, and scientific capacity to address the data-limited assessments in the region. Based on recommendations from the data-limited workshops and a recent GCFI questionnaire survey (described in the next section 1.2), priority should be given to developing the next generation of experts in the application of ocean technology to improve transboundary stock assessments. Therefore, the GCFI-NOAA Ocean Innovation Strategic Initiative partnered with the SouthEast Acoustic Consortium (SEAC), Kongsberg-Simrad and Echoview to organize a symposium and workshop on the use of Acoustic Technologies to Improve Reef Fish Ecosystem Surveys during the 70th Annual GCFI conference in Merida, Mexico over 4-10 November 2017.

1.2 Priorities for Building Scientific Capacity in the Region

The GCFI-NOAA Ocean Innovation Strategic Initiative strives to develop innovative approaches to improve survey efficiencies, analytical tools, and scientific capacity to address the data-limited assessments in the Gulf of Mexico and Caribbean region. To guide this initiative and the framework for its workshops, a questionnaire survey was conducted among the GCFI community comprised of scientists, managers, and stakeholders to obtain broader perspectives on the mission priorities and requirements in the region (Figure 1-1).

The survey results provided perspectives from various sectors of 14 countries (Figure 1.2) on priorities and requirements to improve scientific information for the conservation and management of living marine resources, with recognition of the connectivity of marine populations across the many geopolitical jurisdictions in this region.

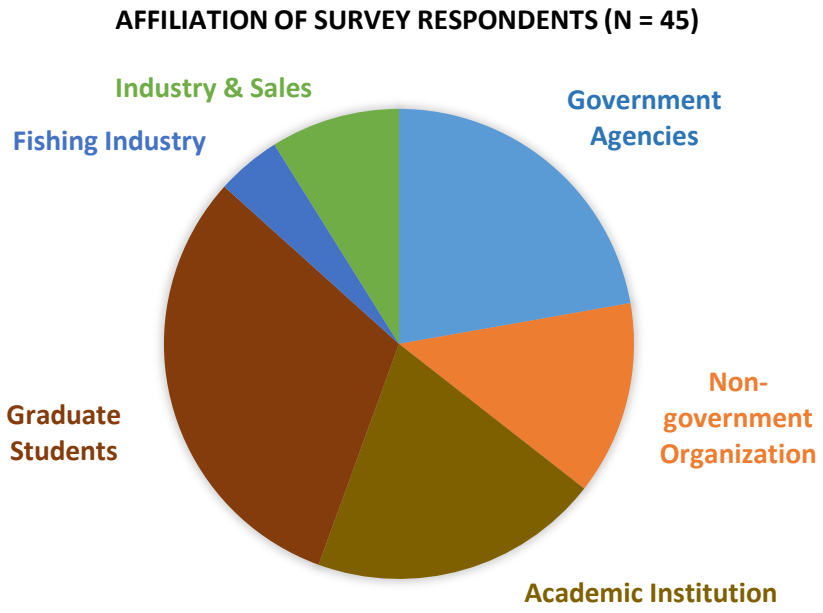


Figure 1-1. The pre-workshop survey respondents (n=45) represented various sectors interested in improving scientific capacity for the sustainability of living marine resources in the Gulf of Mexico and Caribbean region.

There are unique challenges in collecting scientific information due to the complexity of life history and habitat use patterns of marine populations in the Gulf of Mexico and Caribbean region. Furthermore, much of the essential habitats in this region, such as coral reef habitats, are difficult to sample. For these reasons, the questionnaire survey was designed to identify which technologies are the most promising to advance the mission priorities relevant to the sustainability of living marine resources. Approximately half of the survey respondents considered the need to improve fishery independent surveys, ecosystem research and marine protected areas as important mission priorities (Figure 1-3), while protecting endangered species and fish spawning aggregations were also identified as priorities in this region. Each of these mission priorities require improvements in stock and habitat assessments which are generally considered to be data-limited in this region.

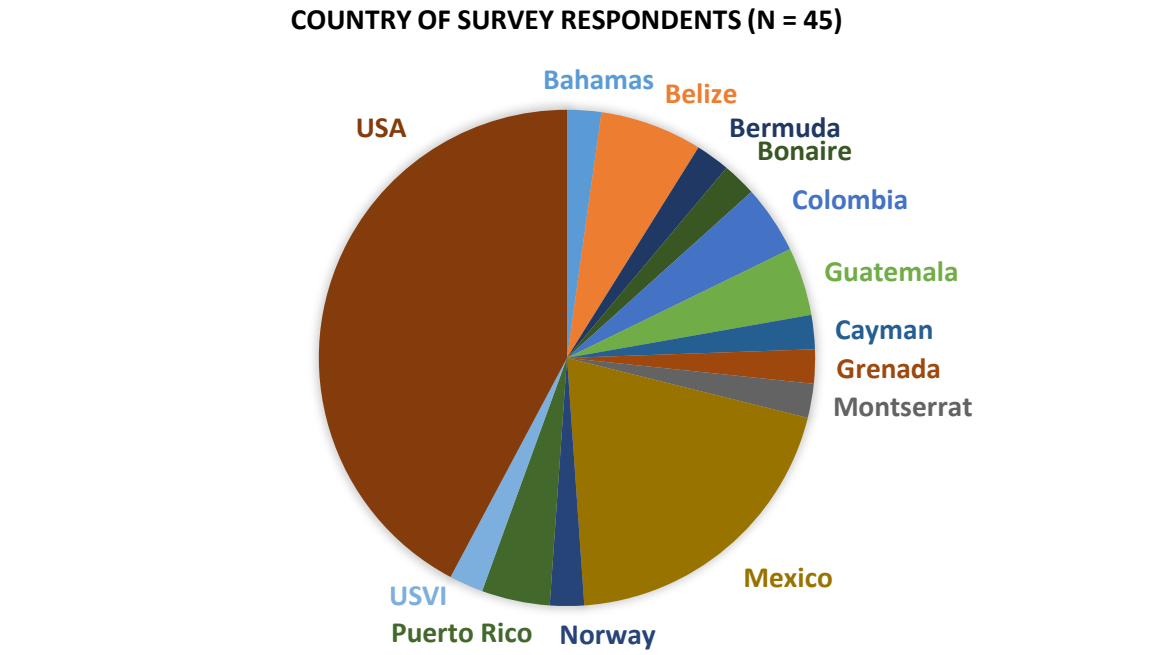


Figure 1-2. The survey respondents provided perspectives from various countries working on improvements in scientific information for the conservation and management of living marine resources in the region.

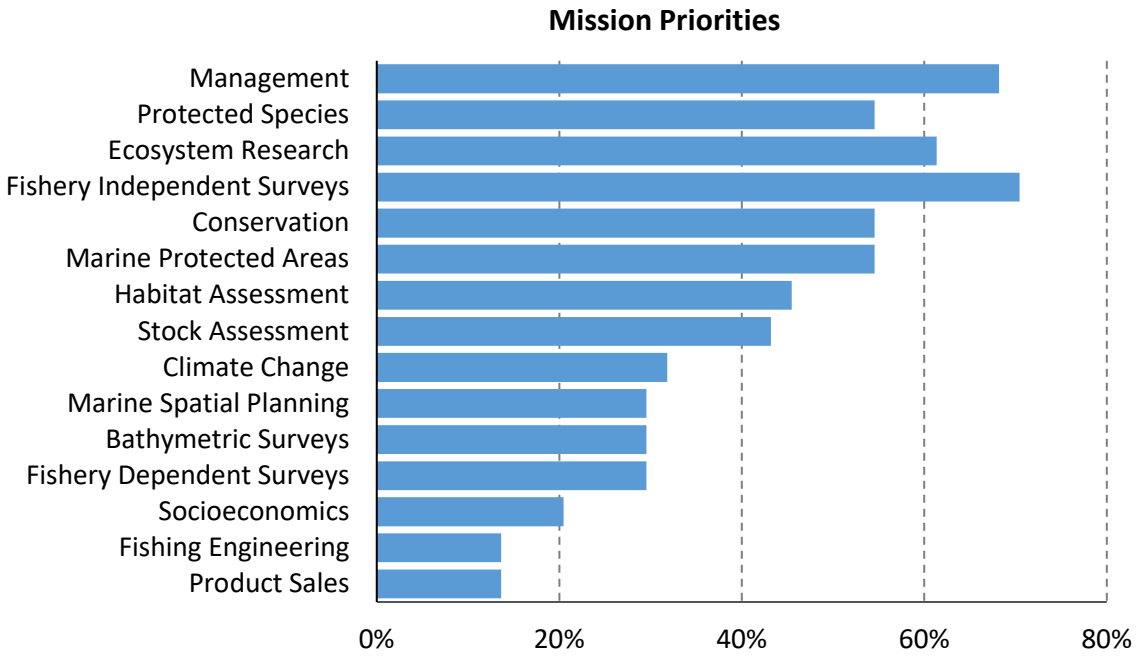


Figure 1-3. Approximately half of the survey respondents (n=45) considered fishery independent surveys, ecosystem research and marine protected areas as important mission priorities, while protecting endangered species and fish spawning aggregations were also important in the region. Stock and habitat assessments were key requirements for the conservation management in the region.

The survey results suggest the integration of acoustic and optic sampling technologies can enhance survey operations in the reef fish habitats of the region (Figure 1-4). The survey results showed interest and experience in a wide range of active acoustic technologies for seafloor and watercolumn operations, and this provided the framework of developing the acoustic workshop. The use of optical, acoustical and environmental sensing technologies appears to be the highest priority for the region, and about half of the respondents, who attended the workshop, had some experience with these technologies. The survey results also showed a high interest and experience in underwater camera systems as expected for reef fish surveys in this region, therefore next year's GCFI workshop will focus on optical technologies. The special session provided a wider forum to address advances in active and passive acoustics, and acoustic telemetry (refer to abstracts in Appendix A).

Integration of acoustic and optic sampling technologies can enhance survey operations in reef fish habitats.

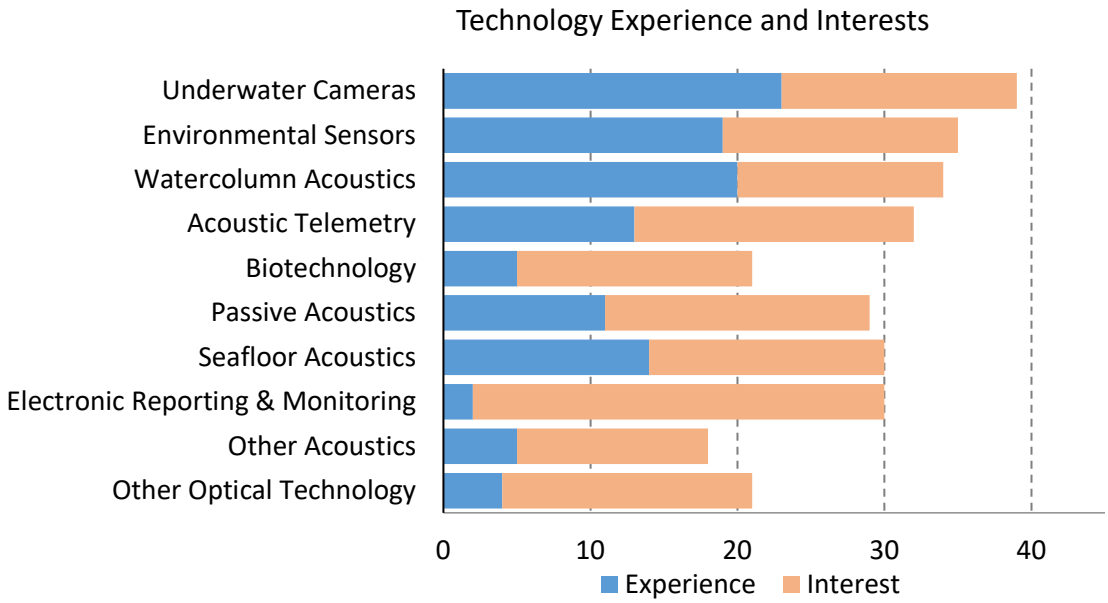


Figure 1-4. Nearly all of the survey respondents (n=45) expressed interest in using acoustic and optical technologies to improve scientific capability for the sustainability of living marine resources in the Gulf of Mexico and Caribbean region. About 25% of the respondents had some combination of experience with optical, acoustical and environmental sensing technologies.

In this region, there is a high reliance on fishery dependent data collections as reflected with data collections from fishing vessels and shore-side sampling (Figure 1-5). Access to research vessels and chartered vessels is limited; therefore, the need to optimize fishery independent sampling with remote sensing technologies is critical for resolving data-limited assessments in this region. The survey also indicated that labor intensive SCUBA diving is commonly used for data collection in coral reef habitats, while the interest in alternative platforms with integrated optical and acoustic technologies can improve the efficiency of sampling these habitats with increased spatial and temporal resolution.

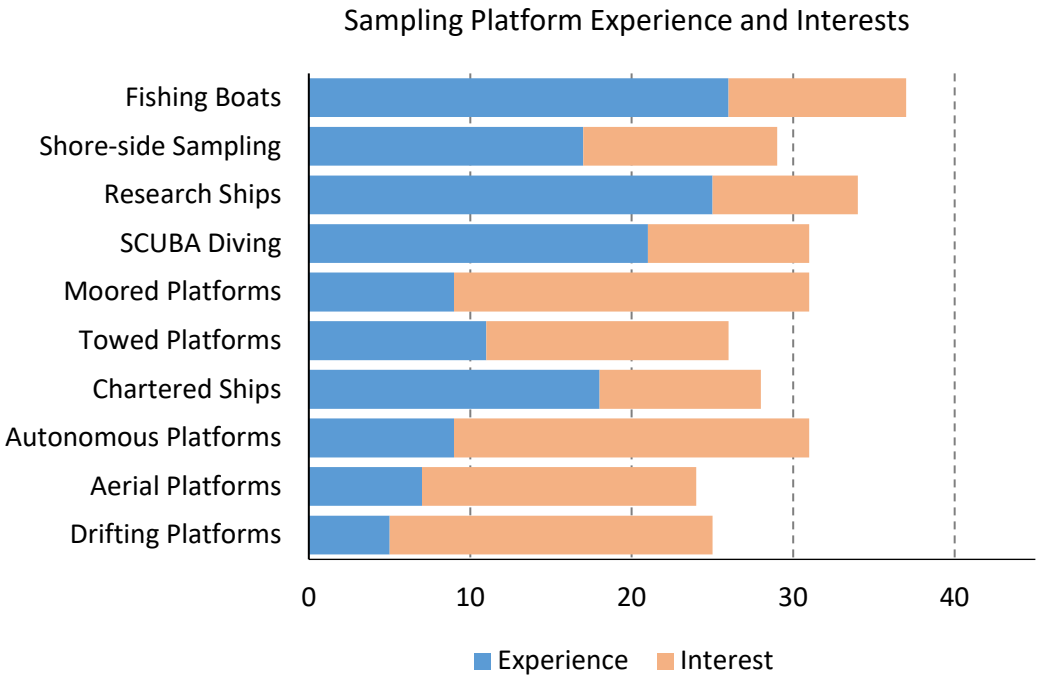


Figure 1-5. More than half of the respondents (n=45) had experience sampling from research and fishing vessels as well as Scuba diving operations. There was a high degree of interest in using alternative sampling platforms to enhance survey operations. The survey also showed considerable reliance in this region on fishery dependent data collections from fishing vessels and shore-side sampling.

Enhanced survey operations using acoustic, optic, and environmental sampling technologies provide synoptic science information to improve spatial and temporal resolution for ecosystem assessments.

The operational sampling priorities in the region equal emphasis the scientific information on marine populations and their habitats (Figure 1-6). While there is considerable effort to collect scientific data on the abundance and distribution of demersal and pelagic fish populations, there are also operational priorities for bathymetric mapping, seafloor and habitat characterization and oceanographic features. As reflected by the survey results, there is considerable interest in enhanced survey operations that use acoustic, optic and environmental sampling technologies to provide synoptic scientific information with improved spatial and temporal resolution for integrated ecosystem assessments. There is recognition that technologies can enable synoptic sampling of both biotic (biomass) and abiotic (bathymetry and environmental) features which are required for the delineation of marine protected areas and protection of spawning aggregations, each of which are some of the management priorities in this region.

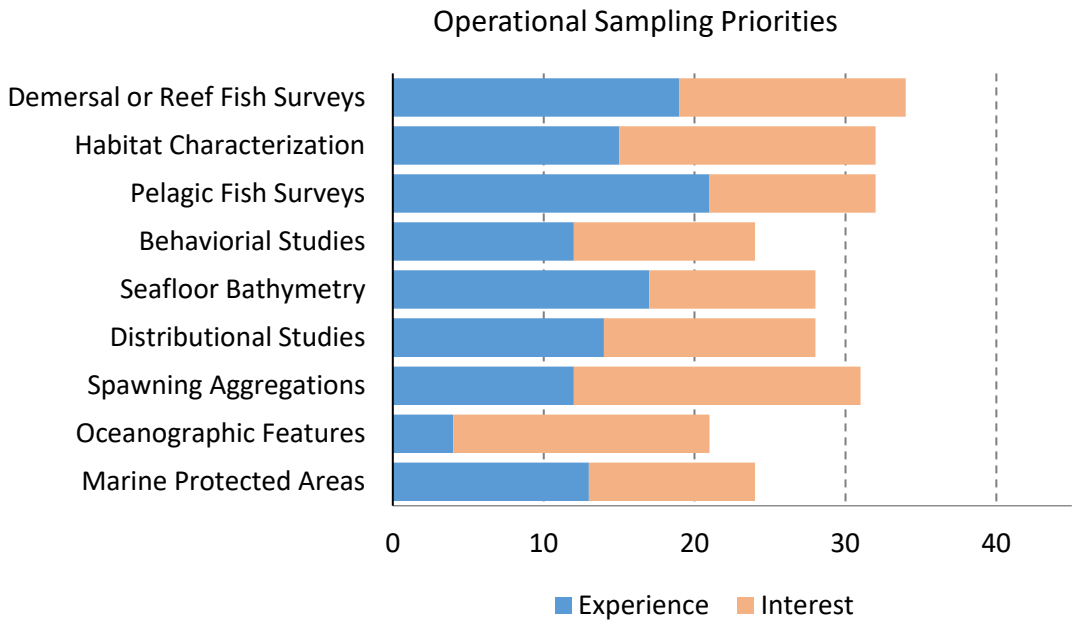


Figure 1-6. The respondents identified a variety of operational priorities ranging for demersal and pelagic fish surveys, to bathymetric mapping and habitat characterization. Overall, there was an interest in collecting synoptic scientific information on biological, geophysical and oceanographic features to address various management priorities in the region such as fish stock assessments, protection of spawning aggregations, and delineation of marine protected areas.

The pre-workshop survey emphasized efforts and interests in utilizing a variety of acoustic technologies such as active and passive acoustic systems, including telemetry of acoustic tags (Figure 1-7). It is noteworthy that half of the respondents attended the acoustic workshop, and most of these participants had some experience using scientific echosounders or other acoustic systems. Most of the respondents that had little or no experience with acoustic systems emphasized a priority on the ease of use in the operating acoustic systems, while the respondents who had some experience with acoustics emphasized the priority to obtain absolute abundance estimates (Figure 1-8). This reflected that those who obtained some initial training with acoustic systems were no longer concerned with ease of operational use of acoustic systems. Although there was interest in obtaining absolute abundance from acoustic technology, there was recognition that relative abundance estimates were equally importance, especially for operational objectives like monitoring spawning aggregations of grouper-snapper complexes. There was interests in low cost acoustic systems to increase its availability and use during survey operations in the wider Caribbean, but not at the expense of sacrificing the quality and integrity of the scientific data.

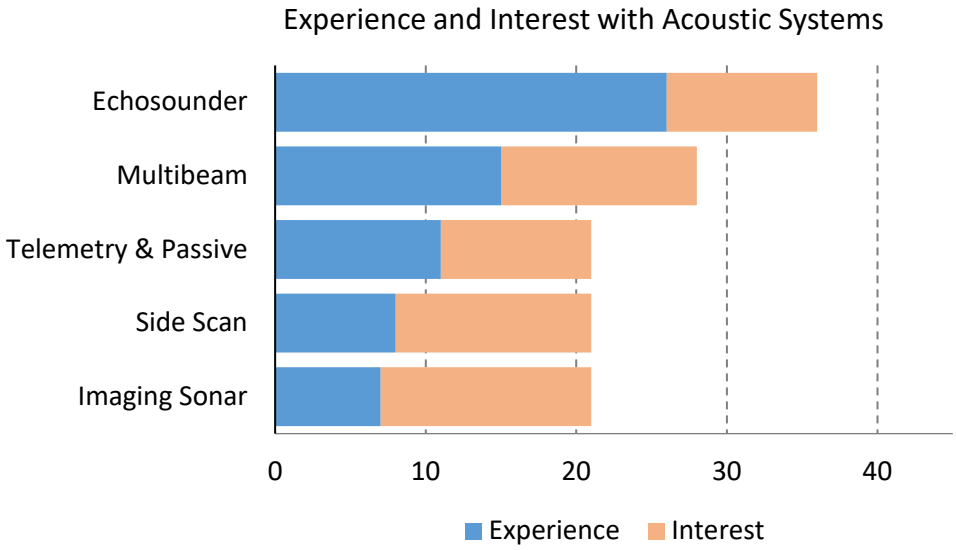


Figure 1-7. The pre-workshop survey showed interest and experience with various active and passive acoustic systems, including the use of telemetry of acoustic tags. More than half of the respondents had some experience with scientific echosounders.

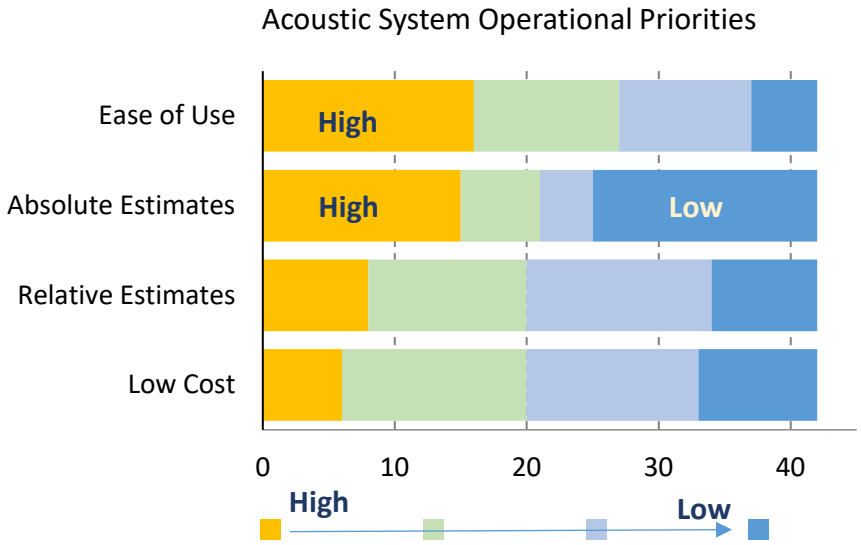


Figure 1-8. The respondents that had little or no experience with acoustic systems emphasized higher interest in acoustic systems that had ease of use, while the respondents that had some degree of experience with acoustic systems had more interest in obtaining absolute abundance estimates. Overall, there was recognition that relative abundance estimates are useful for a variety of operational objectives such as locating and monitoring spawning aggregations.

The pre-workshop survey emphasized the need for acoustic training as the highest priority in the region (Figure 1-9). Recommendations also requested a special session at a GCFI conference on the recent advances in acoustic technologies, and the need for developing a technical report on the best practices for conducting acoustic surveys in reef fish ecosystem.

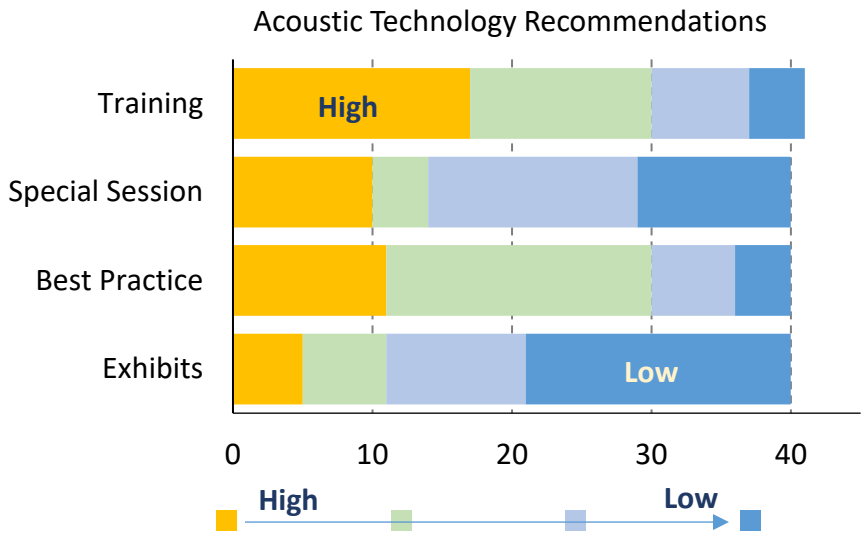


Figure 1-9. The 2016 respondents place an equally high priority on the acoustic special session and workshops to provide acoustic training and establish best practices for conducting acoustic surveys in the region. As expected, the 2017 respondents who will participate during the GCFI acoustic training placed a higher priority in this training.

There is consensus that the integrity of utilizing technologies to enhance survey operations is strengthened through training and collaborative network of experts to assure standard calibration and operational procedures are implemented. The results of this pre-workshop survey provided the framework for the acoustic symposium and concurrent acoustic workshop as reported herein. The GCFI-NOAA Ocean Innovation Initiative partnered with the SouthEast Acoustics Consortium (SEAC), Simrad, and Echoview to organize this acoustic technology symposium and workshop to promote collaboration among the academic, government, and private sectors to build a pool of acoustic expertise in the Gulf of Mexico and Caribbean regions to improve stock and ecosystem assessments.

1.3 Terms of Reference for the GCFI Acoustic Symposium and Workshop

Approximately 330 participants from 30 countries attended this GCFI conference which featured the symposium entitled "Acoustic Technologies for Surveying Reef Fish Ecosystems." This symposium showcased twelve selected presentations that provided perspectives on the current state of the science, applications, and recommendations for integrating active and passive acoustic technologies to enhance reef fish ecosystem surveys. The abstracts for this symposium can be found in Appendix A. Acoustic measurements were shown to have applicability to estimate reef fish abundance, map distributions, delineate spawning aggregations, observe behavior, and characterize community structure. In addition to remote sensing of the biological community, presentations showed acoustics to provide seafloor classification and bathymetry of their habitats. This symposium demonstrated the advances of scientists who strived to integrate sampling operations with active acoustic (echosounders) and passive acoustic (hydrophones and acoustic tags) instruments to locate and monitor spawning

Training workshops and working groups will develop our future collaborative network of experts to ensure technologies are effectively implemented to enhance ecosystem surveys.

aggregations, monitor aquatic ecosystem integrity, and investigate the impact of ocean noise on marine resources. This session served to communicate how integrating acoustic technologies into reliable and sustained survey and observation systems will provide socioeconomic benefits from the scientific gains.

A three-day workshop entitled "Acoustic Technologies to Improve Reef Fish Ecosystem Surveys" was held during this GCFI conference to build scientific capacity and acoustic expertise to increase acoustic expertise and collaborative efforts for enhancing research and surveys in reef-fish ecosystems, and to build scientific capacity for assuring the sustainability of living marine resources in the Gulf of Mexico and Caribbean region.

This workshop and competitive scholarships for eight graduate students were funded by the GCFI-NOAA Ocean Innovation Strategic Initiative grant, Kongsberg-Simrad and Echoview companies. Acoustic expertise, planning and logistic support was provided by Kongsberg-Simrad, Echoview and the SouthEast Acoustic Consortium (SEAC). The terms of reference and agenda of this workshop can be found in Appendix B.

The first day of the workshop on November 4th involved 33 participants from 10 countries, including eight scholarship awardees. The participant list is available in Appendix C. The participants departed from the city of Progreso aboard the boat MV *Isla Mujeres* for training on the use of three versions of the Simrad EK80 wideband echosounder: EK80 WBTs (for ships), EK80 WBAT (for autonomous platforms), and portable EK80 EcoSounder. Acoustic data was collected on reef fish and reef habitat approximately 18 miles offshore. The Echosounder System section of this report provides the key principles and best practice highlights of this first day of training. The following group photograph of the participants was taken aboard the boat *Isla Mujeres* during the first day of training (Figure 1-10).

Figure 1-10. Group photograph of workshop participants on board the MV Isla Mujeres.

During the second day (November 5th), participants received an overview of echosounder data processing and analytical methods using Echoview software, with a focus on reef environments (Figure 1-11). Participants learned how to load, calibrate and clean their acoustic data, how to detect, track and classify reef fish, and how to quantify their distribution and abundance. Refer to the Echosounder Data Processing section of this report for further information from the second day of training.

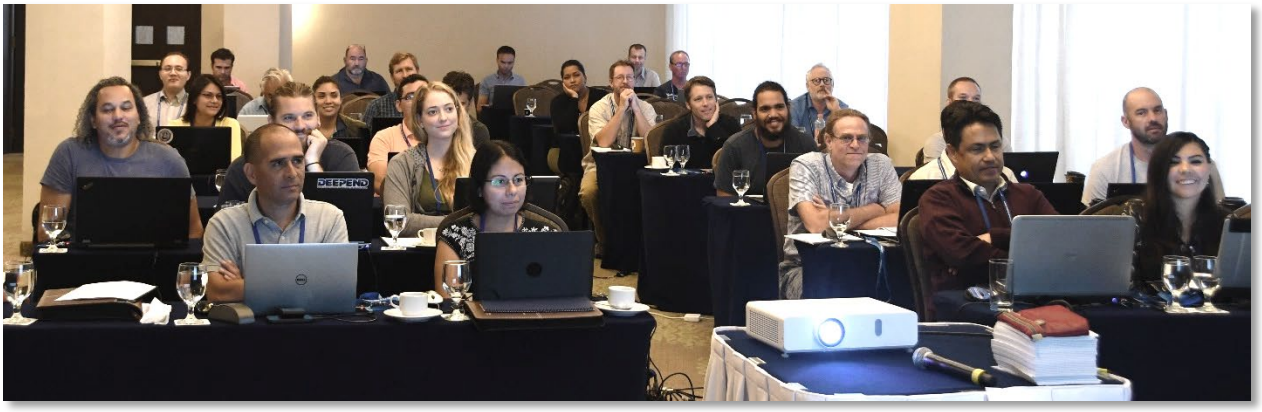


Figure 1-11. Workshop participants learned analytical tools and best practices in echosounder data processing.

The third day of the acoustic workshop held on November 9th brought together diverse perspectives of 57 participants from 13 countries to address the operational challenges of conducting acoustic reef fish ecosystem surveys (Figure 1-12). Case studies were presented by experts on various topics to consider when conducting acoustic operations in reef fish habitats, such as statistical survey design. Participants also worked in breakout sessions to prioritize management objectives and resources to achieve operational objectives. This workshop provided the framework for developing a technical report to provide guidance on the best practices for conducting acoustic reef fish ecosystem surveys in the region.

Figure 1-12. Breakout groups discussed management drivers and operational challenges to implementing acoustics in fishery ecosystem assessments.

Recommendations were also provided for future workshops and training on the integration of acoustic and optical technologies, with the goal of improving the scientific information available for the sustainable management of reef-fish resources in the Gulf of Mexico and Caribbean region. It is also recommended that opportunities are provided during the next year to make equipment and expertise available in the region to provide additional case studies on conducting acoustic studies in reef-fish habitat. This will promote collaborations and build expertise to help resolve data-limited situations in a region where there is considerable connectivity of marine resources across the many geopolitical jurisdictions of the region.

The workshop provided training in the calibration, operation, and post-processing of data from scientific echosounders, with hands-on use of the next-generation EK80 wideband acoustic system. Presentations covered acoustic technologies and methods to improve reef-fish surveys, such as recent advances in equipment, operational objectives, survey design, and data analysis. Case studies examined the

challenges and lessons learned while conducting acoustic surveys in the Gulf of Mexico and Caribbean region. Participation from all attendees, including presenters and participants from the training workshop, stock assessors, managers, and stakeholders, provided diverse perspectives to establish priorities and best practices for conducting acoustic surveys in reef fish ecosystems. The results and recommendation from this workshop are reported herein as guidance on the best practices for conducting acoustic operations to improve reef fish ecosystem surveys and research to address data-limited situations in this region. Additionally, this workshop builds an international network of collaborative experts to be considered as a working group, who will forge scientific capacity building efforts for the sustainability of living marine resources in the Gulf of Mexico and Caribbean region.

2 Suggested Sources for Understanding Acoustic Theory (K. Boswell and D.A. Demer)

This report outlines considerations for best practices in designing and implementing acoustic surveys to inform fishery and ecosystem management in coral reef ecosystem. The interested reader will note that there are many resources available in print and online where background information on the theoretical and practical applications of acoustics can be located. Acoustical oceanography is a relatively young field, and owes its early development to the measurements from Colladon and Sturm (1827). It was not until the onset of World War II, did the field of underwater acoustics begin to rapidly expand (Laskey, 1977). Substantial investment in the development of acoustic methodologies has followed within the many decades since and the use of underwater acoustics to examine processes in the oceans, for biological and physical processes, in addition to developments in communication and exploration has greatly expanded. It is our intention to point interested readers to several accessible sources which can serve as the basis of reference for developing a foundational understanding of underwater acoustics. For readers who are interested in the technical aspects of underwater acoustics, several excellent texts exist, and we recommend an initial exploration of the following: Urick (1983), Medwin and Clay (1998) and Lurton (2002). For those with interests in the application of acoustics for the quantification of fisheries resources, we guide the readers to the following: Johannesson and Mitson (1983) Gunderson (1993) and Simmonds and MacLennan (2005).

Online and digital resources are available to provide background, terms and definitions in proper use of underwater acoustics for fishery ecosystem assessments.

There also exist several resources online that offer practical context towards the operational aspects of the use of acoustics in fisheries science. Perhaps the most notable ("Acoustics Unpacked" http://www.acousticsunpacked.org/) was derived from a standard operation procedure developed to standardize surveys for Great Lakes stock assessment efforts (Parker-Stetter et al., 2009). The FAO supported an early effort to outline best practices for performing acoustic surveys in European waters (Bazigos, 1981). An important consideration for all users of acoustic technologies who are interested in quantifying biological resources is the successful and frequent completion of a system calibration, and a recent effort was made to summarize the best practices for a variety of contemporary acoustic devices (Demer et al., 2015). Finally, common terms and expressions encountered in describing acoustically sensed distributions of animals with underwater acoustics can be found in the first table in MacLennan et al. (2002), and we encourage all interested readers to become familiar with these terms and their interdependencies.

3 STATISTICAL DESIGN (P.J. SULLIVAN)

Acoustic surveys have a variety of objectives ranging from observations of animal behavior, predator-prey and biotic-abiotic interactions, to marine resource assessments. In all cases, the survey results are for the survey area and time period. For assessment surveys, define the sampling area with consideration to the potential distribution of the target species at the time of the survey, the acceptable estimation uncertainty, and ultimately the availability of ship time and other survey resources. When possible, efficiently and accurately conduct assessment surveys of aggregated monospecific stocks, e.g., when the target species is spawning.

A critical first step in the sampling design is to understand the spatial distribution of the target organisms (Gunderson, 1993), when the survey is to be conducted. Often, this knowledge is gained iteratively from the literature, characterizing potential habitat (e.g., Zwolinski et al., 2011; Demer et al., 2012), and adaptive sampling. Initial surveys should be considered exploratory, to identify the geographic, bathymetric, and oceanographic limits of the target population, and its diel and seasonal behaviors. Then, use this information to ensure that the survey area spans the entire stock, so the estimated population biomass is unbiased.

For the biomass estimate to be usefully precise, ensure that the acoustic and trawl samples are sufficient in number and location relative to the population size and distribution. Again, this optimization may require knowledge gained from an exploratory survey. In general, however, allocate the available sampling effort mostly to the regions with highest animal densities. Without prior information about the stock distribution, adaptively move, extend, and add transects to span the animal distributions, and vary transect spacing inversely to the regional animal density.

Consideration of the potential distribution of the target species is critical to a robust survey design and estimate of density or abundance.

Unbiased estimates of abundance require that samples be taken under a simple random sampling design, or randomly sampled parallel transects when using cluster sampling, or in situations where no correlative processes are likely to cause bias when sampling systematically laid out points or transects. The sampling design will influence estimates of mean density and global abundance regardless of the statistical approaches used, be it standard estimates of the mean and variance assuming independent and identically distributed input or even when a geostatistical approach is used that assumes autocorrelation in the observations. Here we demonstrate how certain sampling patterns on reefs may over estimate abundance and how that can be remedied by employing either a random, stratified or systematic sampling design for data collection.

3.1 Basic Summary Statistics

It is useful to review some of the basic summary statistics that we use to characterize populations. These include:

Mean – Average Density	$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$
Variance – Variation in Density	$s^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \bar{x})^2$
SD – Standard Deviation – Variation in Density in Units of the Mean	$s = \sqrt{s^2}$
SE – Standard Error – Variation in the Mean Density	$s_{\bar{x}} = s / \sqrt{n}$ $= SE(\bar{x})$

where *x* is a measure of density (e.g. number of fish per unit area) and *n* is the sample size. These basic statistics rely on an unbiased sample taken through Simple Random Sampling. In Figure 3-1 an idealized map of relative changes in fish density is provided simulating a situation where fish are gathering around some attractor, like a reef. If the goal is to estimate the average density of fish for the region, or to take that density per unit area and scale up to the total area, then simple random sampling and the equations above will provide an unbiased estimate (Figure 3-1). The sample locations here were generated using a uniform distribution over easting and then northing (as might be applied to a Universal Transverse Mercator projection of a region). To get an unbiased sample each region must have an equal probability of being sampled. There is a tendency for many professionals to spend more time in the areas where fish density is highest. Of course, fishers who target fish aggregations do this too. However, in surveys for determining an overall mean, it is just as important to know where the fish are not and thus to gain a representative sample.

In surveys for determining an overall mean, it is just as important to know where the fish are not and thus to gain a representive sample.

3.2 CLUSTER SAMPLING

In the case of gathering acoustic estimates, it is often easier to take the samples along a transect rather than at specific isolated points. In that case, the observations taken along each transect are not independent of one another in terms of statistical sampling. There is a correlation in how they are taken. There may also be a correlation in what is observed. To keep this correlation from sneaking into the estimate and potentially biasing the results, one can treat each transect as an observation (as long as the transects are laid out in a parallel simple random or systematic design). In such instances we can calculated a weighted estimate of the mean where the weights are determined by the length of the transect and the effective sample size is then the total number of transects (and not the total number of observations along each transect summed over all the transects). This method, outlined below, can be found in several statistical survey design textbooks including *Elementary Survey Sampling* 7th Edition by Scheaffer et al. (2012), (although earlier editions will suffice for this estimation method).

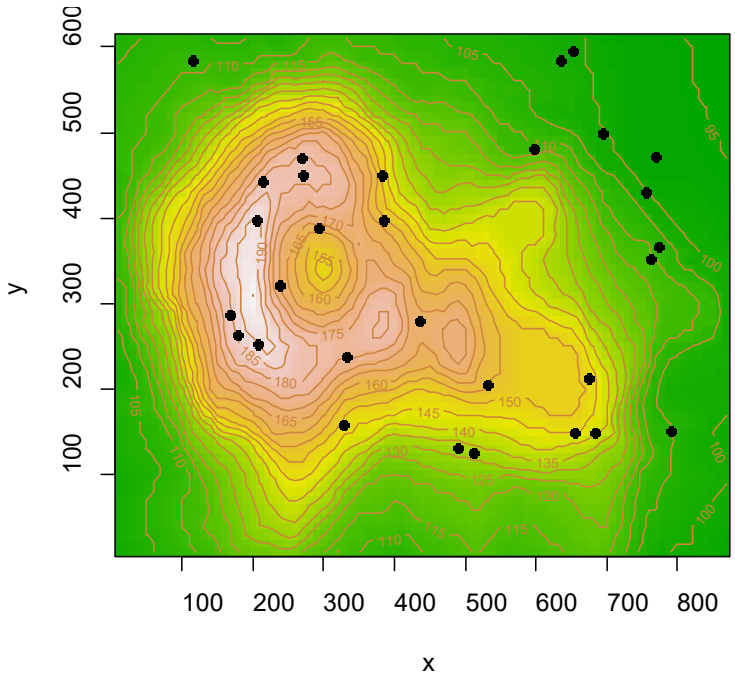


Figure 3-1. A map of fish abundance over a hypothetical sampling domain. Points represent locations of observations. Interpolated contours show magnitude of abundance values (green for low values to white for high values). Random sampling on an autocorrelated process, such as fish density on a sea mount, results in an unbiased estimate of mean density. Samples locations need to unbiasedly represent both areas of high fish density as well as areas of low fish density if the mean is to be used to expand to total abundance or average mean density over the area.

$$\bar{z}_{clu} = \sum_{i=1}^{n_T} x_i \Big/ \sum_{i=1}^{n_T} m_i$$

$$s_{clu} = \sqrt{\frac{1}{n_T - 1} \sum_{i=1}^{n_T} \left(x_i - \bar{z}_{clu} m_i\right)^2}$$

$$SE(\bar{z}_{clu}) = \frac{1}{\bar{m}} \frac{s_{clu}}{\sqrt{n_T}}$$

where x_i is the number of fish summed over transect i and the m_i is the number of sample units in transect i (basically the length of the transect). The term n_T represents the total number of transects and thus is the effective sample size while z_{clu} represent fish density per unit area (where unit area is determined in the specification of m). This sampling design had been used to estimate mysid (opossum shrimp) densities in Lake Ontario (Canada and USA) by researchers at Cornell University as shown below (Figure 3-2).

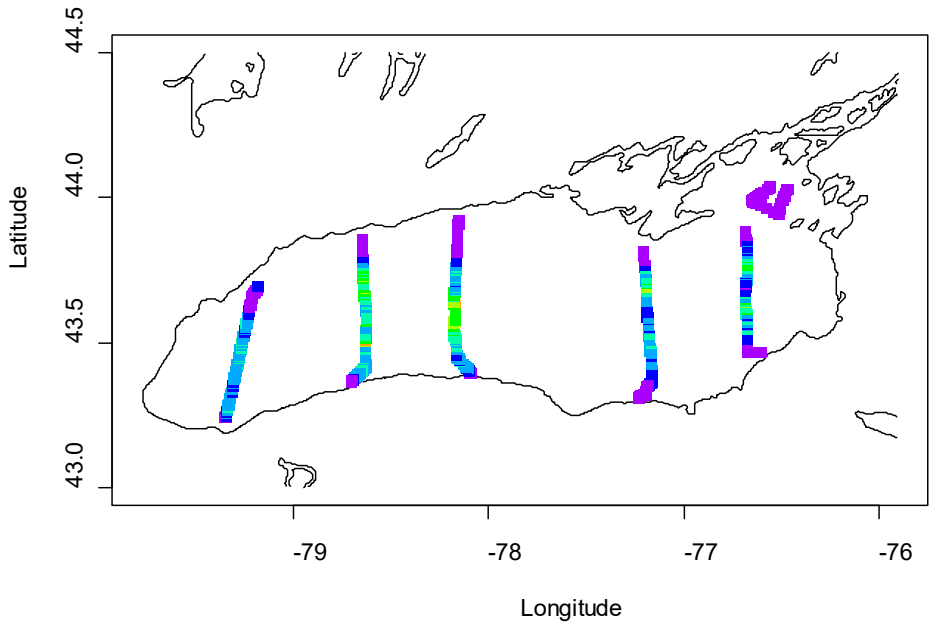


Figure 3-2. Changes in relative density of mysid shrimp along acoustic transects in Lake Ontario. Samples are taken along a transect, so a cluster sampling approach is appropriate for statistical analysis. The transects are then the effective sample unit and the averages for each transect are weighted to compute the global mean.

3.3 Estimation Methods

There are a number of approaches that one can use to estimate abundance (assuming an appropriate sampling design), but each method carries assumptions that must be recognized. The different estimation methods reflect, in some sense, different paradigms for how we view the world. The two methods discussed previously only assume that the data are taken through a random sampling design. These are called design-based approaches. However, one may wish to apply a model such as, for example, a linear or nonlinear regression model or a geostatistical spatial correlation model. These would be referred to as model-based estimates. In such instances one further assumes that the model correctly represents what is going on in the system. Such an assumption may seem reasonable, but care should be taken in recognizing the significant constraints (or perhaps expansiveness of the belief) this engenders.

There are a number of approaches that one can use to estimate abundance (assuming an appropriate sampling design), but each method carries with it assumptions that must be recognized.

Consider the overly simple, extreme case, shown below where fish abundance increases linearly from west to east (with no variation). A simple random sample may be taken, as shown by the circles overlaid on the line. An estimate of the mean and standard error will appropriately and unbiasedly estimate the actual mean density and characterize how that mean will vary under repeated random sampling of the system. The global abundance can similarly be calculated by an area expansion. But, what if we applied a linear regression to this data and calculated the mean density over the whole region of equivalently total abundance (Figure 3-3). The estimate of the mean fish density that we would get would be very similar to that using the earlier method, but the variance would be zero! This is because our belief in what the model line provides us is very high and of course in this over simplified simulation it is perfect.

How often are our assumptions perfect? The resulting estimates are shown in the accompanying table (Table 3-1).

