OCS Study
BOEM 2020-009

Literature Synthesis: Passive Acoustic Monitoring Projects and Sound Sources in the Gulf of Mexico

U.S. Department of the Interior
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ABOUT THE COVER

Photo credits: (Top) glider and towed acoustic transponder set for test deployment, Scripps Institution of Oceanography at University of California San Diego; (bottom left) sperm whale with DTAG (digital-recording acoustic tags) deployed during Sperm Whale Seismic Study (SWSS), Texas A&M University; (bottom right) autonomous surface vehicles getting ready to work in the Gulf of Mexico, Littoral Acoustic Demonstration Center.

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List of Abbreviations and Acronyms

Short Form	Long Form
ADCP	acoustic Doppler current profiler
AFTT	Atlantic Fleet Training and Testing
AMAPPS	Atlantic Marine Assessment Program for Protected Species
ASV	autonomous surface vehicle
AUV	autonomous underwater vehicle
BIA	Biologically Important Area
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
CAAMP Monitoring Program	Coastal Alabama Acoustic Monitoring Program
CEE	controlled exposure experiment
CetSound	cetacean & sound mapping
CV	coefficient of variation
dB	decibel(s)
dB re 1 µPa/m	decibels referenced to 1 microPascal per meter
dB re 1 µPa^2	decibels referenced to 1 microPascal squared
dB re 1 µPa	decibels referenced to 1 microPascal per meter
dB re 1 µPa @ 1 m	decibels referenced to 1 microPascal at 1 m
dB re 1 µPA^2/Hz	decibels referenced to 1 microPascal squared per Hertz
dB re 1 µPa [rms] m	decibels referenced to 1 microPascal (root mean square) at 1 m
dB re 1 µPa^2 s	decibels referenced to 1 microPascal squared second
DIFAR	directional frequency analysis and recording
DoN	Department of the Navy
DP	dynamic positioning
DSG	Digital SpectroGram
DTAG	digital-recording acoustic tag
EARS	environmental acoustic recording system
EBRV	Energy Bridge™ Regasification Vessel
EEZ	Exclusive Economic Zone
EIS	environmental impact statement
ERMA	energy ratio mapping algorithm
GAM	generalized additive model
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GEMM	Gulf Ecological Monitoring and Modeling
GMM	Gaussian mixture model
GOM	Gulf of Mexico
GoMRI	Gulf of Mexico Research Initiative
GRIIDC	GoMRI Information and Data Cooperative
GulfCet	Gulf of Mexico Cetacean Study
HARP	high-frequency acoustic recording package
Hz	hertz
IOOS	US Integrated Ocean Observing System
kHz	kilohertz
LADC	Littoral Acoustic Demonstration Center
LADC-GEMM	Littoral Acoustic Demonstration Center–Gulf Ecological Monitoring and Modeling
LIDO	Listening to the Deep Ocean Environment
LLC	limited liability company
LNG	liquefied natural gas
MARMAM	Marine Mammals Research and Conservation Discussion
MARU	marine autonomous recording unit
MMO	Marine Mammal Organisation

Short Form	Long Form
MMS	Minerals Management Service
NMFS	National Marine Fisheries Service
NMFS SEFSC	NMFS Southeast Fisheries Science Center
NOAA	National Oceanic and Atmospheric Administration
NSWC PCD	Naval Surface Warfare Center Panama City Division
OBIS-SEAMAP	Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations
OCS	Outer Continental Shelf
ONR	Office of Naval Research
PAL	passive acoustic listening
PAM	passive acoustic monitoring
PK	peak sound pressure level
psu	practical salinity unit
ppt	parts per thousand
PTS	permanent threshold shift
RMS	root mean square
ROCCA	real-time odontocete call classification algorithm
R/V	research vessel
SEFSC	Southeast Fisheries Science Center
SEL	sound exposure level
SELcum	cumulative sound exposure level
SPL	sound pressure level
SST	sea surface temperature
SWAMP	Sperm Whale Acoustic Monitoring Program
SWSS	Sperm Whale Seismic Study
TL	transmission loss
T-POD	Timing Porpoise Detector
US	United States
USV	unoccupied surface vessel
WGH	Wave Glider HARP

Summary

Purpose

Available and relevant literature and data on previous and ongoing passive acoustic monitoring in the Gulf of Mexico (GOM) were compiled. This information was reviewed to characterize potential sound sources and their distribution in the GOM and to identify existing methodologies for acoustic source detection, localization, tracking, and classification. Acoustic sources encompass weather events, industrial and military activities (including the use of explosives), shipping, animal vocalizations, and geologic events. This review was conducted under the Bureau of Ocean Energy Management's (BOEM) Passive Acoustic Monitoring (PAM) Program for the Northern GOM. The primary objective of the program is to design and implement a multi-year acoustic data collection and monitoring plan for both the acoustic and the biotic environments in the GOM further defining the associated baseline soundscapes.

The objective of this literature synthesis was to collect and review published literature and available datasets of previous and ongoing PAM projects in the GOM for the following purposes:

1. Characterize potential sound sources in the GOM.
2. Summarize the state of current knowledge on GOM baseline acoustic noise levels.
3. Investigate existing methodologies for acoustic source detection, localization, tracking, and classification of marine mammals.
4. Identify by spatial mapping previous and current study areas.
5. Identify the most appropriate field methodologies and protocols for measuring the acoustic environment in the GOM.

Approach

Readily available literature and data on previous and ongoing PAM projects in the three BOEM planning areas in the GOM (Eastern, Central, and Western) were searched and compiled through the use of online databases and literature and World Wide Web. The search focused on gathering a variety of literature types on biological and physical ambient noise levels in the GOM. The review also focused on PAM projects for marine mammals in the GOM and on anthropogenic sound sources in the region. The focus was on collecting information from the last 15 years of studies; some research in the GOM as far back as 1991was included.

Commercial databases, search tools, and email list servers were used in the search for data on PAM projects in the GOM. Key search terms and phrases were used to conduct methodical queries of databases and the World Wide Web. The search included terms in all fields (title, abstract, etc.) referencing noise and/or sound, research method, marine mammal species of interest, specific BOEM planning areas and GOM features of interest, and/or specific researchers and/or institutions, funding sources, and monitoring programs. Studies generally pertained to PAM studies in the Northern GOM. Selected references on research methods and PAM studies were consulted that occurred outside the region because similar studies may be lacking or nonexistent in the Gulf , but may be useful either to characterize PAM work in general and/or to provide suggestions on the future BOEM PAM Program for the Northern GOM.

Key Findings and Recommendations

Since 1991, thirty-two projects have been conducted in the GOM using PAM. Eight of these reviewed studies were specifically designed to gather data on ambient noise in the GOM; the other 24 studies were designed to gather information on marine mammals using PAM. The majority of data collection efforts focused primarily upon the Eastern and Central GOM. Additionally, PAM surveys have tended to be in waters of the continental shelf and slope down to approximately 2,000 meters (6,562 feet) deep; only two surveys were in waters extending to approximately 3,200 meters (10,499 feet).

A preliminary experimental design has been proposed for the acoustic data collection under the BOEM PAM Program for the Northern GOM. This design has included deployment of a carefully selected network of stationary and mobile PAM platforms at strategically identified locations within Mississippi and De Soto canyons in the Northern GOM. Based on the findings from literature review, the following recommendations are made to enhance the preliminary experimental design for the BOEM PAM Program for the Northern GOM:

- Focus the first two-year deployment effort in areas of the Mississippi Canyon and/or valley where many ambient noise sources are present and the majority of previous baseline data collections were conducted. However, expand the sensor deployment to shallow water and abyssal plain.
- If possible, establish at least one stationary monitoring site in BOEM Western or Eastern planning areas to understand the differences in soundscapes among regions with at minimum two years of deployment.
- Investigate the using mobile PAM platforms (gliders and autonomous surface vehicles) for ambient noise measurements, where consistent with study goals and objectives.
- Investigate using oil and gas facilities as opportunistic platforms for data collection, particularly to characterize near-field anthropogenic noise features of drilling and construction activities.
- Conduct comprehensive oceanographic data collection simultaneously with acoustic measurements to assure proper input into propagation models to study their effectiveness in predicting acoustic energy distribution from different sources.
- Focus on long-term multi-year continuous calibrated PAM data collection over a broad frequency range while understanding a need for designing special requirements for the systems that will be monitoring different frequency bands (hydrophone sensitivities and dynamic range, system response curves, etc.).
- Implement rigorous unified hydrophone and/or system pre-deployment calibration protocols across different PAM instruments to ensure quantitative data compatibility and comparability across different PAM platforms.
- Develop common data processing workflows and reporting metrics across the program, in consultation with BOEM.
- Incorporate goals to design experimental data collection in a way that allows benchmarking modeling results for the GOM against newly collected data through the program for different propagation scenarios (range-independent, range-dependent, canyon propagation, etc.).
- Recommend appropriate PAM methodologies for different GOM regions (e.g., shallow water, continental slope, deep-water, industrially active) and for different study objectives (e.g., baseline noise measurements, anthropogenic soundscapes, species abundance, habitat use, etc.). Consider an ecosystem-based approach to PAM data gathering that would allow biological soundscapes relevant to species that have not been extensively studied in the GOM, such as fish and invertebrates.
- Make all data available to the stakeholders and public through NOAA, the GOM Research Initiative Information and Data Cooperative, and other data sharing databases after analyzing and vetting the data and data sharing databases.
- At a later date, support further effort into the comprehensive review of PAM information available for the GOM to include development and implementation of a scientific advisory group.
- Develop and implement protocols to determine acoustic detection ranges and false positive and negative rates within these ranges.
- Develop and implement protocols to determine acoustic sound production rates for species of interest.

1. Introduction

1.1 Study Background

Available and relevant literature and data on previous and ongoing passive acoustic monitoring in the Gulf of Mexico (GOM) were compiled. This information was reviewed to characterize potential sound sources and their distribution in the GOM and to identify existing methodologies for acoustic source detection, localization, tracking, and classification. This review was conducted under the Bureau of Ocean Energy Management's (BOEM) Passive Acoustic Monitoring (PAM) Program for the Northern GOM.

The primary objective of the program is to design and implement a multi-year acoustic data collection and analysis plan to characterize baseline noise level across the GOM. There is considerable concern about the potential effects of anthropogenic noise on marine mammals, sea turtles, and fish. Worldwide, the ocean becomes a very noisy habitat for marine animals when ambient noise levels rise as a result of anthropogenic activities and global warming. Cetaceans rely on sound as a primary sense for vital life functions, so increased noise levels may mask important sounds (including conspecific vocalizations), temporary threshold shift in an animal auditory system, and to direct permanent physical damage, including death. As ambient noise levels have increased in some areas, cetaceans have shifted the frequency band in which they vocalize in order to adapt to communication in a noisy environment (Parks et al. 2007).

In 2006, the National Oceanic and Atmospheric Administration (NOAA) conducted a National Passive Acoustics Workshop (Van Parijs et al. 2007), which recognized the need for a passive acoustic oceans observing system worldwide. This need is perhaps especially acute in places like the GOM, which is extensively industrialized. Cetaceans in the GOM inhabit a highly industrialized environment with multiple anthropogenic acoustic inputs including shipping, oil and gas activities, and military operations. Though a national program is still not in place, smaller scale PAM programs exist in some areas (e.g., Bering Sea, Stellwagen Bank National Marine Sanctuary). These programs have proven effective in measuring ambient noise levels, detecting marine mammal presence, and monitoring anthropogenic noise (e.g., seismic, vessel noise).

The Gulf of Mexico Coastal Ocean Observing System (GCOOS) was established in 2005 under the Global Ocean Observing System (GOOS) and the US Integrated Ocean Observing System (IOOS). GCOOS works under a member/partnership model, with data collected by partners (e.g., data from oceanographic buoys) that then stream the data to GCOOS. The GCOOS data portal is located online[1]; GCOOS can be a repository for data products and modeling (Kirkpatrick 2015).

Of additional interest for the GOM is the Southeast Regional Acoustics Consortium (SEAC), a working group initiated in 2012 that brings together academic institutions, federal and regional fisheries and environmental management agencies, and private industry that conduct acoustics research in the coastal environments of the US from North Carolina to Texas and the US Caribbean.