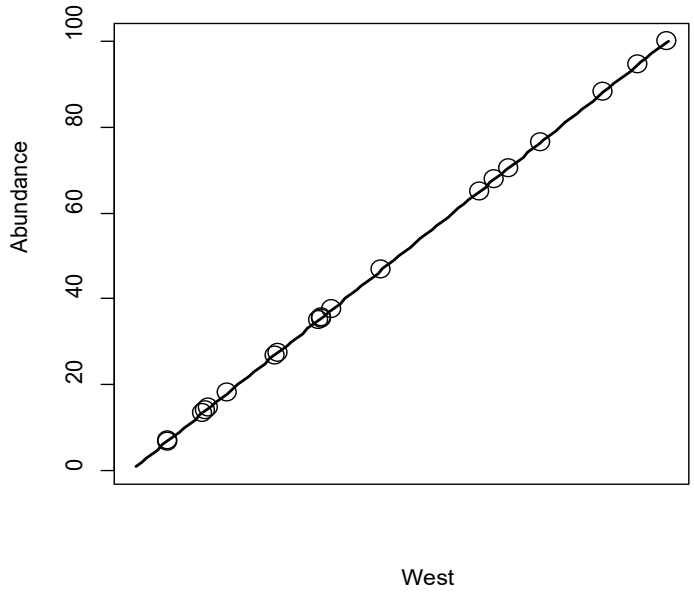


Figure 3-3. Abundance of an organism calculated along a series of transects distributed west to east in a sampling domain. Estimated mean and standard error are presented for random sampling and linear model estimation methods, providing a hypothetical linear trend in fish abundance. Randomly sampled points result in a mean and variance that are consistent under repeated sampling. Assuming a linear model imposes information (which may or may not be valid) on the estimate, in this case, the linear trend is assumed to be true results in an exact estimate with zero variance. How often is such an assumption valid?

Table 3-1. Estimated mean and standard error assuming random sampling and linear model of an acoustic survey using parallel transects.

Parallel Transect Survey	Mean	SE
Mean – Random Sampling	51.2	6.0
Linear Model	50.5	0.0

Another model-based method is a geostatistical method known as kriging, where the autocorrelation between points is modeled and this model is used to derive a weighted estimate for each point in the system (X in the case of the figure below, but more generally the spatially interpolated estimates of all of the points in the region). People often erroneously assume that a good survey design is not needed when a geostatistical method such as the one described here is applied. But, that is not the case. Consider trying to estimate the average elevation of a mountain range by sampling only the elevations at the peaks (Figure 3-4). Even a geostatistical interpolator would not be able to accurately estimate the elevations in the valleys with such information.

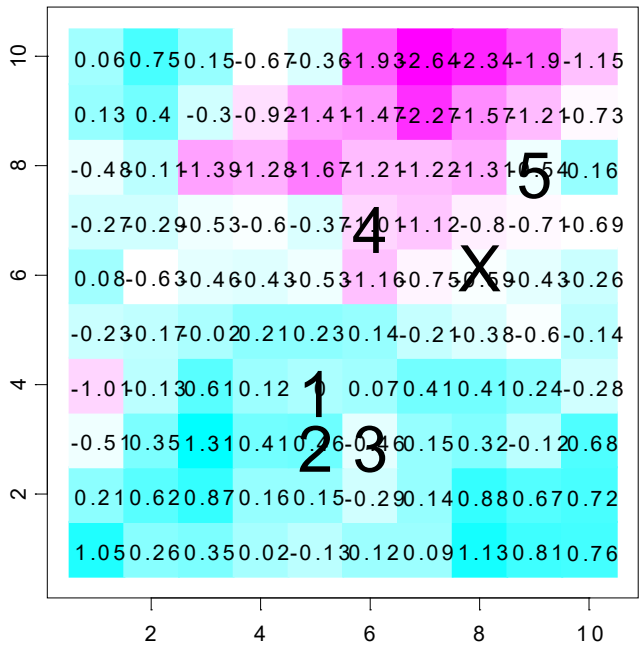


Figure 3-4. An example domain with each cell showing the value of response and corresponding color (magenta to cyan). Samples of the distribution are taken at 1, 2, 3, 4 and 5. The samples are used to estimate the value at X. Hypothetical variation from the mean in fish density. Geostatistical methods, such as kriging, spatially interpolate, in other words estimate, the value at a point X based on samples, taken at locations 1 through 5 say, whose values are used to determine a weighted average, where the weights are an inverse function of the distance to the point being estimated while accounting for correlation between sample points (i.e. samples 1-3) that are close together.

$$\hat{W}_{s^*} = \sum_{i=1}^{n} \lambda_i W_{s_i}$$

$$\boldsymbol{\lambda} = \mathbf{K}^{-1}\mathbf{k}$$

The formula above describes the estimate of fish density *W* at some new location *s** using a weighted average of the observations W_s taken at other locations s_i. The weights λ are a function of the correlations ***k*** between the observed points and the point to be estimated and the inverse of the correlations ***K*** between each observation and each other observations. The correlations themselves are typically characterized as a function of the distance between points.

3.4 Example Application to Reveal Implications of Sampling Design Assumptions

Consider the survey experiment conducted by Kevin Boswell and Allison White (Florida International University) on several reefs off the east coast of Florida to explore this problem. Note that two survey designs were employed. One is a parallel transect design along the lines of what we've discussed earlier. The second is what might variously be called a "flower" or "star" survey design, which is often employed but may lead to biased estimates as we shall see (Figure 3-5).

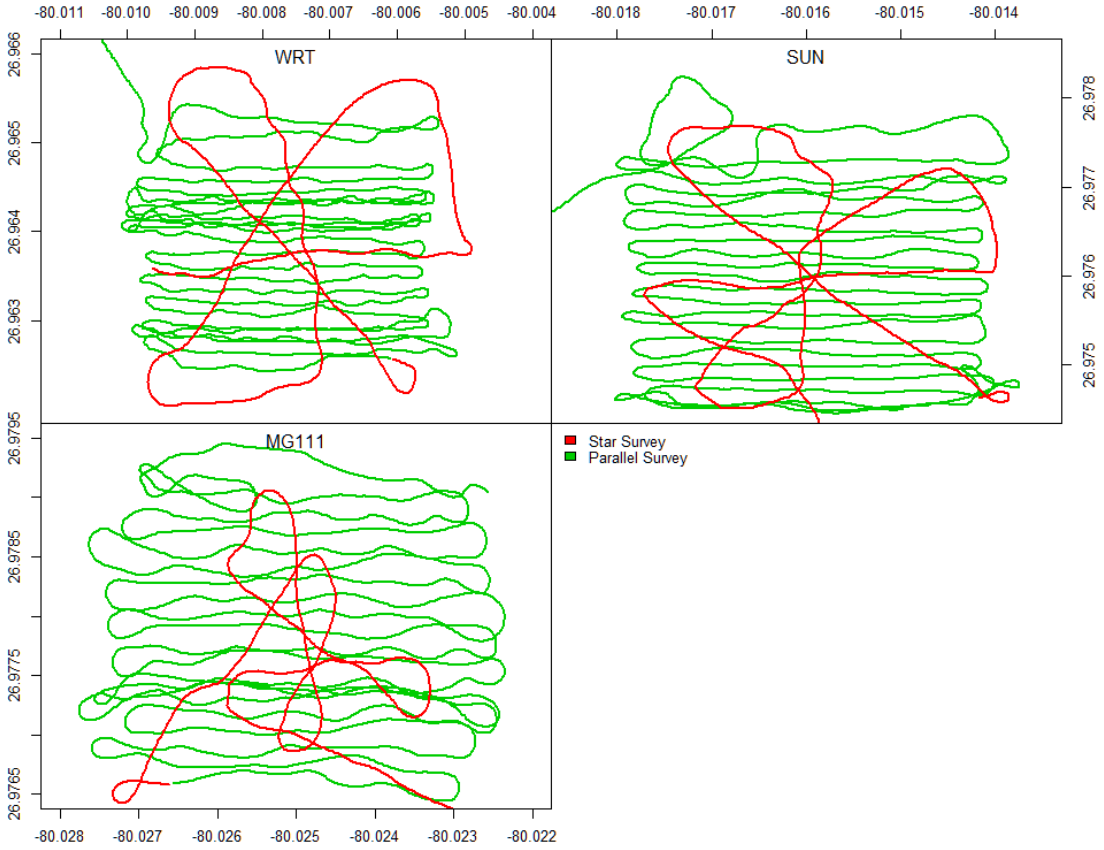


Figure 3-5. Example survey designs in study area MG111 demonstrate acoustic data collected using a parallel transect design in contrast to a "flower", also known as "star", design (acknowledgements to Kevin Boswell FIU for use of this data). Red line represents the "flower" or "star" pattern centered on the reef. Green is systematic parallel lines also centered over the reef.

Consider an application to the MG111 site. Below is shown a bubble plot that indicates changes in relative fish density along each transect. Further note, the higher density area seen in the center of the survey region (Figure 3-6). We shall now go through a series of estimators that make different assumptions about how the data were collected relative to how the estimates are calculated. First, let's just apply a simple mean and standard error calculation to each set of samples. The observations are provided as the $\log_e$ of the Nautical Area Backscattering Coefficient (NASC) often denoted as sA.

We note that the simple mean is not appropriate because the individual points were not taken via simple random sampling. Nevertheless, we see that the two means are different. We further note that the standard error for the flower design is higher. This is not so much due to the design itself, but the reduced sample size (number of transects) used in this particular experiment. Still the comparison is instructive.

Now consider an application of the cluster sampling method, described above, to the parallel transect data. Note that this application is appropriate as the data represent random or systematic parallel transects and the number of transects and the number of observations per transect are appropriately accounted for.

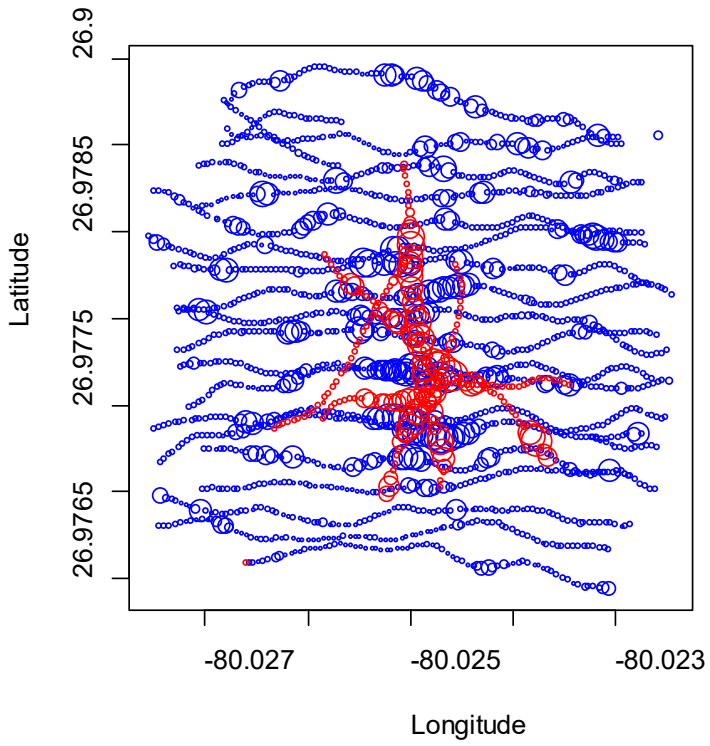


Figure 3-6. Bubble plot showing variation in fish density for study area MG111 shown in the previous Figure 2-5. Size of symbols is proportional to magnitude of abundance. Note the higher concentration (over sampling) of observations taken on the high density areas using the "flower" design (red) in comparison to the parallel (blue) survey design.

Table 3-2. Comparison of means and standard errors of fish density from two survey designs over a reef (MG111 study area) described above. Note the (biased) higher mean associated with the "flower" design. The different in standard error is due to sampling intensity.

Density (Log NASC)	Mean	SE
Parallel Transect Survey	3.72	0.05
Flower Transect Survey	4.91	0.21

Note, perhaps not surprisingly (as mathematically, the calculations of the average are equivalent), that the cluster sampling estimate matches that for the simple mean. The standard error estimate is now appropriate and represents how the estimate itself would vary under repeated sampling. Let's now apply a geostatistical model-based estimation procedure to the parallel transect data. First, we must estimate the variogram (spatial correlation) model (Figure 3-7).

Table 3-3. Mean and standard error for three sampling designs to estimate abundance of fish over a reef (MG111 study area). Here a statistically more appropriate cluster sampling analysis has been applied. The mean is identical to that derived assuming the data are from a random sample, however the standard error of the estimate has increased and is now more realistically represents the correlation in how the samples were taken, namely along transects.

Density (Log NASC)	Mean	SE
Parallel Transect Sampling	3.72	0.05
Flower Transect Sampling	4.91	0.21
Cluster Sampling	3.72	0.11

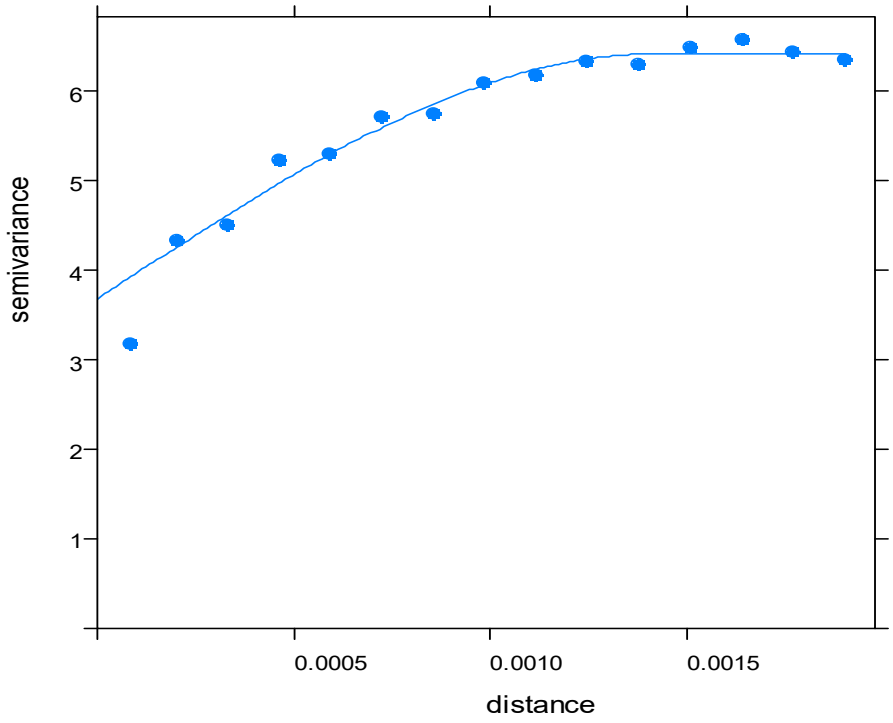


Figure 3-7. Sample variogram modeling of the spatial autocorrelation between points with distance of the parallel transect design has been applied to the transect observations taken from the MG111 reef area.

The variogram model can be used to estimate, through geostatistical spatial interpolation as described earlier, density (in log NASC) for each location in the region (Figure 3-8). Similarly, we can estimate variance of the predictions for each location in the region.

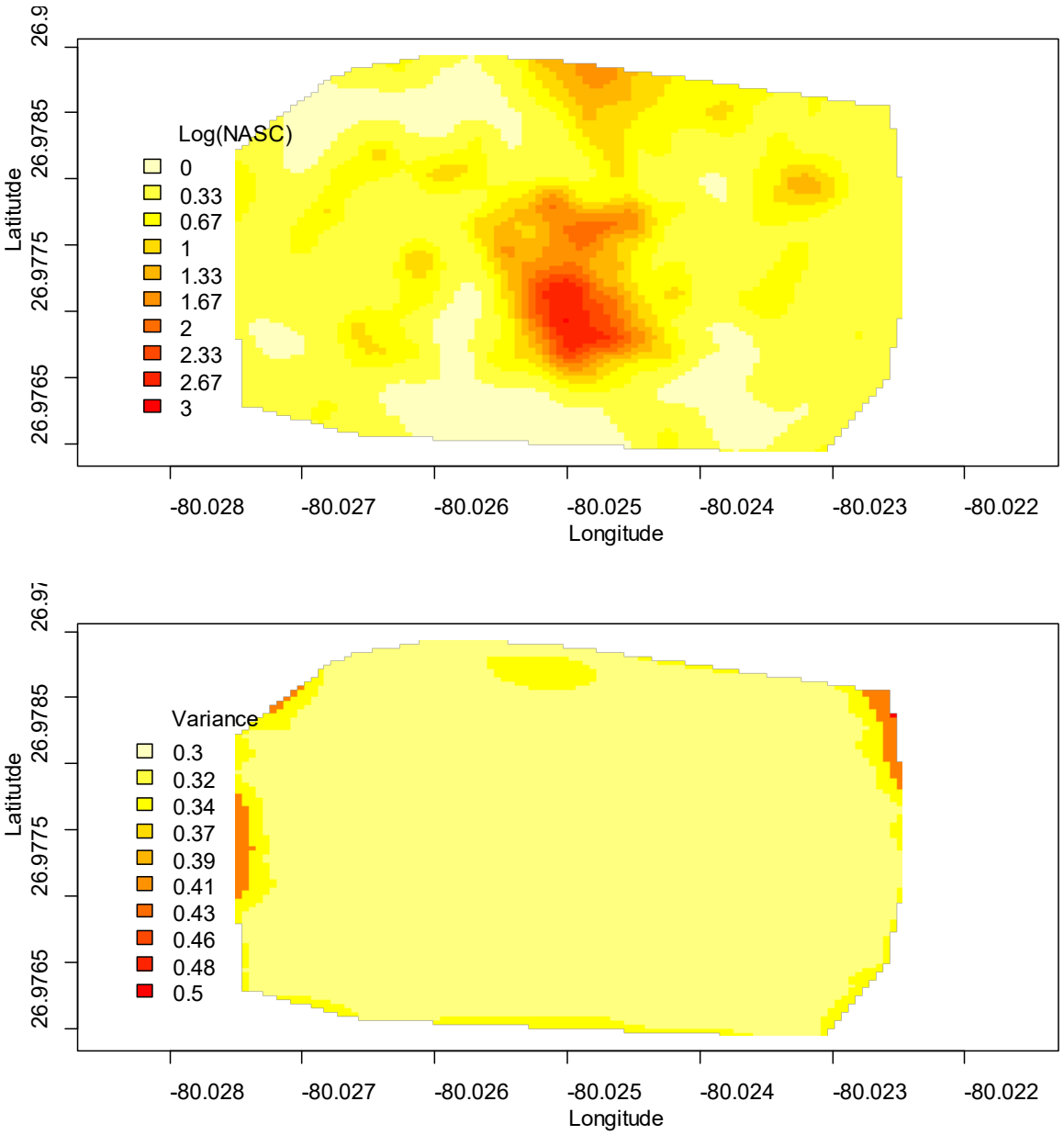


Figure 3-8. The variogram model was used to conduct a geostatistical analysis as applied to the data collected using the parallel transect design. Spatial interpolation using a kriging system and the spatial autocorrelation of sampled values from the parallel survey design of the MG111 site are shown for predicted density (log NASC) values (top figure) and variance in predictions (bottom figure).

Table 3-4. Mean and standard error for the survey designs over a reef described above using various forms of sampling statistics from the surveys. The geostatistical estimates on the data collected from the cluster transect design are provided for comparison. Note the similarity to the mean assuming random sampling and the mean under cluster sampling. The standard error is quite lower because, as discussed earlier, we are imposing some information (in this case a variogram model) to globally summarize our findings.

Density (Log NASC)	Mean	SE
Parallel Transect Sampling	3.72	0.05
Flower Transect Sampling	4.91	0.21
Cluster Sampling	3.72	0.11
Geostat Parallel	3.70	0.02*

Again, note the similarity in the estimates of mean log relative density (Table 3-4. Mean and standard error for the survey designs over a reef described above using various forms of sampling statistics from the surveys. The geostatistical estimates on the data collected from the cluster transect design are provided for comparison. Note the similarity to the mean assuming random sampling and the mean under cluster sampling. The standard error is quite lower because, as discussed earlier, we are imposing some information (in this case a variogram model) to globally summarize our findings., where the mean and standard error for the survey designs over a reef is described above using various forms of sampling statistics from the surveys. The geostatistical estimates on the data collected from the cluster transect design are provided for comparison. Note the similarity to the mean assuming random sampling and the mean under cluster sampling. The standard error is quite lower because, as discussed earlier, we are imposing some information (in this case a variogram model) to globally summarize our findings. Note the standard error is lower than that based on the simple mean or cluster sampling. That is in part due to the model-based assumption, is also in part due to the fact that when we use the estimated variogram parameters to characterize the correlation we used those estimates without error, but is mainly due to not accounting for the spatial correlation in how the estimates are derived. Here I simply averaged the variances. There are better ways to do this, but for now we can compare within methods in a relative way. To see examples of how to include error from various intermediate steps in determining the overall variation using a hierarchical Bayesian approach to acoustic data please refer to the work of Sullivan and Rudstam (2016). Further note, the relative uniformity of the variance in the predictions in the variance figure due to the uniform coverage of the sampling design.

Consider now a geostatistical approach applied to the flower survey design. Both the spatial mean estimates and the spatial variances are shown (Figure 3-9. Spatial interpolation of the MG111 site for density (Log NASC) value using a kriging system and the spatial autocorrelation of sampled values using the flower survey design. Note the design misses observing fish away from the center of the survey, and the variance in the predictions increases as we move away from the center of the survey.), in which spatial interpolation of the MG111 site for density (Log NASC) value is derived using a kriging system and the spatial autocorrelation of sampled values using the flower survey design. Note the design misses observing fish away from the center of the survey, and the variance in the predictions increases as we move away from the center of the survey

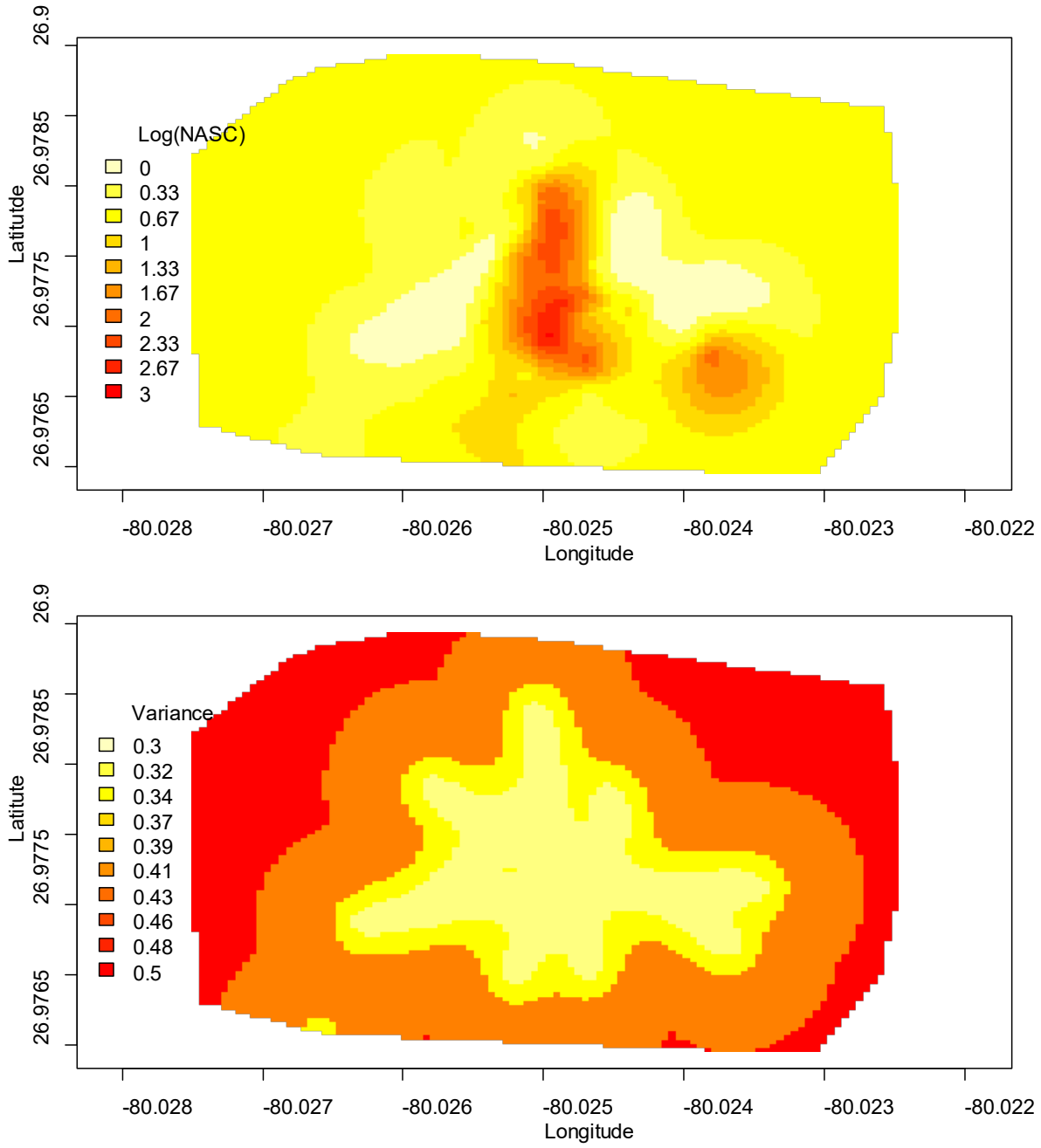


Figure 3-9. Spatial interpolation of the MG111 site for density (Log NASC) value using a kriging system and the spatial autocorrelation of sampled values using the flower survey design. Note the design misses observing fish away from the center of the survey, and the variance in the predictions increases as we move away from the center of the survey.

Note that the flower design is again biased high. The standard error is low for the same reasons as given above, but are still comparable in a relative sense between methods (Table 3-5). Further note, how the variance increases in the spatial variance figure as the prediction locations move away from the central area where the observations were taken.

Finally, consider two sets of predictions (parallel and flower) using a Generalized Additive Model (GAM). The GAM creates a nonparametric smoothed regression curve through the observations to derive an overall estimate (Table 2-6). We shall show first the application to the parallel survey design and then to the flower survey design.

Table 3-5. Mean and standard error for the survey designs over a reef described above using various forms of sampling from the surveys. The GAM applied to the parallel transect data again gives estimates of the mean that are similar to those derived using other methods. The standard error is lower because of the structure added by the model. One should recognize that assuming a model, while sometimes appropriate, does impose information on the estimates.

Density (Log NASC)	Mean	SE
Parallel Transect Sampling	3.72	0.05
Flower Transect Sampling	4.91	0.21
Cluster Sampling	3.72	0.11
Geostat Parallel	3.70	0.02*
Geostat Flower	4.14	0.03*
GAM Parallel	3.70	0.003**

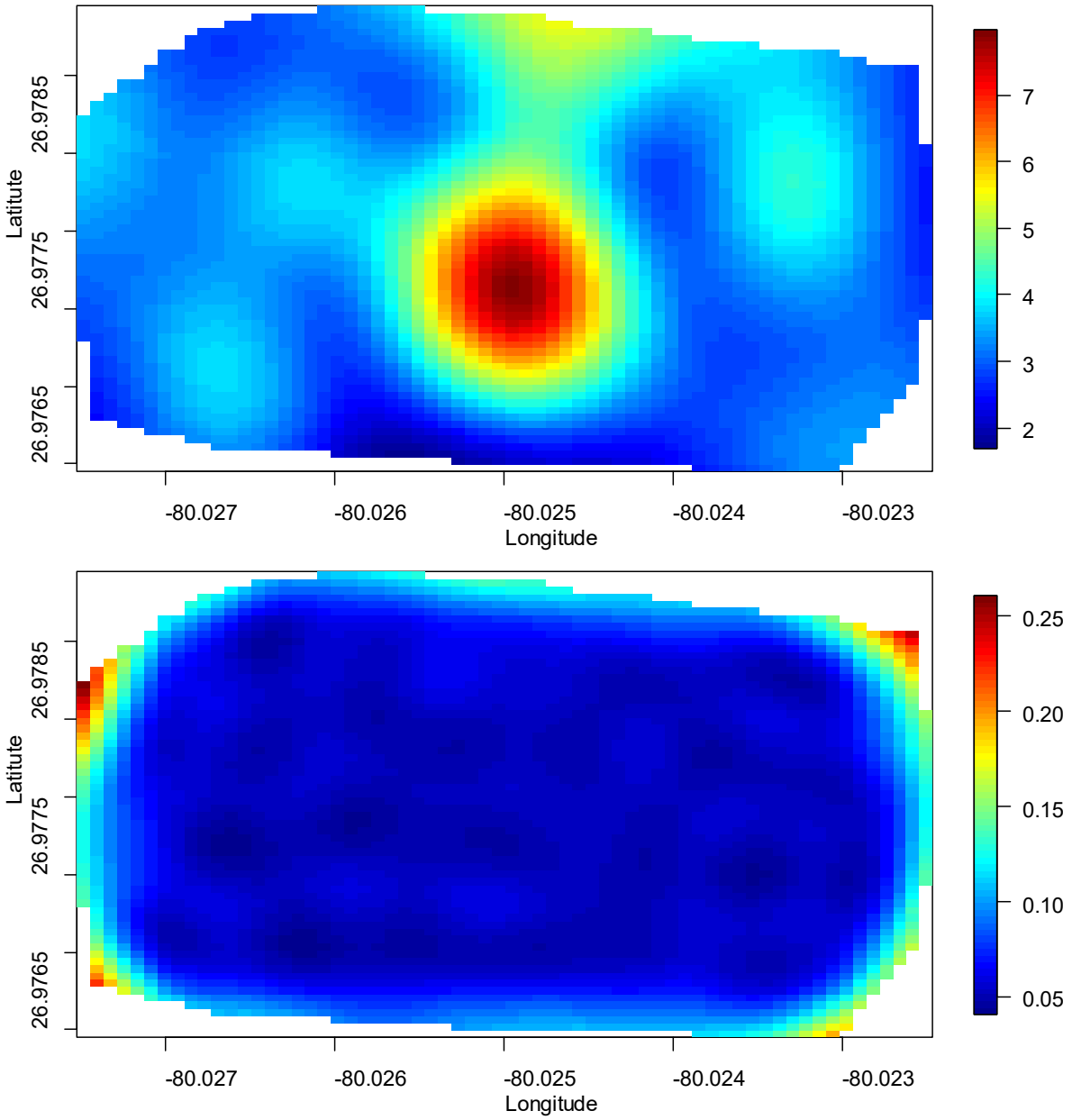


Figure 3-10. Spatial interpolation of the MG111 site for Log (NASC) value using a generalized additive model (GAM and sampled values from the parallel survey design. Predictions resulting from a GAM applied to the "flower" transect data. The predicted density (log NASC) values (top figure) and variance in predictions (bottom figure) are shown here. Note that poor sampling design coverages leads to poor spatial estimates.

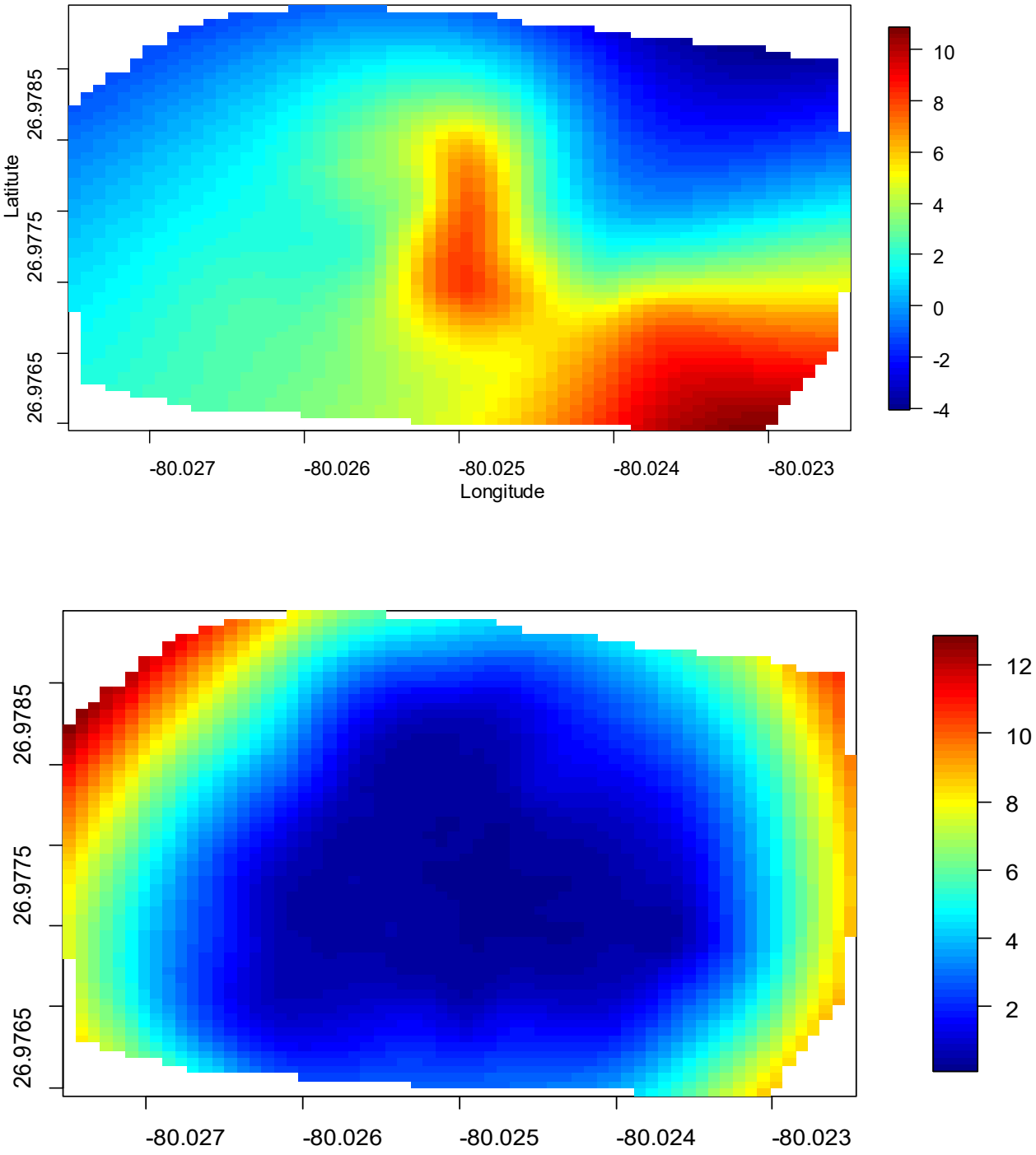


Figure 3-11. Spatial interpolation of the MG111 site for Log (NASC) value using a generalized additive model (GAM and sampled values from the flower survey design. The predicted density (log NASC) values (top figure) and variance in density (bottom figure) from a GAM applied to the "flower" transect data. Note predictions resulting from a GAM applied to the "flower" transect data show poor sampling design coverages leads to poor spatial estimates while variance increases as the sample size decrease.

Table 3-6. Mean and standard error for the survey designs over a reef described above using various forms of statistical sampling and model-based estimates from the surveys. The GAM applied to the "flower" transect data results in bias estimates of the mean, however this time the biases are in the opposite direction and the GAM model slopes to zero on the edges. The standard error is lower because of the structure added by the model.

Density (Log NASC)	Mean	SE
Parallel Transect Sampling	3.72	0.05
Flower Transect Sampling	4.91	0.21
Cluster Sampling	3.72	0.11
Geostat Parallel	3.70	0.02*
Geostat Flower	4.14	0.03*
GAM Parallel	3.70	0.003**
GAM Flower	2.54	0.003**

Note again the general consistency in the estimates based on the parallel survey design. We see some departure from the flower mean in the GAM estimate as the smoothed fit appears to taper off to zero at the edge of the range (Figure 3-10 and Figure 2-11). Again, please note that the standard errors as computed for both the geostatistical and GAM methods represent the square root of the simple averages of the prediction variances under each method (Table 3-6). Simple averaging does not take into account that the predictions themselves are autocorrelated in space and while this spatial correlation should be adjusted for in the estimates of the standard errors when doing a global estimate, we did not perform that calculation here.

3.5 SUMMARY OF SURVEY DESIGN CONSIDERATIONS

Survey design matters, and should provide representative sampling across the domain, rather than concentrating only on your perceived area of interest.

Coral reef ecosystems present a complex seascape to design a robust survey for assessing abundance of reef fishes. To summarize: survey design matters and should provide representative sampling across the domain, rather than concentrating only on your perceived area of interest (e.g., a reef). Different estimation methods have their strengths and weaknesses, however model-based estimation methods make a broader set of assumptions and those assumptions impose information that may be erroneous and lead to biases. To determine the best estimation method to employ and how to appropriately design a survey consider what the objectives are for the study. Is it to estimate density or abundance? Is it to study behavior? These two objectives might lead to very different sampling designs and analysis methods.

Finally, keep in mind the estimation of the variance and standard errors. As demonstrated in the caveats given in the discussions above, determining the variance of the estimates can sometimes be tricky. Nevertheless, simple exercises like plotting the spatial prediction variances and looking at relative changes in variance under alternative survey design assumptions can be informative and highlight how a survey or an analysis might be improved.

In the end, even a sophisticated data analysis package cannot compensate for poor collection methods or poor survey design. A sampling design that allows equal representation of all elements of the system

is important. It is just as important to collect information from areas with low fish density as it is from areas with high. More focused sampling designs that include higher sampling of high density areas can be achieved through pre-stratifying sample allocation. One can put more samples into what has, prior to the survey, been defined as a high density area as long as samples have also been included in low density areas. Stratification must take place before the survey, not after, to achieve unbiased estimates.

4 ACOUSTIC SURVEY OPERATIONS (D.A. DEMER AND K. BOSWELL)

The survey operations and survey design are driven by the mission priorities and operational objectives, and will likely include the integration of various sampling technologies (Section 13.1 provides a summary of mission priorities and operational objectives). Survey platforms come in many configurations from fully instrumented fisheries survey vessels (FSV) to basic vessels of opportunity where transducers have to be mounted from the vessel by the operators. In the latter case, depending on the goals of the survey, resources available, and environmental conditions, transducers may be mounted from a rigid pole or affixed to a towbody. As presented in the Section 10 and 12 case studies, acoustic technology can also be deployed on stationary and autonomous platforms. In all cases the operators must be aware of the proper installation of both the transducers and the transceivers. In this section, we focus primarily on the deployment of echosounders on vessels for the purpose of conducting a spatial survey to estimate the abundance of a reef fish population. Sections 9-12 in this report provide discussions on deployment strategies to achieve various operational objectives, while this section summarizes some of the basic considerations for conducting acoustic survey operations.

Survey operations and survey design are driven by the mission priorities and operational objectives, and will likely include the integration of various technologies.

4.1 POLE OR HULL MOUNTING OR TOWBODIES

When hull-mounted transducers are not available on the survey vessel (Figure 4.1), the two main approaches to deploy a transducer is with a secure pole deployment (Figures 4.2, 4-3, 4-4) or mounted within a towed body (Figure 4-5). The simplest pole mount options include a single transducer mounted to a flange at the end of a pole (Figures 4-3, 4-4). Depth of the transducers should be determined by the sea conditions and draft of the vessel that may generate wake and bubbles. When multiple transducers are needed, a mounting plate or fared body can be used to house transducers to reduce drag and eliminate cavitation at the transducer face (example images). In both cases, care needs to be taken to ensure that cables are protected and secured within the pole, or along the outside of the pole to reduce the potential for cables to vibrate (i.e., strumming) when the vessel is under way. It has been previously demonstrated that cables can weaken overtime when strumming is not eliminated. A good rule of thumb is to secure the cables every 25-50 cm.

When the only option is to put the transducers on a towed body (for example, when the vessel does not permit permanently affixing mounting brackets or cannot structurally support a reinforced mount), a towbody may be used. Several commercial towbody options exist if resources are available, however a simple structural design can also suffice (Figure 4-5). When a towbody is used, the echosounder cables

also need to be secured to prevent physical damage from strain and pinching/cutting. Often when using a towbody, the speed of the vessel will determine the depth at which the towbody flies in the water column. Consequently, when the vessel slows or performs a turn the towbody will sink. Thus, it is important to be mindful of the water column depth and any potential underwater hazards when adopting this survey approach.

Figure 4-1. A hull-mounted five-frequency transducer array (far to near: Simrad ES70-7C, ES18-11, ES200-7C, ES38B, ES120-7C). The array is temporarily attached to the hull using angle steel that is bolted through the fiberglass. The cables are routed through a standpipe with a 3" diameter ball valve to the echosounder transceivers. The laminated HDPE fairing redirects bubbles away from the transducers.

Figure 4-2. A retractable bow mount for deploying a down-projecting 200-kHz split-beam transducer (orange cylinder), side-projecting 120-kHz split-beam transducer (orange boat shape), and two 500-kHz multi-beam transducers (black, only port-side is fully visible). A sensor package mounted on top of the apparatus (black box) provides attitude, heading, heave, position, and velocity information. To deploy, the transducer array is pushed forward, rotated down into the water, and stabilizing struts attach to the gunwale on each side of the bow.

Figure 4-3. A portable four-frequency transducer array (top-bottom: Simrad ES70-7C, ES38-12, ES120-7C, and ES200-7C). To deploy, the array in lowered into the water such that the transducers are > 1-m deep and projecting downward, and stabilizing lines are ratcheted tightly, fore and aft.

Figure 4-4. A transom-mounted retractable pole with 120-kHz split-beam transducer (Simrad ES120-7F). For deployment, the pole is lowered into the water and locked with a pin such that the transducer is deeper than the propeller, to reduce bubble noise, and project downward.

Figure 4-5. A simple towbody towed from the side of a research ship. The simple frame holds a single transducer. The rear tail stabilizes the towbody while underway.

4.2 POWER REQUIREMENTS AND GROUNDING

When installing an echosounder system onto a new vessel, there are multiple elements which need to be considered to ensure proper installation that will yield high-quality data. First and foremost among these is access to a clean and stable power source. In many cases, a 12 VDC power supply will often provide the cleanest power aboard a survey vessel. On smaller vessels, an inverter-generator can provide consistent clean power for many hours before refueling is required. In the absence of a DC power source, some vessels may provide AC power regulated at 120 V (~60 Hz), which may impart electrical noise within the acoustic data.

Often a proper ground will help to eliminate sources of electrical noise, which are generally related to the vessel's electrical system; however, the effectiveness will be a product of the power source and the characteristics of each vessel. If grounding to the vessel is not effective, a grounding strap deployed overboard (immersed in seawater) can be effective to eliminate some of the observed electrical noise.

4.3 SURVEY AND VESSEL SPEED CONSIDERATIONS

The speed of the vessel during an acoustic survey will generally be dependent on sea state conditions, the selected deployment approach of the transducers (i.e. towbody, pole mount, hull mounted) and the vessel configuration. In both a pole mounted and towbody deployment, normal operating speeds ~7-11 km hr^{-1} (~4-6 knots) should result in high-quality data. In these two deployment approaches, greater speeds can result in increased bubble noise and cavitation at the transducer face if the transducers are

not properly enclosed in a faring. Often, a vessel with hull mounted transducers can operate at speeds nearly twice that of pole-mounted or towbody systems.

4.4 NOISE SOURCES AND INTERFERENCE FROM OTHER SYSTEMS

A variety of noise sources can be detected when installing an echosounder system aboard a survey vessel, regardless of the vessel class or purpose. Aside from the electrical noise mentioned in the previous section, the most common source of noise observed in an echosounder is the operation of other sensors installed on the ship. For example, the ship's depth finder which can overlap in frequency bandwidth with the installed echosounder can create persistent pulses observed as high-intensity responses radiating vertically through the echogram. Other sensors can also interfere with the echosounder systems and should be examined carefully through a systematic approach powering on/off devices to determine the prominent sources of interference. Depending on which sensors are identified as interfering, accommodations may be possible such as the use of an external trigger for multiplexing (i.e., transmitting at alternative times), or powering them down during acoustic operations.

4.5 GPS AND MOTION SENSORS AND OTHER ANCILLARY DATA

Precise position data is needed to add spatial context to acoustic data and permit the quantitative analysis for assessment efforts. At minimum, a WAAS-enabled Global Positioning System (GPS) should be available and connected directly to the echosounder to write position data to recorded acoustic data files. Most consumer-level GPS systems available today are WAAS-enabled and capable of outputting an ASCII format readable by the echosounders (e.g., National Marine Electronics Association format; GPGGA, HDT, etc.) through a serial communication protocol. It is important to take note of the correct port settings (e.g., baud rate, parity, etc.) to ensure successful port communication. In addition to vessel position, motion sensors can be useful to correct the acoustic data for the motion of the survey vessel and, by extension, the transducers. In general, this option is most effective for transducers that are mounted to the vessel (i.e., pole or hull mounted) and referenced to the vessel's center of gravity. A correctly configured and calibrated motion sensor will permit the integration of heading, pitch, roll and heave into the recorded acoustic data file.

Providing measured or estimated sound-speed measurements for the acoustic data is critical for accurately determining range of the target from the transducer. Similarly, temperature, salinity, pH and depth or pressure influences the rate of absorption of transmitted sound, especially at higher frequencies. Acquisition software from all manufacturers will require values for sound speed and absorption or environmental parameters from which the software will calculate the sound values. Most manufacturers for scientific echosounders require a single surface value. A surface conductivity-temperature-depth probe is most useful here. Full water column profiles can provide important information on water chemistry and potential stratification in temperature or salinity that could explain the distribution of biological organisms, or the transmission of sound through the watercolumn.

4.6 ECHOSOUNDER CALIBRATION

Calibrating the scientific echosounder (i.e. quantifying its operating parameters) is a fundamental requirement for surveys that collect acoustic measures for deriving quantitative abundance estimates. A report by the International Council for the Exploration of the Sea (ICES) Working Group on Fisheries Acoustics, Science and Technology (WGFAST) provides a recent update to the practice for calibrating a variety of sonars and echosounder systems (Demer et al., 2015). Further details on the echosounder configuration and calibration settings are also described in Section 6 on the Scientific Echosounder System. Here we outline the steps for calibrating echosounders and direct the reader to the report for additional recommendations for other sonars.

Calibrating the scientific echosounder is a fundamental requirement for surveys that collect acoustic measures for deriving quantitative abundance estimates.

Each survey or project should include a calibration each time the system is installed on a vessel or platform, or when a survey is conducted in a new temperature, salinity or depth regime. The purpose of the calibration is to establish appropriate gain and transducer beam pattern parameters accounting for power sources, which allows for monitoring of instrument performance, degradation or component failure. Depending on the echosounder manufacturer, the acquisition software may contain automated routines for conducting a standard sphere calibration. In its most simple form, the calibration procedure involves suspending a metal sphere with known acoustic backscatter properties in the acoustic beam and comparing the theoretical target strength with observed target strength. The spheres are typically copper or tungsten carbide with a cobalt binder, with material and size depending upon operating frequency (Table 4-1).

Table 4-1. Recommended calibration spheres for common echosounder frequencies. Spheres are made from copper (Cu) or tungsten carbide (WC).

Frequency (kHz)	Material and diameter
38	WC/38.1mm, Cu/60mm
70	WC/38.1mm, Cu/32.0mm
120	WC/38.1mm, Cu/23.0mm
200	WC/38.1mm, Cu/13.7mm

The sphere is suspended under the transducer using monofilaments and, if currents are present, a weight may be used to reduce unwanted movement (Figure 4-6). If the transducer is mounted on a pole, a single line suspended from a fishing rod is sufficient. If the transducers are mounted in the hull of the ship, three or more monofilament lines are needed to move the calibration sphere into the appropriate position in each transducer beam.

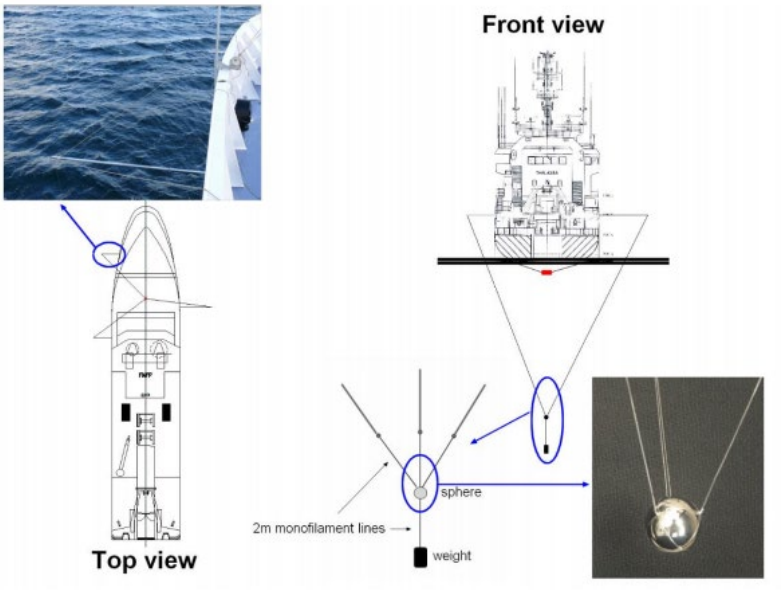


Figure 4-6. Three-line method for suspending a sphere under a hull-mounted transducer (from Demer et al. 2015).

Choosing a calibration location is as important as selecting the calibration sphere. The calibration is conducted using the same echosounder parameters as planned for the survey, including transmit power, pulse length and operating frequencies. Water temperature, salinity and pH measurements are used to calculate sound absorption and sound speed. The range to the sphere should be sufficient so that it is in the far-field of the transducer – usually greater than 10 meters. The watercolumn should be well mixed, with minimal fish, plankton or other targets that could interfere with the backscatter from the sphere. Temperature and salinity measurements through the watercolumn can be collected using a CTD or similar sensor to measure sounds speed. These measurements are used in the echosounder equations, but also for estimating the theoretical target strength of the sphere. NOAA's Southwest Fisheries Science Center Advanced Survey Technologies Program provides a web application for estimating theoretical target strength for spheres (https://swfscdata.nmfs.noaa.gov/AST/SphereTS/).

The sphere is lowered to a desired depth and maintained at a constant range from the transducer. Raising and lowering lines or moving the fishing rod with single monofilament moves the sphere slowly through the transducer beam to place the sphere on the acoustic axis. Depending on the acquisition software, the location of the sphere in the acoustic beam should be visible for real-time adjustment on split-beam systems. Record several hundred pings while on the acoustic axis. The sphere can then be moved slowly through the acoustic beam to measure target strength and characterize the shape of the acoustic beam off axis. Repeat the procedure for each transducer frequency. At the conclusion, the acquisition software may use the calibration results to automatically update the properties of the transducer during data logging. It is highly recommended to record all the output from the calibration routine so that it can be confirmed or used in the analysis and interpretation of the data.

5 DIRECT AND INDIRECT BIOLOGICAL DATA (C.H. THOMPSON)

To support the analyses and interpretation of acoustic data described in Sections 7 and 8, it is necessary to estimate the composition of fish species and/or the size distribution of the targets responsible for the acoustic signals being analyzed. Direct and indirect biological sampling is often necessary to validate the composition of acoustic backscatter measurements. There are situations where many species are present, and it may be difficult to apportion the acoustic scattering among species. In other situations, species can be segregated either by depth or geographic location or can be distinguished by properties of the acoustic scattering they produce. Multifrequency analysis and visualization of the echograms may also distinguish frequency dependence difference between species (e.g., Jech and Michaels, 2006), and wideband acoustic systems hold promise for improvements in acoustic species classification. At the time of this writing an ICES publication on target classification is in progress that summarizes methods of target classification (refer to http://www.ices.dk/community/groups/Pages/WGTC.aspx).

This section discusses methods for collecting physical or visual samples of the fish anticipated to be present (responsible for the acoustic signals) in data from an echosounder survey. These methods include physical sampling with nets, traps, or hook and line, and visual sampling by divers or camera systems. Biases inherent in any such sampling method should be minimized or accounted for to avoid misinterpretation of the echosounder data. Biases in species composition and size distributions can arise because of biases in susceptibility of fish present to the sampling gear used (catchability), behavioral response of the fish, mismatch between the sampling volume of the method compared to that of the echosounder, and for other reasons. An assessment of advantages and disadvantages of visual survey tools is reported in Yoklavich et al. (2012).

Similar principles should be applied to analysis of these data as those discussed by MacLennan and Simmonds (1992) for analysis of trawl samples supporting a traditional acoustic-trawl survey to determine the species and size composition of the local surveyed population. To estimate these compositions, if individual sample sites produce large numbers of samples, then species and size distributions from the sites can be averaged together. If, however, samples are sparse, then it is best to combine samples from all sites into a single distribution.

5.1 CAMERA SYSTEMS

Optical and acoustic sampling technologies are often complimentary, and camera systems are well suited to providing information on species and size composition of reef fish. Significant research has been performed on using underwater video systems for observing fish populations, including methods of estimating abundance. A good overview of methods

Optical and acoustic technologies are often complimentary, and camera systems are well suited to providing information on species and composition of reef fish.

and systems, and a wealth of literature references (Cappo et al., 2006; Somerton and Gledhill, 2005; Rooper et al., 2011). In relatively shallow and clear water, light levels during daytime are frequently sufficient to negate the need for auxiliary artificial lighting (Figure 5-1).

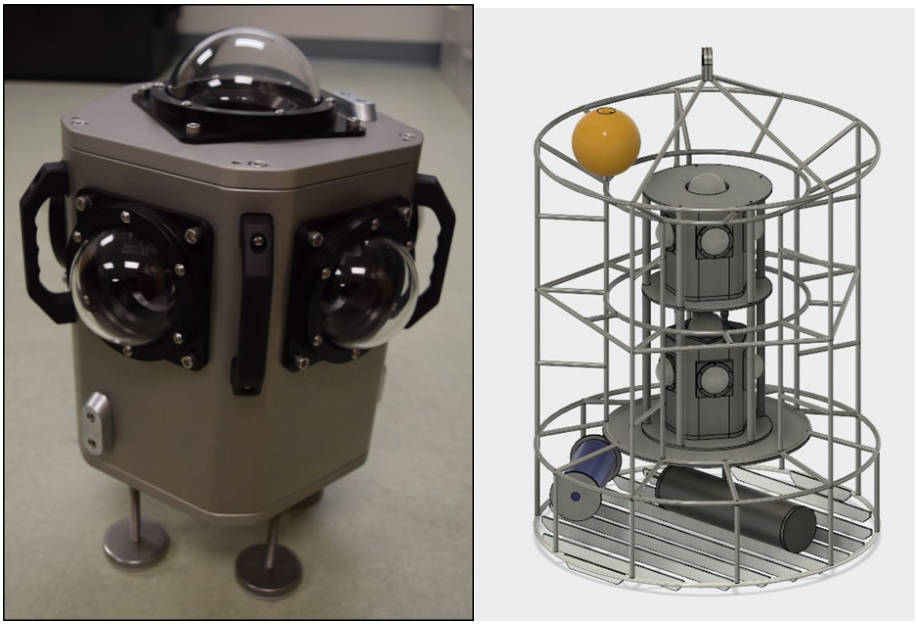


Figure 5-1. The camera system shown at left, recently developed at NOAA's Southeast Fisheries Science Center, Mississippi Laboratories, provides underwater video in a 360° circle around the camera system as well as a hemispherical overhead view. Identical units can be stacked vertically as in right image to provide synchronized and calibrated stereo video.

5.2 SPECIES COMPOSITION

Inexpensive underwater camera systems can be dropped to the seafloor, left to record for a period of time and then retrieved, are sufficient for sampling species composition. Biases using such stationary cameras arise due to the limited sample volume and time, which are small compared to the area typically covered in an acoustic survey. Cameras on the seafloor generally cannot provide good information on acoustic targets that are in the water column well above the seafloor, thus care should be taken to not misattribute the source of acoustic scattering to species that do not inhabit the volume sampled by the echosounder. Mobile camera systems, either towed or deployed on a remotely operated vehicle (ROV) or autonomous underwater vehicle (AUV), are capable of sampling a larger volume than stationary- or drop-camera systems but introduce additional biases due to behavior of the fish in response to the moving platform (Laidig et al., 2012). Some fish may avoid the platform while others may be attracted to it. Reactions may be species dependent and also dependent on light level, noise generated by the platform, how accustomed the population is to vessel traffic, and other variables. The variety of responses can make accurate estimates of species composition difficult and is a topic of current research in NOAA's Fisheries Untrawlable Habitat Strategic Initiative. Figure 5-2 shows a generic depiction of how the observed density of fish or fish schools might vary with range from the camera sampling platform. Near the camera system, the density may be dependent on attraction or avoidance reactions; at greater ranges, the ability to identify species can be degraded by image quality (system-dependent resolution, depth of field and environmental effects such as turbidity); and at some further range, even detection becomes impossible.

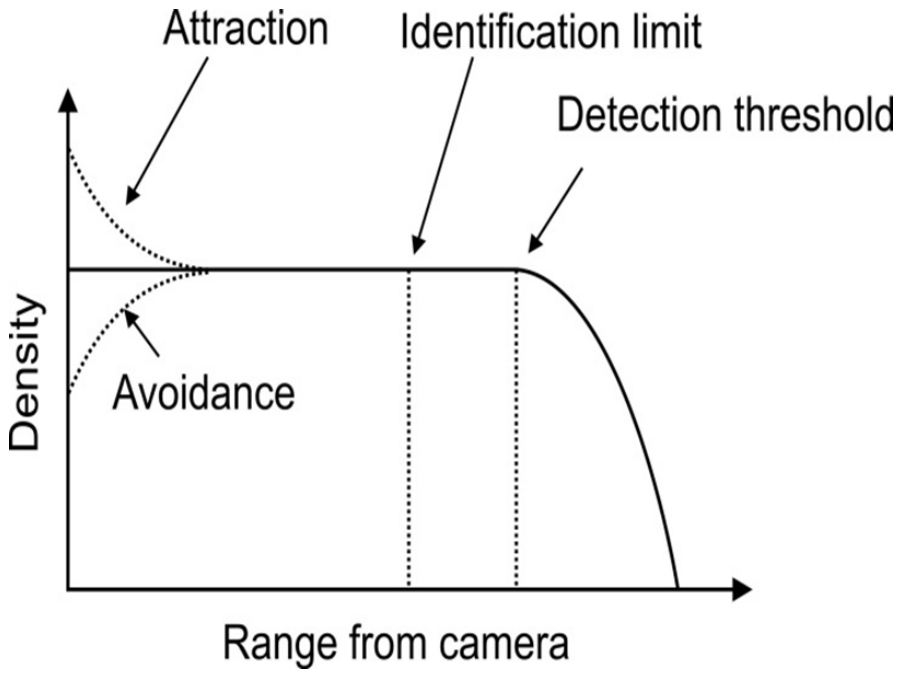


Figure 5-2. General dependence of observed fish density as a function of range from an underwater camera system. The shape of the curve may depend on camera location and geometry as well as fish behavior, and may be different from the undisturbed or naturally occurring densities.

5.3 SIZE COMPOSITION

Calibrated stereo-camera systems are being increasingly used for improved identification and length measurements of fish in reef habitats.

Abundance estimates that incorporate size- or age-composition data can improve the accuracy and precision of stock assessments, especially for data-limited assessments common to reef-fish ecosystems. For this reason, calibrated stereo-camera systems are increasingly used for improved identification and length measurements of fish in reef habitats. Stereo pairs of cameras with relative orientations that are precisely determined through calibration can accurately measure the 3D location of points in the camera view and thus the length of observed fish (Figure 5-3). The accuracy of the measurement depends on the geometry and image resolution of the camera system and on the range to, and aspect angle of, the measured length. Limited information on fish sizes can be obtained using parallel laser beams, referred to as 'laser calipers' with a known distance between the beams. Fish lengths are estimated by simple proportionality when they pass in front of the lasers and the laser spots can be observed on the fish's body. In practice, this method provides fewer length measurements than a stereo camera system.

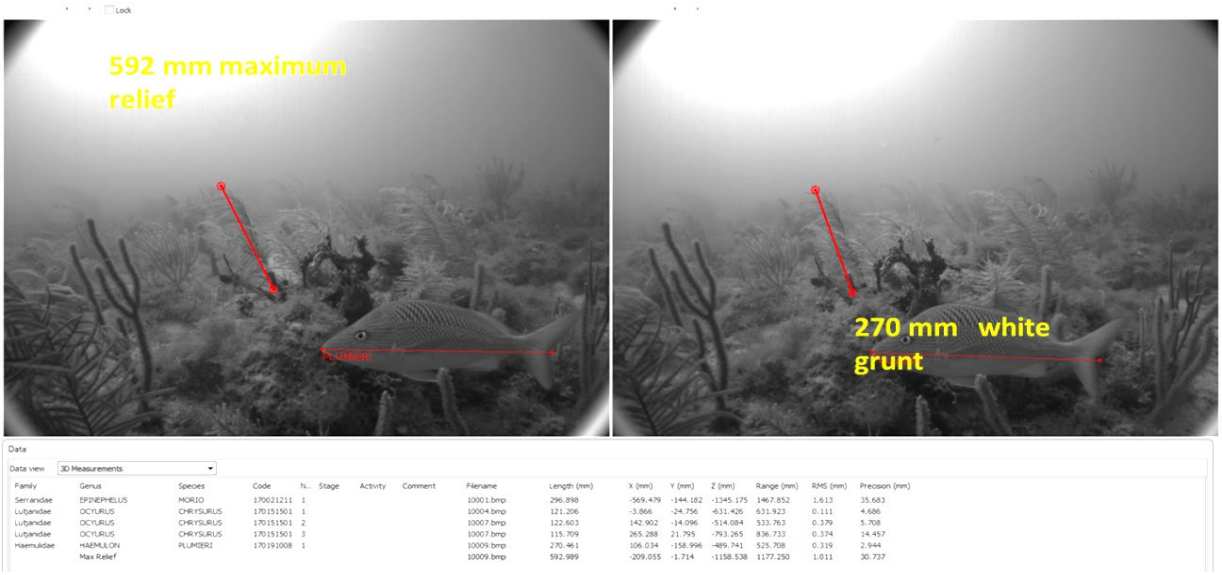


Figure 5-3. Example of stereo image of a white grunt. Calibrated stereo images allow for measurements of fish size composition but also descriptions of the reef relief and other habitat metrics.

5.4 DIVER SURVEYS

Similar to stationary and mobile camera systems, diver surveys are conducted using point census or strip transects, and by towing divers behind a surface vessel. Methods for estimating species composition by scuba divers are well documented. SCUBA visual methods range from transects, point census and quadrats (Bortone et al., 1986; Bortone et al., 1991; Sale and Douglas, 1981; Bohnsack and Bannerot, 1986; Buckley and Hueckel, 1989). In general, no visual method eliminates all bias (Thresher and Gunn, 1986; Greene and Alevizon, 1989; Murphy and Jenkins, 2010). Diver surveys can under-sample or over-sample species, and produce estimates of abundance, size, and species composition that vary with diver experience, method of sampling, visibility, sampling duration and fish behavior.

5.5 PHYSICAL SAMPLING - NETS, TRAPS, HOOK AND LINE

Compared to visual methods, most physical sampling methods exhibit greater selectivity for species and fish size (Bacheler et al., 2013). Both hook size (Campbell, 2014; Ralston, 1990) and mesh size in traps and nets (Millar and Fryer 1999, Mahon et al 2001) are known to bias estimates of species and size composition. Other variables such as the length of time a trap is deployed (Bacheler et al., 2013), habitat (Streich et al., 2018) and fish density (Gobert, 1998) can also result in sampling biases.

Acoustic operations and complimentary biological sampling must consider statistical survey design to provide representative samples of the population for unbiased density estimates.

In summary, there are considerable options for direct and indirect biological sampling to help validate the acoustic measurements, species composition and density estimates. However, the acoustic operations and complimentary biological sampling must consider statistical survey design to provide representative samples of the population for unbiased density estimates as described in Section 3 on Statistical Design.

6 SCIENTIFIC ECHOSOUNDER SYSTEM (F.R. KNUDSEN)

There is recognition that scientific echosounders can be used for a variety of operational objectives, such as quantitative abundance estimates of organisms in the watercolumn (described in Sections 7 and 8). The scientific echosounder and other sonar systems can also be used for seafloor mapping and habitat characterization. The ICES report from Anderson et al. (2007) provides a comprehensive overview of using acoustic systems for seafloor characterization. The scope of this training workshop focused mainly on watercolumn data collection procedures for conducting fish acoustic survey operations. Participants received shipboard training on the principles of scientific echosounder systems and operations using two wideband echosounder systems: the Simrad EK80 and autonomous Simrad WBAT. Based on the questionnaire survey results (Section 1), high priority was given to the need to develop expertise on the operation of scientific echosounders to improve reef fish ecosystem research and surveys in the region.

Part of the survey planning is correct choice of echosounder hardware and settings. During the survey, frequent observation of the echosounder screen is important to tune settings so that high quality data are recorded. This will reduce the data analysis effort and secure sound biological estimates. This section focuses on the principles and operational consideration for the scientific echosounder system, with recognition that other acoustic systems have applicability for improving reef fish surveys.

6.1 TRANSDUCERS

Scientific echosounder transducers typically cover frequencies from 18 to 500 kHz, and have narrow acoustic beams. A modern transducer can generate both continuous wave (CW) and broad band (chirp) pulses. Examples of different transducers are found in Figure 6-1 and Figure 6-2. Low frequencies are primarily used to obtain long ranges like 1000 m and more. Low frequency transducers are physically large and heavy, therefore not suited for portable use and installation on smaller vessels. For operation from smaller platforms, transducers operating at frequencies above 70 kHz are recommended unless a wider beam can be accepted. Wider beam transducers are physically smaller (Figure 6-1). Scientific transducers are preferably split-beam providing accurate sizing and positioning of single targets in the acoustic beam (Bodholt, 1991).

Figure 6-1. Transducers come in different sizes and shapes depending on frequency and beam width. For the same beam width, transducers become smaller as frequency increases and wider beam transducers are physically smaller. Most transducers generate circular acoustic beams, but some generate elliptical beams. Mind that lower frequency transducers are not suited for portable use due to size and weight. The largest transducer in the picture (top right) is 18 kHz, has a diameter of 63 cm and weighs 85 kg.

Transducer performance changes with temperature, and they must be kept out of direct sunlight and high temperatures. Before use, the transducer should be acclimated to the actual water temperature. Make sure to enter the correct water temperature and salinity in the echosounder settings. Further, transducer cables are vulnerable. Do not lift the transducer by the cable or step on them. Do attach them properly so they are not vibrating in the water during mobile surveys, otherwise the conductors in the cable will soon become work hardened and then break. To check echosounder functioning and performance, regular calibrations are recommended.

Figure 6-2. The Simrad ES38-18/200-18 omni-transducer combines the 38 kHz and 200 kHz frequencies which can be utilized to improve target discrimination and identification. Due to the relatively wide beam width (18° at both frequencies) the transducer is small (416x172x94 mm) and with a weight of 7.3 kg, it is suitable for portable use. The boat shape is chosen for good hydrodynamic performance.

In addition to size and weight, choice of transducer will primarily depend on the required beam width and frequency, but side lobes and near-field should also be considered. The acoustic beam can be described as in Figure 6-3**.**

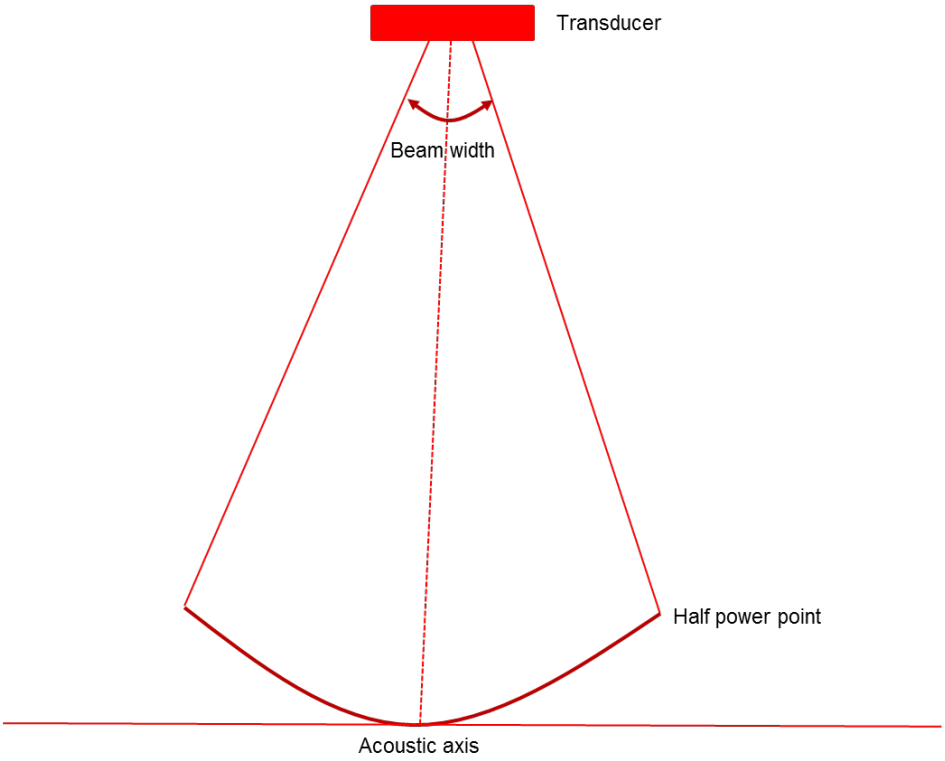


Figure 6-3. Illustration of the acoustic beam. At the acoustic axis the sound intensity is highest and it drops off at increasing angles from the axis. The beam width is defined as the combined angle to each side of the acoustic axis where the sound intensity is r.

Choice of beam width is a compromise between sampling volume and resolution of single targets in the water column and near the bottom. Transducer beam widths ranges roughly from 3 to 30 degrees, while most transducers for fish assessment have beam widths of 5-18 degrees. A large sampling volume (wide beam) is good because it will detect more fish, but will compromise resolution of single targets e.g. needed for fish sizing. Using a 7 degrees circular beam as an example, the beam footprint will have a diameter of 1.2 m at 10 m and 12 m at 100 m (Figure 6-4). If two or more fish in the acoustic beam are at the same range from the transducer, they will merge into one echo and will be excluded as single targets (Bodholt and Solli, 1992). However, they are not excluded in the calculation of the total abundance (Bodholt, 1990). To improve the horizontal resolution of single targets, a narrower beam is needed.

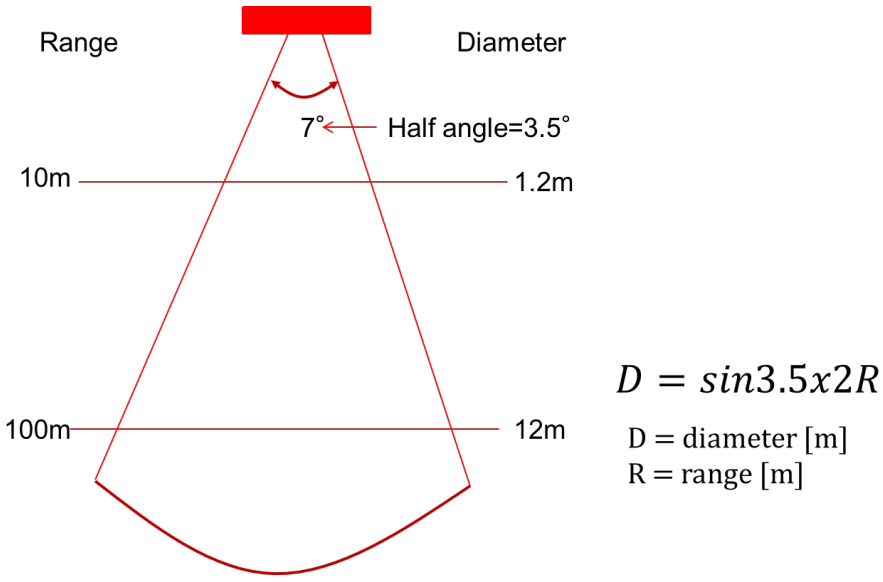


Figure 6-4. Illustration of a 7° beam width acoustic beam (not to scale). The beam diameter at 10 m is 1.2 m and 12 m at 100 m. If two or more fish are at the same range from the transducer, they will not be detected as single targets, but will contribute in the calculation of total abundance. Using the beam width half angle, the beam diameter at different ranges is found by the above formula.

A narrow beam is also better for resolving fish near the bottom. If the echo from the bottom is returned before the echo from a fish, the fish echo will be masked in the bottom echo and will not be detected (Figure 6-5). The resolution of fish near the bottom must also take into account the bottom dead zone (described below). An alternative to the single-beam echosounder is the multibeam. Quantitative multibeams for fish assessment are available like the Simrad ME70. A multibeam is typically shaped like a swath consisting of many narrow single beams. The swath is normally oriented athwartship. A multibeam will secure both a large sampling volume and good resolution of single targets in the water column and near the bottom. There is sound energy outside the half power angle. A narrow beam width will produce beam patterns like in Figure 6-6, consisting of a main lobe and side lobes. During transducer mounting, care should be taken so that the side lobes are not directed towards the hull of the vessel or any other structure. A continuous line at a fixed range in the echogram indicates echoes from side lobes. It could also be a reflection from the water surface caused by transducer back radiation or other multi-pathing. Adjusting transducer position and depth will reduce or remove these artifacts.

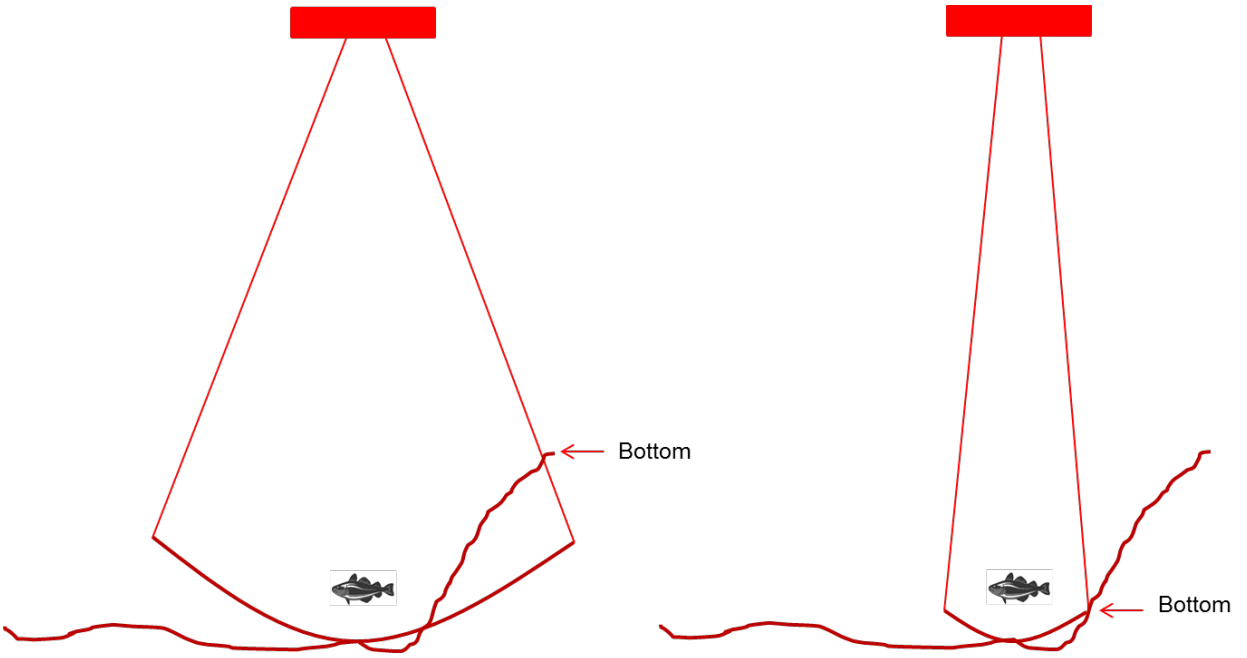


Figure 6-5. Illustration of wide (left) and narrow beam (right) with bottom profile. The wide beam will hit the bottom first and the fish will be masked in the bottom echo and not detected. The narrow beam will hit the fish before the bottom and the fish will be masked in the bottom echo and not detected. The narrow beam will hit the fish before the bottom and the fish will be detected.

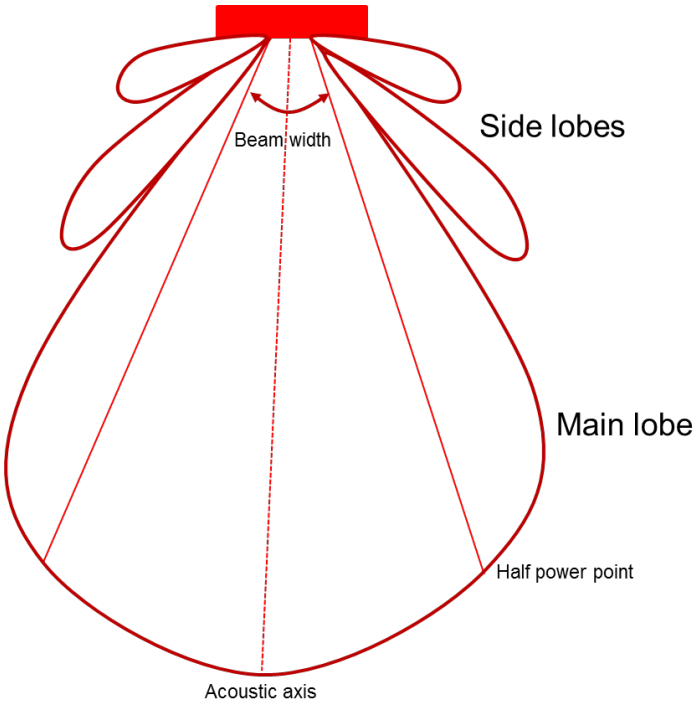


Figure 6-6. Illustration of the acoustic beam pattern with main lobe and side lobes. The sound intensity in the side lobes is much lower than in the main lobe, but they can produce "false" echoes.

The transducer nearfield is a zone in front of the transducer where data is unreliable (Lockwood and Willette, 1973) and must be avoided in analysis. The nearfield can be approximated by the formula:

$$NF = \frac{\pi\lambda}{4\beta^2}$$

where, NF=near field [m], λ =wavelength [m], and β=-3 dB beam width [radians]. The near field at common frequencies for 7 degrees transducers is given in Table 6-1.

Table 6-1. Transducer nearfield approximation for selected 7 degrees transducer frequencies. The nearfield must be discarded in data analysis.

Frequency [kHz]	Near field [m]
38	2.1
70	1.2
120	0.7
200	0.4

6.2 FREQUENCY

Choice of frequency depends on the required range and size of targets to be detected. When comparing data between frequencies, the maximum range that can be used is given by the maximum detection range of the highest frequency. Detection range for a -32 dB fish and bottom for different frequencies is given in Table 6-2**.**

Table 6-2. Detection range for fish (TS= -32 dB re. 1m2) and bottom (Sb=-30 dB/m2) for common 7 degrees echo sounder transducers.

Frequency [kHz]	38	70	120	200	333
Fish [m]	1000	570	400	310	138
Bottom [m]	2700	1270	750	550	262

For detection of smaller targets like zooplankton, a high frequency is needed. This is due to the relationship between the target echo strength and the wavelength of the acoustic pulse. The wavelength is given by the formula:

$$\lambda = \frac{c}{f}$$

where, λ= wavelength [m], c=speed of sound in water [m/s], and f=frequency [Hz]. A general rule is that the target of interest should be larger than the wavelength of the echosounder operating frequency. When the target is smaller than the wavelength, reflection is weak but increases steeply as target size approaches the wavelength (Rayleigh scattering). When the target is larger than the wavelength, it will reflect sound as a planar surface (geometrical scattering) and be relatively strong and stable with frequency. Targets with gas inclusions, like swimbladder fish, are resonant when they have a size similar to the wavelength (Horne and Jech, 2005). In Table 6-3**,** echosounder frequencies and corresponding wavelengths are given. The best frequencies for fish are the lowest because they will have little interference from smaller targets. At 70 kHz, the wavelength is 2 cm thus giving a weak echo from targets smaller than 2 cm. At 333 kHz, the wavelength is 5 mm, and targets larger than 5 mm will have a relatively strong echo.

Table 6-3. Common echosounder operating frequencies and the corresponding wavelength. A general rule is that the target of interest should be larger than the wavelength.

Frequency [kHz]	Wavelength, λ [mm]
18	83
38	39
70	21
120	13
200	8
333	5

A combination of frequencies (CW or chirp) is often used to improve target identification and species discrimination (Korneliussen and Ona, 2004; Jech and Michaels, 2006; Lavery et al., 2007; Bassett et al., 2017).

6.3 TRANSMIT SIGNAL

The transmit signal is described by its frequency, duration and amplitude. Frequency is number of periods per second. One period is illustrated in Figure 6-7. The wavelength of the period at different frequencies is given in Table 6-3. To generate a discrete frequency, a minimum of 6-7 periods are needed. This defines the shortest pulse length at different frequencies. Therefore, the shortest pulses available are frequency dependent (Table 6-4). The sound pulse can be described by both its length (m) and duration (s).

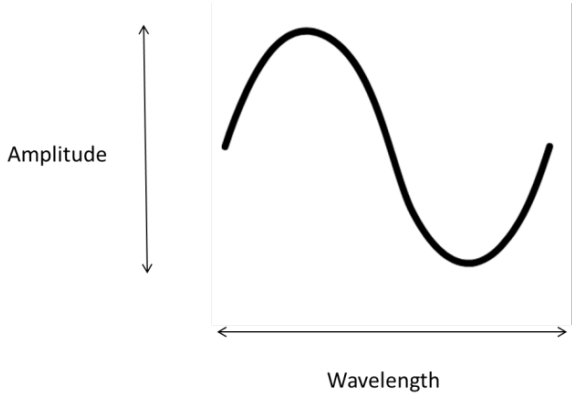


Figure 6-7. Illustration of one period of a sound pulse. The wavelength of the period is inversely related to the frequency of the transmit signal. At least 6-7 periods are needed to generate discrete frequencies. The amplitude of the period is the strength of transmitted sound.

In a CW pulse, the wavelength is constant while in a chirp pulse the wavelength decreases or increases causing a frequency up-sweep or down-sweep. CW pulses have durations from less than 100 microseconds (µs) to many milliseconds (ms). Short pulses are used when a good vertical resolution is needed, and long pulses are used when longer ranges are needed. When combining several echosounder frequencies, it is recommended to use the same pulse duration at all frequencies. To get comparable data, the acoustic beams should also have the same width and overlap as much as possible (Korneliussen et al., 2004). Available pulse durations for the Simrad EK80 echosounder in CW for different frequencies is given in Table 6-4. The pulse duration varies from 64 µs to 8192 µs. This

corresponds to pulse lengths from 96 mm to 12.3 m. A standard pulse duration for larger surveys is 1024 µs (1 ms) corresponding to a pulse length of 1.5 m. The currently shortest chirp pulse is 512 µs. A frequency modulated (FM) pulse is also available in the Simrad EK80, transmits across a bandwidth depending on the frequency and transducers. It is a current topic of research in fisheries acoustics discussed in other reports (Demer et al., 2017).

Table 6-4. The x-axis is pulse duration in µs and the y-axis echosounder operating frequency in kHz. "X" means that the pulse duration is available for the given frequency.

Frequency	64	128	256	512	1024	2048	4096	8192
18 kHz				X	X	X	X	X
38 kHz			X	X	X	X	X	
70 kHz		X	X	X	X	X		
120 kHz	X	X	X	X	X			
200 kHz	X	X	X	X	X			
333 kHz	X	X	X	X	X			

The amplitude of the transmit signal is relevant in relation to environmental impact, and regulators might request that the sound pressure level of the echosounder is reported. The average sound pressure level at 1 m can be calculated as follows:

$$SPL_{rms} = G + 10\log\left(\frac{P}{4\pi}\right) + 181.76$$

where, SPL_{rms}=average sound pressure level [dB re 1µPa@1m], G=transducer gain, P=electrical transmit power [W]. The transducer gain is found from calibration of the echosounder or in transducer data sheets. The electrical transmit power is user selected in the echosounder operational software.

6.4 Power

A high transmit power is mostly needed at the lower frequencies (<70 kHz) to obtain long ranges. Transmit power at low frequencies are often more than 1 kW. Such high transmit powers are not recommended for frequencies relevant to reef studies. At the higher echosounder frequencies (>100 kHz) the sine wave of the pulse will be distorted at high transmit power into a saw tooth shape pulse rendering the data useless for scientific purposes. This sine wave distortion is called a non-linear effect (Tichy et al., 2003) There is a recommended maximum transmit power at different frequencies (Korneliussen et al., 2004) to avoid non-linear effects (Table 6-5).

Table 6-5. Maximum recommended transmit power at different frequencies.

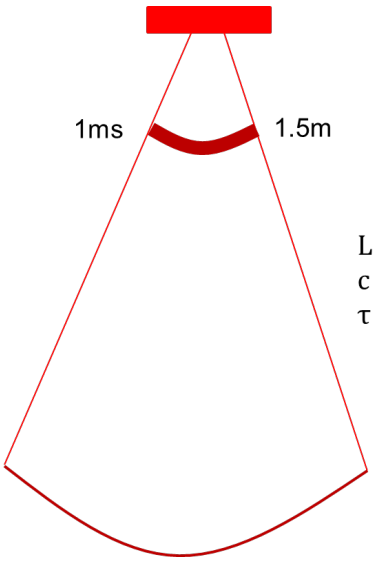
Frequency [kHz]	Max power [W]
18	2000
38	2000
70	750
120	250
200	150
333	50

6.5 PULSE LENGTH

Traditionally echosounders transmit CW pulses. Choice of pulse length is a compromise between the required range and vertical resolution. A long pulse will give a longer range, but will compromise vertical resolution. For a CW pulse the vertical resolution is given by:

$$VR = \frac{c\tau}{2}$$

where, VR=vertical resolution [m], c=speed of sound in water [m/s], and τ= pulse duration [s].



$$L = c\tau$$

L = pulse length [m]
c = speed of sound in water [m/s]
τ = pulse duration [s]

Figure 6-8. Illustration of the acoustic beam and sound pulse with duration of 1 ms and pulse length of 1.5 m.

Assuming pulse duration of 1 ms and sound speed of 1500 m/s, the pulse length will be 1.5 m (Figure 6-8) and the vertical resolution 75 cm. Two fish must be separated with more than 75 cm in range to be detected as individual targets. If they are closer than 75 cm, their echoes merge into one larger echo. A vertical resolution of 75 cm is likely too poor for reef studies and shorter pulses are recommended. Try the shortest pulse available at the relevant frequencies. Since most reefs are not deep, choice of pulse length can be based on the required vertical resolution. If several frequencies are used simultaneously, it is recommended that they all have the same pulse duration.

Resolving fish near bottom must also take into consideration the pulse length (valid for CW pulses). The bottom dead zone (Ona and Mitson 1996) for a flat bottom is illustrated in Figure 6-9.

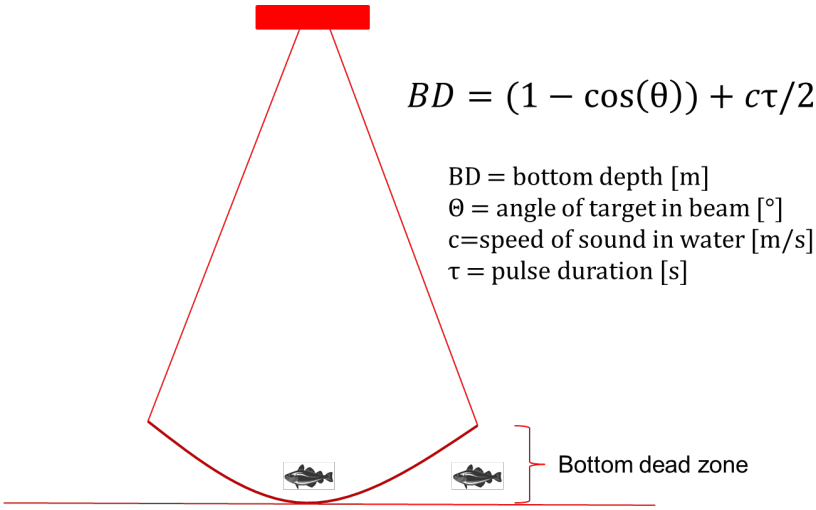


Figure 6-9. Illustration of bottom dead zone. The bottom dead zone is given by the angle of the target in the beam and the pulse duration (valid for CW pulses).

For chirp pulses the vertical resolution is not dependent on pulse duration, but on the band width of the pulse according to the formula:

$$VR = \frac{c}{2 \times BW}$$

where, VR=vertical resolution [m], c=speed of sound in water [m/s], and BW=band width [Hz]. A 200 kHz chirp transducer can sweep from 150-250 kHz covering a band width of 100 kHz, in case the vertical resolution is 7.5 mm. Using chirp pulses, long pulse duration can be used without compromising vertical resolution.

6.6 Pulse Repetition Rate

The factor limiting pulse repetition rate (PRR) is the water depth according to the formula:

$$PRR = \frac{c}{2xD}$$

where, PRR=pulse repetition rate [Hz], *c*=speed of sound in water [m/s], and d=water depth [m]. At a water depth of 750 m, the maximum PRR is 1 pulse per second, or 1 Hz. At 75 m it will be 10 Hz. When data are recorded, a recording range (see below) that is greater than the water depth will become the factor which limits PRR. For a standard biomass assessment survey, a PRR of 1 Hz might be sufficient. A higher PRR is relevant for tracking the direction and speed of single targets.

Some combinations of PRR and water depth may result in a "ghost bottom" appearing on the echogram and thus in the water column data. This is caused by pulses that have already travelled to the bottom and back to the transducer reflecting from the sea surface, travelling to the bottom, and back to the transducer again. It is important to recognize when this is occurring, and adjust PRR to avoid data contamination caused by these multiple reflections.

6.7 Recording Range

Scientific echosounders store data for later processing and replay. The recording range must be somewhat longer than the maximum water depth of interest. In addition, it is recommended to record some files with the echosounder in passive mode. Passive recordings are used to identify and remove noise sources. The recording range for passive recordings should be a least 300 m. Echosounder settings must be the same for passive as for normal (active) operation.

Part of the survey planning is correct choice of echosounder hardware and settings.

6.8 Summary considerations on echosounder selection and settings

The intent of this section is to provide a good understanding of the prerequisites for scientific echosounder operations to assure good data quality, correct data interpretation and reliable quantitative estimates. Some key operational principles and recommendations to consider when conducting acoustic fish reef surveys are:

1. Beam width. A narrow beam will improve resolution of fish both in the water column and near the bottom. A wider beam will see more fish and provide more representative data for the fish distribution.
2. Acclimate transducer to the actual water temperature before calibration and survey. Enter the correct temperature and salinity in the echosounder settings.
3. Adjust transducer during mounting to avoid echoes from side-lobes and other false echoes.
4. Attach transducer cable properly to prevent vibrations.
5. Always know your transducer near-field. Data in the near-field are unreliable.
6. A low frequency is best for detecting fish while higher frequencies are better for detecting zooplankton. Consider a transducer combining a low and a high frequency.
7. Know your wavelength. When targets are smaller than the wavelength of the transmit pulse, measurements are unreliable.
8. Reduce transmit power. A high power is primarily needed to obtain long ranges.
9. Use short pulse length to improve target resolution. Long pulses are primarily for long ranges.
10. The pulse repetition rate is dictated by the water depth, but aim for a high rather than a low rate. A rate of 2-3 pulses per second is fine for most surveys.
11. Make sure your recording range is always longer than the range of interest.
12. Observe the echosounder screen during survey and adjust settings to optimize data quality.

7 ECHOSOUNDER DATA PROCESSING (T. JARVIS)

7.1 OVERVIEW

In order to work effectively with single-beam echosounder (SBES) data and/or multibeam echosounder (MBES) data, a data analyst needs to be familiar with a range of topics across a number of different disciplines:

1. **Echosounder theory:** This is the knowledge that underpins the use of echosounders in studies of aquatic ecosystems. It requires an understanding of both underwater sound (a physics-based discipline) and electronics (an engineering discipline). See Sections 2, 6 and 14.
2. **Digital-signal-processing (DSP) theory:** This is the knowledge that underpins the processing of digital samples, such as those obtained from an echosounder or a digital camera. There are many DSP techniques in use in other disciplines (e.g. photography, telecommunications) that may prove useful for echosounder data processing, but have yet to be adopted. Wider reading on the general subject will undoubtedly lead to a range of new ideas for echosounder data-processing applications (e.g. Peña, 2016).
3. **Data-processing-software specifics:** Some sort of software is required to visualize and process echosounder data. A good understanding of the specific structure, terminology and design components of one or more of the available software tools is essential for effective data visualization and efficient and accurate data processing.
4. **Data-processing workflow:** It is possible to identify a common sequence of broad-level processing steps (a workflow) that can be applied to the data from any echosounder (SBES or MBES) for any ecological application (e.g. coastal reef-fish studies, open-ocean fish-stock surveys, fish passage in rivers, plankton studies, etc.). This workflow serves as a useful checklist to ensure that the necessary processing steps are carried out in the appropriate order. Depending on the aims of the study, the end products from the echosounder workflow are typically combined with the products from other instruments (e.g. trawls, video cameras, CTDs, current meters, etc.) and analyzed with an appropriate spatial and/or statistical model (see sections 3 and 8). The term “post-processing” is commonly used to describe the fact that the “raw” echosounder data being considered (e.g. received electric power, derived from the received voltage) has already undergone significant “pre-processing” by the echosounder system (analog-to-digital conversion, bandpass filtering, downsampling, etc.).

The following subsections describe the echosounder data-processing workflow in more detail. Examples are provided from an echosounder dataset collected by NOAA Ship *Nancy Foster* at the Tortugas Banks in the Florida Keys Marine Sanctuary in Aug 2017 (Figure 7-1). This dataset contains examples of fish (e.g. jacks, snappers, angelfish, groupers, triggerfish, surgeon, barracuda), plankton and coral reef detected simultaneously with hull-mounted, vertically oriented SBES and MBES systems (Simrad EK80 at 38, 120 and 200 kHz; RESON SeaBat 7125 at 200 kHz).

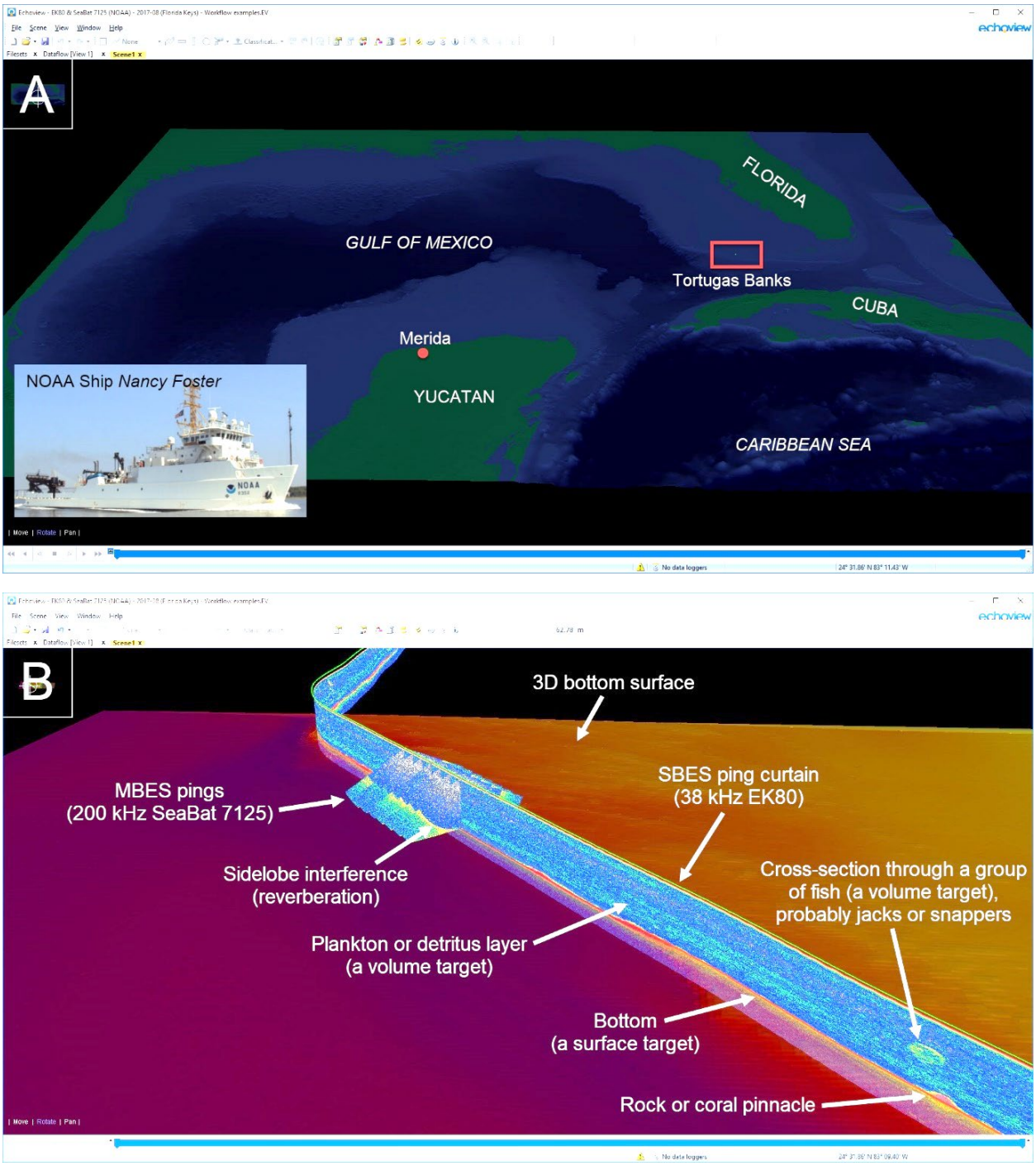


Figure 7-1. Overview of the example echosounder dataset collected from NOAA Ship *Nancy Foster* in Aug 2017 (see Section 7.1). [A] Survey location at the Tortugas Banks in the Florida Keys Marine Sanctuary. [B] 4D view of the data (looking north) showing a section of the SBES ping curtain and 7 pings of the MBES data (every 40th ping is shown). Water depth along the survey track was ~55 m. The 3D bottom surface was generated from a previous MBES survey.

7.2 DATA EXPLORATION

Data exploration is the preliminary process of visualizing and inspecting the data to establish its broad characteristics prior to detailed processing.

Visualization

Once the required data files have been located and their contents read into a suitable software environment, the stored measurements can be visualized in the form of echograms, graphs, tables, maps and 4D displays (Figure 7-2).

Inspection

Thorough inspection of the data is encouraged as a first step to ascertain:

- Where and when the data was collected.
- Issues such as gaps in the data, errors or offsets in the ping locations and times, data thresholds, transducer ringdown, time-varied-gain (TVG) errors etc.
- How the data was collected in terms of transducer orientation, pulse duration, power, frequency, recording range etc.
- What sorts of noise and backscatter features are present (see Sections 4.4 and 7.4), and how they relate to each other spatially and temporally.
- The distribution of TS and S_v values for different components of the echograms.

This information will help to identify any issues with the data and inform the appropriate approaches to take for the remaining workflow steps.

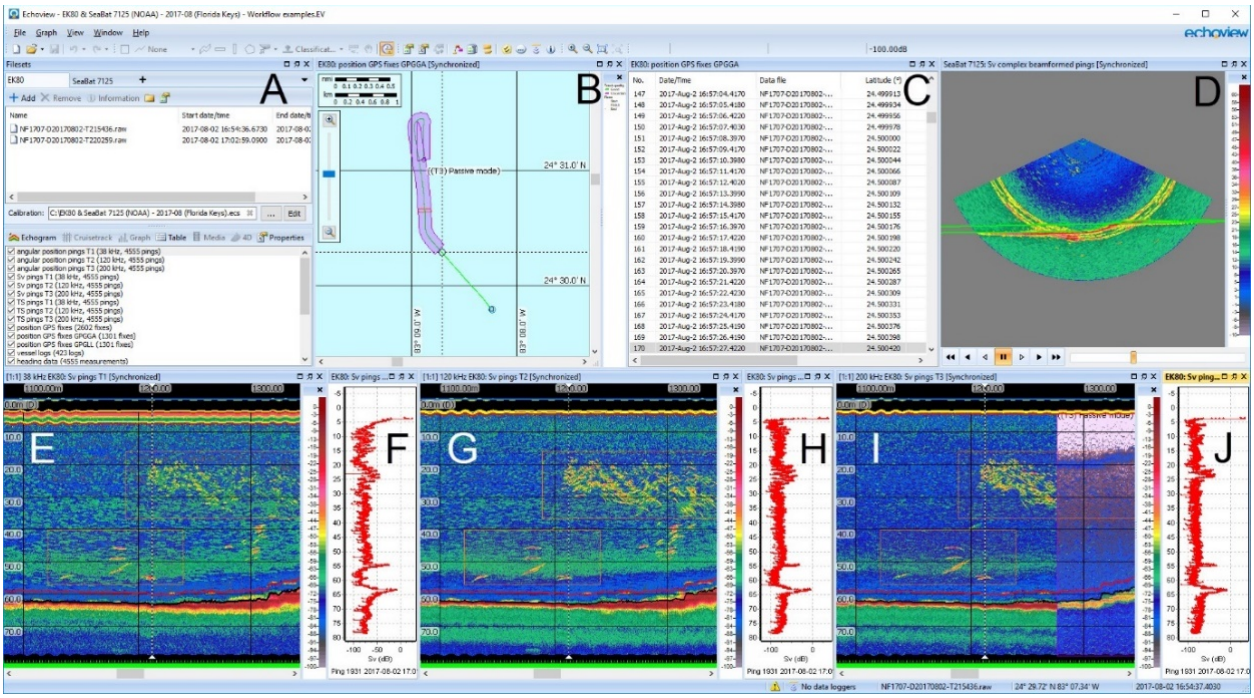


Figure 7-2. Some of the ways in which echosounder data can be visualized and inspected. [A] The raw data files being considered and the readable information within. [B] Survey track. [C] Table of GPS fixes. [D] Multibeam S_v echogram showing a single ping from the SeaBat 7125 MBES. [E, G, I] Single-beam S_v echograms showing multiple pings from each of the three EK80 SBES systems (38, 120 and 200 kHz). [F, H, J] S_v profile of the ping indicated by the vertical dotted line on the echogram to the left. The survey track, echograms and ping profiles are all synchronized to indicate the same moment in time.

7.3 DATA CALIBRATION

Data calibration is the process of establishing:

1. The correct real-world location and extent of each sample in terms of latitude, longitude, time, range and depth.
2. The correct backscattering-strength value of each sample.

Note the distinction between data calibration, which we are describing here, and instrument calibration (described in Sections 4.6 and 7.7).

Latitude, longitude and time

Latitude, longitude and time are measured with a GPS receiver at an appropriate rate (e.g. 1 Hz) and are commonly (but not always) recorded in the echosounder data file (Figure 7-2). The GPS times can then be matched to the echosounder ping times to ascertain the latitude and longitude of the platform at the time of each ping. If the XYZ (3D) offset of each transducer from the GPS is known (Figure 7-3), it is also possible to ascertain the latitude and longitude of the transducer at the time of each ping.

GPS times are typically Universal Time Coordinated (UTC), while ping times depend on the system clock of the echosounder computer. It is good practice to synchronize the system clock to the GPS clock to avoid complexities with time offsets. A single offset can then be applied during post-processing to adjust both the GPS and ping times to the local time zone if desired.

Sample range

Sample range (r in m) is derived based on the water sound speed (c_w in m s^{-1}) and the echosounder's measurements of time for each sample (t_h), the latter of which are highly precise and accurate for scientific-grade echosounder systems. Simmonds and MacLennan (2005, p116-117) discuss how to factor target extent and receiver delay (t_{del}) into the calculation of target range (Figure 7-4). Demer et al. (2015, p42) recommend that c_w should be estimated as the harmonic mean over the propagation path.

Sample depth

Sample depth (d in m) is a trigonometric function of sample range, transducer depth and transducer orientation (pointing direction) (Figure 7-3). It is therefore important to know the depth of the transducer and its pointing direction (azimuth and elevation in degrees).

For mobile platforms whose depth changes significantly from moment to moment (e.g. heave for a surface vessel, diving or ascending for an underwater vehicle), it is important to make measurements of those changes in depth at an appropriate rate (e.g. 10 Hz) and incorporate them in the calculation of sample depth.

For target-tracking applications, it is also important to know the rotation of the transducer (around the beam axis) in relation to the platform, and to measure any changes in platform heading from moment to moment (Figure 7-3).

Sample backscattering strength

The equations to convert the raw echosounder measurements to TS and S_v vary from instrument to instrument, but they all represent a rearrangement of the general echosounder equation (Figure 7-4). The Simrad EK80 equations for narrowband data are described by Demer et al. (2015, p61), and are effectively identical to those shown in Figure 7-4. The SeaBat 7125 is not generally recommended for quantitative use (but see Dunlop et al., 2018; and references therein).

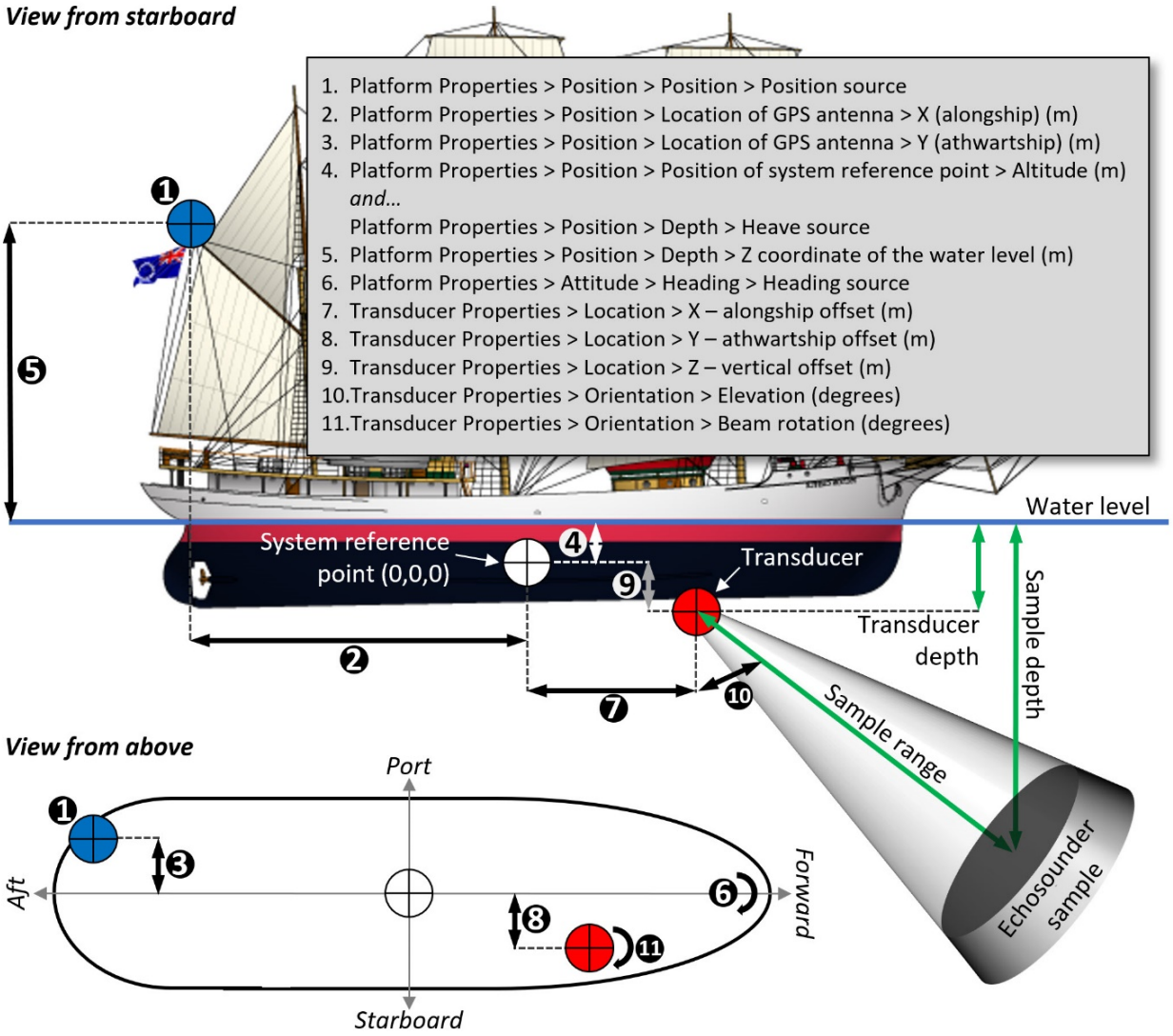


Figure 7-3. Factors contributing to the calculation of latitude, longitude, time and depth for a given echosounder sample. In this example the echosounder platform is a mobile surface vessel, but the principles can be extended to other mobile and stationary platforms such as towed bodies, autonomous underwater vehicles, probes, moorings and landers. The text box represents Echoview 8 settings.

[A] $\underbrace{E_{Received}}_{Measured} = \underbrace{(E_{Sent} + E_{LostOut}) - (E_{Reflected} + E_{LostBack})}_{Estimated}$

where: E = sound energy in dB, e.g. dB re 1 µPa

[B] $TS_c = \underbrace{P_{er}}_{Measurement} + \underbrace{40\log_{10}\left(c_w(t_h - t_{del})/2\right)}_{Spreading\ loss} + \underbrace{2\alpha_a\left(c_w(t_h - t_{del})/2\right)}_{Absorption\ loss} - \underbrace{10\log_{10}\left(\frac{p_{et}g_0^2\lambda^2}{16\pi^2}\right)}_{Transducer\ efficiency} - \underbrace{20\log_{10}\left(\frac{g(\alpha,\beta)}{g_0}\right)}_{Beam\ pattern}$

where: TS_c = compensated target strength in dB re 1 m² (i.e. accounting for the beam pattern and the off-axis location of the target in the beam)
P_{er} = received electric power in dB re 1 W
c_w = water sound speed in m s^{-1}
t_h = time elapsed in s between pulse transmission and echo reception (measured at the half-amplitude point on the echo envelope)
t_{del} = the electronic delay in the receiver in s
$c_w(t_h\text{-}t_{del})/2$ = range, r (distance from transducer to target) in m
α_a = absorption coefficient in dB m^{-1}
p_{et} = transmit electric power in W
g_0 = on-axis transducer gain (dimensionless, i.e. 0-1) (the proportion of sound pressure transferred to voltage by the transducer, and *vice versa*)
λ = acoustic wavelength in m (used as a proxy for the effective receiving area of the transducer)
α,β = off-axis location of the target (in the x,y plane) in degrees
$g(\alpha,\beta)$ = transducer gain (dimensionless, i.e. 0-1) in the direction of α,β

[C] $S_v = \underbrace{P_{er}}_{Measurement} + \underbrace{20\log_{10}\left(c_w(t_h - t_{del})/2\right)}_{Spreading\ loss\ minus\ spreading\ gain} + \underbrace{2\alpha_a\left(c_w(t_h - t_{del})/2\right)}_{Absorption\ loss} - \underbrace{10\log_{10}\left(\frac{p_{et}g_0^2\lambda^2}{16\pi^2}\right)}_{Transducer\ efficiency} - \underbrace{10\log_{10}\left(\frac{c_w\tau\Psi}{2}\right) - 20\log_{10}\left(\frac{\tau_{eff}}{\tau}\right)^{0.5}}_{Sampling\ volume\ (NB.\ sample\ range\ is\ incorporated\ in\ the\ 'spreading\ gain'\ term\ at\ left)}$

where: S_v = volume backscattering strength in dB re 1 m² m^{-3}
Ψ = equivalent two-way beam angle in dB re 1 steradian
τ = pulse duration in s
τ_{eff} = effective pulse duration in s
$(\tau_{eff}/\tau)^{0.5}$ = "s_a correction factor"
and the remaining terms are as per equation [B]

Figure 7-4. The echosounder equation. [A] In its general form (also referred to as the "sonar equation", e.g. Rudstam et al. 2012, p6). [B] Solved for point targets (see Figure 7-6). [C] Solved for volume targets (see Figure 7-6). Equations B and C are rearranged to make $E_{Reflected}$ the subject (i.e. the acoustic properties of a target such as a single fish or an aggregation of fish). In these examples, $E_{Received}$ and E_{Sent} are presented in terms of electric power (W or dB re 1 W), which can be calculated from the received voltage (volts, V) as V × current (amperes, A), or V^2/impedance (ohms, Ω) (see Demer et al., 2015).

7.4 DATA CLEANING

Data cleaning is the process of removing or mitigating unwanted components of the data, where "unwanted" is subjective and depends on the aims of the study. The voltage measurements made by the echosounder receiver represent the sum of backscatter (often referred to as "signal") and noise (i.e. anything else that contributes to the received voltage).

Unwanted components can include:

1. Samples from certain times, locations or ranges.
2. Backscatter from targets that are not part of the study.
3. Stochastic variation in the signal.
4. Acoustic and electrical noise.
5. Reduced backscatter due to pulse/echo attenuation or transducer motion.
6. Measurements with a low signal-to-noise ratio.
7. Non-linear effects.

Unwanted samples

Samples collected at unwanted times, locations or ranges during a survey can be quickly identified and removed during a first pass of the data. For example, it may be desirable to disregard pings recorded during the day when animal targets are dispersed or beyond the range of the echosounder, or pings collected during transit between transects.

Unwanted targets

Backscatter from unwanted targets is sometimes referred to as "reverberation" (e.g., Simmonds and MacLennan, 2005). For example, backscatter from near-surface bubbles, zooplankton and the bottom (Figure 7-5) might be considered reverberation in a study of reef-fish distribution and abundance. Backscatter from near-surface bubbles in data collected from a surface vessel is typically dealt with by creating a 2D line that identifies the maximum range of the bubbles in each ping, and then excluding from further analysis all samples between the transducer and this line (Figure 7-5 shows examples of 2D lines for delineating various phenomena, although near-surface bubbles are not apparent in this dataset). Similarly, backscatter from unwanted targets such as zooplankton and the bottom can be excluded from analysis once they have been detected (see Section 7.5 and Figure 7-5).

Stochastic variation in the measurements

For effectively unknown or unknowable reasons, repeated echosounder measurements of the same volume of water will yield a different value, even if the conditions remain essentially unchanged. This variation will typically be small and random (i.e., normally distributed), hence the term "stochastic" (which is used to describe something that is randomly determined).

This variation may not be an issue when characterizing the data at a single frequency. For example, the sample-mean S_v of a cross-section through an aggregation of fish would be calculated on the basis of 100s or even 1000s of samples, such that the variation would be mitigated by central-limit theorem. However, when wishing to compare backscatter measurements between frequencies (e.g. for multifrequency classification analysis; see Section 7.6), it is generally recommended that steps are first

taken to reduce the variation at each frequency. This can be achieved by either smoothing or resampling the data.

Acoustic and electrical noise

In order to work effectively with single-beam echosounder data and/or multibeam echosounder data, a data analyst needs to be familiar with a range of topics across a number of different disciplines.

Acoustic noise in the echosounder signal can arise from phenomena such as pulses and echoes from other echosounders, engine noise, breaking waves, collapsing air bubbles (cavitation) and vocalizing animals. Electrical noise can arise from grounding issues, inverters, transducer cables running next to each other, and so on (see Sections 4 and 6). In addition, the transducer elements can continue to vibrate for a short period of time after transmission (commonly referred to as "ringdown"). Figure 7-5 shows examples of noise in the SBES data from Tortugas Banks.

Various algorithms are reported in the literature for removing many of the acoustic and electrical noise phenomena commonly found in echosounder data (e.g. De Robertis and Higginbottom, 2007; Ryan et al., 2015; Peña, 2016). While these algorithms can be effective in many cases, it is recommended that all possible avenues are pursued for the collection of noise-free data in the first place.

Ringdown may contribute to the signal over 40 m of range or more for older transducers consisting of tonpilz ceramic elements. Newer transducers with composite ceramic elements may only ring for a few meters or less. Ringdown can be removed by creating a 2D "exclusion" line as for near-surface bubbles. The range of this line is generally determined by eye as the maximum range at which the signal is significantly affected, although it is also possible to conceive of automated algorithms to perform this calculation.

Reduced backscatter

In addition to spreading loss and absorption (which are factored into the calculation of sample backscattering strength; see Section 7.3), the energy in the pulse and/or echo can be significantly attenuated by highly reflective and/or highly absorbent targets along the propagation path. Common scenarios are air bubbles in front of the transducer at short range, and dense schools of fish. With a mobile surface vessel, close-range air bubbles can be caused by breaking waves (which can aerate the water column to considerable depth in very bad weather) and/or the design of the hull (which can cause bubbles to be swept down and across the transducers as the vessel moves). Turbulence in high-flow environments such as rivers and tidal channels can also entrain air bubbles in front of the transducer.

Ryan et al. (2015) describe an algorithm for identifying and removing pings whose sample values are significantly weaker (due to bubble attenuation) than those nearby ("ping dropouts"). While we might expect the level of attenuation for any given ping to vary from 0 to 100 %, the Ryan et al. (2015) algorithm removes only those pings above a given attenuation threshold.

Transducer motion can also cause up to a twofold reduction in measured backscatter if the pointing direction changes between transmission and reception (Stanton, 1982). Dunford (2005) describes a single correction function for a wide range of circular transducers based on vessel motion (pitch and roll)

and the transducer beam pattern. Pitch and roll measurements are made with a motion reference unit (MRU) and must be made at a rate sufficient to capture the change in pointing direction between transmission and reception (~10-100 Hz).

Signal-to-noise ratio

If an estimate of the noise contribution to the measurement can be provided for any given sample, then the signal-to-noise ratio for that sample can be calculated (where signal = measurement – noise). It is then possible to filter out samples whose ratio is lower than a desired quality threshold.

The background-noise-removal algorithm described by De Robertis and Higginbottom (2007) incorporates such a threshold (which in this case describes the ratio of signal to background noise, but not any other noise sources). In this paper, the authors explain how the optimum threshold depends on "the equipment used, the operational settings, and the extent to which data are averaged". A more detailed appraisal of the broader topic can be found in Kieser et al. (2005).

Non-linear effects

At very close range the multiple curved wavefronts generated by the spaced transducer elements result in a non-linear relationship between the sound pressure and the particle velocity (Simmonds and MacLennan, 2005, p39). This close range is known as the "near field" or "Fresnel zone" (as opposed to the "far field" or "Fraunhofer zone"), where any backscatter measurements will be variable and untrustworthy. The effective near-field range can be calculated for a given transducer via a simple equation (see Section 6.1). This range can be used to create a 2D "exclusion" line as for near-surface bubbles.

A number of other conditions can lead to further non-linear effects in which the propagating sound waves no longer obey simple rules (see Simmonds and MacLennan, 2005, p35; and references therein). Although these effects can be significant, they have rarely been considered in published data-processing workflows.

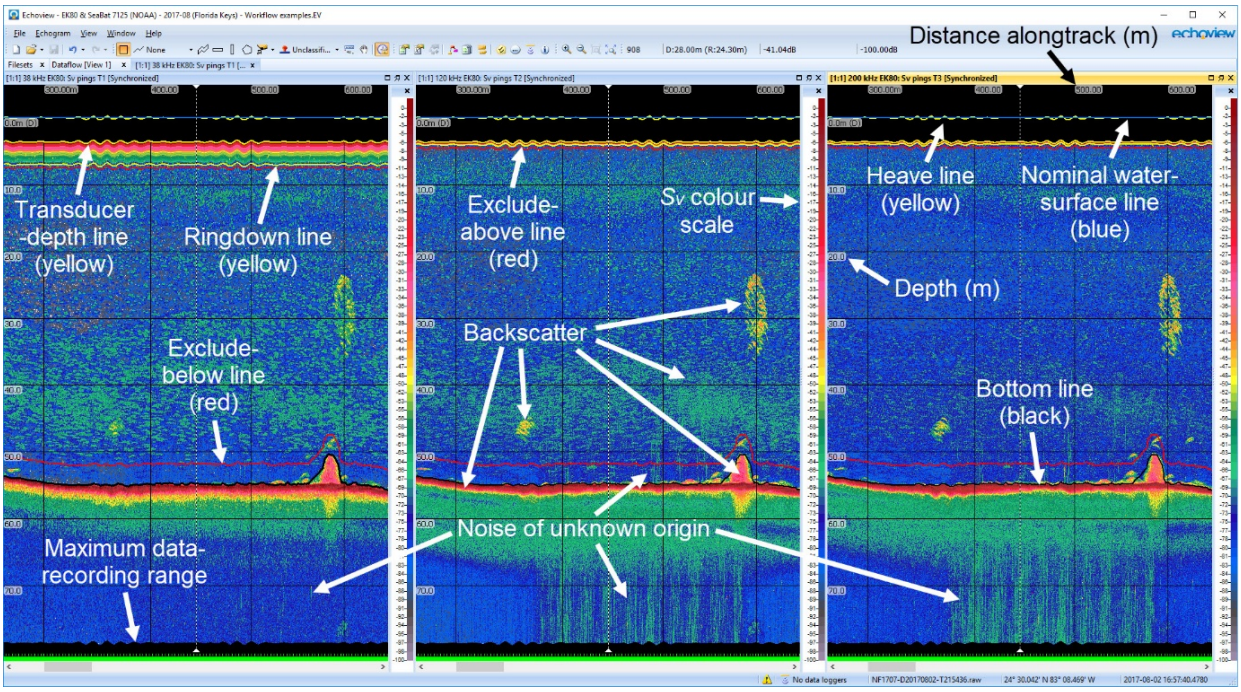


Figure 7-5. EK80 narrowband SBES echograms with nominal center frequencies at 38 kHz (left), 120 kHz (middle) and 200 kHz (right), showing some of the concepts discussed in Sections 7.3 and 7.4.

7.5 TARGET DETECTION AND TRACKING

Target detection is the process of delineating targets (Figure 7-6) in the cleaned echograms. Once delineated, targets can be characterized (e.g. depth, size, backscattering strength etc.; see Sections 7.6 and 7.7), filtered as required (Section 7.4) and (where possible) tracked through space and time over multiple pings (Section 7.5).

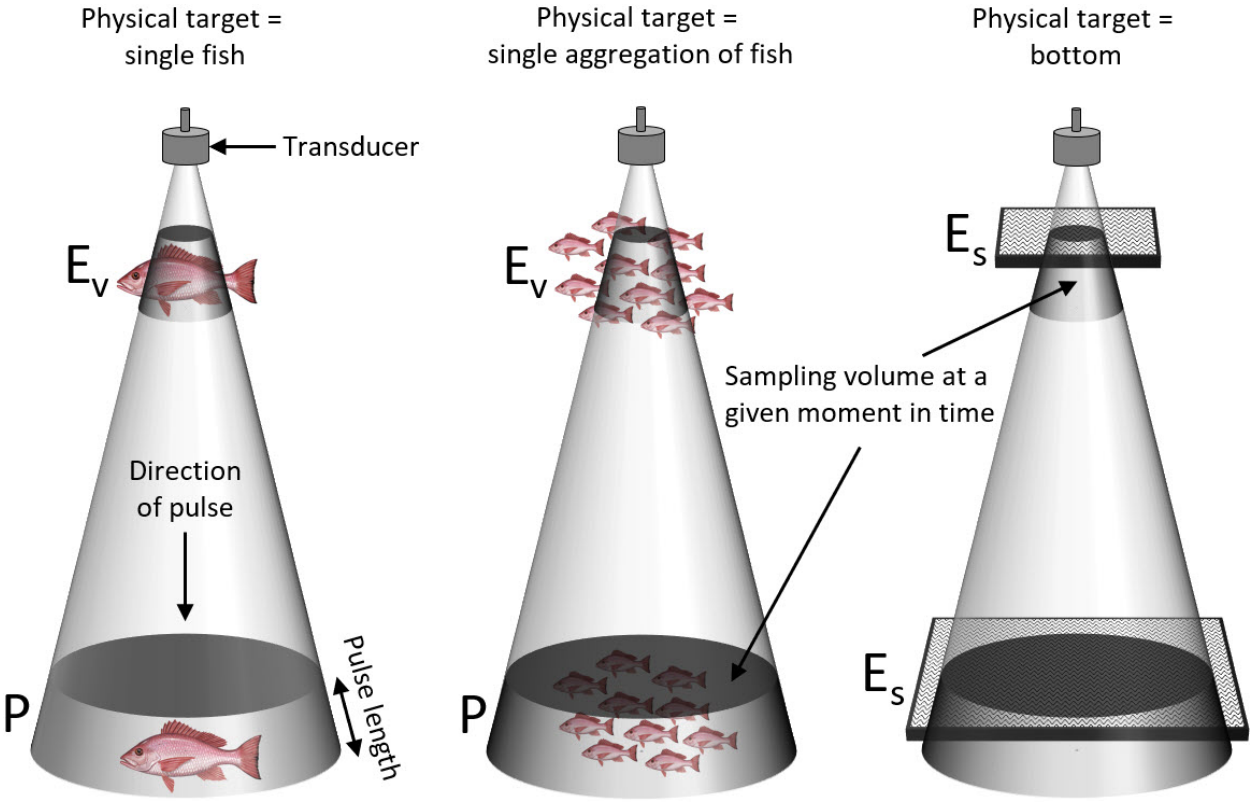


Figure 7-6. The relationship between targets defined in a physical context (e.g. a single fish, a single aggregation of fish, the bottom) and targets defined in the context of an SBES (point targets, P, and extended targets, E; after Lurton, 2002). Point targets arise when the physical target is considerably smaller than the sampling volume, such that the echoes from each facet of the target reach the transducer at essentially the same time and from the same direction. Extended targets can be further divided into volume targets (E_v) and surface targets (E_s). Notice how a single fish and a single aggregation of fish can both be either P or E_v depending on the situation. Care must therefore be taken when using echosounder data to infer how, or even if, an individual animal such as a fish is aggregated in an ecological sense (see Parrish and Hamner, 1997).

Point targets

In SBES data, point targets (Figure 7-6) are most commonly detected on a ping-by-ping basis by looking for peaks of a certain shape and amplitude in the *TS* ping profile (Figure 7-7 [B]). For MBES data, where the target cross-section can be discerned across multiple beams in each ping, the approach is to delineate contiguous clusters of above-threshold samples in a single ping (see Figure 7-7 [E] and Dunlop et al., 2018) in the same way that the cross-section of a volume target (such as an aggregation of fish) is delineated in SBES data across multiple pings (see Figure 7-7 and "Volume targets" below).

The most commonly used SBES point-target-detection algorithm is the "standard phase deviation algorithm" described by Soule et al. (1996). While this algorithm is almost universally adopted, it is

important to note that it is “not foolproof and will often accept multiples” (i.e. multiple echoes) “when resolution densities are exceeded”, explaining why “large inconsistencies are evident in *in situ TS* results reported for pelagic fish” (Soule et al., 1996).

While there is merit in exploring alternative point-target-detection algorithms for SBES data (as discussed in Soule et al. 1996), no further studies appear to be published in this regard. However, algorithms have been proposed for identifying situations in which the point-target-detection algorithm is likely to have failed, i.e. when it has detected multiple echoes (e.g. Sawada et al., 1993; Demer et al., 1999).

Point targets can be tracked if they are detected repeatedly over multiple pings (Figure 7-7 [A] and [C]). The most commonly used tracking algorithm is the “multiple-target tracking” algorithm described by Blackman (1986), although other techniques have also been described (e.g. Hedgepeth et al., 2000; Xie, 2000; Handegard et al., 2012).

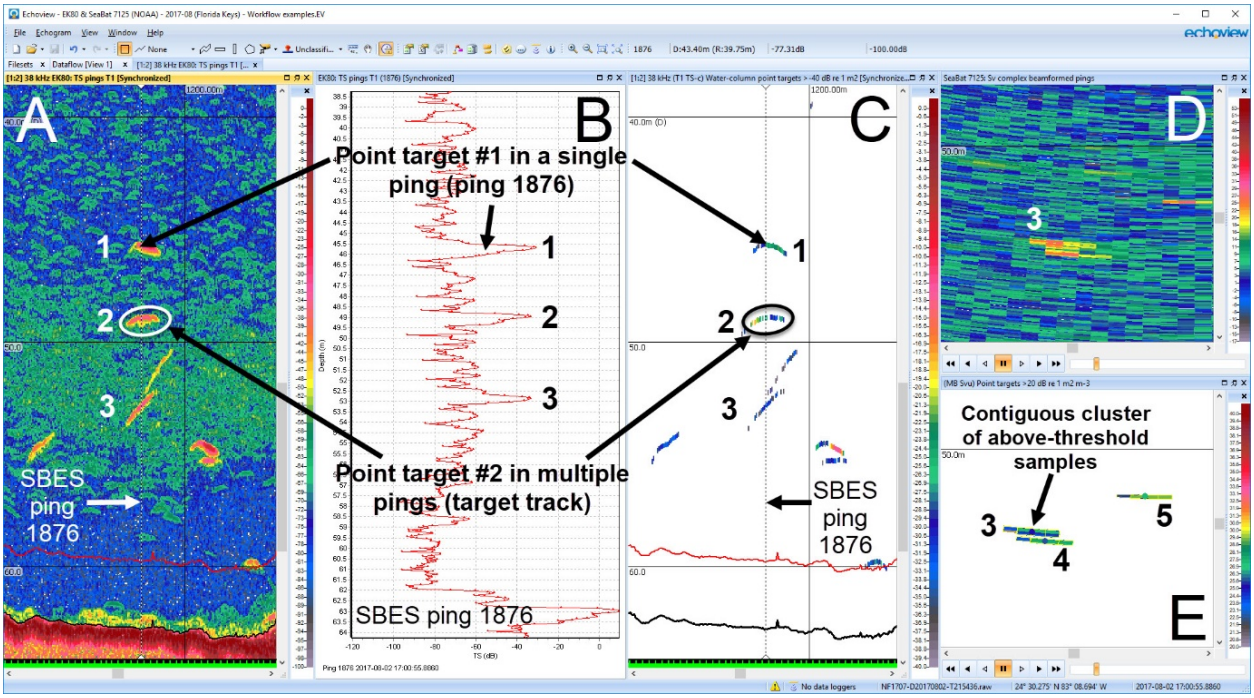


Figure 7-7. Point targets in SBES and MBES data. [A] SBES raw TS_u (uncompensated *TS*) samples echogram (zoomed view). [B] TS_c (compensated *TS*) profile of ping 1876 from echogram A. [C] SBES TS_c point-targets detected from echogram A. [D] MBES raw S_v echogram (uncalibrated) from the same point in time as SBES ping 1876 (zoomed view). [E] MBES S_v point targets detected from echogram D. Note targets 4 and 5 in the MBES data that are not apparent in the SBES data.

Volume targets

Volume targets (Figure 7-6) are detected in SBES data by delineating contiguous clusters of above-threshold samples across multiple pings (identical in concept to point-target detection in individual MBES pings; see Figure 7-7 [E] and “Point targets” above). The result is a 2D polygon (region) that describes the intersection of the target cross-section with the survey track (Figure 7-8). For MBES data, the volume-target cross-sections are delineated in each ping as for MBES point targets (Figure 7-7 [E])

and combined across pings on the basis of proximity (assuming no target movement between pings), resulting in a 3D object that describes the entire target (or portion thereof if not completely insonified within the MBES swath).

The most commonly used SBES volume-target detection algorithm is the "SHAPES" algorithm described by Coetzee (2000). The term "school detection" is commonly used, but note that a school is a specific biological phenomenon (see e.g. Parrish and Hamner, 1997) while the SHAPES algorithm is simply a tool for delineating contiguous clusters of samples (and hence can be used to detect shapes in the echogram caused by other phenomena, such as bubble clouds and plumes). Once the 2D cross-section is created, it is necessary to correct its dimensions to account for the beam pattern (Diner, 2001). The corrected dimensions can then be used to derive a range of metrics that can be used to say something about the nature of the target and its ecology (e.g. Nero and Magnuson, 1989; Scalabrin et al., 1996; Reid et al., 2000; Lawson et al., 2001). Although beam-pattern corrections are technically required for target cross-sections in both SBES and MBES data, it is perhaps surprising to note that they are not commonly applied when processing MBES data.

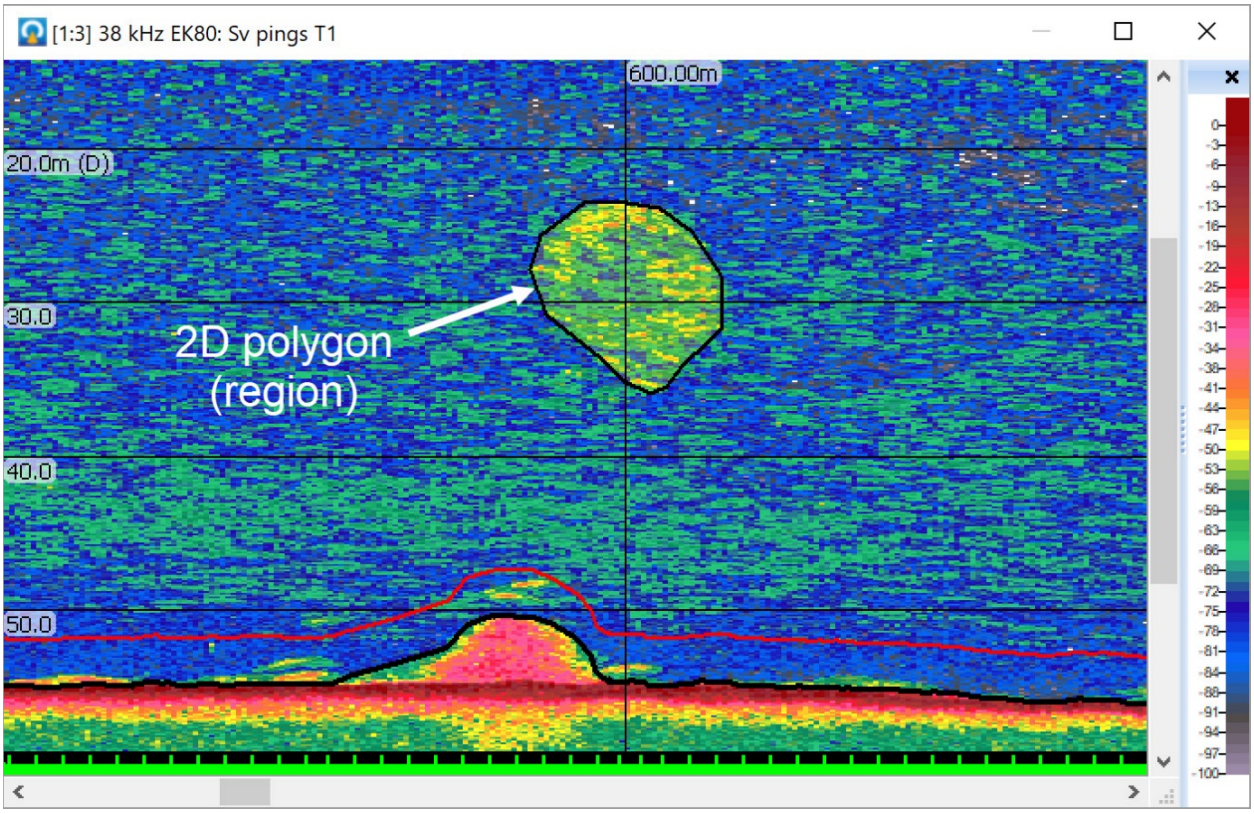


Figure 7-8. An example of a volume target in SBES data, likely representing a cross-section through an aggregation of jacks or snappers. The 2D region delineates a contiguous cluster of S_v samples, with each sample satisfying the volume-target condition (see Figure 7-6).

The bottom

The bottom (which is an example of a surface target; see Figure 7-7) is typically detected on a ping-by-ping basis in SBES data by looking for a peak of a certain shape and amplitude in the S_v ping profile (Figure 7-9 [A] and [B]). The result is a 2D line that describes the location and range/depth of the bottom in each ping (Figure 7-9[A]). For MBES data, the SBES approach is applied to each beam in each ping (Figure 7-9 [C] and [D]) and the resulting detections used to generate a 3D bottom surface (Figure 7-1 [B]).

Bottom-detection algorithms vary in their level of sophistication, from simply identifying the range/depth of the maximum S_v sample in each ping, through to identifying the range/depth at which the split-beam angles (when available) cross through zero (see Demer et al. 2009 and references therein). The aim with SBES data is typically to identify the bottom depth directly below the transducer at any given instant, but split-beam angle measurements also make it possible to estimate the slope and roughness of the bottom within the beam footprint (Demer et al., 2009). Nevertheless, an accurate SBES bottom-detection algorithm that is robust across all situations remains one of the "Holy Grails" of quantitative echosounding.

An added complication is the so-called "dead zone", which arises due to the curved wave front of the transmitted pulse. A number of algorithms have been described for determining the extent of the dead zone (see Demer et al., 2009; Tušer et al., 2013; and references therein), which can then be delineated on an echogram via one or more 2D lines.

Targets on the bottom

Targets attached to the bottom such as kelp, seagrass and shipwrecks may act as either volume or surface targets depending on their acoustic properties. They are typically detected in a similar way to the bottom, by looking for a particular point (e.g. a strong gradient) in the S_v ping profile (Figure 7-9) and generating a 2D line.

Other density discontinuities and boundaries

It is possible to detect phenomena such as thermoclines, pycnoclines and oxyclines if the density change is sufficient, or if they cause an accumulation of biotic or abiotic targets. As for the bottom and targets on the bottom, it may be possible to detect the extent of a cline based on diagnostic features within the S_v ping profile. For example, Bertrand et al. (2010) found that the oxycline depth off Peru was the point at which 98% of the S_v cumulative sum was reached.

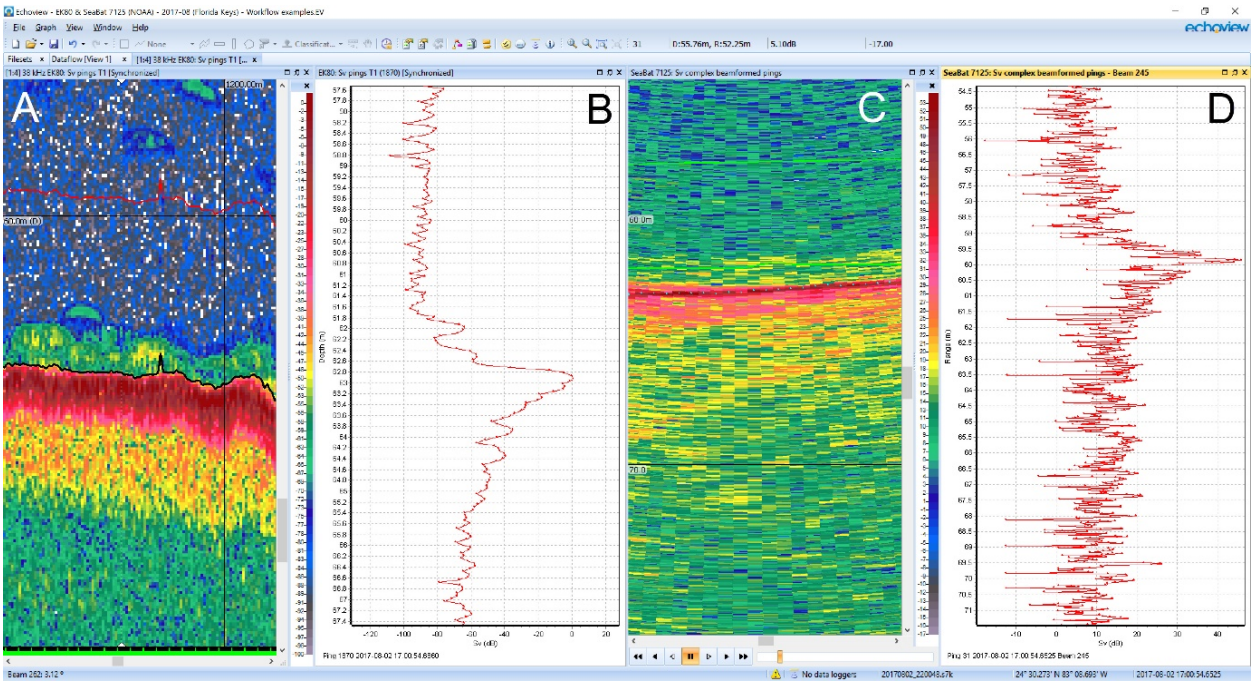


Figure 7-9. Examples of the bottom (a surface target) in SBES and MBES data. [A] SBES raw S_v echogram of a number of pings zoomed in to the area around the bottom. The black line shows the bottom detection. [B] S_v profile of one ping in the echogram to the left. As the sound pulse reaches the bottom, the S_v increases rapidly to an extremely high level (0 dB re. 1 m^2 m^{-3}) before decreasing again at a slower rate. [C] MBES raw S_v echogram of a number of beams in a single ping, zoomed in to the area around the bottom. The turquoise dot in each beam shows the bottom detection. [D] S_v profile of one beam in the echogram to the left. The profile is similar to panel [B] but with more variation from sample to sample (note also that this is not calibrated backscatter, hence the unrealistically high S_v values).

7.6 TARGET CLASSIFICATION

Target classification is the process of differentiating and categorizing the detected targets. It represents another "Holy Grail" of quantitative acoustics (Horne, 2000) because the derivation of ecologically relevant categories (taxonomic group, body size, life-history stage, bottom type etc.) from the indirect measurements made by an echosounder (voltage, time and phase/bearing) is not a straightforward task.

Point targets

The characteristics of SBES-derived point targets that could be used to classify them include their distribution, volume number density (ρ_v), *TS* as a function of frequency (*TS(f)*), *TS* ping-profile characteristics (length, symmetry etc.) and ping-to-ping characteristics. The most common approach has been to classify point targets on the basis of *TS* at a given frequency, although other target characteristics have been explored (e.g. Stanton and Clay, 1986; Vray et al., 1990; Burwen and Fleischman, 1998; Spampinato et al., 2010). The focus to date has been on narrowband data, but we can expect greater emphasis on wideband data into the future (e.g. Stanton et al., 2010).

Although *TS* is less likely to be available for MBES-derived point targets due to the difficulties associated with calibration (see Demer et al., 2015, p86-94), a range of additional characteristics can be extracted from the target cross-sections in each ping (length, height, perimeter etc.) and used to provide a basis for classification. Note, however, that the cross-section geometry should be corrected for the beam pattern to avoid range effects.

Volume targets

Volume targets representing aggregations of fish (Figure 7-6) have formed the focus of much of the SBES target-classification literature (e.g. Reid et al., 2000; Fernandes et al., 2005; Jech and Michaels, 2006; Korneliussen et al., 2016). Reid et al. (2000, p17) grouped the characteristics of volume targets as follows:

1. **Positional:** Latitude, longitude, time and depth
2. **Morphometric:** Length, height, perimeter, compactness etc.
3. **Energetic**: S_v statistics, e.g. mean, minimum, skewness etc.
4. **Environmental:** Water depth, temperature, currents etc.

Early SBES studies explored relatively sophisticated classification techniques for volume targets, such as forward and inverse modelling (see Martin et al., 1996; and references therein), echo statistics (e.g. Stanton and Clay, 1986) and artificial neural networks (e.g. Haralabous and Georgakarakos, 1996). Since this time, most studies have focused on more straightforward analysis of the frequency response ($S_v(f)$), quantified in one of the following ways:

1. The difference in S_v at different frequencies (ΔS_v, ΔMVBS or dB difference; e.g. Kang et al., 2002)
2. The sum of S_v at different frequencies (ΣS_v; e.g. Ballon et al., 2011)
3. The statistics of ΔS_v (e.g. De Robertis et al., 2010)

As with SBES point targets, the focus to date for SBES volume targets has been on narrowband data, but we can expect greater emphasis on wideband data into the future (e.g. Jech et al., 2017).

Fewer studies have focused on classification of MBES-derived volume targets in the water column (see Colbo et al., 2014; and references therein). The characteristics of these targets can be grouped in the same way as for SBES targets (see above), but with less of an emphasis on the energetic parameters and more on the morphometric ones due to the different instrument characteristics.

The bottom

The characteristics of the bottom echo that can be used to classify it include depth, backscatter (S_b) and (more generally) ping-profile, beam-to-beam and ping-to-ping characteristics (see Anderson et al., 2007; and references therein). As with point and volume targets in the water column, the strength of SBES data typically lies in the ability to yield calibrated backscatter, while MBES data provides better spatial coverage.

The general data-processing sequence for SBES bottom classification involves:

1. **Bottom detection:** Identifying the range/depth of the bottom in each ping.
2. **Feature extraction:** Deriving quantities from the bottom-backscatter samples in each ping or group of pings (interval), e.g. water depth, maximum S_v, time taken to rise to the maximum S_v value etc.
3. **Statistical analysis (multivariate analysis and clustering):** Defining which features are responsible for most of the variation across pings or intervals, and clustering these pings or intervals into those with the most similar features.

Perhaps the most commonly extracted features are the backscattering energy in the tail of the first bottom echo and the backscattering energy in the entire second bottom echo (referred to as E1 and E2 respectively; Chivers et al., 1990), although many more features have been variously devised and used (e.g. Hamilton, 2001).

There are two general approaches for MBES bottom classification (see Brown and Blondel, 2008; and references therein):

1. **Geoacoustic**: This aims to solve the so-called inverse problem by matching the S_v or S_b ping-profile shapes to those expected from different bottom types.
2. **Feature-based:** This considers individual or multiple features (water depth, angular response etc.) as described for SBES data (see above).

As for point- and volume-target classification, the perennial challenge for bottom classification is to robustly match the echosounder-derived features to the ecological features of interest (which for the bottom include hard/soft, rough/smooth, rocky/sandy, etc.).

7.7 CHARACTERIZATION

Characterization is the process of calculating metrics from the calibrated, cleaned and classified data to describe:

1. The distribution, density, abundance, biomass and acoustic properties of the detected and classified water-column targets.
2. The water depth and the acoustic properties of the bottom.
3. The extent of the dead zone.
4. The performance of the echosounder (referred to as instrument calibration).

Point targets

Point-target volume number density is estimated by echo counting (Ehrenberg and Lytle, 1972), from which target abundance and biomass can be calculated (see "Volume targets" below). For mobile SBES surveys, in which sequential pings are grouped into time-, ping- or distance-based intervals, a number of echo-counting models have been described (see Kieser and Ehrenberg, 1990; and references therein):

1. ***Cone model***
   Volume number density, ρ_v (number m^{-3}) = Σ point-target detections / Σ 3dB beam volumes
2. ***Trace model***
   Volume number density, ρ_v (number m^{-3}) = Σ tracks / Simple wedge volume
3. ***Wedge model***
   Volume number density, ρ_v (number m^{-3}) = Σ tracks / Complex wedge volume
4. ***Acoustic-detection-volume model***
   Volume number density, ρ_v (number m^{-3}) = Σ point-target detections / Σ *TS* beam volumes

Although the acoustic-detection-volume model is the most sophisticated, most studies have employed either the cone or the trace model, perhaps because these are easier to compute and/or are available in existing software. While both the cone and trace models should yield similar results, the added

complexity and uncertainty introduced by detecting tracks means that the cone model (which doesn't require targets to be tracked) provides perhaps the best balance of simplicity and accuracy.

Echo counting is rarely performed for mobile MBES surveys (see e.g. Dunlop et al., 2018). For stationary SBES and MBES surveys, target tracking enables target flux to be measured (number of targets passing a fixed-point during a given time interval) without the need to explicitly consider sampling volume. However, the cone model can be applied on a ping-by-ping basis to monitor the change in volume number density over time.

Volume targets

The volume number density of individuals within a volume target is calculated by echo integration (Ehrenberg and Lytle, 1972), from which the abundance and biomass of those individuals can then be calculated. Although the concept of echo integration is simple (i.e. the total amount of backscattering energy in a given volume of water is the sum of the backscattering energy from all of the individual targets in that volume), it took considerable work in the 1970s and 80s to show that this assumption of linearity could be robustly applied in practice (see Foote, 1983; and references therein).

The echo-integration equations are similarly simple. Working with the common metrics (s_v, S_v, s_a and s_A) for describing the backscattering energy of a given group of samples (analysis domain), it is possible to calculate the density, abundance and biomass of individuals as follows:

1. ***Density***
   Volume number density, ρ_v (number m^{-3}) = $s_v/\langle\sigma_{bs}\rangle$ **or** $10^{(Sv-\langle TS\rangle)/10}$ **or** $(s_a/\langle\sigma_{bs}\rangle)\Delta z$ **or** $s_A/\langle\sigma_{bs}\rangle 4\pi 1852^2 \Delta z$
   Area number density, ρ_a (number m^{-2} re. Δz) = $s_a/\langle\sigma_{bs}\rangle$ **or** $s_a/10^{\langle TS\rangle/10}$
   Area number density, ρ_A (number nmi^{-2} re. Δz) = $s_A/(4\pi\langle\sigma_{bs}\rangle)$ **or** $s_A/(4\pi 10^{\langle TS\rangle/10})$
   Volume mass density, m_v (kg m^{-3}) = ρ_v x $\langle m_i\rangle$
   Area mass density, m_a (kg m^{-2} re. Δz) = ρ_a x $\langle m_i\rangle$
2. ***Abundance for a given water volume (V) or area (A)***
   n_b (number) = $\langle\rho_v\rangle$ x V **or** $\langle\rho_a\rangle$ x A
3. ***Biomass for a given water volume (V) or area (A)***
   m_b (kg) = $\langle m_v\rangle$ x V **or** $\langle m_a\rangle$ x A

where:

- s_v is the mean volume-backscattering coefficient (m^2 m^{-3}) of the samples in the analysis domain (where $s_v = 10^{Sv/10}$, and S_v is defined below)
- S_v is the mean volume-backscattering strength (dB re. 1 m^2 m^{-3}) of the samples in the analysis domain
- s_a is the area-backscattering coefficient (ABC; m^2 m^{-2} re. Δz) of the samples in the analysis domain
- s_A is the nautical area-scattering coefficient (NASC; m^2 nmi^{-2} re. Δz) of the samples in the analysis domain
- $\langle\sigma_{bs}\rangle$ is the backscattering cross-section (m^2) of a representative individual in the analysis domain
- $\langle TS\rangle$ is the target strength (dB re. 1 m^2) of a representative individual in the analysis domain

- Δz is the average range extent (m) of each ping in the analysis domain
- $\langle m_i \rangle$ is the mass (kg) of a representative individual

These equations show that if you wish to know the density of individuals, then the goal of the echosounder data-processing workflow is to provide accurate measurements of the backscattering energy due solely to the individuals of interest in a given volume of water (expressed as either s_v, S_v, s_a or s_A). The ability to achieve this depends on the successful completion of each workflow step in turn (i.e. calibration, cleaning, detection and classification).

These equations also show that another critical value is required, namely the backscattering energy from a representative individual in each volume (as either σ_{bs} or *TS*, where <…> denotes "representative"). This is perhaps the most challenging task in quantitative acoustics (see Ona, 1999; and references therein).

Accurate measurements of s_v, S_v, s_a or s_A can only be obtained from a calibrated echosounder, i.e. one that is stable from ping to ping and whose performance characteristics can be quantified (see Demer et al., 2015; Section 4.6 and Section 6 on the Scientific Echosounder System). Currently there are more SBES systems available fitting this description than MBES systems, but this may change in the future (see e.g. Andersen et al., 2007; Mosca et al., 2016).

The bottom

Once the bottom has been detected as a 2D line or 3D surface (Figure 7-9), it can be characterized in terms of latitude, longitude, depth and time. As described in Section 7.6, it is also possible to characterize the bottom in terms of its backscatter features. These features can be used to classify the bottom, illustrating that the data-processing workflow can also work in an iterative and non-linear way.

The echosounder system

Detections of a target with known acoustic properties (e.g. a 38.1 mm-diameter tungsten-carbide sphere) can be used to estimate some of the parameters in the echosounder equations for *TS* and S_v, most notably on-axis gain and the s_a correction factor (Fig. 7-4 [B] and [C]). This is typically referred to as "calibration" (see Section 4.6; Demer et al., 2015; and references therein), but note the distinction between this (which is a procedure performed to characterize the performance of the echosounder, i.e. instrument calibration) and data calibration (Section 7.3). As for any other echosounder-based procedure, a calibration experiment involves data collection (Section 4.6) and data processing (Section 7).

8 ACOUSTIC DATA INTERPRETATION AND ABUNDANCE ESTIMATION (D.A. DEMER)

Stock abundance may be estimated by echo-integration analysis of echosounder data collected along transects that span the target stock distributions. Basically, animal density is estimated by summing the echoes received from all of the sampled animals, and dividing that by the echo representative of an average individual. The abundance is estimated by multiplying the estimated density by the sampled area. This section summarizes the steps of an echo-integration survey analysis.

8.1 TARGET STRENGTH ESTIMATION

To estimate the mean backscattering cross-sectional areas (σ_{bs}, m^2; MacLennan et al., 2002) for individual fish of the dominant species within each trawl catch or camera image, the length distributions from the catches or images are input to models of target strength, $TS = 10\log(\sigma_{bs})$ versus fish length. The *TS* models may be obtained from the literature, or derived from *TS* and length measurements made from *in situ* or *ex situ* fish.

8.2 BIOMASS ESTIMATION

Animal densities are estimated by dividing the nautical area scattering coefficients (s_A; m^2 nmi^{-2}) (MacLennan et al., 2002) for each species by their respective length-weighted average σ_{bs} (Simmonds and MacLennan, 2005; Demer et al., 2012). The biomass densities within each acoustic transect are averaged to comprise the sample unit (Simmonds and Fryer, 1996).

Because each species does not generally span the entire survey area (Zwolinski et al., 2014), their natural patchiness is delineated by statistically-independent, stationary, post-sampling strata (Johannesson and Mitson, 1983; Simmonds et al., 1992). Each stratum should have: 1) at least three transects, all of them have approximately equal spacing, 2) fewer than three consecutive transects with zero-biomass density, and 3) bounding transects with zero-biomass density.

The mean biomass density of each stratum is calculated by a transect-length weighted average of the transect-mean densities (Demer et al., 2012; Zwolinski et al., 2012), which is equivalent to the arithmetic mean of all individual samples in the stratum.

An estimate of abundance is obtained by multiplying the average estimated density in the stratum by the stratum area (Demer et al., 2012). The variance is calculated through non-parametric bootstrap of the transect-mean densities. The total abundance in the survey area is the sum of abundances in all strata. The total variance is the sum of the variance in each stratum.

8.3 Uncertainty Estimation

Acoustic survey estimates have random and systematic components of measurement and sampling uncertainty (Demer, 2004). Random measurement and sampling error, or precision, is reduced by averaging independent measures. Because there are usually numerous measurements comprising a sampling unit, e.g., a transect, measurement error is generally negligible. On the other hand, random sampling error, typically summarized by the coefficient of variation (CV), depends on the distribution of the animals sampled and the number of independent sampling units, e.g. transects.

Provided that each stratum has spatially independent transect means (i.e., densities on nearby transects are not correlated), random-sampling estimators provide unbiased estimates of variance. Transect-mean densities are treated as replicate samples, and the variance is calculated for each post-sampling stratum using non-parametric bootstrap resampling (Efron, 1981).

The 95%-confidence intervals for the mean biomass densities are estimated as the 0.025 and 0.975 percentiles of the distribution of 1000 bootstrap survey-mean biomass densities. The bootstrap estimates are constructed by resampling with replacement, the transects within the strata (Efron, 1981). Coefficient of variation (CV) values are obtained by dividing the bootstrapped standard errors by the estimated means (Efron, 1981).

It is essential to first identify and mitigate all significant components of measurement and sampling bias, then sample the animals of interest such that the CV is small enough to detect meaningful change.

Often, more insidious than random error is the systematic estimation uncertainty, which varies in time and space. Examples are variable biases due to diel and seasonal migratory behaviors and environmental changes, which affect animal distributions and their detectability; and the accuracies of echo classification and target strength estimation, which change according to the species present, and their ontogeny and demographics. Measurement and sampling biases are non-random, so their effects must be either negligible, or their estimates must be considered in the accounting for uncertainty. These variable biases may be positive or negative (e.g., Demer, 2004; Simmonds and MacLennan, 2005). If they are not negligible, and their variable magnitudes are unknown or not accounted, then the estimates cannot be statistically evaluated for change.

To evaluate change in a time-series of survey estimates, it is therefore essential to first identify and mitigate all significant components of measurement and sampling bias, then sample the animals of interest such that the CV is small enough to detect meaningful change. The requisite sampling for a targeted level of uncertainty may be learned from past survey results, estimated from simulated sampling of a hypothesized animal distribution, or both.

9 CASE STUDY: FISHERY ACOUSTIC SURVEYS TO LOCATE, ASSESS AND MONITOR REEF FISH SPAWNING AGGREGATIONS (B. BINDER, J.C. TAYLOR AND K. BOSWELL)

9.1 BACKGROUND

The formation of fish spawning aggregations (FSAs) is a vital part of the life cycle of many reef fishes, and represents the sole reproductive opportunity for many aggregating species (Domeier and Colin, 1997). Additionally, FSA's play a key role in promoting overall reef health (Archer et al., 2014), and stimulate increases in reef fish abundance and diversity (Heyman et al., 2005; Schärer et al., 2009). Unfortunately, spatial and temporal knowledge of these resources is predominately limited to experienced anglers, which has led to many cases of decline and extirpation after extended periods of heavy fishing (Sadovy De Mitcheson et al., 2008). However, increases in participation by resource users in the design of fisheries management strategies have led to the discovery and protection of several spawning aggregations throughout the Unites States and Greater Caribbean (Burton, 1998; Lindeman et al., 2000; Nemeth et al., 2006 and 2012; Zeigler and Hunt, 2012). For example, the commercial fishing community was directly responsible for identifying the decline of goliath grouper catches in south Florida; and the subsequent management actions that resulted in the complete moratorium on their harvest in 1990 (SAFMC, 1990; Lindeman et al., 2000; Ferreira et al., 2014). Following the closure, additional resource user driven survey initiatives were developed to monitor the recovery of the species, and have provided evidence of a measurable recovery throughout their range in Florida; including the reformation of multiple spawning aggregations on the east and west coasts of Florida (Koenig and Coleman, 2009; Cass-Calay and Schmidt, 2009; Mann et al., 2009; Collins, 2014). Additionally, a user-driven initiative to protect a failing snapper fishery in the Dry Tortugas led to the development of the Tortugas South Ecological Reserve in 2001. The fishery has seen a significant recovery since inception, with direct observations of spawning individuals, and as many as ~4000 aggregated snapper (Burton et al., 2005; Zeigler and Hunt, 2012).

The cumulative body of knowledge from targeted research as well as resource users accumulated over generations of fishing and their contributions as 'citizen scientists' has improved our understanding of the spatial and temporal dynamics of aggregation activity but is lacking in the peer reviewed literature (Lindeman et al., 2000; Koenig and Coleman, 2009). But surveys to confirm the location and timing of aggregations and to assess trends in spawner abundance has relied primarily on visual surveys which are inefficient in covering large areas, inherently risky in deep environments, and may not be able to provide robust estimates of abundance in very dense aggregations. Fishery acoustics provides advantages to in-water visual surveys in the ability to cover large areas relatively quickly providing an index of biomass from the acoustic backscatter, and pinpointing the location of aggregations. Here, we provide case

studies of acoustic applications for locating, assessing abundance and monitoring trends in reef fish spawning aggregations.

9.2 Approaches

Numerous reports have found reef fish spawning aggregations located in close proximity to prominent geomorphological features such as promontories, seamounts, or outer reef ridges. But these features may extend several kilometers, leading to inefficiencies in searching for or monitoring by scuba divers. To examine the changes in aggregation density and abundance at spawning sites, hydroacoustic and diver visual surveys were conducted over consecutive 2-3 day periods around peak lunar phases (new and full moon) throughout the spawning season of the target species. The suite of devices implemented in the hydroacoustic surveys have included multiple frequencies to differentiate fish aggregations from aggregations of other taxa such as plankton (e.g., 38, 70 and 120 kHz). Multibeam sonars are also used to simultaneously map the seafloor to provide further inference on the habitat use by aggregations. Watercolumn backscatter from multibeam echosounders can also provide indicators for the presence of large aggregations. Survey design, as described earlier in this report can involve systematic parallel transects, as well as "flower" shapes, with important assumptions to consider as described in the sampling design section of this report. Acoustic backscatter can provide estimates of abundance, but require groundtruthing to validate species presence. Roving and drifting visual surveys with divers or remotely operated vehicles are used to ground truth estimates derived from acoustic surveys. Detailed discussions on survey design and estimating abundance are in previous sections.

9.3 Searching for Aggregations in the Florida Keys National Marine Sanctuary

Beginning in 2009, NOAA began a project focused on locating and examining the status of FSAs in the Florida Keys National Marine Sanctuary. Partnering with commercial fisherman from the region, we first investigated historically known to aggregation sites in the Florida Keys. These reports were provided as geographic coordinates, or points on a paper map or nautical chart, with descriptions of the bathymetry and sometimes geomorphology of the seafloor. The precision of the geographic location varied considerably. Initially, large-scale acoustic surveys were conducted to develop bathymetric profiles for the study areas that could be used to predict the precise locations of aggregation activity. We then used an exploratory survey method using parallel lines, a grid or transects, or clover leafs around geomorphological features such as promontories, to pin-point areas of high biomass using a split-beam echosounder. When we detected high acoustic backscatter in the watercolumn, we adapted the surveys with a tighter clover leaf to pinpoint the location of the aggregation and quickly deployed divers on these hotspots to confirm the presence of target spawning species, quantify their abundance, and document spawning activity (Figure 9-1). Using this approach, aggregations of black grouper, mutton snapper, and gray snapper were detected near historically reported aggregations sites, confirming association with unique bathymetric features. The large scale acoustic surveys also documented additional aggregations other species that were not the focus of management, but pointed to evidence of multi-species spawning aggregation sites.

9.4 Estimating Abundance of Goliath Grouper in the Southeast Florida

Building on what we learned in the Florida Keys, an extension of the original project was undertaken along the East coast of South Florida. Using information gathered from a network of commercial and

recreational resource users, we developed a comprehensive database of historical FSA reports that were considered in a wide-scale re-zoning effort in the Southeast Florida Coral Reef Initiative regions (Figure 9-2 and Figure 9-3).

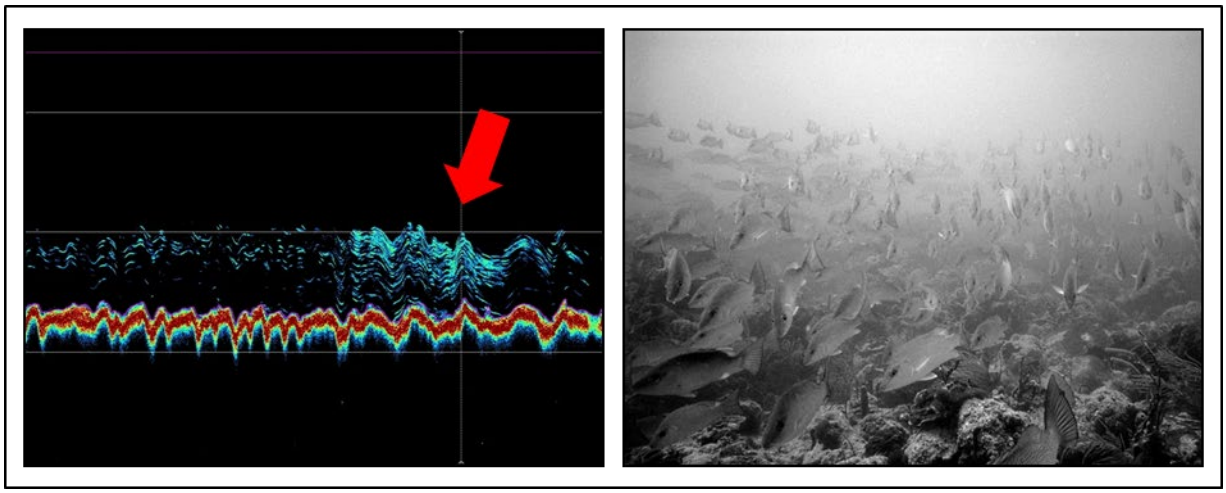


Figure 9-1. Real-time monitoring of acoustic data acquisition allows for the rapid deployment of divers to visually confirm the presence of aggregating fish. Once an area of elevated backscatter was pin-pointed using the echogram (Left), divers were deployed. In the provided example, divers were rapidly deployed on an area of interest and confirmed the presence of a large aggregation of gray snapper (Right) that had eluded researchers in preceding months.

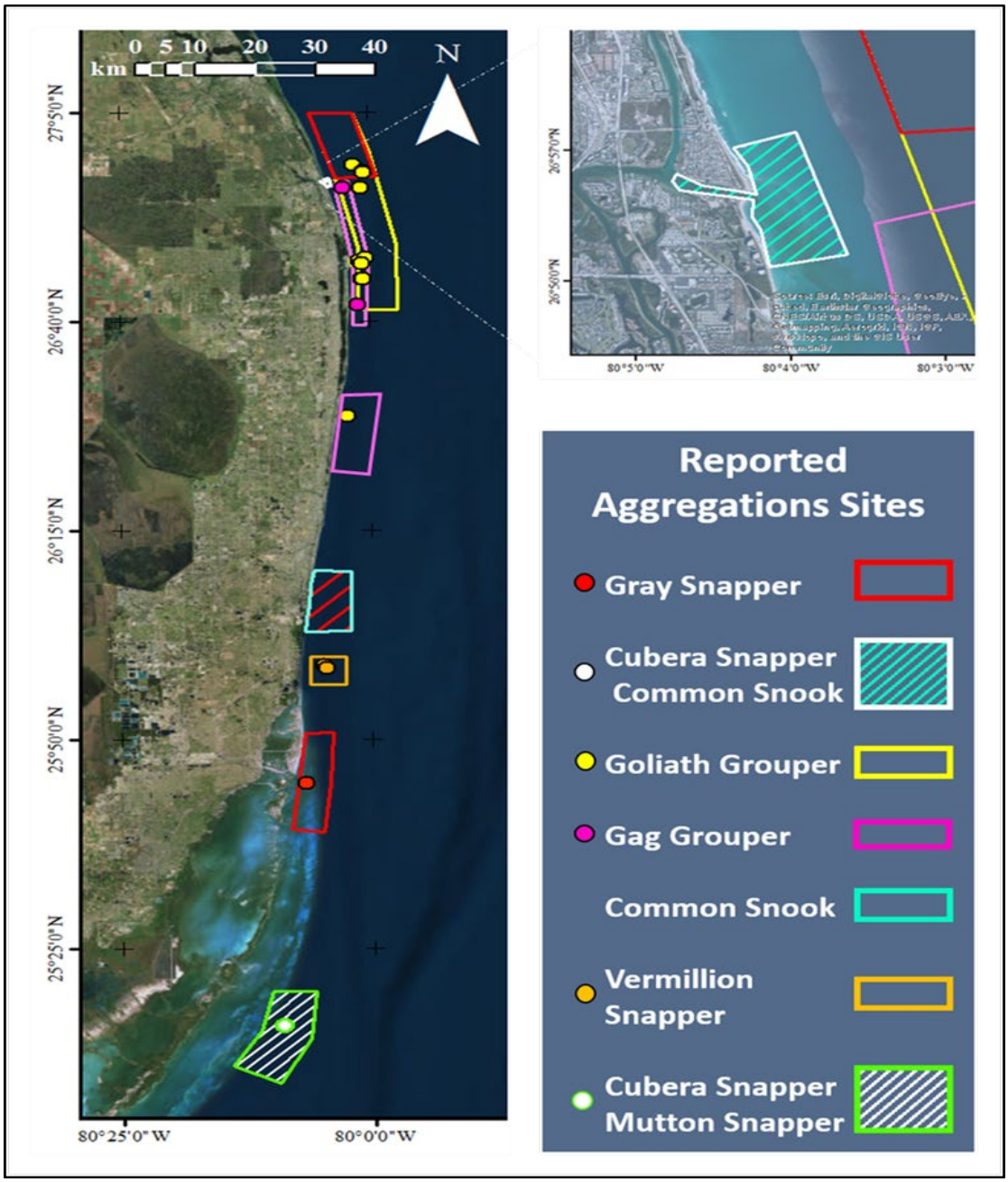


Figure 9-2. Information gathered from a network of commercial and recreational resource users was used to develop a comprehensive geospatial database of historical FSA reports that were considered in a wide-scale re-zoning effort through the Southeast Florida Coral Reef Initiative.

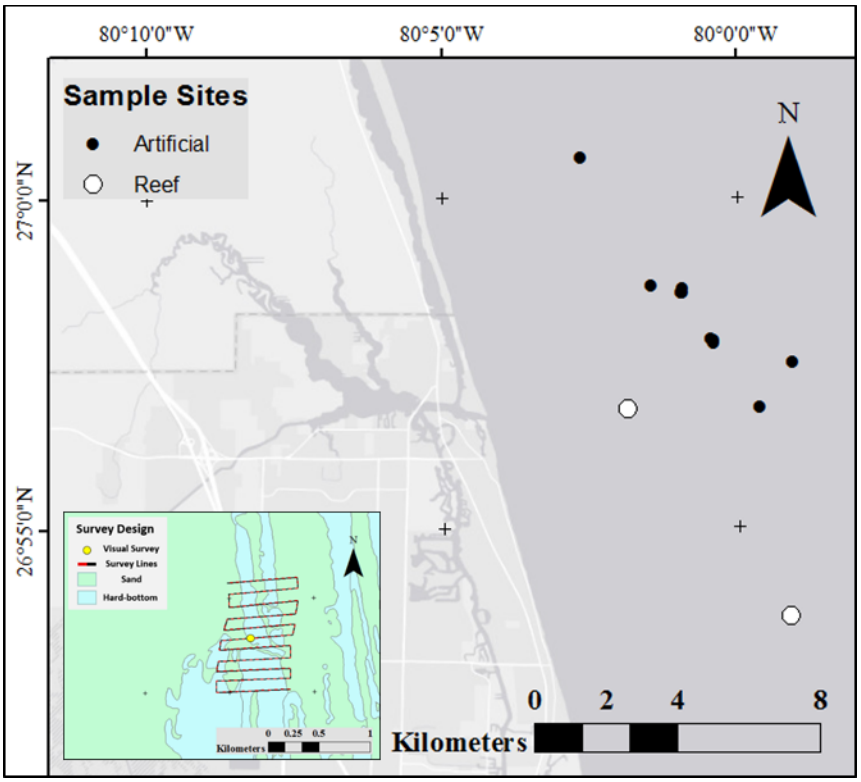


Figure 9-3. Following information gathering, systematic survey transects were established centered on a known wreck where the goliath grouper aggregate.

Using techniques described in the abundance estimation section in this report, abundance estimates were made for each survey leading to better understanding of the timing of the goliath aggregations. Despite our efforts, data pertaining to the precise location and timing of FSAs was sparse, making a dedicated multi-species acoustic survey effort impractical. We used acoustic surveys to estimate abundance of a reef fish community and the target species, goliath grouper near Jupiter, Florida (Figure 9-4).

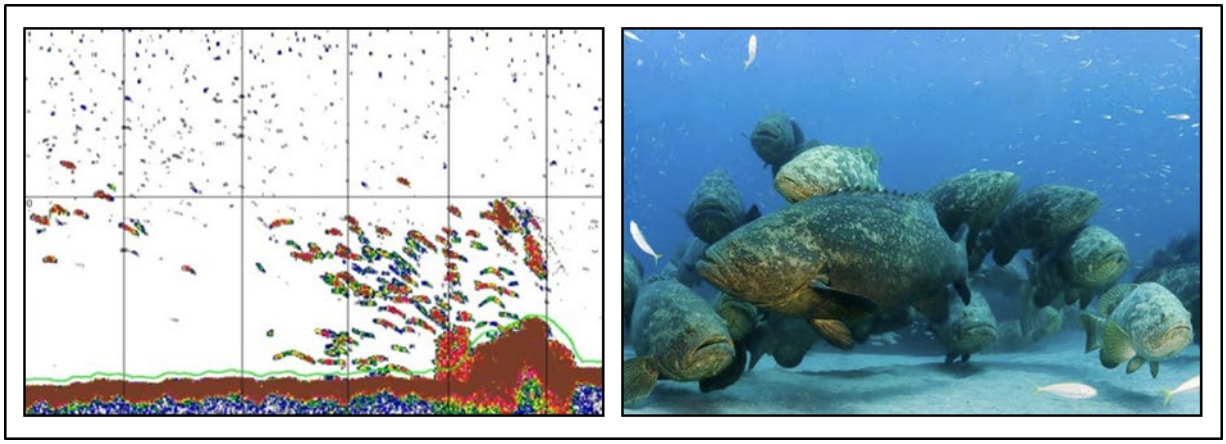


Figure 9-4. An echogram (left) showing an aggregation of large individual targets over structure on the seafloor. Right image shows the same group of goliath grouper observed by divers.

9.5 Multibeam Echosounders for Estimating Aggregation Abundance

Calibrated splitbeam echosounders provide the best means for estimating target strength of individuals and measuring backscatter for estimating abundance of aggregations. But the splitbeam echosounder typically uses a narrow transducer beam resulting in a narrow slice through the watercolumn. By example, a typical transducer beam has a 7-degree opening angle, resulting in swath at the seafloor of about 12% of depth (e.g., 12 m wide at 100 m depth). A wider transducer beam angle increases the search volume, but also increases the acoustic deadzone and occlusion of individuals close to the reef interface. Studies in coral reefs have successfully used multibeam echosounders to increase the swath and search volume by orders of magnitude. Multibeam echosounders used for hydrographic and seafloor mapping surveys can also collect backscatter from objects in the watercolumn. A typical multibeam sonar has a beam fan angle as large as 140 degrees, or 10 to 20 times a typical splitbeam echosounder. Instead of a slice through part of the aggregation, the multibeam swath can image the three-dimensional volume and shape of the aggregation. Multibeam echosounders are not generally calibrated, so data from these systems will not provide useful measures of backscatter to estimate abundance. Instead, the sequence of cross sections at each multibeam ping can be combined to estimate the volume of the aggregation. Densities calculated using the splitbeam echosounder can then be scaled up to estimates of total abundance in the aggregation.

Taylor and Ebert (2012) used watercolumn backscatter from multibeam echosounders collected during a seafloor mapping survey of El Seco, a feature near Vieques Island, Puerto Rico and the Flower Garden Banks National Marine Sanctuary in the Northwest Gulf of Mexico to locate and measure the size, shape and abundance of fish in large schools and aggregations. The survey evaluated the combination of splitbeam and multibeam echosounders and demonstrated the ability to increase search volume to detect relatively small aggregations of reef fish, providing precise estimates of abundance as validated by video from a remotely operated vehicle. The approach also documented unusually large school of reef fish at West Flower Garden Banks (Figure 9-5). Repeated surveys further reported a consistent hotspot of fish biomass in that area.

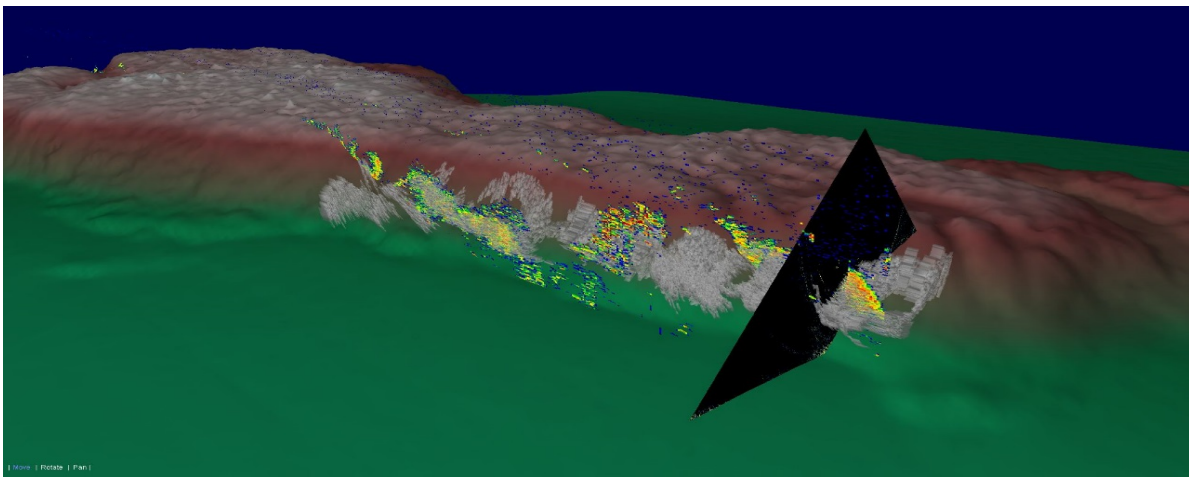


Figure 9-5. Example of a large fish (Atlantic creole fish) aggregation mapped using both multibeam and splitbeam echosounder surveyed over the coral reef cap in Flower Garden Banks National Marine Sanctuary. The blue-orange-red curtain represents backscatter and cross-section of the aggregation from the splitbeam echosounder. The grey shaded volume represents the 3-dimensional shape of the aggregation resolved using a multibeam echosounder, with a single ping multibeam fan shown. Multibeam derived bathymetry is shown from pink (shallow) to green (deep). Data source: Unpublished, JC Taylor and EF Ebert, NOAA National Centers for Coastal Ocean Science.

9.6 Implications for Fisheries Management

FSAs are important to the reproductive success and continuity of reproducing species, and contributes to the enrichment of genetic diversity (Sadovy De Mitcheson et al., 2008). The implications for developing an FSA monitoring program that incorporates the local community and fisheries acoustics are considerable. Indeed, in regions where invested fisherman have assisted scientists in managing and studying FSAs, there are numerous cases of recovery following decades of heavy fishing pressure (Burton et al., 2005; Heyman et al., 2005; Schärer et al., 2009). Thus, by integrating local knowledge with the existing literature, and implementing a wide-scale quantitative acoustic survey approach, we promote a methodology to address the spatial and temporal aspects of FSAs that can be used as a basis to apply a similar non-invasive monitoring methodology in other regions deficient in their knowledge of FSAs.

10 Case Study: Stationary Acoustic Measurement Instruments and Methods (J.C. Taylor and K. Boswell)

Ecological processes on coral reefs occur over a continuum of spatial and temporal scales. Elsewhere in this report, authors have described several advantages provided by fisheries acoustics, especially where surveys can cover large areas relatively quickly at very fine spatial resolution. But these surveys usually provide a single snap-shot of the distribution of biological organisms. This raises some challenges in interpreting habitat use at finer scales in the complex mosaic of habitats. For example, in coral reefs, several species groups migrate from the reef onto adjacent habitats during dusk to feed on benthic organisms emerging from soft sediments. Observing these behaviors is made difficult by reduced light levels and the chance that divers as observers may disrupt the behavior of interest. Marine organisms also use the watercolumn as habitat, and migrate vertically to feed on pelagic organisms queued by light levels, temperature or other environmental influences. These vertical movements could also be related to interactions with the underlying benthic habitats. Observations from stationary platforms can elucidate these very fine-scale individual movement and behaviors over time scales of seconds to years. In this case study, we present areas of research with management applications using stationary platforms and fishery acoustic systems to:

1. Detect and observe movements of reef organisms in complex reef habitats,
2. Observe predator-prey interactions on coral reefs.

As described previously in this report, split-beam echosounders transmit and collect backscatter from the watercolumn multiple times per second. Splitbeam echosounders can be deployed on a mooring looking upward or buoy looking downward (Figure 10-1). A single point target can be located in split-beam during sequential pings, providing "tracks" depicting movement of the organism through the acoustic beam. These tracks can be placed in real-world space to position the target relative to the location of the acoustic system and other features in the environment or habitats. Large schools of fish or layers of plankton can be analyzed as volume targets to track vertical or horizontal movement of groups of animals. Multibeam sonars and their imaging sonar relatives provide a wider field of view compared to the narrow beam of the splitbeam echosounders. Imaging sonars like Dual-frequency Identification Sonars (DIDSON, http://www.Soundmetrics.com) and ARIS imaging sonars operate at very high frequencies (1-3 MHZ) to produce video-like images in the view field (Belcher et al., 2002). These sonars can resolve size and shapes of groups of organisms and body shape and movement of individuals. In the early application of these systems, they were employed on stationary platforms to observe anadromous fish during spawning migrations up rivers, reporting counts

Observations from stationary platforms can elucidate very fine-scale individual movement and behaviors over time scales of seconds to years.

and timing of migration as well as sizes of species like salmon. In coral reefs, they can provide high resolution images of individuals as well as images showing the complexity of the habitats (Figure 10-1).

Figure 10-1. Example of a stationary deployment for imaging sonars (left panel showing DIDSON and Kongsberg M3), a diver deploying an imaging sonar and video camera (middle panel), and an upward facing split-beam echosounder (right panel) deployed near Aquarius Reef Base in the Florida Keys.

10.1 DETECTING AND TRACKING MOVEMENTS OF REEF ORGANISMS IN COMPLEX HABITATS

Several species of reef fish make regular migrations between reefs and adjacent habitats. A well-known example involves groups of smaller snappers (Lutjanidae) and grunts (Haemulidae) that use the reefs during the day as refuge from predation (Hobson, 1972; Helfman, 1984). Around dusk, individuals or groups of fish migrate off the reef and feed over adjacent sediment, likely consuming invertebrates emerging from the soft sediment. It is thought that the migration at dusk is queued to light levels that may inhibit predators from detecting the smaller fishes. The migration may be selective for certain habitat types adjacent to the reefs, such as macroalgae or other vegetation, rather than unvegetated sand. Movements of animals over the seascape is studied using various forms of tag and telemetry systems where individuals are implanted with transmitters that report location on deployed receivers scattered around the seascape (Pittman et al., 2014). This lagrangian-type observatory has made important discoveries of animal movements across seascapes, but may not be able to estimate rates of movement in terms of number of individuals or fine temporal scales of movement across habitat transition zones due to limits in the number of tags that can be deployed. Observations using stationary acoustic imaging platforms can provide measurements of the sizes and movement rates of individuals to provide insights into the connectivity of coral and adjacent habitats. An acoustic imaging system can be set at the interface between a coral reef and adjacent sediment or

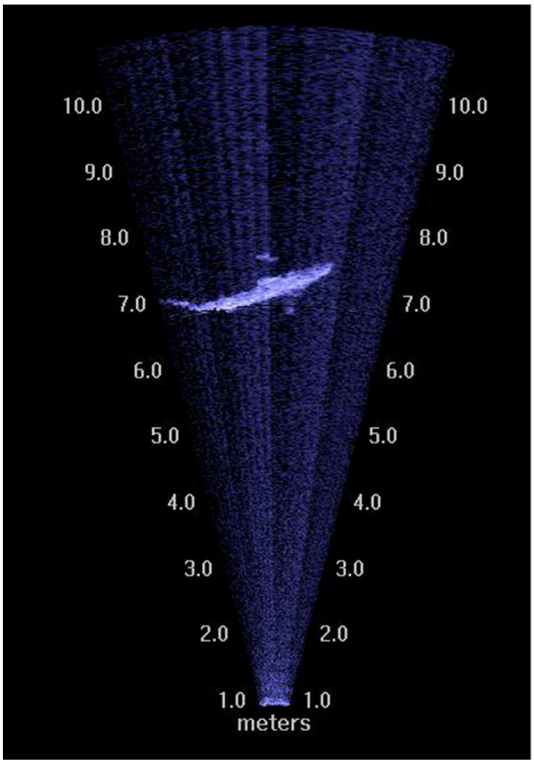


Figure 10-2. Figure 4 2. An example image of a reef shark captured by a DIDSON imaging sonar from McCauley et al. (2016). The body shape and movement (in the acoustic video) allow for measurement of individual lengths.

vegetated habitats. Measurements of fish movement between habitats can provide measures of flux of biomass across boundaries. The key challenge is to select a representative location for the observation that will provide meaningful and interpretable data.

Top predators like sharks or groupers are often elusive during certain life stages or are transient and move through coral reef habitats at night. Detection of these large animals requires well-placed observing systems that minimize interference with behaviors such as the use of lights or other devices. Imaging sonars have been used to detect and enumerate reef sharks in remote habitats (McCauley et al., 2016). Timing of habitat use by shark species can be tracked using autonomous platforms with sonars or echosounders deployed for extended periods. Individuals can be enumerated to provide an index of abundance and with length information, biomass estimates can also be derived.

Rare and elusive species of reef fish pose challenges to enumeration and assessments to guide management and species conservation. By example, goliath groupers (*Epinephelus itajara*) are IUCN listed species whose harvest is severely restricted throughout much of its range in the western Atlantic Ocean. Juvenile stages of goliath groupers use mangrove root systems as part of their nursery habitats before moving into deeper reef habitats as adults (Koenig et al., 2007). The highly complex structured habitats of the mangroves are challenging to survey to understand habitat use by the fish and enumerate and assess rare or endangered species. Imaging sonars used like acoustic cameras have been deployed successfully to detect and estimate abundance of juvenile goliaths in mangrove habitats in southern Florida, USA (Frias-Torres and Luo, 2009). In examples provided by Frias-Torres and Luo (2009), the DIDSON imaging sonar was able to detect individuals that were not seen in videos due to poor water clarity (Figure 10-3).

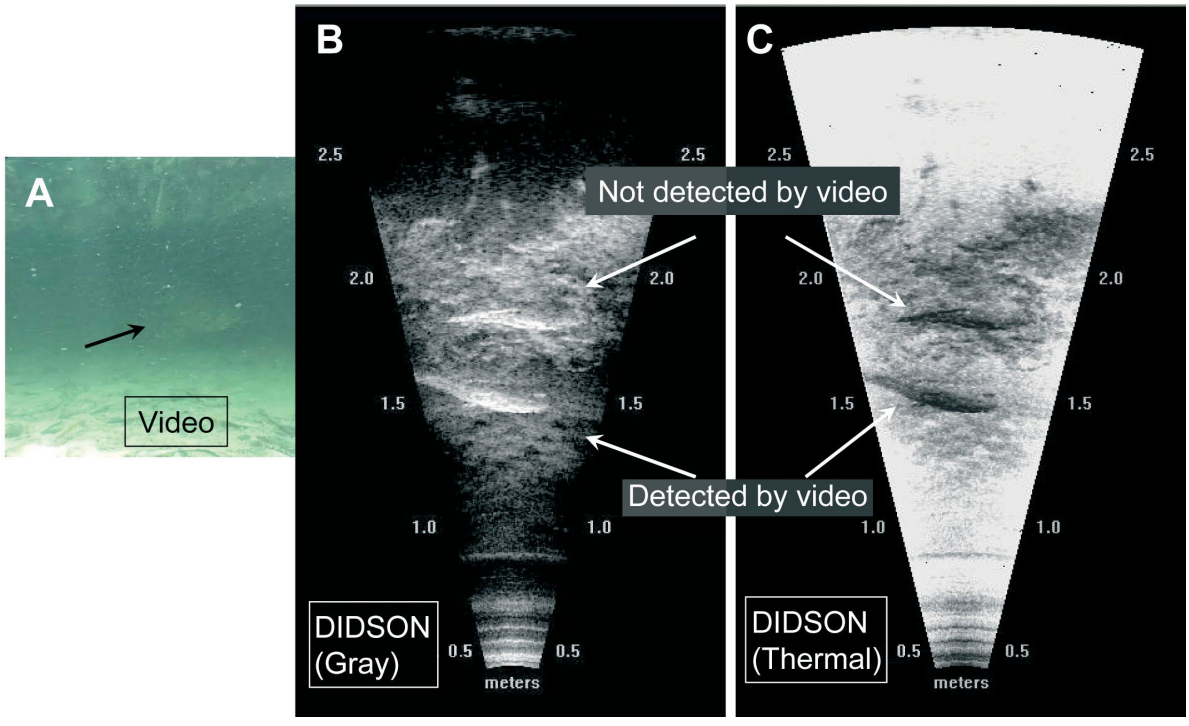


Figure 10-3. Example video image of goliath grouper deep in a mangrove habitat (A). Corresponding imaging sonar image (DIDSON) of same fish showing individuals that were not detected by video. Example source: Frias-Torres and Luo, 2009.

10.2 PREDATOR-PREY INTERACTIONS

When conditions are favorable, imaging sonar data can be directly coupled with video data from underwater cameras to provide species identification and to help identify members of the biological community in addition to the interactions among individuals and between species. For example, Boswell et al. (unpub.) and Catano et al. (2016) have examined the effects of large predators on herbivory rates in coral reef ecosystems of the Florida Keys. Coupling underwater video data with imaging sonar data allowed direct quantification of the rates of herbivory relative to the threat of predation (Figure 10-4 and Figure 10-5). The high-resolution data that are provided from imaging sonars offers researchers the ability to directly quantify interaction rates, organismal size, speed and direction (Boswell et al., 2010; Handegard et al., 2012).

Imaging sonar data can be directly coupled with video data from underwater cameras to provide species identification and observe predator prey interactions at the scale of action.

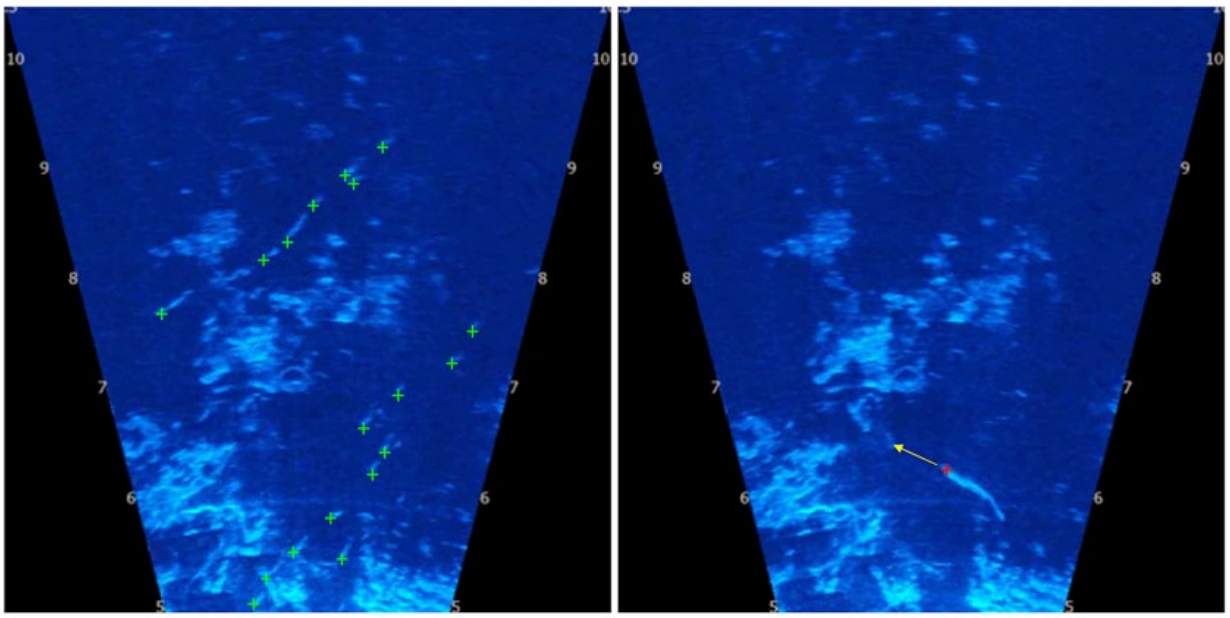


Figure 10-4. Example of shoaling prey (left panel) response to predator (right panel) in a reef ecosystem. Prey are identified by green '+' symbols and predator is identified by a red '+' symbol. The prey were observed rapidly exiting the field of view prior to the predator entering. The difference between the two images is approximately 3 sec. Data source (Boswell unpublished).

Stationary deployments can offer direct insight into the interactions between predators and prey (e.g., schooling behavior and predator disturbance; Figure 10-4 and Figure 10-5; Handegard at al., 2012; Price et al., 2014; Rieucau et al., 2011). At present, this approach allows researchers to quantify important ecosystem processes at the local scale. These data may be useful for parameterizing ecosystem models and understanding rates of energy transfer and changes in interaction rates as a function of ecosystem character end stability.

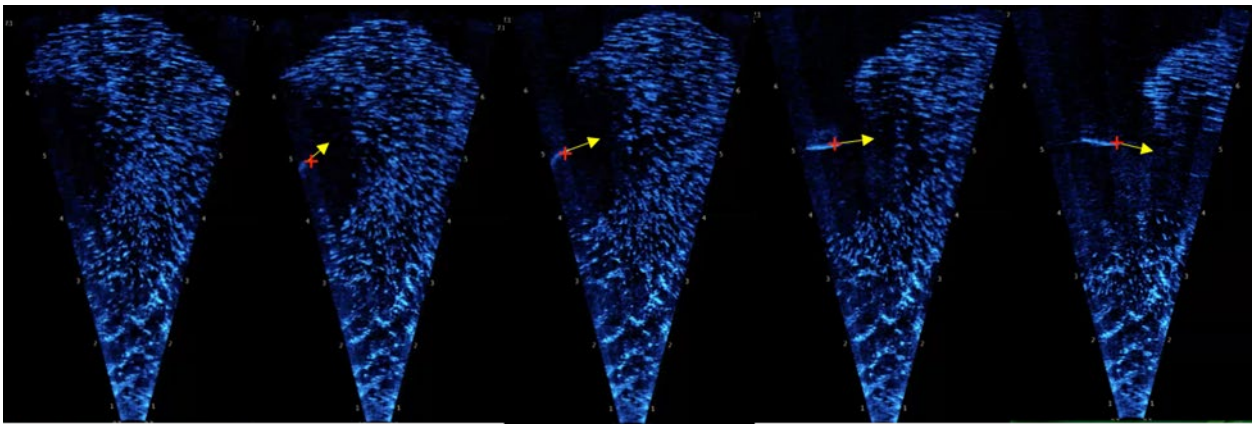


Figure 10-5. Sequence of imaging sonar data illustrating a solitary barracuda (Sphyraena barracuda, 48 cm) identified by red '+', interacting with a school of juvenile menhaden (Brevoortia tyrannus). Data source (Boswell unpublished).

While imaging sonars can provide fine scale perspective of interactions across complex habitats, upward looking deployments can provide unique perspectives of processes that occur in the water column and above the seabed (Figure 10-6). Traditionally, these observations are conducted with upward looking echosounders to quantify biological scatterers and examine their vertical distribution patterns across time and possibly related to oceanographic processes. This perspective can be very useful in ecosystems with complex habitats, where boundary effects can prohibit examination of organisms within a couple meters of the sea bed. For example, an upward looking echosounder (configured with a wide-angle transducer,) can provide distributional data of nekton within 1 m of the sea bed. In contrast, traditional downward looking echosounders would likely be unable to detect fish near the complex habitats due to the acoustic dead zone. This approach has been implemented across a suite of ecosystems and habitats, ranging from shallow reefs to deep-water open ocean systems. As seen in Figure 10-6, high resolution data can be gathered to quantify nekton interactions within the water column across time. This is particularly important, when considering the interest in tracking changes in the biological community across time. For example, seasonal pulses of large planktonic forage fish schools moving into reef ecosystems can be observed and quantified to study pulses of biological material and nutrients into these systems.

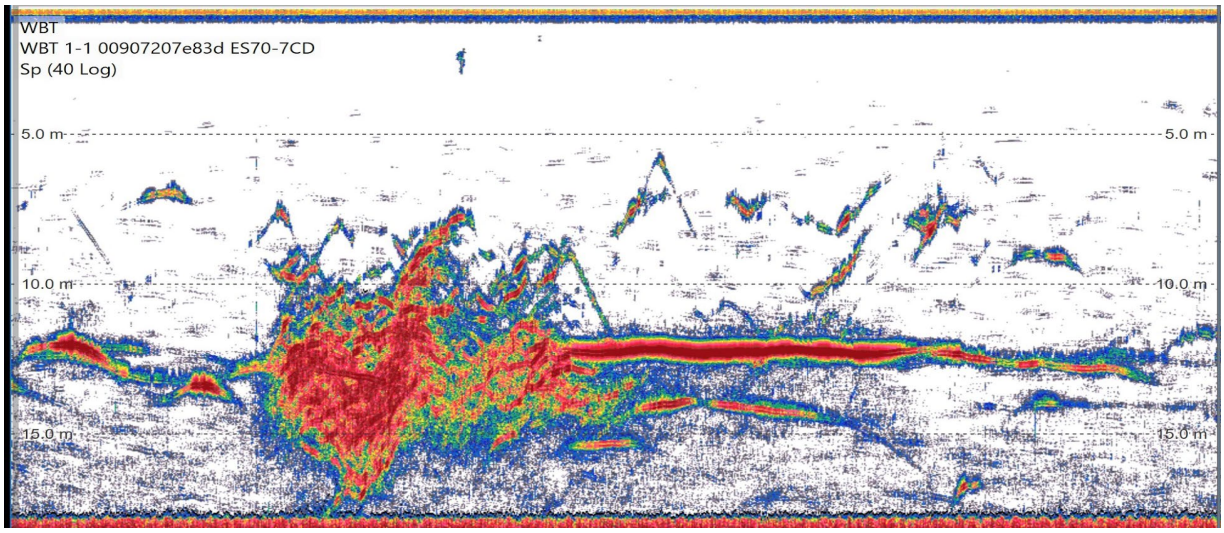


Figure 10-6. Example echogram from a bottom mounted split-beam echosounder (70 kHz Simrad EK80) illustrating a school of white grunt (Haemulon plumieri) interacting with a barracuda (Sphyraena barracuda) near the Aquarius reef base In the Florida Keys.

Stationary methodologies are constrained by logistical and practical concerns. Perhaps one of the most important considerations is matching the spatial and temporal scale of the observation relative to the hypotheses examined. Stationary systems can be deployed to the seafloor with tethered cables to a surface acquisition computer. Because ecological processes occur over various temporal and spatial scales, thus the duration and periodicity of observation need to be determined prior to sampling. Controllers and computers encased in submersible housings can be used to operate sonars on a duty cycle and extend data collection periods to ensure data are collected at relevant intervals to capture the process of interest. Power supply can be provided through submersible batteries, with necessary limitations to endurance of the deployment. Establishing a duty cycle will allow users to extend the deployment relative to power requirements and sample rate needed to address the specific hypothesis.

Other important considerations for conducting stationary acoustic observations are the location of deployment and environmental conditions. When conducting stationary observations, it is important to be aware of the potential environmental variation (e.g., prevailing current direction and strength, sea state, noise sources, habitat stability, etc.), all of which can influence data quality. For example, when deploying a stationary imaging sonar on the seabed to examine the distribution of nekton associated with the habitat, it is imperative to ensure the sonar tilt/elevation angle is appropriate for the data that are desired (Figure 10-7). For upward looking echosounders, wave/wind induced noise at the air-sea interface can impart significant artifacts in the acoustic record, and depending on the depth and intensity of the event, air bubbles can be detected many meters below the surface and potentially occlude signals from nekton in the upper water column (Figure 10-8).

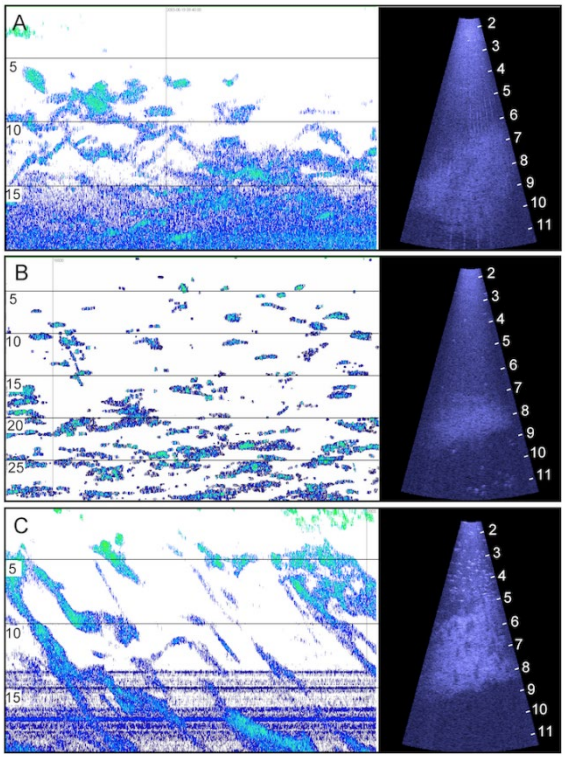


Figure 10-7. Example echograms derived from a horizontally aligned split-beam echsounder (A-C; 400kHz BioSonics DTX) and imaging sonar (Right panels; DIDSON) illustrating the effect of transducer angle on acoustic responses in shallow waters (~2 m depth). Panels A–C (left) illustrate the effect of substrate and surface reverberation when aimed (A) +4◦ upward from horizontal, 15 m range; (B) +1◦ upwards from horizontal, 30 m range; and (C) –4◦ downwards from horizontal 13 m range. Effects can be observed in both the echosounder and the imaging sonar data, where the +4◦ condition indicates surface detection between 6 and 10 m range; +1 Indicates slight bottom grazing from 7–9 m range; and –4◦ shows extensive bottom grazing from 3.5 to 9 m range. The horizontal lines on the echograms represent 5 m range intervals. Figure adapted from Boswell et al. (2007).

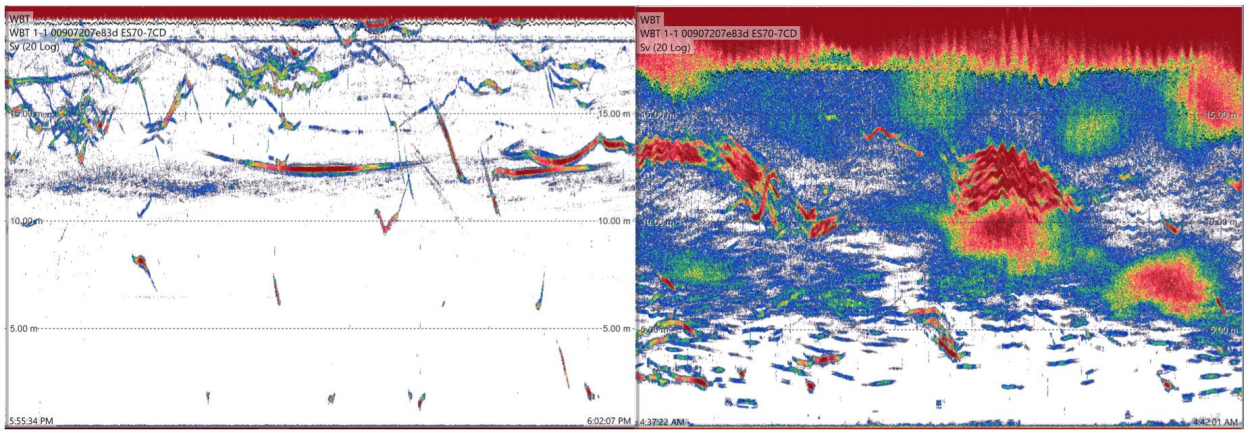


Figure 10-8. Example echograms from a stationary upward looking echosounder (Simrad 70kHz EK80) illustrating two conditions of sea state from a deployment near the Aquarius reef base in the Florida Keys. In the left panel the seastate is very calm, seas at 0m, whereas as in contrast, the right panel illustrates sea states ~1.5 m. Data source (Boswell unpublished).

We have described a few examples of how the use of stationary sonars can be implemented for studying fine-scale behavioral interactions. Well-placed stationary echosounders can be used like turnstile gates to observe and quantify fish movement between adjacent habitats. Imaging sonars can be used like acoustic cameras to observe fish within complex habitats in poor water clarity or low light situations. Lastly, observations from imaging sonars can provide unique insights into prey behaviors during predation events. In a carefully designed observational study, stationary deployments offer advantages by reducing the potential for disturbance and permitting observations across a longer temporal scale from seconds to years.

11 Case Study: Modelled Day-Night Biases in Spatial Structure of Jack Mackerel (*Trachurus murphyi*) in Chile (J.E. Paramo, C. Lang, S. Lillo)

11.1 Introduction

The Jack mackerel (*Trachurus murphyi*) (Nichols, 1920) is a pelagic species widely distributed in the Southeastern Pacific Ocean, from Ecuador (1º30'S) to the south of Chile (55ºS), reaching the coasts of New Zealand, Tasmania and Australia to the west. This area is known as the jack mackerel belt (Serra, 1991; Grechina, 1992; Vasquez et al, 2013). The fishery of jack mackerel is developed mainly in the coasts of Chile and Peru. In Chile it has a great economic significance since it is one of the main fisheries resources, reaching landing levels between 1.6 and 1.3 million tons between 2001 and 2006 (Sernapesca, 2011). The center-south industrial fleet contributed with 48% of these levels, which includes the ocean sector off the EEZ. Numerous studies have been developed around this resource, about biology, spatial distribution, population dynamics and migration. Serra (1991) describes the existence of a seasonal migration of the Chilean sub-population of *T. murphyi* related to feeding and spawning processes (Quiñones et al., 1997; Miranda et al., 1998). Towards the Austral winter in southern of Chile (30 ° -40 ° S) a feeding area is identified where congregate adults and regularly occurs juvenile recruitment of 2 to 3 years (Arcos et al., 2001; Sepulveda et al., 2003), during this period jack mackerel has been evaluated with hydroacoustic methods (Cordova et al., 2002) in order to estimate the biomass of the resource in the area.

In the other hand, this species shows a gregarious behavior, commonly found in dense schools with a high commercial interest. In this sense, Soria, 1994; Gerlotto, 1996; Bertrand, 2004 suggest that spatial structures and density suffer alterations, varying cyclically according to physiological (feeding and reproduction) and environmental factors, presence or absence of predators, as well as changes in light intensity during the 24-hour cycle. According to Bertrand et al. (2004), mackerel behavior varies substantially between diel periods, forming deeper small schools during the light period, while in the night the pattern differ strongly and distributed in surface waters. This spatial organization changes with a slight decrease in occupancy of space by aggregations and increase in acoustic density within measurement unit area. The objective of this work is to characterize the jack mackerel structures during the day-night periods and their implications of differences in the estimation of biomass during the austral winter in the Southeast Pacific Ocean.

11.2 Materials and Methods

The survey was carried out in oceanic waters off Chile (35°S – 42°S) in 2002 and the sampling survey used was systematic with transects perpendicular to the coast separated by 20 nautical miles (n.mi). The

elementary distance sampling unit (EDSU) was 0.5 n.mi. fragment of track. The density of Jack mackerel was obtained from the nautical scattering coefficient (NASC; $m^2/n.mi.^2$) of a scientific echosounder SIMRAD EK500 with a transducer of 38 kHz, using the target strength equation of Jack mackerel, TS = 20log L – 68.91 (Lillo et al., 1996). Generalized Additive Models (GAM) (Hastie and Tibshirani, 1990) were used in order to find the relationship between biomass with diel periodicity. GAM is a modern statistic tool which allow to fit models according to ecological theory (Katsanevakis and Maravelias, 2009). The biomass estimation approach of Jack mackerel of acoustics data was likelihood-based geostatistics. The method estimates the effective stock area using a generalized linear spatial model on presence/absence data and the logit link function (Roa-Ureta and Niklitschek, 2007).

11.3 RESULTS

Jack mackerel showed a marked diel pattern in acoustics biomass (P = 0.00) with high values of biomass found at night hours (18:00 to 6:00 hours) and lowest values during daylight hours (Figure 11-1). According to layers in the water column (Figure 11-2), higher biomass were related to 1:00 to 6:00 hours in the 0-50 and 50-100 layers. Higher biomass related to deeper layers were found at 17:00 hour in the 100-150 layer and between 11:00 to 13:00 hours in the 150-200 layer (Figure 11-2). On the day, schools of jack mackerel were formed in compact higher densities, while at night, these schools were joined to form large aggregations in extensive layers. However, at dawn the schools were separating and deepening to form again the compact higher densities **(**Figure 11-3).

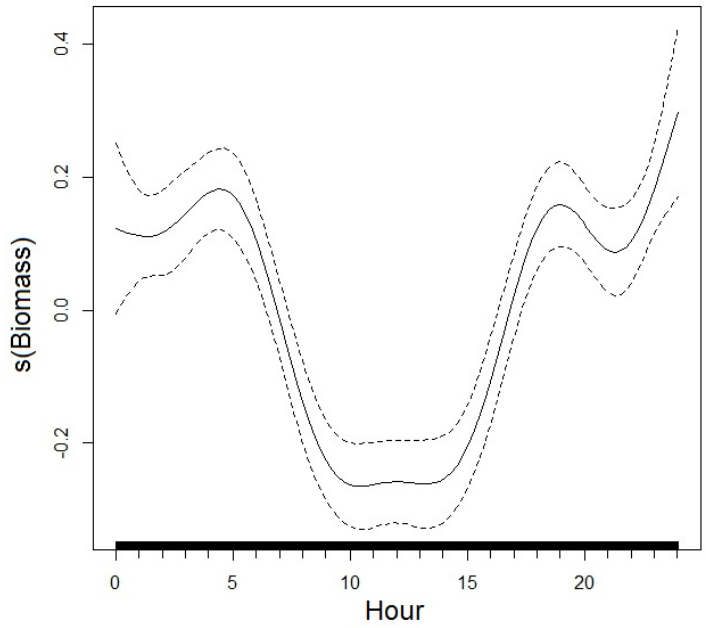


Figure 11-1. Modelling of functional relationships between biomass with diel periodicity.

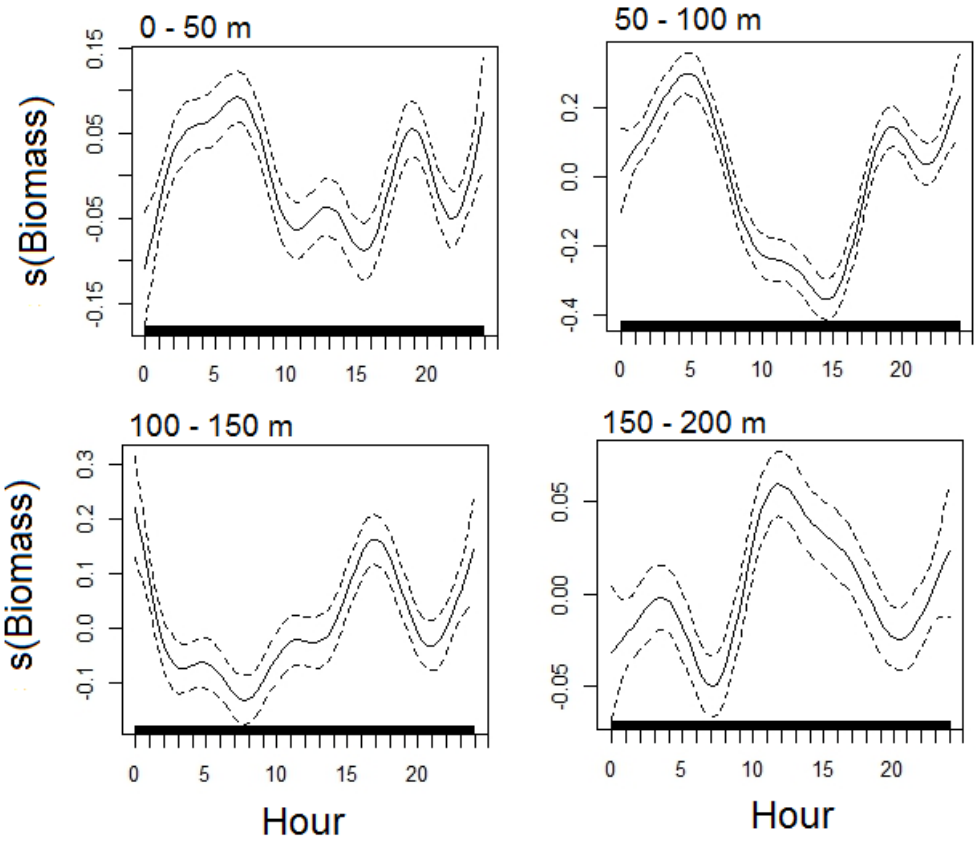


Figure 11-2. Modelling of functional relationships between biomass with diel periodicity by layers.

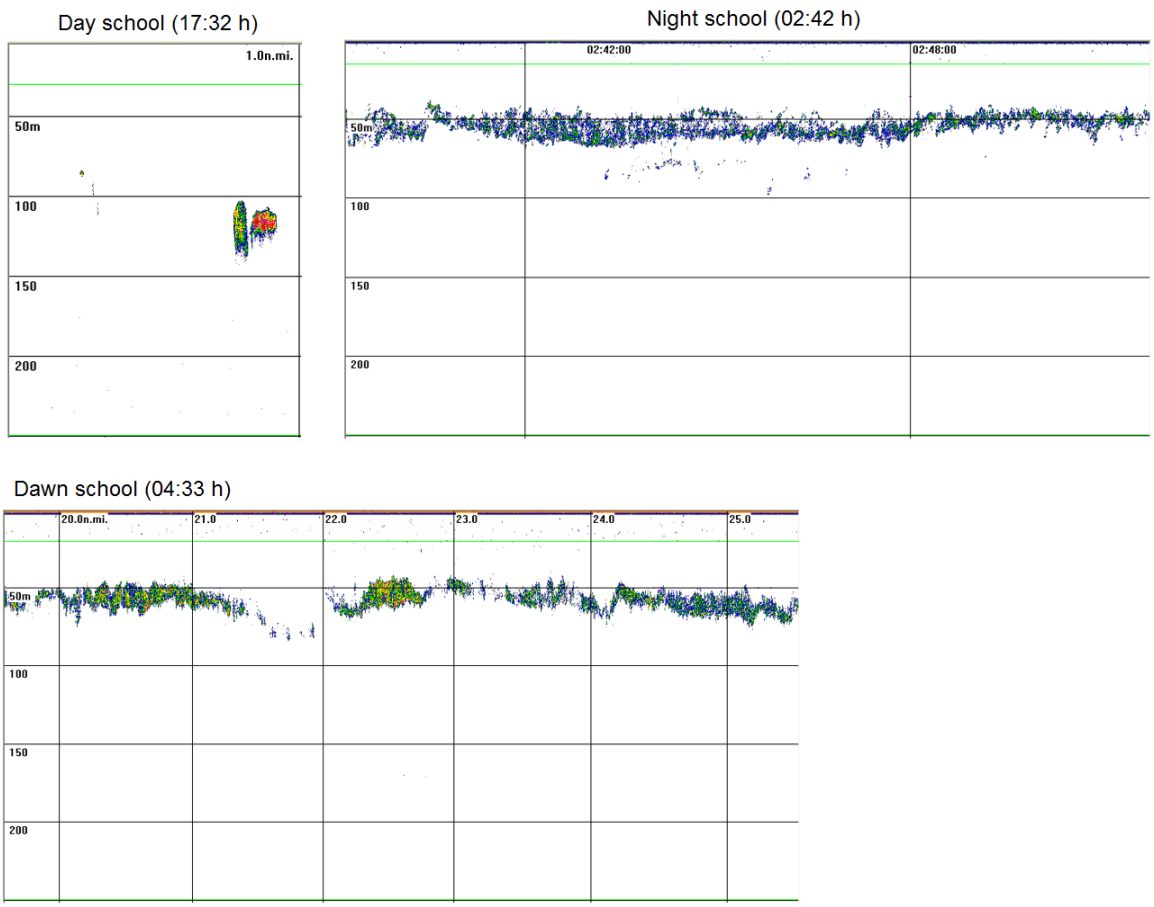


Figure 11-3. Fish school behavior of jack mackerel during day, night and dawn.

The diel behavior of fish schools were assessed by variograms (Figure 11-4 in order to characterize the spatial structure of fish density. In general, variograms showed differences in the day-night spatial structure. The day variogram showed a higher nugget effect than night. The percentage of variance unexplained by the sampling design (sill/nugget) was 62.64 in the day variogram and 34.25% at night variogram and 32.70% in the day-night variogram (Table 11-1). An intense schooling behavior during the day is likely to be responsible for this increased small-scale variability. The night variogram were characterized by a smaller range of autocorrelation than day variogram (Table 11-1). These features may be caused by differences in schooling behavior which exists in jack mackerel with respect to day and night.

On the day, schools of Jack mackerel were formed in compact higher densities that were distributed in a more extensive aggregation (variogram range 20.31 n.mi.), but occupying minor area of spatial distribution (30831.11 n.mi.^{2}). While at night, these schools were joined to form large aggregations in extensive higher densities layers (variogram range 12.84 n.mi.), but occupying more area of spatial distribution (46615.07 n.mi.^{2}) (Table 11-1). The biomass estimation was different at day, night and day-night, the night estimation was double compared to day (Table 11-1).

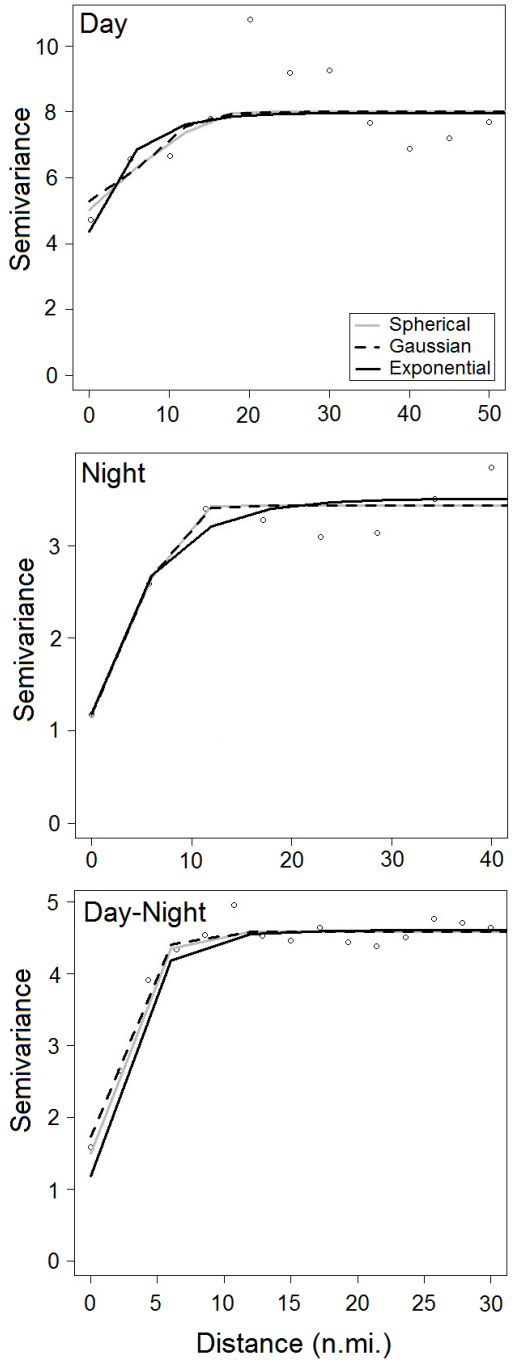


Figure 11-4. Variograms for biomass of jack mackerel showing differences in the day, night and day-night spatial structure.

Table 11-1. Maximum likelihood estimation of jack mackerel during day, night and day-night.

Quantity/Parameter	Day	Night	Day-Night
Number of null observations	834	724	1558
Number of positive observations	1186	1937	3123
Minimum distance (n.mi.)	20.00	20.00	20.00
Maximum distance (n.mi.)	481.66	481.66	496.79
Box-Cox transformation, lambda	0.20	0.10	0.10
Nugget	5.02	1.18	1.50
Sill	3.00	2.26	3.09
% Sill	62.64	34.25	32.70
Range (n.mi.)	20.31	12.84	7.84
Distribution area of stock (n.mi.^{2})	30831.11	46615.07	70073.41
Mean biomass (ton/n.mi.^{2})	34.64	42.73	35.63
C.I. low mean (ton/n.mi.^{2})	31.45	38.04	33.63
C.I. up mean (ton/n.mi.^{2})	37.84	47.42	37.63
Probability of observing the stock	0.62	0.84	0.78
Biomass (ton)	1068076.90	1991935.13	2496775.86
C.I. low Biomass (ton)	969.53	1773.42	2356.38
C.I. up biomass (ton)	1166.62	2210.45	2637.18
Variance	2.66	5.72	1.05
Standard deviation	1.63	2.39	1.02
CV (%)	4.71	5.60	2.87

11.4 Discussion

Since the early 90s, the importance of fish school behavior has been recognized as critical in fisheries acoustics (Anon., 1993), for various reasons such as avoidance of predation, physiological facilitation, feeding, mating, etc. (Pitcher and Parrish, 1993; Parrish and Turchin, 1997) as well as effects of fishing pressure, which takes advantage of the fish schooling behavior to increase catches (Fréon and Misund, 1999). Studies have been developed due to its migratory nature of jack mackerel to neritic and epipelagic environments to feed, as confirmed by Medina and Arancibia (1992) for the north of Chile. This shows a pattern that determines the seasonal availability of the resource in the coastal and ocean fisheries. In fact, jack mackerel is an opportunistic consumer, foraging mainly on macro-zooplankton and micronekton (Konchina, 1981). Therefore, that feeding behavior is a determining factor of jack mackerel distribution (Quiñones et al., 1997; Grechina, 1998), due to the predator-prey relationships that can affect its diel vertical migration (Bertrand et al., 2004). In terms of spatial occupation, jack mackerel is more aggregated during the night than during the day, related to their nocturnal active foraging behavior (Bertrand et al., 2004). Indeed, the night variogram were characterized by a smaller range of autocorrelation than day variogram. These features may be caused by differences in schooling behavior which exists in jack mackerel with respect to day and night. On the day, schools of Jack mackerel were formed in compact higher densities that were distributed in a more extensive aggregation (variogram range 20.31 n.mi.), but occupying minor area of spatial distribution (30831.11 n.mi.^{2}). While at night,

these schools were joined to form large aggregations in extensive higher densities layers (variogram range 12.84 n.mi.), but occupying more area of spatial distribution (46615.07 n.mi.^{2}). This behavior is according to a model for Jack mackerel in relation to their biotic and abiotic environment (Bertrand et al., 2006). In this sense, the Jack mackerel and their prey (mainly euphausiids and mesopelagic fish) perform vertical migration in which during the day the prey are generally distributed between 250 and 400 m, out of reach of Jack mackerel. Then, the prey become available at dusk, when they migrate toward the surface (Bertrand et al., 2006). This fish school behavior is typical of a diel vertical migration (Type I) in which fish move up in the water column at the onset of night, and down with the onset of day (Neilson and Perry, 1990). Therefore, the lower day time biomass could be associated with reductions in the volume of gas in the swim bladders of Jack mackerel due to deep schools. This can be explained because Target Strength (TS) of Jack mackerel during the day could be uncertain because multiple targets in dense deepest school are passing the single target detector, although fish schools are easily separated on echograms. The TS by night are more reliable with fewer multiple targets and the biomass estimates will be more precise due to the less clumped spatial distribution (Knudsen et al., 2009). These differences in the form of school aggregation have strong implications for the estimation of biomass in the interpolation process by kriging. Finally, the major difference in biomass observed between day-time and night-time suggest that hydro-acoustic surveys for the assessment of fish biomass should be conducted at night.

Differences in the form of school aggregation have strong implications for the estimation of biomass.

12 Case Study: Passive Acoustic Monitoring in Coral Reef Ecosystems (L.M. Cherubin)

12.1 Background

Ambient noise in coral reef ecosystems is largely composed of sounds generated by abiotic sources such as wind and waves, and biotic sounds produced by various marine organisms (Kerman, 1984; Deane and Stokes, 2010). However, a third sound source, generated by underwater anthropogenic activities is increasingly becoming part of many marine soundscapes, especially in coastal environments (Scharwz, 1985; Slabbekoorn and Bouton, 2008; Lobel et al., 2010). Together, these sources combine to create the acoustic signature of an environment. Such signatures, or soundscapes, provide a set of acoustic cues that can influence many aspects of a marine organism's behavior, including mating, feeding activity, predator or prey detection, orientation and territory's defense (Montgomery et al., 2006; Schwarz, 1985; Lobel et al., 2010; Parmentier et al., 2010; Simpson et al., 2010; Bertucci et al., 2015). Data regarding the nature of marine soundscapes now exists for many locations globally, including sites within the Pacific (Andrew et al., 2002; McCauley and Cato, 2010a, b; Chapman and Price, 2011; Freeman and Freeman, 2016; Bertucci et al., 2015), Atlantic (Axelrod et al., 1965; Urick et al., 1972; Butler et al., 2016) and Indian Oceans (Cato, 1967; McCauley, 2011; Parsons et al., 2013), allowing preliminary descriptions of variation in acoustic activity between and within environments to be made.

12.2 Reef Habitat Soundscape

Reef sounds vary on a daily basis, by moon phases, and by seasons. For example, in Australian waters, the combined vocal activity of fishes and crustaceans is most intense at dusk, with an increase of 20 dB above the mean ambient noise level (Cato, 1992; Cato, 2002). However, the biotic noise signature can also vary over longer temporal scales due to interspecific differences in vocal behavior, with the vocal activity of some marine organisms increasing during certain seasons (McCauley et al., 2010, McCauley, 2001; McCauley, 2012), while that of others appears to remain consistent throughout the year (Radford et al., 2010, 2014; Nedelec et al., 2015). Localized acoustic variability between adjacent habitats, i.e. those separated by less than 1 km, has only recently been highlighted (Bertucci et al., 2015). On coral reefs for instance, how the soundscape of an inner reef crest differs from that of a barrier reef, and how temporally variable these soundscapes are, is largely unknown. However, recent evidence suggests that spectral differences between spatially associated reef habitats can be largely due to variation in the sonic activity of marine organisms, i.e. soniferous fishes and snapping shrimps (Radford et al., 2014). Another recent study comparing the soundscapes of a temperate urchin-dominated rocky reef to a sandy beach identified significantly higher sound amplitude in frequencies between 800 Hz and 2500 Hz on the rocky reef as well as diel variations in the temporal and spectral composition of these soundscapes (Radford et al., 2010). Different, but spatially associated, marine habitats (including inner, barrier, fringing reefs, mangrove and reef pass) surrounding Moorea Island, French Polynesia were

shown to exhibit differences in the temporal and spectral acoustic features (Bertucci et al., 2015). While habitats close to the shore showed no significant diel variation in sound intensities, sound levels increased at the pass during the night and barrier reef during the day. Because many coral reef-associated species have highly specialized habitat requirements, biotic variation between habitat types can create unique acoustic signatures that could provide key information for larval marine organisms during settlement.

Noise signature can also vary over longer temporal scales due to interspecific differences in vocal behavior, with the vocal activity of some marine organisms increasing during certain seasons

12.3 Reef-Specific Sounds and Larval Settlement

Indeed, most recently, the soundscape has garnered attention as an additional sensory cue for larvae (Montgomery et al., 2006; Simpson et al., 2008; Stanley et al., 2012). The acoustic characteristics of the marine environment have the potential to provide rich sensory information to settling organisms, reflecting both the presence and quality of the adult habitat over relatively broader spatial scales (e.g., meters to kilometers) than localized chemical and substrate cues (Radford et al., 2014; Lillis et al., 2014; Piercy et al., 2014). Acoustic characteristics have been implicated in the orientation and settlement of larval fishes, crustaceans, and molluscs (Simpson et al., 2004; Stanley et al., 2012; Lillis et al., 2013; Lillis et al., 2015), and a variety of marine invertebrates are known to be sensitive to the water- and substrate-borne vibrations (i.e., particle motions) generated by sound waves (Budelmann, 1989; Budelmann, 1992). Simpson et al., (2004) experimented the effect of sound played by underwater speakers on settlement-stage reef fish at Lizard Island, Great Barrier Reef, Australia. They saw a 67% increase in the traps with broadcast reef noise. Lillis et al. (2016) reported that sounds at the loudest reef generated significantly higher coral larvae settlement during trials compared to the quietest site (a 29.5 % increase). Their results suggest that soundscapes could be an important influence on coral settlement patterns and that acoustic cues associated with reef habitat may be related to larval settlement. Parmentier et al. (2015) demonstrated the species-specific influence of sound on coral-reef fish larvae behavior. They showed that coral-reef fish larvae react to habitat sound by being either attracted or repelled. Moreover, the strategy used and the habitat chosen varied between species within families, highlighting the importance of conducting studies of sound influence on behavior at the species level. Coastal habitat noise heterogeneity appears to be used adaptively by different fish species.

12.4 Reef Health Acoustic Signature

As more studies link the ecological processes of larval recruitment and soundscape production, it will become increasingly important to monitor and conserve coastal soundscapes. Soundscape ecology – the study of sounds that emanate from a land-scape – is a growing field whose roots lie in terrestrial ecology (Pijanowski et al., 2011), but now include many studies in marine ecosystems (Harris and Radford, 2014). This field of science merges aspects of psychology, behavior, humanities, and ecology to examine how soundscapes (i.e., all sounds emanating from a specific landscape) vary over space and through time, how anthropogenically generated and naturally generated sounds interact, and how best to monitor and conserve soundscapes for their intrinsic and ecological value (Pijanowski et al., 2011). Unfortunately, habitat degradation, whether by anthropogenic influences or natural disturbance,

disproportionately affects near-shore environments (Vitousek et al., 1997; Limburg, 1999; Watanabe et al., 2002; Lotze and Milewski, 2004), where the nursery habitats of many marine organisms occur. Marine habitat restoration and restoration ecology are becoming indispensable tools not only to repair damaged environments, but also to test ecological theories (Peterson and Lipcius, 2003; Halpern et al., 2007). Butler et al. (2016) have document the sound loss associated with the degradation of sponge habitat in South Florida. Over the past two decades, the hard-bottom communities of Florida Bay have experienced large sponge die-off events (Butler et al., 1995; Stevely et al., 2011), eradicating nearly all sponges, including the structurally dominant loggerhead sponge *S. vesparium*, from large portions of the central and lower bay. The widespread loss of shelter for snapping shrimp has likely led to a loss of shrimp populations within sponge die-off areas, and thus the loss of the biological cacophony produced by the shrimp. This change was evident by comparing recordings of hard-bottom communities within the sponge die-off area to recordings of hard-bottom outside the die-off area. Mangrove, healthy hard-bottom, and restored hard- bottom habitats had higher soundscape spectra levels than seagrass and degraded hard-bottom whether at noon or dusk during new or full moons. There were also higher numbers of snapping shrimp snaps in mangrove, healthy hard-bottom, and restored hard-bottom habitats than in degraded hard- bottom and seagrass beds, especially during the prominent dusk snapping shrimp chorus. Butler et al. (2016) further demonstrated that near-shore tropical habitats have unique soundscapes that are diminished by habitat degradation, but can be reestablished by habitat restoration, at least in the case of sponge-dominated hard-bottom. Freeman and Freeman (2016) showed that oceanographic habitat grouped along a principal component defined by an acoustic sliding scale: from protected or more remote sites at which lower frequencies were more dominant, to degraded sites which produced soundscapes dominated by higher frequency sound. Freeman and Freeman (2016) indicated that this acoustic sliding scale enables rapid, inexpensive and spatially integrative remote sensing of the ecological state of coral reefs. Such quantitative methods could be used to ecologically assess vast areas of reef habitat autonomously in near real-time and could be important for remote in situ detection and characterization of subtle but significant ecological changes brought about by climate change and other more localized anthropogenic impacts.

12.5 Sound Production in Fish Spawning Aggregations

Studies have shown that more than 800 fish species can produce sounds for diverse purposes (Kaatz, 2002; Rountree et al., 2006). Among the soniferous fishes are some of the most abundant and important commercial fish species, including many codfishes, drum fishes, grunts, groupers, snappers, jacks, and catfishes (Rountree et al., 2006). Some invertebrates with important fisheries also produce sounds, including mussels (*Mytilus edulis*), sea urchins (Fish, 1964), white shrimp (*Penaeus setiferus*, Berk, 1998), spiny lobsters (Moulton, 1957; Fish, 1964; Patek, 2002), American lobster (*Homarus americanus*, Fish, 1966; Henninger and Watson, 2005), and perhaps squid (Iversen et al, 1963). Most of the sounds are emitted at low frequencies (Ladich, 2004), usually below 1000Hz. However, some pulses can reach 8kHz (Zelick e al., 1999; Tavolga et al., 2012) or present more complex characteristics (Vasconcelos et al., 2011). In addition, these emissions are typically broadband short-duration signals (Figure 12-1). Fish generate sounds through several mechanisms, which depend on the species and a variety of circumstances, such as courtship, threats or defending territory (Kaysumian, 2008). Passive acoustics has been used for over 60 years in fish biology and fisheries survey (see Fish et al., 1952 and Fish and Mowbray, 1970 for review) and is used routinely today to determine habitat use, delineate and monitor spawning areas, and study the behavior of fishes (Hawkins, 1986; Rountree et al., 2003a, b, 2006).

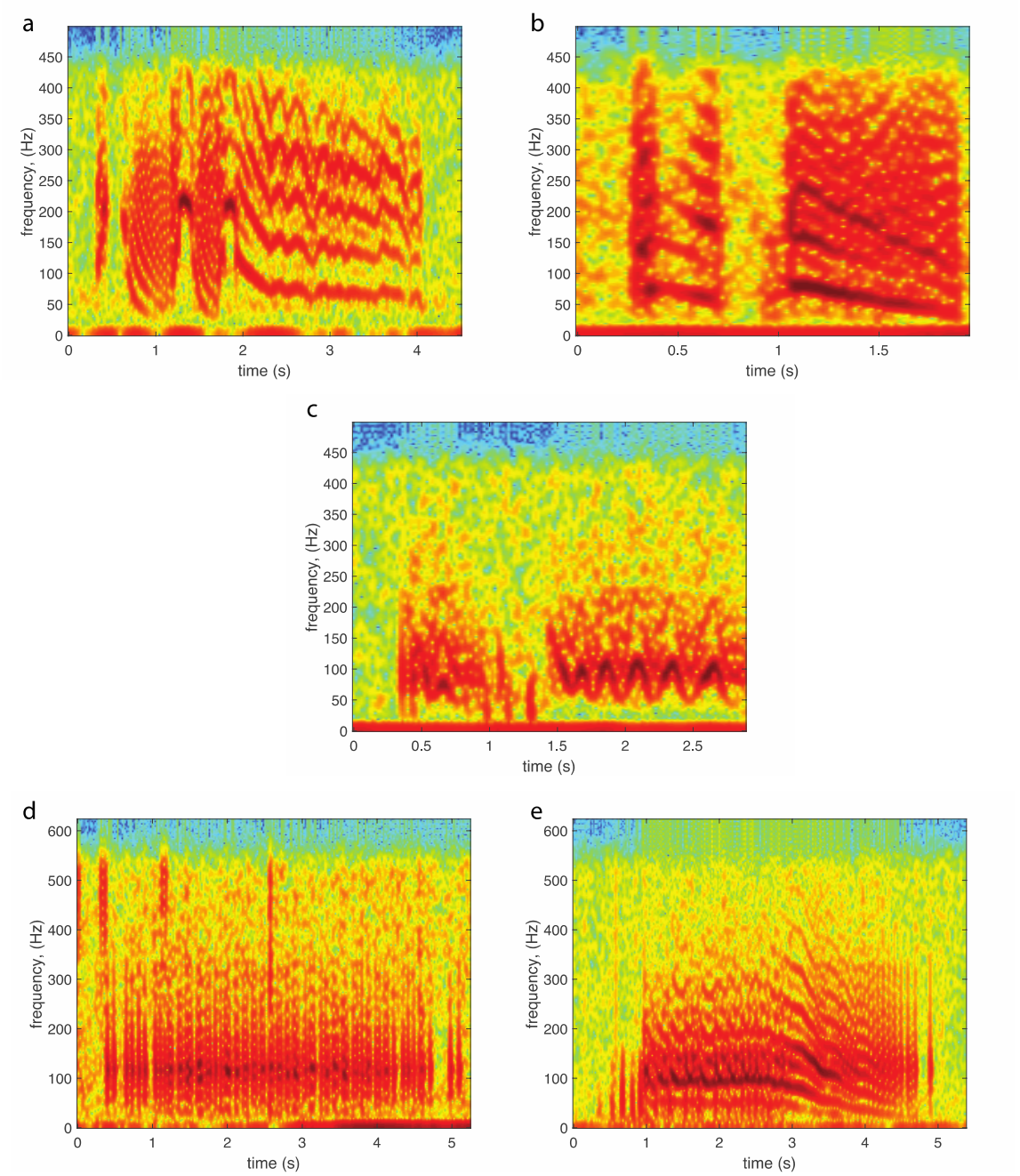


Figure 12-1. Grouper courtship associated sound spectrograms. (a) Red Hind tonal call (E. guttatus). (b) Nassau grouper tonal call (E. striatus). (c) Black grouper tonal call (M. bonaci). (d) Yellowfin grouper pulse calls (M. Venenosa). (e) Yellowfin grouper tonal call (M. venenosa).

Mature adults of many fish species swim long distances and gather in high densities for mass spawning at precise locations and times (Domeier and Colin, 1997). Worldwide depletion of large predatory fishes has already caused top-down changes in coral reef ecosystems and biodiversity loss (Mumby et al., 2006). Moreover, most known fish spawning aggregations (FSA) sites are shared by many species at different times (Heyman and Kjerfve., 2008) and as such, represent breeding hotspots requiring some form of protection (Erisman et al. 2017). It is critical that their role in the persistence of marine

populations be elucidated. FSAs share common features such as high density of large body-sized individuals, strong site fidelity, temporal predictability and geomorphological attributes, (i.e. shelf-break, capes) (Claro and Lindeman, 2003; Kobara and Heyman, 2010; Kobara et al., 2013). Once located, they are easily over-exploited and depleted (Sadovy, 1997; Sala et al., 2001; ICRS, 2004). Despite numerous historical records of Caribbean-wide FSAs (Smith, 1972; Eklund et al., 2000) only a few are documented to date and many remain unprotected (Sadovy et al., 2008).

Sound production in a number of species is known to be associated with courtship, territoriality, or reproduction, warranting the use of passive acoustics to locate spawning aggregations (Luczkovich et al., 1999, 2008; Walters et al., 2009; Rowell et al., 2011) and determine temporal spawning behavior and habitat use by different species (Locascio and Mann, 2008; Mann et al., 2009, 2010; Nelson et al., 2011; Schärer et al., 2012). The existing FSAs in the Caribbean Sea, Gulf of Mexico and the Bahamas Region (i.e., the Intra-America Seas) are where a number of vocalizing grouper species such as the Nassau (*Epinephelus striatus*), yellowfin (*Mycteroperca venenosa*), red hind (*Epinephelus guttatus*) and black grouper (*Mycteroperca bonaci*) (Figure 12-1), among others, aggregate to spawn (Nemeth, 2005; Rowell et al., 2015). Most of these species spawn during the winter and spring months (December to May) in the northern hemisphere (Nemeth, 2012). The timing of spawning is usually cued to the moon and daylight, but also to water temperatures and local current conditions (Nemeth, 2009). Because remaining FSAs often occur at remote locations, are most active at dusk and are in water depths between 30 and 80 m, near the shelf break, spawning activities and fish population are challenging to observe, and thus to monitor (Kobara et al., 2013).

While many of these sites are known to fishers and represent areas of intensive harvest, not all fish spawning locations have been documented. As such, there may be significant number of unreported FSAs, which, if located, could provide a better estimate of the status of certain populations of grouper species such as Nassau, Warsaw (*Hyporthodus nigritus*), Black, Red Hind, Goliath (*Epinephelus Itajara*) and others. Data on the FSA dynamics of these species is critical to the management of these stocks, which involve the South Atlantic, Gulf of Mexico and Caribbean Fishery Management Councils (SAFMC, GMFMC, CFMC), as well as local or state entities such as the Puerto Rico Department of Natural and Environmental Resources (PR-DNER), USVI Department of Planning and Natural Resources (DPNR), Florida Fish and Wildlife Conservation Commission (FWC). Determination of the timing, duration and intensity of spawning will be of direct utility for the design and evaluation of management actions, stock assessment and effective conservation measures.

Passive acoustic monitoring (PAM) is thus a fisheries-independent approach that can provide *in-situ* observations of soniferous fishes, such as groupers (Mann et al., 2010; Rowell et al., 2011 and 2015; Schärer et al., 2012, 2014; Wall et al., 2014, 2017). Additionally, PAMs can be relatively non-intrusive and provide data on grouper behavior and distribution, critical for understanding their biology and ecology. As particular grouper populations begin to recover from overfishing, new or previously lost aggregations may reform, also making this technology particularly relevant for surveying and evaluating the recovery of groupers. To date, fisheries monitoring efforts using PAMs have primarily used an Eulerian approach; recordings are made from fixed stations at known FSAs (Rowell et al., 2012).

12.6 Persistent Presence Robotic Approach for Detection and Characterization of Fish Spawning Aggregations

FSAs are known to be spatially dynamic and can shift outside the range of fixed stations in a relatively short period. As such, more mobile approaches with PAMs are required to best encapsulate FSA dynamics. For example, the use of autonomous platforms such as buoyancy-driven gliders or wave-gliders that are equipped with PAM systems can be programmed more accurately to encompass FSA spatial extents as well as scout regions of the shelf edge in the exploration of unknown FSAs. Wall et al. (2014) used Slocum gliders, buoyancy driven autonomous underwater glider (AUG) to conduct a large-scale spatial mapping across the West Florida shelf of Red Grouper (*E. Morio*) sound production. A similar survey was conducted with the same technology along the southeast U.S. (Wall et al., 2017). This survey was conducted during winter when fishery-independent survey data were lacking from traditional ship-based approaches (due to prolonged periods of inclement weather) and covered the winter-spawning dynamics of multiple species managed by the SAFMC. According to the SAFMC, the importance of increasing collection/detection and interpretation of acoustic signatures of managed species is long overdue in the South Atlantic Bight.

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These surveys were conducted with low power acoustic recorders (DSG - Loggerhead Instruments; www.loggerheadintruments.com), which are self-contained acquisition-only devices that are not integrated to their host, and do not allow for onboard processing and analysis. Therefore, these devices are not capable of characterizing a FSA in real-time, nor can they provide information such as the species composition of FSA aggregates, precise location and timing, population size and the fish behavior or distance from the glider. But automated data collection means that surveys can take place at times and in places where it would be too expensive or dangerous to send human observers (Marques et al., 2013).

Chérubin et al. (2018) conceived a real-time detection and classification PAM system that can be integrated on any glider. Their glider of choice was the SV3 wave glider (WG) because of its continuous real-time transmission and positioning capabilities, which are crucial to the localization of FSAs that are most of the time ephemeral events. The SV3 wave glider is a self-propelled, unmanned persistent mobile data-gathering platform that harvests both solar and wave energy for propulsion and power. A simple, Web-based interface, called WGMS transmits control system and sensor data from the WG to shore and commands back from shore to the WG during a mission. It also provides a precise and intelligent navigation web interface. Two-way transmission via cellular network or Iridium satellite provides real-time navigational, operational, and sensor control as well as real- or near-real-time data reporting (Greene et al., 2014). The PAM system consists of a SIMRAD NSS7 Evo2 echosounder with structurescan sonar and with frequency modulation (CHIRP) sonarhub. Sonar screen movies are recorded for sound detection validation. The sonarhub is mounted on the aft of the WG. (2) An onboard AST4000 pressure sensor. (3) A Turner C3 Fluorometer, which measures CDOM, Chlorophyll-a, and backscattering fluorescence. (4) Hydrophones. (5) A fish sounds detection and classification algorithm. The PAM records 10s audio files every 30 seconds. Each audio file is analyzed by the detection algorithm

and if there is a detection, a 3 second snippet that contains the sound detected is produced by the software.

The PAM computer operates in real-time the fish acoustic detection algorithm research (FADAR) program, an automated identification scheme for fish vocalizations based on the auditory analysis for feature extraction followed by a machine-learning algorithm for classification (Ibrahim et al., 2018). Experimental results showed that the overall percentage of identification using the best combination of the selected feature extractor Weighted Mel Frequency Cepstral Coefficients and sparse classifier achieved 82.7 % accuracy overall, although the accuracy varies per species. *E. gutattus* and *M. venenosa* were the most successfully classified species, while *E. striatus* was slightly lower than the previous two and *M. bonaci* had the lowest accuracy rate of all. The algorithm was initially developed in MATLAB and was then converted into a C executable, which is embedded on the PAM computer of the tow-body package.

During a U.S. Virgin Islands survey in February 2017, the target species was red hind which aggregate to spawn around the full moon from December to February at the Red Hind Bank, on the southern shelf of St. Thomas and just west of Grammanik Bank (Figure 12-2). The aggregation usually peaks in January and spawning can occur from 0 to 4 days before the full moon (Nemeth, 2005). Result from the survey showed a scattered distribution of red hind grouper CAS and most of them were localized inside the Red Hind Bank MCD and a few near the Grammanik Bank (Fig. 2X). Nassau and yellowfin grouper were also recorded, in particular at Grammanik Bank where Nassau groupers are known to aggregate for spawning (**Fig. 10.4b**). This pattern was previously documented with hydrophones from fixed sites combined with acoustic telemetry of tagged Nassau grouper (Rowell et al., 2015).

A similar survey along Puerto-Rico's west coast known FSA sites within the MCDs at Abrir la Sierra (ALS) and Bajo de Sico (BDS), located along the shelf edge in the Mona Passage. ALS has FSA sites of red hind grouper at a depth of 30 m, which occur from December to March and peak 7-9 days after the full moon (Rowell et al., 2012). BDS is a submerged seamount approximately 27 km west of Puerto Rico, surrounded by depths of over 250 m to the southeast near the Puerto-Rican insular shelf and over 1000 m to the north. This site, where Nassau groupers aggregate to spawn was documented in 2012 and intensively studied with hydrophone by Schärer et al. (2012b). BDS is also a spawning site for black grouper (Schärer et al., 2014; Sanchez et al., 2017). Results from the glider survey confirmed the presence of CAS for red hind and Nassau grouper with species segregation between ALS and BSD. Red hind sounds were detected only near ALS, though at two distinct locations (Fig. 3X), whereas Nassau grouper sounds were detected only at BDS, although at two separate locations, which provides new information for this site (Figure 12-3).

In August 2016, the wave glider was deployed from aboard the NOAA ship Nancy Foster, near Riley's Hump (RH) in the FKNMS, which is a FSA site for at least two species of snappers (e.g. Cubera snapper (*Lutjanus cyanopterus*) and mutton snapper (*Lutjanus analis*) in summer months and one species of grouper (black grouper) in winter months (Locascio et al., 2016; Sanchez et al., 2017). Although no grouper CAS were identified during the summer survey in the Dry Tortugas, numerous red grouper (*Epinephelus morio*), squirrel fish (*Holocentrus* spp), and grouper alarm calls were identified in addition to other unidentified marine sounds, near the documented FSA site (Figure 12-4).

These data also provide insights into diurnal, environmental, and spatial soundscape variability at the scale of hours to day and between different spawning sites around the Caribbean and in the Gulf of Mexico.

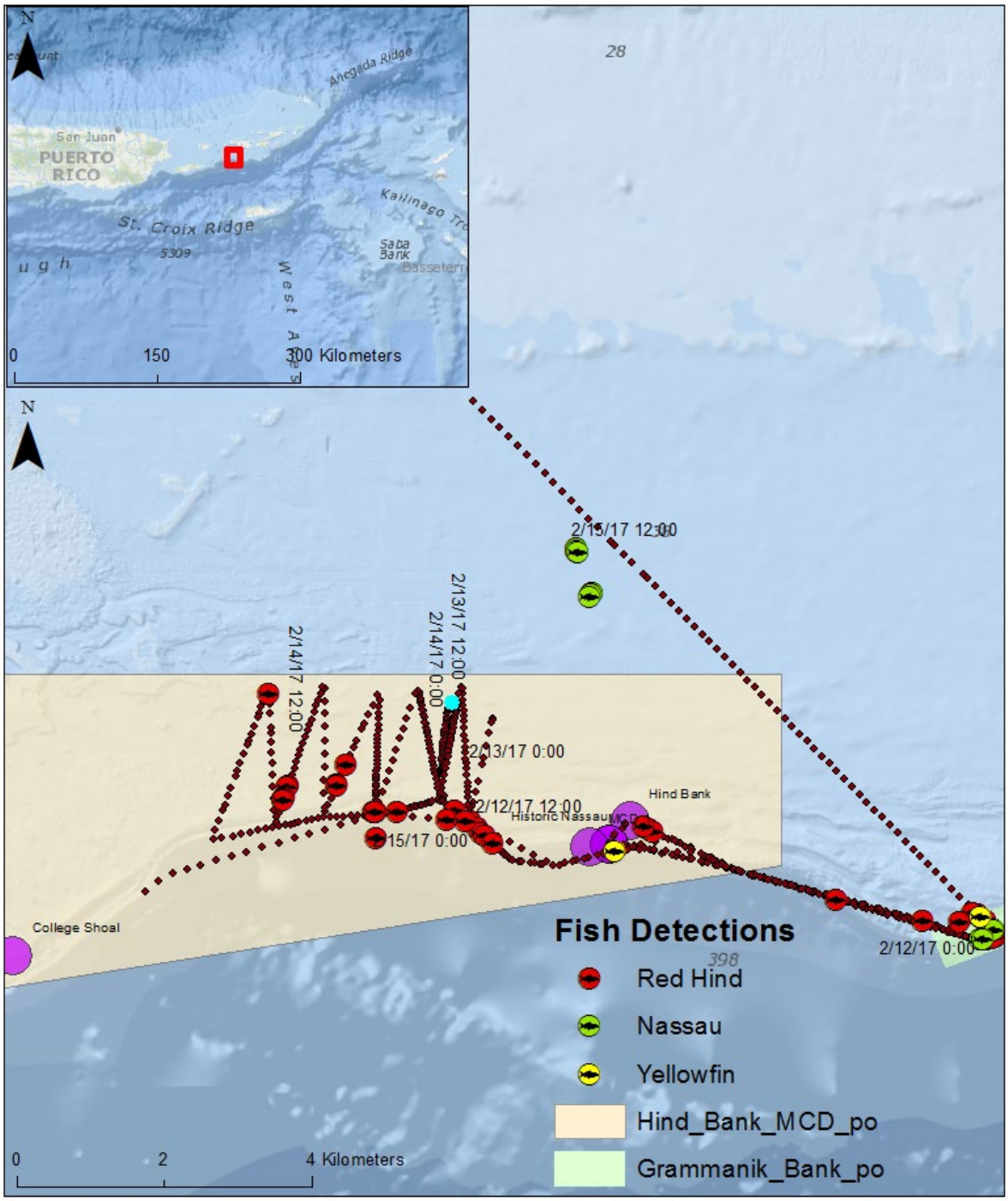

Figure 12-2. Glider surveys fish detection in St. Thomas, U.S. Virgin Islands, 7-15 February 2017. Shaded areas show marine conservation areas. Brown dots show the glider path. Purple circles are specific monitoring or known FSA sites that were targeted with the wave glider. Red (red hind), green (Nassau grouper) and yellow (yellowfin grouper) dots show fish detections. Dates and times along the glider track are also indicated.

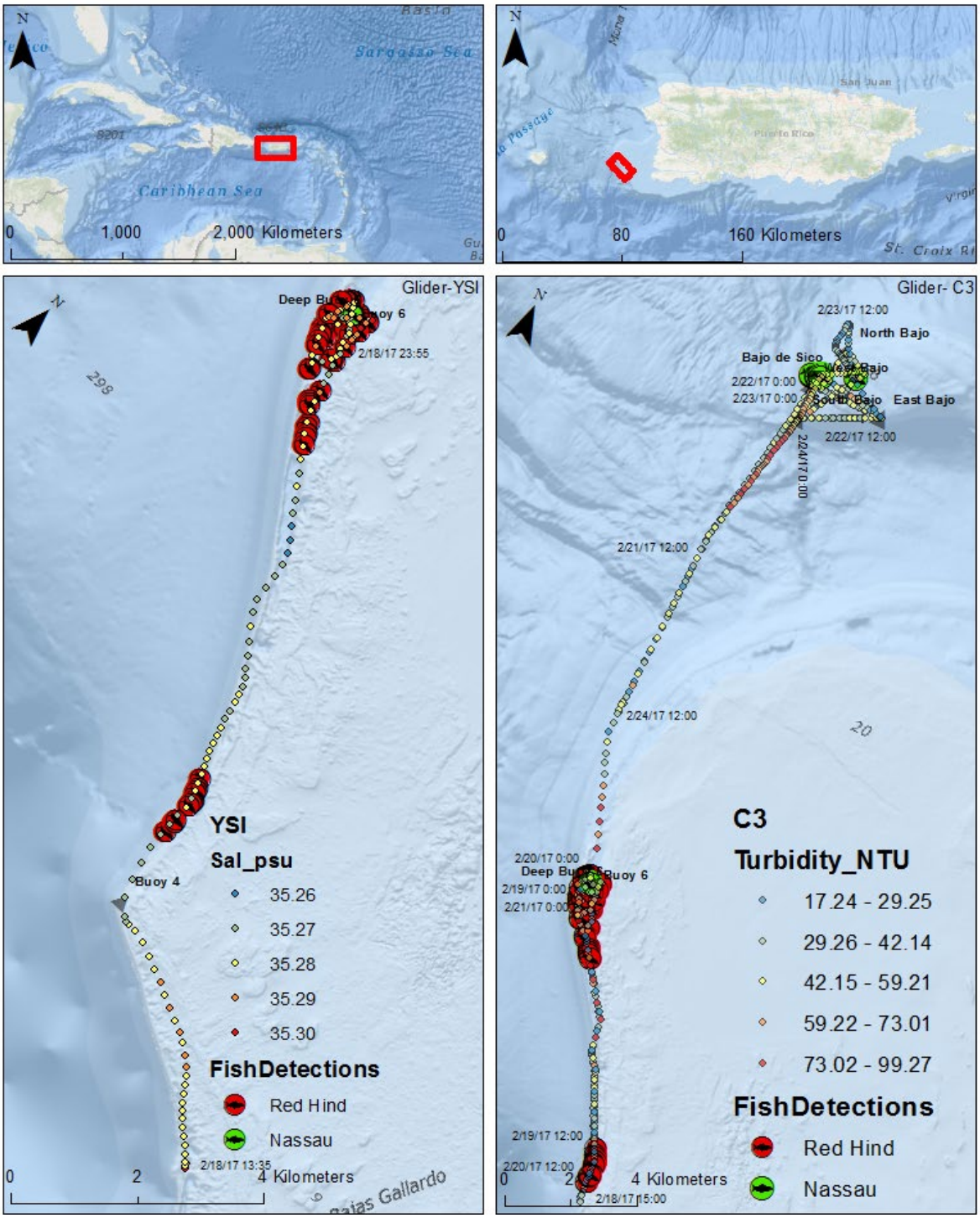

Figure 12-3. Glider tracks, fish detection and environmental parameters along Puerto-Rico's western shelf. Colored dots show salinity (psu) on the left plot and turbidity (NTU) on the right plot. Left plot shows the lower part the right plot, south of Abrir la Sierra only. Red (red hind), green (Nassau grouper) and yellow (yellowfin grouper) dots show fish detections. Dates and times along the glider track are also indicated.

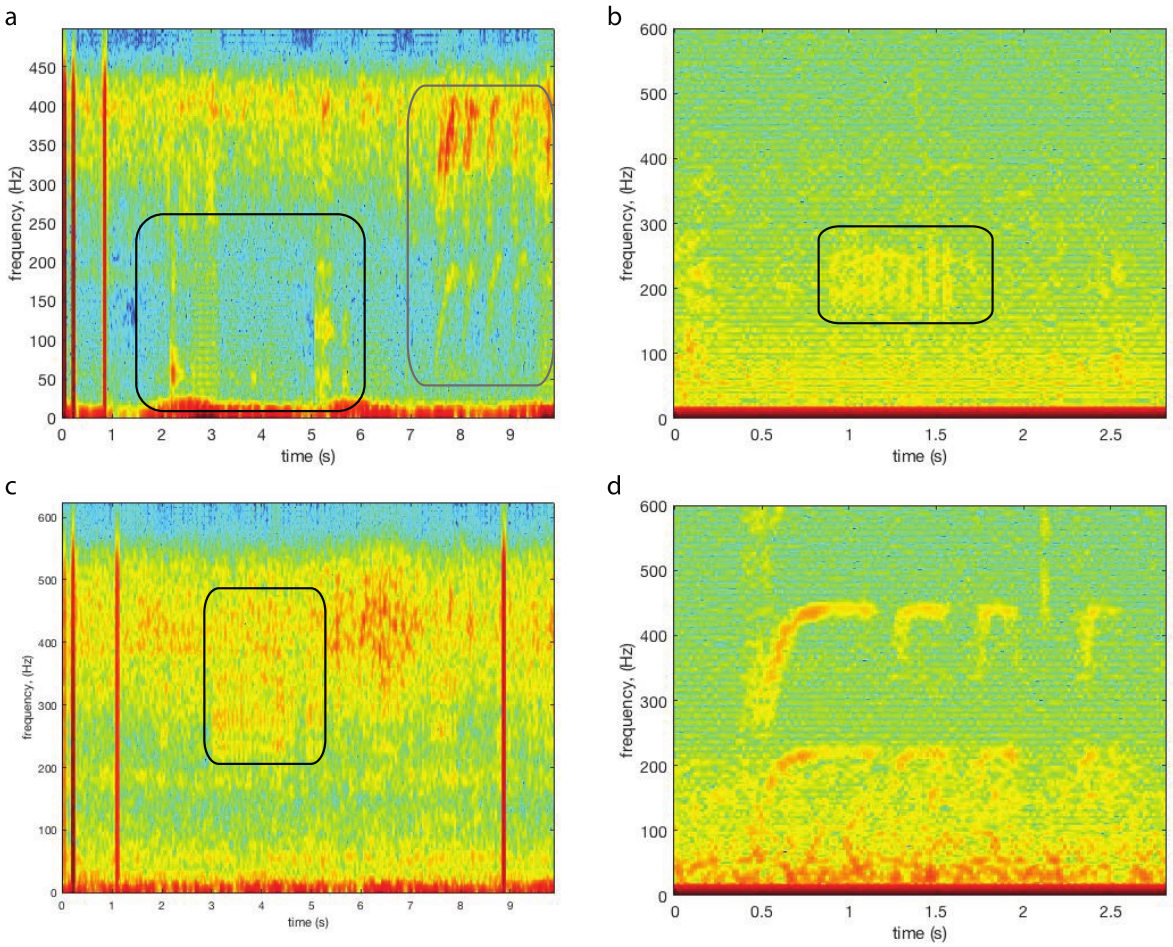

Figure 12-4. Fish call spectrograms recorded with the wave glider PAM at Riley's Hump. (a) Red grouper (lower left rectangles) and unknown calls. (b) Grouper alarms calls. (c) Squirrel fish. (d) Unknown calls.

The WG PAM is a new concept that includes simultaneous measurements of soundscape, environmental data but also sonar data. At, this stage the sonar on the WG does not provide quantitative information nor does the acoustic information. However, recent progress in sonar data classification, as exemplified in this report, could provide complementary information to CAS at FSAs. Namely, the development of broadband frequency response models and associated target strength for individual and group of fish for large adult fish such as groupers and snappers would provide a mechanism to validate fish detection and ultimately assess fish abundance. Correlation between CAS numbers and fish abundance were shown to be significant at grouper FSAs when repeated at regular intervals (Rowell et al., 2012). It appears then, that such correlation could also be established between sonar and passive acoustic data, significantly increasing the degree of confidence in the biomass assessment. Such approach for biomass estimation is currently use in the tuna fisheries. Sonar buoys are used to provide accurate biomass quantification that are used to direct the fishing effort. We believe that the integration of sonar measurements and PAM on the WG and persistent presence platforms in general, in addition to fixed monitoring stations will become one of the most promising approach to monitor reef ecosystem health in the future.

13 Conclusion (W.L. Michaels)

13.1 Priorities for Building Capacity with Technologies

The workshop was designed with the recognition that management and operational objectives drive the implementation of acoustic technologies to improve reef fish ecosystem surveys and research. Acoustic surveys and research in reef fish ecosystems present unique challenges, such as the complexity of reef fish life-history patterns and difficulties with sampling reef fish habitat. Recent advances in acoustic technologies and alternative platforms for deploying integrated sensing arrays have become more available for improving reef fish ecosystem surveys, yet a technical report providing guidance on the best practices for conducting acoustic operations in reef fish habitats is lacking. This workshop brought together diverse perspectives from acoustic experts, scientists, managers, and stakeholders who strive to improve scientific information for the sustainability of reef fish and their habitats. The third day of the workshop was devoted to establish the framework for this report on the best practices for using acoustic technologies to conduct reef fish ecosystem surveys. During the third day of the workshop, participants addressed the following trigger questions:

1. What are your top three management objectives pertinent to reef fish ecosystems?
2. What are your top three operational challenges relevant your management objectives?
3. How have you been addressing these challenges?
4. What additional resources might help you achieve your operational objectives?

Before the workshop, the participants provided some initial feedback on these questions (Appendix D). During the third day of the workshop, presenters provided overviews and case studies on the principles and key considerations for conducting acoustic surveys operations in reef fish habitats. The presentations from both the acoustic symposium and the workshop emphasized the applicability of acoustic technologies for a range of management priorities and operational objectives. This increased the perspectives and exchange of information among the participants, and breakout sessions were conducted to collectively discuss and prioritize the responses to the four trigger questions above. The overall intent of these trigger questions is to highlight the lessons learned and recommendations on the best practices for conducting acoustic surveys and research in reef fish ecosystems.

There is recognition on the importance of networking and training to build expertise with technologies, and creative approaches for validating acoustic estimates when sampling is limited.

During the workshop breakout sessions, participants collectively discussed these questions by management objective categories, and prioritized the following management objectives for the region (Table 13-1). The working group considered the priorities for utilizing acoustic technology were to improve abundance estimates from long-term surveys in support of stock assessments, locating and monitoring fish spawning aggregations, to improve spatial coverage of monitoring to understand distributional and migration patterns and connectivity between stocks, and use of essential habitats.

Table 13-1. Priorities for marine resource management objectives in the region summarized from workshop breakout sessions.

Rank	Priorities for marine resource management objectives in the region.
1 (n=28)	Abundance and biomass estimates of marine populations
2 (n=21)	Marine resource use and anthropogenic impacts
3 (n=20)	Distribution, spatial variation and connectivity of marine populations
4 (n=10)	Survey design and operational efficiencies to support assessments
5 (n=6)	Delineation and conservation of marine protected areas (MPAs)
6 (n=5)	Spawning aggregation location and monitoring
7 (n=4)	Essential habitat identification and characterization
8 (n=2)	Ecosystem health and environmental impacts

The working group considered validation of acoustic backscatter estimates by species and length for abundance estimates the greatest challenge when conducting acoustic operations (Table 13-2). The second challenge is the spatial uncertainty in sampling operations, especially when there is limited availability boat time. Other challenges include the difficulty of sampling near bottom due to the acoustic deadzone, and the steep learning curve involved with becoming proficient with acoustic instrumentation and methods.

Table 13-2. Priorities for operational challenges related to management objectives summarized during workshop breakout sessions.

Rank	Priorities for operational challenges relevant to management objectives.
1 (n=19)	Lack of expertise and collaboration in acoustic technology
2 (n=14)	Funding constraints and access to acoustic equipment
3 (n=10)	Detection of marine organisms near seafloor and reef structure
4 (n=7)	Improve standard operating procedures (SOPs) to reduce data processing time
5 (n=6)	Validation of species composition and length data from acoustic surveys
6 (n=6)	Acoustic classification of seabed and habitat
7 (n=5)	Uncertainty in estimates due to behavioral and environmental variation
8 (n=5)	Need simplified methods to engage stakeholders and citizen science
9 (n=4)	Spatial variation in distribution, connectivity and habitat use
10 (n=1)	Lack of enforcement relevant to harvest regulations

Several researchers have utilized other acoustic technologies, such as telemetry tags and passive acoustics like fish sounds, to collect data and monitor fish aggregations (Table 13-3). Optical technologies are widely used to collect information from reef habitats. There is recognition on the importance of networking and training to build expertise with technologies, and creative approaches for validating acoustic estimates when sampling is limited, such as correlations with landings catch data.

Furthermore, cameras and side-looking acoustics has been used to address the acoustic deadzone near bottom.

Table 13-3. Priorities for operational challenges related to management objectives summarized during workshop breakout sessions.

Rank	Priorities for addressing operational challenges.
1 (n=26)	Building pool of acoustic expertise through training and collaborations
2 (n=12)	Integrated sampling and survey design efficiencies by coupling technologies
3 (n=10)	Best practice guidance on acoustic data collection and post-processing
4 (n=5)	Guidance on acoustic methods, tools and analysis
5 (n=6)	Acoustic equipment loan or lease, and technical support from vendor
6 (n=4)	Address lack of baseline data and literature searches on acoustic operations
7 (n=1)	Cooperative research among stakeholders, fishers and citizen science

The working group considered training and networking the key solution for building regional expertise and collaborations for improving reef fish ecosystem surveys in the region. Access to acoustic instrumentation or upgrades to existing acoustic instrumentation, including multifrequency capabilities, is considered the second priority. Building collaborative partnerships is recognized as a means for funding support, and complimentary sampling is necessary for interdisciplinary research and survey operations (Table 13-4).

Table 13-4. Priorities for addressing operational challenges summarized from workshop breakout sessions.

Rank	Priorities for resources to achieve operational objectives in the region.
1 (n=35)	Build acoustic expertise in the region through training and collaborative studies
2 (n=25)	Improve equipment accessibility with loans, lease and collaborative efforts
3 (n=14)	Optimize survey design and sampling efficiencies with integrated technology
4 (n=12)	Develop long-term monitoring programs and time series
5 (n=9)	Funding opportunities with collaborative partnership and cooperative research
6 (n=6)	Collaborative efforts on research and developing analytical methods
7 (n=3)	Increasing boat and platform sampling opportunities, and citizen science
8 (n=2)	Cooperative research and sampling with fishers

13.2 Lessons Learned and Recommendations

There was consensus from the steering committee and participants that the acoustic workshop was successful in establishing the necessary technical guidance on the best practices for conducting acoustic surveys in reef fish ecosystems. The scientific community and stakeholders in the Gulf and Caribbean region, a region comprised of 42 geopolitical jurisdictions, recognized that cost-effective technologies such as acoustic technology can enhance research and survey operations in reef fish ecosystems (Section 1). The integration of acoustical and optical technologies was considered a priority for addressing data-limited assessments relevant to the challenges of sampling reef fish habitats. Section 2 and 4 highlighted the principles and logistical considerations for conducting acoustic surveys, while experts provided hands-on training at-sea with the configuration, calibration and operation of state-of-the-art EK80 scientific echosounder (Section 6). The importance of collecting biological data for species

composition and interpretation of the acoustic data was scribed in Section 5. In the classroom setting, on-hands training in the use of Echoview software demonstrated post-processing and analytical procedures for deriving quantitative estimates (Section 7). Technical guidance on the interpretation of the acoustic data was also provided for deriving species-specific target strength and biomass estimates, as well as interpretation of uncertainties in the estimates. Critically important, is the need to establish a statistically sound survey design. As described in Section 3, a survey must be established based on knowledge of the distributional patterns to assure the survey design captures a target population such as reef fish in a standardized manner to provide unbiased biomass estimates. For deriving overall mean biomass estimates over time, the survey design must not be biased towards an area of known aggregations because it is equally important to know where fish are not to gain a representative sample. Section 3 on Statistical Design provides an overview of statistical approaches for deriving unbiased abundance estimates depending on the survey design, and with each method carries assumptions that must be recognized. The case studies (Sections 9-12) emphasis the importance of the best practices described in this report; and recommend that the integration of various types of technologies ranging from active and passive acoustics, optical technologies, and alternative sampling platforms can best achieve the cross-functional mission and operational objectives.

The acoustic workshop forged collaborative partnerships and provided direction for future training workshops on the integration of acoustic and optical technologies. There was consensus that next year's GCFI workshop should be focused on the integration of optic (stereo imagery) and acoustic (EK80 wideband) technologies to improve reef fish ecosystem surveys. As described in Sections 1 and 13.1, these collaborative efforts are critical for building the next generation of experts, whose role will be to optimize survey operations with technologies for improving the sustainability of living-marine-resources in reef-fish ecosystems with connectivity across the geopolitical jurisdictions of the region.

14 GLOSSARY

- **Backscatter**: Sound energy from the echosounder pulse reflected from a target back to the transducer and measured by the receiver.
- **Backscattering strength**: Metrics of backscatter expressed in terms of intensity (i; W m^{-2}), where 1 W = 1 J s^{-1}, 1 J = 1 N m, and 1 N is the force needed to accelerate 1 kg of mass at 1 m s^{-1} s^{-1}. In the context of an echosounder, the sound intensity is considered in terms of [a] the incident intensity (i_{inc}, the energy from the echosounder pulse striking the target), and [b] the backscattered intensity (i_{bs}, the level of incident intensity backscattered by the target). See Demer et al. (2015), Jackson and Richardson (2007) and references therein for a complete definition and derivation of the terms described below.
  - **Point-target backscattering**
    - **Backscattering cross-section (σ_{bs}; m^2)**: The ratio of i_{bs} and i_{inc}, i.e. (i_{bs} $r^2 10^{\alpha r/10}$)/i_{inc}, where i_{bs} = ([σi_{inc}/$10^{\alpha r/10}$]/$4\pi r^2$)F, σ (m^2) is the scattering cross-section of the target (the area of the target that intercepts the incident sound pulse), α (dB m^{-1}) is the absorption coefficient, r (m) is the distance (range) between the target and the measurement position (i.e. the transducer) and F is a factor (0-1) describing the reflectivity of the target. It follows from the equations above that a perfectly reflecting (F = 1) sphere of radius 2 m would yield a σ value of 12.6 m^2 ($\pi 2^2$, i.e. the area of a circle) and a σ_{bs} value of 1 m^2 (when solved for any values of i_{inc}, α and r). Traditional definitions of σ_{bs} consider i_{bs} at a reference range of 1 m from the target (r_0 = 1 m); it is necessary to specify a reference range because i_{bs} decreases as a function of r^2 (due to spreading loss). An r_0 value of 1 m is implicit in the σ_{bs} equation above because we are using SI units with 1 m as the unit of distance, and because the range dependence of i_{bs} is removed by multiplying by r^2. A more logical term for σ_{bs} might be *point backscattering coefficient* (s_p).
    - **Target strength (*TS*; dB re 1 m^2)**: $10\log_{10}(\sigma_{bs})$. Fish and zooplankton will have σ values that are significantly less than 12.6 m^2, and F values less than 1, so their σ_{bs} values will be significantly less than 1 m^2 and their *TS* values will be negative (because $10\log_{10}(1)$ = 0, $10\log_{10}(0.5)$ = -3, $10\log_{10}(0.1)$ = -10, etc.). TS_c and TS_u denote whether or not the measurements have been compensated for the off-axis location of the target in the beam (see Figure 7-4 [B]). A more logical term for *TS* might be *point backscattering strength* (S_p).
  - **Volume-target backscattering**
    - **Volume backscattering coefficient (s_v; m^2 m^{-3})**: The sum of the backscattering cross-sections from the targets within a given volume of water (V), normalized to 1 m^3, i.e. $\Sigma\sigma_{bs}$ / V.
    - **Volume backscattering strength (S_v; dB re 1 m^2 m^{-3})**: $10\log_{10}(s_v)$.
  - **Surface-target backscattering**
    - **Bottom backscattering coefficient (s_b, dimensionless i.e. 0-1)**: …
    - **Bottom backscattering strength (S_b; dB re 1)**: …
- **Beam pattern**: The intensity of the sound pulse decreases away from the beam axis, in the same way that the light from a torch/flashlight fades towards the edges of the beam. The beam pattern is the shape of the graph describing sound intensity vs. off-axis distance.

- **Broadband**: See “wideband”.
- **Depth (*d* in m)**: Vertical distance below the water surface.
- **Echo**: See “backscatter”.
- **Echosounder**: An active-sonar instrument consisting of transceiver, transducer and computer (for transceiver control and data recording). Echosounders can be categorized in a variety of ways, the simplest of which is to group them based on the number of transmit and/or receive beams into ***single-beam echosounders (SBES)*** and ***multibeam echosounders (MBES)***. Note, however, that the terminology around active-sonar instruments is diverse and is often market/application specific (e.g. scientific/recreational, fishery/hydrographic etc.), and does not always subscribe to the simple dichotomy defined above.
- **Multiple echo**: Backscatter due to closely-spaced targets, such that the individual targets cannot be resolved in time (hence in range) in the data. With narrowband echoes, targets need to be at least half a pulse length ($c_w\tau/2$) apart in range for the echoes from each target to be completely separated in time. With wideband echoes, the minimum range separation is a function of bandwidth.
- **Narrowband**: A pulse consisting of a narrow range of frequencies (<10% of the center frequency). Note that narrowband is often referred to as “continuous wave” (CW), which is not strictly true since a continuous (sinusoidal) wave represents only a single frequency (which in practice is effectively impossible to generate with a transducer).
- **Noise**: All contributions to the signal other than backscatter. Noise can be either acoustic or electrical in origin. Variations in amplitude and duration can be used to categorize the noise, for example:
  - **Background noise**: Low-amplitude, long-duration (100s to 1000s of pings) acoustic noise.
  - **Impulse noise**: High-amplitude, short-duration (<1 ping) electrical or acoustic noise.
  - **Transient noise**: High-amplitude, medium-duration (1 to 10s of pings) electrical or acoustic noise.
- **Ping**: See “pulse”.
- **Pulse**: A short burst of sound energy generated (transmitted) by a transducer. Note that once the pulse is backscattered by a target, it is referred to as an echo.
- **Range (*r*; m)**: Distance from the transducer face to the target along the beam axis.
- **Reflection**: See “scattering”.
- **Sample**: The echosounder receiver measures voltage over time as an analog (continuous) signal. This continuous signal is broken up (digitized) into short periods of time (time gates) by the receiver’s analog-to-digital converter (ADC). The voltage representing each time gate is referred to as a sample.
- **Scattering**: The redirection of sound energy when it interacts with a target.
- **Signal**: The component of the value recorded by the echosounder receiver that is due to backscatter.
- **Target**: An object with a density sufficiently different to the surrounding medium, such that it causes the sound energy from the echosounder pulse to be scattered in different directions. The definition of an individual object and an individual target depends on the context (Figure 7-6). In a physical context, we might define an individual target as a single gas bubble, a single fish, a component of a single fish (e.g. swimbladder, cranium etc.), a cluster of bubbles or an aggregation of fish. In an acoustic context, an individual target is defined based on the

relationship between the properties of the object and the sampling volume and frequency content of the echosounder pulse as follows:

- **Point target**: A target significantly smaller than the sampling volume, such that the backscatter arrives at the transducer face effectively from a single direction. Its backscattering strength, expressed as σ_{bs} (see above), is therefore a property of the target (i.e. independent of its range or the sampling volume). Other terms commonly used to describe this scenario include "single targets", "single echoes", "single-target echoes", "single scatterers", "single-fish echoes", "resolved scatterers" and "echo pulses". Care must be taken, however, when using these terms. For example, "single target" is commonly used to mean "single fish acting as a point target", but unless explicitly defined it could logically refer to a range of scenarios (e.g. "single component of a fish acting as a point target", "single aggregation of fish acting as a point target" or even "single aggregation of fish acting as a volume target").
- **Volume target**: A target whose volume is larger than the sampling volume, such that its backscattering strength, expressed as s_v (see above), will depend on the geometric intersection of the target with the sound beam.
- **Surface target**: A target whose surface extends beyond the sampling volume, such that its backscattering strength, expressed as s_b (see above), will depend on the geometric intersection of the surface with the sound beam.

- **Transducer**: An instrument that converts (transduces) voltage to sound pressure, and *vice versa*.
- **Wideband**: A pulse consisting of a wide range of frequencies (>10% of the center frequency). This is sometimes referred to as a "chirp" or a "frequency-modulated" (FM) pulse.

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16 APPENDICES

16.1 APPENDIX A. SYMPOSIUM TERMS OF REFERENCE AND ABSTRACTS

Symposium on Acoustic Technologies for Surveying Reef Fish Ecosystems

Terms of Reference: The Gulf and Caribbean Fisheries Institute (GCFI) and SouthEast Acoustic Consortium (SEAC) will held a special session entitled "Acoustic Technologies for Surveying Reef Fish Ecosystems." Given the complexity of the life history and habitat of reef fish, the difficulties of sampling reef ecosystems have resulted in data-limited assessments in the Gulf of Mexico and Caribbean regions. Ongoing advances in both active and passive underwater acoustic technologies have brought a variety of tools to scientists for improving surveys and experimental research in reef habitats that can address a variety of operational research objectives. For example, active acoustics instruments (echosounders) provide measurements to estimate reef fish abundance, map distributions, delineate spawning aggregations, observe behavior, and characterize community structure. In addition to remote sensing of the biological community, active acoustics can also provide seafloor classification and bathymetry of their habitats. As scientists strive for integrated sampling operations, passive acoustic instruments (hydrophones and acoustic tags) are also used to locate and monitor spawning aggregations, monitor aquatic ecosystem integrity, and investigate the impact of ocean noise on marine resources.

The objective of this special session is to provide the current state-of-the-science, challenges, applications, and recommendations on the best practices for integrating active and passive acoustic technologies into reef fish and ecosystem surveys to provide high quality and timely scientific information for the management of living marine resources. This session also serves to communicate how integrating acoustic technologies into reliable and sustained survey and observation systems will provide socioeconomic benefits from the scientific gains. Abstracts for this special session should be submitted by the abstract submission deadline in the GCFI announcement.

The following abstracts were accepted during the Joint GCFI-SEAC Symposium on Acoustic Technologies to Improve Reef Fish Ecosystem Surveys.

Developing a strategic initiative to transition technologies into operations for improving reef fish ecosystem surveys

Desarrollar una iniciativa estratégica para las tecnologías de transición en operaciones para mejorar las encuestas de ecosistemas de peces de arrecife.

Développer une initiative stratégique visant à transformer les technologies en opérations visant à améliorer les enquêtes sur les écosystèmes de poissons de récifs.

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ABSTRACT

Scientific information is often data-limited for the conservation and management of reef fish and their habitats due to the difficulties in sampling these complex ecosystems. Advances in the integration of sensor, platform, communication, and processing technologies have great potential for improving the quality, quantity, and timeliness of scientific information. Management priorities and information gaps should drive technology investments, and a change in the mindset of the corporate culture is often required with this strategic planning. In the evaluation of technologies, proven feasibility, calibrations, and stability in measurements are critical considerations when transitioning innovative technologies into sustained and reliable survey operations. For these reasons, evaluation of the technology's performance metrics and cost-benefits is necessary before investing in the transition phase. Ultimately, the transition from traditional sampling gear to technology requires acceptance by the scientific and management community as well as the stakeholders. Rapidly evolving technology presents challenges for survey operations, data management, and maintaining a high level of accuracy and precision in environmental monitoring and survey operations that rely on standardized measures to support our long-term time series. As organizations strive to augment or enhance survey operations with innovative technologies, disruptions should be minimized in existing business practices when the scientific information is used for effective policy decisions.

Hydroacoustic Tools for Monitoring Shrimp Distribution, Movement, and Behavior in Natural and Built Environments

Herramientas Hidroacústicas para Monitorear la Distribución, Movimiento y Comportamiento del Camarón en Entornos Naturales y Construidos

Outils Hydroacoustiques pour la Surveillance de la Distribution, du Mouvement et du Comportement des Séjours dans des Environnements Naturels et Construits

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ABSTRACT

Shrimp and other underwater species have been monitored using both echo sounding and acoustic tagging techniques in various types of environments. These efforts have included sampling in a broad range of environmental conditions from studies in open systems measuring response to environmental disturbances and perturbations to studies in closed systems monitoring species interaction. The same basic principles of sound propagation apply to both echo sounding and acoustic telemetry techniques for shrimp monitoring. The selection of the most suitable hydroacoustic sampling tool will be based on the purpose of the investigation. We will look at strengths and limitations in using echo sounding and acoustic telemetry techniques for shrimp monitoring within several types of environments. Results of shrimp will be presented from hydroacoustic and acoustic telemetry studies.

KEYWORDS: Hydroacoustics, acoustic telemetry, acoustic tags, shrimp

An integrated approach to develop in situ target strength – length relationships for Atlantic Goliath Grouper (*Epinephelus itajara*) on coastal reefs.

Home Idiomas Ingresar a Epistemonikos Búsqueda avanzada Un enfoque integrado para desarrollar in situ las relaciones de fuerza de longitud para el garrido de Goliath Atlántico (Epinephelus itajara) en los arrecifes costeros.

Une approche intégrée pour développer des relations in situ sur la force et la longueur cible pour le mérou de Goliath de l'Atlantique (Epinephelus itajara) sur les récifs côtiers.

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ABSTRACT

Hydroacoustic surveys represent a rapid non-invasive alternative to labor-intensive population assessments using traditional fisheries dependent and independent survey methods. While hydroacoustic surveys provide a wealth of information that can simultaneously address management and ecological questions at enhanced spatiotemporal scales, there are certain limitations that have made studying reef associated and diverse fish assemblages exceptionally challenging. Specifically, the taxonomic discrimination of a species using acoustic approaches requires a comprehensive understanding of their frequency-dependent scattering properties that can be logistically difficult to measure. Here we provide data related to this effort, and present an approach to derive in situ target strength-length relationships for Atlantic Goliath Grouper statistically derived from the comparison between laser-calibrated photogrammetry estimated length distributions and coincident in situ target strength distributions collected from spawning aggregations in Jupiter, Florida. With these data, improvements in estimates of abundance, density, and biomass can be used to augment information needed by resource managers and policy makers to inform management decisions. Additionally, these data provide a framework for the development of similar population assessment efforts related to data poor species that exhibit conspicuous aggregating behavior, similar to goliath grouper spawning. Lastly, considering the advances in available acoustic technologies and the logistical challenges associated with acoustically surveying complex habitats, it is imperative that we consider strategic survey designs that maximize data quality and scope.

Using acoustic and optical methods in fish spatial distribution assessment

Uso de metodos acusticos y opticos para monitorear la distribución espacial de peces

Utilisation de méthodes acoustiques et optiques dans l'évaluation de la distribution spatiale des poissons

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ABSTRACT

This study combined acoustic (echo-sounder) and optical (stereo baited remote underwater video, referred to as stereo-BRUVs) methods to evaluate the distribution and abundance of fish. These techniques complement each other, as the echo-sounder can be used to map the location of fish schools and individuals over a large area, and the visual data can help identify the species composition of a school, which is often non-trivial to attain with acoustic methods alone. The non-extractive and non-invasive characteristics of these techniques are useful, particularly in conservation areas, such as marine parks. The objective of this study was to compare the spatial distribution of fish using acoustic and optical methods over different benthic habitats in Ningaloo Reef Marine Park, Western Australia. Acoustic data was collected using a single-beam echo-sounder at two frequencies 38 and 200 kHz. Optical data was collected using stereo-BRUVs, deployed at 656 different sampling points within the same region. Relative biomass per species was estimated using the stereo-BRUVs data for each point of deployment. Schools and single-targets were extracted and the target strength of the species representing the highest proportion of biomass, according to the stereo-BRUVs data was used as a preliminary way to convert the backscatter energy into relative biomass. Correlations between the relative biomass estimated with both methods were explored. The relative advantages and drawbacks of these methods for monitoring fish populations is discussed.

Underwater acoustics for ecosystem research: current advances and perspectives in Northeast Brazil

Acústica subacuática para la investigación de ecosistemas: avances y perspectivas actuales en el Nordeste de Brasil

Acoustique sous-marine pour la recherche sur les écosystèmes: avancées et perspectives actuelles dans le nord-est du Brésil

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ABSTRACT

Recent improvements (e.g. multifrequency, broad-band echosounders) allow to simultaneously characterize physical structures (e.g. thin layers, internal waves, eddies) and organisms (from zooplankton to whales) patterns of distribution across scales from meters to thousands of kilometers. These progresses open a variety of perspectives for understanding complex processes. On this basis we are developing in Northern Brazil the 'Acoustic along the Brazilian Coast' (ABRAÇOS) project. The main objective is to establish a 3D characterization of the abiotic and biotic compartments and their interactions in coastal and oceanic ecosystems. The project is based on two multidisciplinary at-sea surveys performed on-board the IRD R/V Antea in Sept. – Oct. 2015 and April – May 2017 as well as small scale surveys using vessels of opportunity. The study area includes the Northeast coast Brazil and an oceanic area including the Archipelagos of Fernando de Noronha, the Atoll das Rocas and oceanic seamounts. These campaigns have three specific objectives: (i) characterization of the water masses and their dynamics; (ii) ecosystem acoustics with the collection of multifrequency acoustic data (38, 70, 120 and 200 kHz) coupled with pelagic and bottom trawls, zooplankton net sampling and video images; and (iii) biodiversity and trophic structure with the study of benthic, demersal and pelagic biodiversity, patterns of distribution, trophic ecology and contamination (mercury). First results provide a new vision of the ecosystem structure and dynamics and reveal, among other, the importance of gelatinous in both coastal and oceanic ecosystems. The perspectives include comprehensive mapping of demersal and pelagic patterns of distribution according to the habitat characteristics including coral reef areas.

Acoustic assessment of bathymetry, bottom types and characterization of ichthyofaunal community in shallower waters of Serrana Key Island, Biosphere Reserve Seaflower, Colombia

Evaluación acústica de la batimetría, tipos de fondo y caracterización de la comunidad ictiofaunal en aguas someras de la isla Cayo Serrana, Reserva de la Biosfera Seaflower, Colombia

Évaluation acoustique de la bathymétrie, des types de fond et caractérisation de la communauté ichthyofaunale dans les eaux peu profondes de Serrana Key Island, Réserve de la biosphère Seaflower, Colombie

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ABSTRACT

The Biosphere Reserve Seaflower since its declaration in 2000 has become a strategic region of conservation and sustainable development for Colombia. Therefore, the objective is to assess by hydroacoustics the bathymetry, bottom types and characterize the ichthyofaunal community in shallow waters (5-100 m) in Serrana Key, Reserve of the Biosphere Seaflower. The acoustic survey was carry out onboard in a boat at which a scientific echosounder Biosonics DTX with a 38 kHz transducer was installed. In the bottom types analyzes, fine-sand sediments characteristics (-26.0 db) are shown. However, other types of bathymetric structures other than sediments with an echo of -35.0 dB, which may be a coral structure, are also shown. The depth ranged between 3.62 and 24.98 m (mean 11.39 ±4.17 m). 59 species belong to 13 orders and 23 families were registered, being the more abundant Labridae (19%), Pomacentridae (10%) and Serranidae (9%) and with minor frequency Sphyraenidae and Scianidae (1%). The species Thalassoma bifasciatum, Mulloidichthys martinicus and Chromis cyanea were the more abundant in all sampling stations, while Clepticus parrae, Halichoeres garnoti, Stegastes partitus and Gramma loreto were sporadic. However, the fish species Sphyraena barracuda, Pareques acuminatus, Equetus punctatus, Mycteroperca venenosa, Ginglymostoma cirrat showed lower relative abundances (<1%). The richness, diversity and composition of species were similar in all study area. According to similarity analysis two assemblages were found, the first one associated to bottoms with patches of coral reef with abundant octocorals and bigger coral heads, the second assemblage associated to patches of less complex coral and the infralittoral zone.

Coupling Echosounder and Hydrophone Surveys at Spawning Aggregations: Relationships Between Levels of Fish Sound Production and Density

Combinando Monitoreos entre Ecosondas e Hidrófonos en las Agregaciones Reproductivas: Descubriendo Relaciones Entre el Sonido que Producen los Peces y su Densidad

Couplage d'études par echosondeur et par hydrophone dans les frayères: relations entre les niveaux de production de son et de densité de poissons

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ABSTRACT

Advancements in the use of acoustic methods to characterize, map, and assess spawning aggregations has expanded our understanding of the reproductive biology, life histories, and stock sizes of vulnerable species. The versatility of active acoustics (echosounders) has permitted the estimation of fish abundances and biomasses in challenging environments, such as reefs and estuaries, while the efficiency of passive acoustics (hydrophones) to monitor the sounds produced by aggregating fishes has increasingly been embraced to identify spawning areas and periods. However, a logical and desirable progression to efficiently and accurately estimate fish abundances from their sounds has been hindered by the complexity of fish calling rates and acoustic propagation. In this study, we compared Gulf Corvina (Cynoscion othonopterus) sound levels with simultaneous measurements of densities from echosounder surveys recorded at a spawning aggregation in the Colorado River Delta, Mexico, to investigate empirical relationships between fish sound levels and density. We observed aggregations comprised of more than 1.5 million fish and elevated sound levels distributed over 25 km of the delta. The relationship between sound levels and density varied within surveys but stabilized during the two-hour period of peak spawning, resulting in an equation to estimate densities from received sound levels. Our results support the inclusion of active acoustics into assessments of spawning stock abundance and indicate that sound levels can be used to estimate fish densities when relationships are scaled to the spatial and temporal dynamics of spawning activity. Our approach is applicable to other soniferous, aggregating fishes, providing an efficient method to assess and monitor reproductive stocks using passive acoustics.

Coupling passive acoustic techniques to survey fish spawning habitats in Puerto Rico

Combinando técnicas de acústica pasiva para estudiar hábitats de desoves de peces en Puerto Rico

Couplage des techniques acoustiques passives pour enquêter sur les habitats des poissons reproducteurs a Puerto Rico

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ABSTRACT

Measuring habitat use by reef fishes for spawning aggregations is enhanced with non-invasive passive acoustic monitoring. Some advantages that can be applied to cases where species are known to produce sound associated with reproduction include a low cost of deployment and recovery of the instruments, high sampling frequency, night-time sampling and a record of the soundscape. Some of these pros make passive acoustics instrumental to gather occupation data given the logistical constraints of in-situ surveys during the short time period this critical habitat is used by some species. Notable disadvantages include the technical requirements of signal recognition in large datasets, not being able to verify why fish are not being detected, and masking of sounds by other sound sources including anthropogenic. Nassau grouper produce courtship associated sounds during reproductive behaviors that were recorded simultaneously with two seasons when 29 individuals had been tagged internally with acoustic tags at Bajo de Sico a seamount off western Puerto Rico. Receivers deployed throughout the spawning area allowed for the verification of absence of fish when no sounds were detected. The combination of passive acoustic monitoring techniques and internal tagging of spawning grouper at this site provided evidence of temporal and spatial patterns of diel habitat use continuously during six months. With this information, a remotely monitored component of fish spawning aggregations research can help answer important site specific questions.

Implementation of a passive acoustic monitoring system on a SV3 wave glider and applications

Implementación de un sistema de vigilancia acústica pasiva en un Wave Glider SV3 y aplicaciones

Mise en oeuvre d'un système de surveillance acoustique passive sur un Wave Glider SV3 et applications

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ABSTRACT

Fisheries independent research strives for new technology that can help remotely and unobtrusively quantify fish biomass. Some large fish species, such as groupers vocalize during mating. Fish sounds provide an innovative approach to assess fish presence and numbers. However, large datasets make the detection process by a human ear very tedious and lengthy. We have developed an algorithm based on machine learning and voice recognition methods to identify and classify fish sounds. This algorithm currently operates on a SV3 Liquid Robotics wave glider, which has been fitted to accommodate a passive listening device. Fish sounds detection and classification results, and location, along with environmental data are transmitted in real-time to the science crew who can ground truth the detection with divers. This passive acoustic monitoring system has been deployed in the US Virgin Islands, Puerto-Rico, the Florida Keys and on the East Florida shelf. We will provide an overview of the findings made with this autonomous monitoring system.

Acoustic assessment of zooplankton biomass in the Coast of Magdalena, Colombian Caribbean

Evaluación acústica de la biomasa zooplancton en la costa del Magdalena, Caribe colombiano

Évaluation acoustique de la biomasse du zooplancton dans la côte de Magdalena, Caraïbes colombiennes

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ABSTRACT

Zooplankton is one of the main components of biological communities in marine ecosystems. Traditionally they had been caught with net tows in order to be studied. However, in recent years, new technologies such as acoustics and optical instruments have allowed newer and deeper insights into these organisms. The present study uses a general model to correlate acoustic backscatter with the dry weight biomass of zooplankton. Data for the zooplankton biomass were obtained by a vertical trawl net in specific locations and the acoustic data were taken using a scientific echosounder Biosonics DTX with a transducer of 38 kHz. A linear model was used to correlate hydroacoustic backscatter with biomass. The survey was carried out during May 2016 in the Magdalena Department, localized in the Caribbean Colombian Coast. The relationship between zooplankton dry weight and acoustic backscatter was significant ($p < 0.001$) and explained 54% of variability in dry weight data. The mean mesozooplankton dry weight biomass estimated from plankton net tows and acoustic were not significantly different ($p = 0.99$). The spatial distribution of zooplankton showed higher aggregations in front of Tayrona National Park and Ciénaga Grande of Santa Marta. This work constitutes the first estimation of the acoustic conversion factor for the zooplankton in the Colombian Caribbean Sea.

Monitoring the Soundscape of Paradise Reef, Cozumel:
A Tool for Assessment and Conservation Planning

Paisaje sonoro submarino del arrecife paraíso en Cozumel:
Una herramienta de evaluación, monitoreo y conservación

Paysage Sonore Sous-marin de Paradise Reef, Cozumel:
Un outil pour l'Évaluation, la surveillance et la Conservation

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ABSTRACT

Tourism is an essential ecosystem service provided by diverse coral reefs. The economic benefits derived from these services sustain coastal cultures and social structure, contributing several billion dollars annually to local and national economies. Cozumel is visited by approximately 3 million tourists every year, drawn to the island's coral reefs. Diving and snorkeling tourism in the National Reef Park of Cozumel is the main economic driver of Cozumel. Given the relative importance of this ecosystem service, maintaining healthy coral reefs is essential. Coral reef biodiversity studies have traditionally relied on intensive survey techniques that are costly, infrequent or sporadic, limited to depths accessible to human divers, and generally conducted only during daylight. Sound measurement is an emerging alternative that uses non-invasive, passive acoustic monitoring (PAM) to measure reef soundscapes and biodiversity. JASCO in partnership with the Parque Nacional Arrecifes de Cozumel, deployed an Autonomous Multichannel Acoustic Recorder (AMAR) on Paradise Reef in July 2017. The AMAR recorded two months of continuous acoustic data. The objectives of the study included characterizing the anthropogenic and natural soundscape of this location that is heavily trafficked by cruise ships and dive boats, and is home to the iconic Splendid toadfish (Sanopus splendidus). The data collected will provide information regarding the volume of anthropogenic noise at this location and the potential for effects of on the reef fauna, including masking of biologically important activities, and will facilitate identification of additional Splendid toadfish habitat in future deployments. This initial study is demonstrating the power of acoustics as a tool for biodiversity assessment, monitoring and conservation.

Hydroacoustics for the discovery and quantification of Nassau grouper (*Epinephelus striatus*) spawning aggregations

Hidroacústica para el descubrimiento y cuantificación de Nassau grouper (*Epinephelus striatus*) agregación de desove

Hydroacoustique pour la découverte et la quantification de Nassau grouper (*Epinephelus striatus*) agrégation de frai

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ABSTRACT

Fish spawning aggregations (FSAs) are vital life-history events that need to be monitored to determine the health of aggregating populations; this is especially true of the endangered Nassau grouper (Epinephelus striatus). Hydroacoustics were used to locate Nassau grouper FSAs at sites on the west end of Little Cayman (LCW), and east ends of Grand Cayman (GCE) and Cayman Brac (CBE). Fish abundance and biomass at each FSA were estimated via echo integration and FSA extent. Acoustic mean fish abundance estimates (±SE) on the FSA at LCW (893 ± 459) did not differ significantly from concurrent SCUBA estimates (1150 ± 75). Mean fish densities (number 1000 m-3) were significantly higher at LCW (33.13 ± 5.62) than at the other sites (GCE: 7.01 ± 2.1, CBE: 4.61 ± 1.16). We investigate different acoustic postprocessing options to obtain target strength (TS), and we examine the different TS to total length (TL) formulas available. The SCUBA surveys also provided measures of TL through the use of laser callipers allowing development of an in situ TS to TL formula for Nassau grouper at the LCW FSA. Application of this formula revealed mean fish TL was significantly higher at LCW (65.4 ± 0.7 cm) than GCE (60.7 ± 0.4 cm), but not CBE (61.1 ± 2.5 cm). FSA location examined with reference to seasonal marine protected areas (Designated Grouper Spawning Areas) showed FSAs were partially outside these areas at GCE and very close to the boundary at CBE. As FSAs often occur at the limits of safe diving operations, hydroacoustic technology provides an alternative method to monitor and inform future management of aggregating fish species.

16.2 APPENDIX B. WORKSHOP TERMS OF REFERENCE AND AGENDA

Workshop on Acoustic Technologies to Improve Reef Fish Ecosystem Surveys

Background and Goals: The Gulf and Caribbean Fisheries Institute (GCFI) and SouthEast Acoustic Consortium (SEAC), with sponsorship from the National Oceanic and Atmospheric Administration (NOAA), Kongsberg-Simrad, and Echoview, will hold a three-day acoustic technology workshop in Merida, Mexico during 4-10 November 2017. Although there is no workshop registration fee, you must refer to the GCFI website for the GCFI conference information concerning the GCFI conference registration fee, venue and accommodations. The goals for this 3-day workshop are to increase acoustic expertise and collaborative efforts for enhancing research and surveys in reef-fish ecosystems, and to build scientific capacity for assuring the sustainability of living marine resources in the Gulf of Mexico and Caribbean region.

Day 1: Workshop Agenda
Scientific echosounder operations

Terms of Reference: Participants will receive an introduction to the principles of scientific echosounder systems and operations, and shipboard training using two wideband echosounder systems: Simrad EK80 and the autonomous Simrad WBAT.

Date and Location: November 4, 2017, participants will meet in the main lobby of the Hyatt Regency Merida Hotel at 08:00 AM, and depart by bus from Merida to Progreso in Mexico. Following an orientation, participants will depart aboard the boat *Isla Mujeres* for training. Training aboard the boat will be limited to 30 participants (refer to the attached participant list). The boat will return to Progresso later in the day, acoustic equipment will be removed from boat, and participants will return to the hotel by bus.
Instructor: Frank Reier Knudsen (Simrad-Kongsberg Maritime) with support staff.

Day 1 (November 4, 2017) Agenda: Training with scientific echosounder operations.

08:00	Depart at 8:00 AM by bus from Hyatt Regency Merida Hotel in Merida. The bus trip to the coastal town of Progresso will likely take about 50 minutes.
09:00-09:30	Welcome, introductions and review terms of reference.
09:30-10:00	Embark *aboard the boat Isla Mujeres* and conduct safety drills.
10:00-10:30	Principles of Underwater Sound Propagation and Acoustic Technology • Theory of sound in water (basic sonar equation and terminology) • Environment, sound speed, spreading absorption • Transmit-pulse characteristics
10:30-11:00	Overview of Scientific Echosounder Systems • Echosounder types: single frequency, multi-frequency, broadband and wideband • Transducer types: single-beam and split-beam • Echosounder and software configurations
11:00-12:00	Echosounder and software configurations (hands-on exercises)
12:00-13:00	Lunch aboard *the boat Isla Mujeres*
13:00-14:00	Calibration procedures

14:00-16:00	Data-acquisition software (hands-on exercises)
16:00-17:00	Acoustic systems for various platforms
17:00-17:30	Disembark boat, remove scientific equipment from boat and pack for transportation
17:30-19:30	Dinner at restaurant in Progresso
19:30-20:30	Depart by bus from Progreso, return to Merida, and unpack equipment

Day 2: Workshop Agenda
Echosounder data processing using Echoview software

Terms of Reference: Participants will receive an overview of acoustic data processing and analysis methods using Echoview software, in a classroom setting. This introduction to Echoview software will focus on processing data from scientific echosounders with examples from surveys in coastal and reef environments. It will not include training relevant to other acoustic systems, such as multibeam systems, that are covered in a more comprehensive 5-day Echoview training course. The instructor will utilize presentations and Echoview demonstrations with "follow-me" exercises to provide hands-on training. Printed Echoview Learner Guides will be provided, along with electronic training materials and temporary Echoview license dongles. Trainees will need to bring a laptop computer running Windows.

Date and Location: November 5, 2017 at the Hyatt Regency Merida Hotel (Room: Regency III).

Instructor: Toby Jarvis (Echoview) with support staff.

Day 2 (November 5, 2017) Agenda: Echosounder data processing using Echoview software.

08:00-08:30	Software installation and introductions
08:30-10:00	Overview • Echosounder data-processing workflow • Echoview features Preliminary data exploration
10:00-10:30	Break
10:30-12:00	Apply calibration settings Data cleaning: "bad data" regions Data cleaning: noise-removal algorithms
12:00-13:30	Lunch
13:30-15:00	Seafloor detection: lines and "line pick" algorithms Point scatterers: single-echo detection (narrowband and wideband) and tracking Volume scatterers: detection of fish aggregations
15:00-15:30	Break
15:30-17:00	Multifrequency classification: narrowband and wideband Seafloor classification Density estimation (number and biomass) • Echo integration: by cells and by regions • Echo counting
17:00	Adjourn

Day 3: Workshop Agenda
Best practices for acoustic surveys in reef fish ecosystems

Terms of Reference: Presentations will cover acoustic technologies and methods to improve reef-fish surveys, such as recent advances in equipment, operational objectives, survey design, and data analysis. Case studies will examine the challenges and lessons learned while conducting acoustic surveys in the Gulf of Mexico and Caribbean region. Participation from all attendees, including presenters and participants from the training workshop, stock assessors, managers, and stakeholders, will provide diverse perspectives to establish priorities and best practices for conducting acoustic surveys in reef fish ecosystems. A report of this working group will be used to enhance the scientific capacity in this region and direct future workshops.

Date and Location: November 9, 2017 at the Hyatt Regency Merida Hotel (Room: Regency III).

Moderators: William Michaels, Chris Taylor and Kevin Boswell

Day 3 (November 9, 2017) Agenda: Best practices for conducting acoustic surveys in reef fish ecosystems.

08:30-08:40	Introductions and review of terms of reference
08:40-08:55	Bill Michaels – Strategies and priorities for building scientific capacity with acoustic technologies in the Gulf of Mexico and Caribbean region
08:55-09:15	Lars Nonboe Andersen – Overview of acoustic systems and recent advances in acoustic technologies for improving reef fish ecosystem surveys
09:15-09:45	Break-out session to prioritize management objectives and operational challenges
09:45-10:00	Summary from breakout session groups
10:00-10:30	Break
10:30-10:45	Frank Reier Knudsen - Overview of lessons learned from Day 1 training, and operational considerations for conducting reef fish surveys.
10:45-11:00	Toby Jarvis – Overview of lessons learned for Echoview post-processing and data analysis for conducting reef fish surveys.
11:00-11:20	Jorge Paramo - Case study on acoustic surveys for stock assessments.
11:20-11:40	Dave Demer – Measurement considerations for surveys of reef-fish and their seabed habitats.
11:40-12:00	Ben Binder – Integrating acoustic surveys and fish spawning aggregation research: challenges and lessons learned.
12:00-13:30	Lunch
13:30-13:50	Patrick Sullivan - Statistical considerations for acoustic survey designs and abundance estimation; optimizing data collection for reef fish management.
13:50-14:10	Charles Thompson – Integrated acoustic-optic sampling strategies for improving reef fish ecosystem surveys.
14:10-14:30	Chris Taylor - Fishery acoustic-derived metrics and indicators for assessing and monitoring performance of Marine Protected Areas (MPAs) in coral reef ecosystems.
14:30-14:50	Laurent Chérubin - Acoustic detection and characterization of fish spawning aggregations using a novel, persistent presence robotic approach.
14:50-15:00	Closing discussions and recommendations on case studies.

15:00-15:30	Break
15:30-16:00	Breakout sessions on solutions to challenges with acoustic operations on reef fish habitats, and recommendations for addressing management objectives.
16:00-16:30	Summary from breakout session groups
16:30-16:50	Concluding discussions on best practice recommendations for acoustic surveys in reef fish ecosystems.
16:50-17:00	Writing assignments for the technical report.
17:00	Adjourn.

16.3 APPENDIX C. PARTICIPANT LISTS

Participant list for the GCFI-SEAC Workshop on Acoustic Technologies to Improve Reef Fish Ecosystem Surveys. Day 1 of the workshop provided training with scientific echosounders, Day 2 provided software training, and Day 3 was devoted to establishing best practice guidance for conducting acoustic operations to improve reef fish ecosystem surveys. The asterisk (*) indicates which participants served as instructors or steering committee members.

Last name	First name	Affiliation and email	Attended
Acosta*	Alejandro	Florida Fish and Wildlife Conservation Commission, Fish Wildlife Research Institute, 2796 Overseas Hwy, Marathon, Florida 33050, USA Email: Alejandro.Acosta@myfwc.com	Day 3
Algrøy*	Tonny	Simrad, Kongsberg Maritime, Strandpromenaden 50. NO-3183, Horten, Norway Email: Tonny.Algroy@simrad.com	Day 1,2,3
Andersen*	Lars Nonboe	Simrad, Kongsberg Maritime, Strandpromenaden 50. NO-3183, Horten, Norway Email: Lars.Nonboe.Andersen@simrad.com	Day 1,2
Arvizu Torres	Ximena Alejandra	Blue Core A.C., 77710 Playa de Carman, México Email: e4.ximena@gmail.com	Day 1,2,3
Bassos-Hull	Kim	Mote Marine Laboratory, 1600 Ken Thompson Pkwy, Sarasota, Florida 34236, USA Email: kbhull@mote.org	Day 3
Barona	Tanya	Toledo Institute for Development and Environment, Southern Hwy, Hopeville, Belize Email: tbarona@tidebelize.org Email: tanyabarona@gmail.com	Day 3
Beyea	Rebekah 'Taylor'	School of Fisheries, Aquaculture and Aquatic Sciences, Auburn University, 8300 State Hwy 104, Fairhope, Alabama 36849, USA Email: rtbeyea88@gmail.com	Day 3
Biggs	Christopher	Marine Science Institute, University of Texas at Austin, 750 Channel View Dr., Port Aransas, Texas 78373, USA Email: cbiggs@utexas.edu	Day 1,2,3
Binder	Benjamin	Florida International University, 3000 NE 151 Street, North Miami, Florida 33181, USA Email: bbind002@fiu.edu	Day 1,2,3
Boswell*	Kevin	Florida International University, 3000 NE 151 Street, North Miami, Florida 33181, USA Email: Kevin.Boswell@fiu.edu	Day 1,2,3
Butkowski	Drew	Central Caribbean Marine Institute (CCMI), N Coast Rd. E, Little Cayman, Cayman Islands Email: dbutkowski@reefresearch.org	Day 3
Candelmo	Alli	Central Caribbean Marine Institute (CCMI), N Coast Rd. E, Little Cayman, Cayman Islands Email: acandelmo@reefresearch.org	Day 3

Castro Gonzalez	Erick Richard	La Gobernadora del Departmento de San Andrés, Departmento Archpiélogo de San Andrés, Providencia y Santa Catalina, Km 26 Via San Luis, San Andres Isla, Colombia Email: pescastro@gmail.com	Day 3
Chérubin	Laurent	Florida Atlantic University, Harbor Branch Oceanographic Institute, 5600 N US Hwy 1, Fort Pierce, Florida 34946, USA Email: lcherubin@fau.edu	Day 1,2,3
Coniotty*	Jeff	Simrad, Kongsberg Maritime,19210 33rd Ave., Lynnwood, Washington 98036, USA Email: Jeff.Condiotty@km.kongsberg.com	Day 1,2,3
Coronado Castro	Eva	Centro de Investigación y de Estudios del Instituto Politécnico Nacional (CINVESTAV), Unidad Mérida, Antigua Carretera a Progreso km 6, Cordemex, Loma Bonita Xcumpich, CP. 97310 Mérida, México Email: ev.coronado@gmail.com	Day 3
Cruz Marrero	Wilmelie	Marine Estuarine Environmental Sciences Program, University of Maryland Eastern Shore, 11868 College Backbone Rd, Princess Anne, Maryland 21853, USA Email: wcruz-marrero@umes.edu	Day 3
Cuevas Flores	Eduardo Amir	Departmento de Manejo de Zonas Costeras, Universidad Nacional Autónoma de México (UNAM), Av. Universidad 3000, Copilco Universidad, Coyoacán, Cuidad de México, Distrito Federal 04510, México Email: amir.cuevas@gmail.com	Day 1,2,3
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16.4 Appendix D. Results from the Workshop Breakout Sessions

Before the workshop, participants provided responses to four trigger questions on management objectives, operational challenges, and recommended solutions and resource requirements to address operational challenges. The responses to these questions were discussed and prioritized in breakout sessions during the third day of the workshop, and the results are presented below.

Table 16-1. Summary of pre-workshop and workshop breakout session results for Question 1: What are your top management objectives in reef fish ecosystem management?

Pre-workshop	Workshop Breakout Sessions	Category	Question 1: What are your top management objectives pertinent to reef fish ecosystems?
1 (n=9)	1 (n=28)	Population biomass estimation	Abundance and biomass estimates (from long-term survey operations) *[JC,CT,DD]*; Population size (taking advantage of aggregating behavior) *[KB]*; Distribution and abundance *[TJ]*
	2 (n=21)	Resource use and anthropogenic impact	Understand use of resources by fishers and ecotourism *[KB]*; Sustainable fishing *[TJ]*; Harvest culling *[TJ]*; Monitor fishing pressure and use *[CT]*; Baseline to understand impacts on resources *[JC]*
3 (n=6)	3 (n=20)	Distribution, connectivity, spatial variation	Distribution/migration and connectivity of populations with environmental variability *[PW]*; Migratory behavior (connectivity) *[DD]*; Spatial distribution (closed areas, spawning, stock identification) *[DD]*; Temporal variation in distribution (diel, seasonal, annual) *[DD]*; Understand variation of bias *[KB]*; Baseline to understand environmental changes in distribution and seasonal patterns *[KB]*;
(n=2)	4 (n=10)	Survey operational efficiencies	Technology supplement to existing methods with minimal disruption to assessments *[PW]*; Do not be scared of new technology *[KB]*; Identification of species *[JC];* Validation using instruments *[JC]*; Methods for ships of opportunity *[JC]*
(n=1)	5 (n=6)	MPAs	Delineation of MPAs *[PW]*; Conservation (MPAs) design performance *[TJ]*
2 (n=9)	6 (n=5)	Spawning aggregations	Spawning aggregation location and monitoring *[JC,CT]*; Spatial distribution (closed areas, spawning, stock identification) *[DD]*; Behavior and life history patterns *[PW]*
4 (n=6)	7 (n=4)	Essential habitat	Habitat classification, use and health *[PW]*; Identification of habitat domain *[JC]*; Artificial reef (decommission of gas/oil rigs) *[TJ]*
(n=2)	8 (n=2)	Ecosystem health and changes	Ecosystem health and anthropogenic impacts *[PW];* Trophic rates and ecosystem function *[CT]*; Zooplankton identification and size *[CT]*
	(n=1)	FADs	Fish Aggregation Devices (FADs) effectiveness *[DD]*

Table 16-2. Summary of pre-workshop and workshop breakout session results for Question 2: What are your top operational challenges relevant to your management objectives?

Pre-workshop	Workshop breakout session	Category	Question 2: What are your top operational challenges relevant to your management objectives?
4 (n=5)	1 (n=19)	Lack of acoustic expertise	Steep learning curve with acoustic methods, sensitive instruments, and need for training *[PW]*; Training and empowerment with access to help *[KB,TJ]*; Lack of communication among groups *[KB]*; Combine resources and expertise *[CT]*
(n=1)	2 (n=14)	Funding constraints	Costs and funding *[PW,JC,TJ]*; Access to resources and equipment *[KB]*
3 (n=6)	3 (n=10)	Deadzone	Depth limitations and deadzone (mostly in shallow water, but also deep water) *[PW]*; Fish near bottom difficult to detect with acoustics (deadzone) and video *[CT,DD]*
	4 (n=7)	Protocols	Standard Operating Protocols (SOPs) for data acquisition and processing *[JC]*; Data processing bottlenecks *[JC]*
1 (n=8)	5 (n=6)	Species ID	Identification of species *[DD]*; Difficulties with validation of acoustic classification, species composition and length data *[PW]*; Aggregations of many species and diversity *[CT]*
	6 (n=6)	Habitat ID	Seabed and habitat classification *[DD]*
5 (n=5)	7 (n=5)	Behaviorial and environmental variability	Effect of fish behavior *[DD];* Acoustic measurement uncertainty including impact from environmental variability *[PW]*
(n=1)	8 (n=5)	Equipment	Involve stakeholders *[JC]*; Simplified instrumentation and methods for collection by fishers and citizen science *[PW];* Need acoustic systems that are more portable and easier to use *[CT]*
2 (n=8)	9 (n=4)	Spatial variation	Spatial uncertainty in abundance estimates and habitat use relative to survey design *[PW]*; Understanding connectivity *[KB]*; Low abundance *[CT];* Locating target species *[TJ]*
	(n=1)	Enforcement	Lack of enforcement relevant to harvest regulations *[KB]*
(n=1)		Other technology	Abundance from passive acoustics and telemetry *[PW]*

Table 16-3. Summary of pre-workshop and workshop breakout session results for Question 3: How have you been addressing these challenges?

Pre-workshop	Workshop breakout sessions	Category	Question 3: How have you been addressing these challenges?
3 (n=3)	1 (n=26)	Pool of expertise	Training and networking to build expertise [PW]; Developing networks and collaborations *[KB];* Training opportunities (internships and partnerships) *[KB];* Collaborations *[DD]*
2 (n=8)	2 (n=12)	Integrated technologies	Integrated sampling (e.g., acoustics and cameras) to validation acoustics *[PW]*; Coupling technologies *[DD]*; Adaptive sampling (prioritize sampling effort, observation systems) *[JC];* Autonomous and repeated observations *[DD]*; Technology transfer *[CT];* Underestimate of abundance in acoustic deadzone *[PW]*; Near bottom sampling (e.g., cameras and horizontal acoustics) to address deadzone *[PW]*; Deadzone quantification *[DD*
1 (n=5)		Passive acoustic technology	Use of telemetry and passive acoustics, including fish sound library *[PW]*; Passive acoustics (closer receivers to reduce noise) *[TJ]*; Passive acoustics (receiver range for deeper operational capability) *[TJ]*; Passive acoustics (eaten tags by predators) *[TJ];*
(n=1)	3 (n=10)	Best practice collection and post-processing	Standardize collection of data *[JC]*; More simplified post-processing templates and programming *[PW]*; Automated data processing (sound libraries, discrimination analysis) *[JC]*
(n=1)	4 (n=5)	Analytical methods	Multifrequency classification with validation *[PW];* Spectral and statistical classification *[DD]*; Split-beam imaging *[DD]*; Wideband range resolution *[DD]*
(n=2)	5 (n=4)	Shared equipment and support	Communicate need to vendors for equipment loan/lease *[TJ]*; FAQs *[KB]*; Trouble-shooting and contacting vendors for equipment issues *[TJ]*; More portable deployment alternatives with simplified functionality *[PW]*; Need portable and low-cost echosounders *[CT]*
	6 (n=4)	Baseline	Address lack of baseline data and literature searches *[JC]*
(n=1)	7 (n=1)	Stakeholders	Data collection from fishers and citizen science *[PW]*; Talk to fishers for locating targets/areas *[TJ];* Need cooperative research with commercial/recreational stakeholders *[CT]* Cooperative research *[CT]*
4 (n=3)		Validation	Use of catch landings data in area to validate acoustic species composition *[PW]*

Table 16-4. Summary of pre-workshop and workshop breakout session results for Question 4: What resources would help achieve operational objectives?

Pre-workshop	Workshop breakout sessions	Capacity	Question 4: What resources would help achieve operational objectives?
1 (n=8)	1 (n=35)	Build expertise through training and collaborative studies	Training/networking to build expertise and collaborations *[PW];* Training and online help resources *[TJ]*; Internships and assistantships *[KB]*; Access to literature *[KB]*; Workshops and integrative opportunities *[KB];* Equipment and training *[KB]*; Training events with actual data collection *[CT];* Multi-disciplinary training *[DD]*; Develop network for more multinational collaborations *[CT]*; Email network *[CT]*
2 (n=7)	2 (n=25)	Improve equipment availability	Access to or update acoustic equipment, including multi-frequencies and portable systems *[PW];* Equipment lease/loan opportunities; shared pool equipment *[KB,TJ]*; Pool of sharable equipment *[CT]*; Portable low-cost echosounders that are easier to use for collaboration *[CT]*; Equipment and expertise availability *[DD]*
4 (n=4)	3 (n=14)	Optimize survey design and sampling efficiencies with integrated technology	Use of complimentary sampling gear (e.g., cameras, telemetry) *[PW]*; Ocean observation system (passive/active acoustic) w real-time processing and synthesis (JC); Alternative platforms *[KB];* Increase capacity in remote and under-sampled areas *[JC];* Miniature self-contained acoustic-optical sampler *[DD];* Develop remote sensing (acoustics) to monitor fishing and other impacts *[CT];* Stealth and autonomous instruments *[DD]*; Evaluation of time, cost and performance *[DD]*
	4 (n=12)	Develop long-term monitoring/ time series	Shared data pool and meta-analyses *[TJ]*; Continuous time series *[JC]*; Long-term measurements at fixed stations *[DD]*
3 (n=4)	5 (n=9)	Funding opportunities	Increase in funding opportunities including through partnerships *[PW]*; Consumer responsible for subsidizing the costs *[JC]*; Regional funds *[CT]*
	6 (n=6)	Collaborative efforts on analysis	Dead-zone reduction *[DD];* Data fusion *[DD];* Developing new science for new problems *[KB];* Broadband and wideband experiments to obtain TS curves for Caribbean species *[PW]*
(n=1)	7 (n=3)	Boat availability	More boat time for survey sampling *[PW]*; Alternative platforms (e.g., fishers) *[KB];* Outsourcing vessels of opportunities and citizen science *[TJ]*
	8 (n=2)	Cooperative research with fishers	Cooperative research with commercial or recreational stakeholders *[CT]*