A recent Ocean Conservancy report (Love et al. 2015) provided a gap analysis for existing GOM monitoring programs for species and habitats negatively impacted by the 2010 *Deepwater Horizon* oil spill. The report highlighted the rare and disjointed nature of offshore monitoring and advocated for moving towards a Gulf-wide ecosystem monitoring network. In particular, monitoring was documented as limited and fragmented for marine mammals and fish and often absent for sea turtles. The need for such network and baseline data gathering becomes even more critical with several large coastal restoration projects underway in the Gulf Coast region. The coastal habitat alterations may also negatively impact deep water ecosystems (e.g., Bishop et al. 2017; Heery et al. 2017).

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[1] See the Gulf of Mexico Coastal Ocean Observing System (GCOOS) portal: http://data.gcoos.org.

Data on ambient noise levels in the GOM are extremely limited. Other than some short-term recordings associated with previous studies and recent PAM work done as part of the Natural Resource Damage Assessment for the *Deepwater Horizon* oil spill event, few data exist (Hildebrand et al. 2015a; Estabrook et al. 2016; Snyder 2007, 2009; Newcomb et al. 2002, 2007, 2009).

Noise impacts to protected species (primarily cetaceans) may occur as a result of oil and gas exploration companies undertaking activities (e.g., seismic surveys, platform decommissioning, drilling, vessel noise, etc.) licensed by BOEM and the Bureau of Safety and Environmental Enforcement (BSEE); however, characterizing the impact and trends is difficult without comprehensive baseline data on ambient noise environment (or soundscape) in the GOM. BOEM and BSEE are required to assess potential impacts on protected species, specifically under the Marine Mammal Protection Act, Endangered Species Act, and the National Environmental Policy Act to assist and guide their decision-making. The future BOEM Marine Mammal Protection Act rulemaking for seismic activities in the GOM will have a monitoring requirement associated with it, and data collection on ambient noise and on noise associated with seismic activities. In short, there is an urgent need to implement a systematic and comprehensive acoustic data collection effort in the Gulf. The BOEM PAM Program for the Northern GOM is intended to meet this need.

1.2 Literature Review Goals, Purposes, and Objectives

The objective of the literature synthesis was to collect and review published literature and data about previous and ongoing projects measuring underwater sound in the GOM for the following purposes:

1. Characterize potential sound sources in the GOM and further define the soundscape.
2. Summarize the state of current knowledge on GOM baseline acoustic noise levels.
3. Investigate existing methodologies that have been employed for sound source detection, localization, tracking, and classification (including species vocalizations) for marine mammals.
4. Identify by spatial mapping previous and current study locations.
5. Identify the most effective field methodologies and protocols for measuring the acoustic environment in the GOM.

Observations, findings, and recommendations from the literature synthesis will guide the development of an experimental design for the multi-year acoustic data collection plan to be implemented under the BOEM PAM Program for the Northern GOM.

1.3 Report Organization

This literature synthesis report is divided into six chapters. Chapter 1 is an introduction. Chapter 2 presents the approach, including the boundaries and characteristics of the study area, and the literature and data search methods. Chapter 3 provides an overview of the past and current projects that involve PAM in the GOM. The information includes the locations of PAM projects and explanations of the various types of equipment and research conducted in this area. Chapter 4 provides the current state of knowledge on physical and biological ambient noise and on marine mammal acoustics. Chapter 5 provides recommendations to be considered in developing the experimental design for implementation of the BOEM PAM Program for the Northern GOM. Chapter 6 lists all the references cited in this document. Appendix 1 gives a list of keywords used in the search.

2. Approach

2.1 Identification of Study Area

The Gulf of Mexico (GOM) is a semi-enclosed ocean basin that narrowly connects to the Atlantic Ocean through the opening between Cuba and the Yucatán Peninsula and the Florida Straits. The presence of the Loop Current and warm water eddies separated from the Loop current are dominant oceanographic features of the GOM that considerably influence the Gulf ecosystem/seascape. To assess the information available on passive acoustic monitoring (PAM) in the GOM, a literature search and review was conducted across BOEM's Eastern, Central, and Western planning areas in the GOM (**Figure 1**).

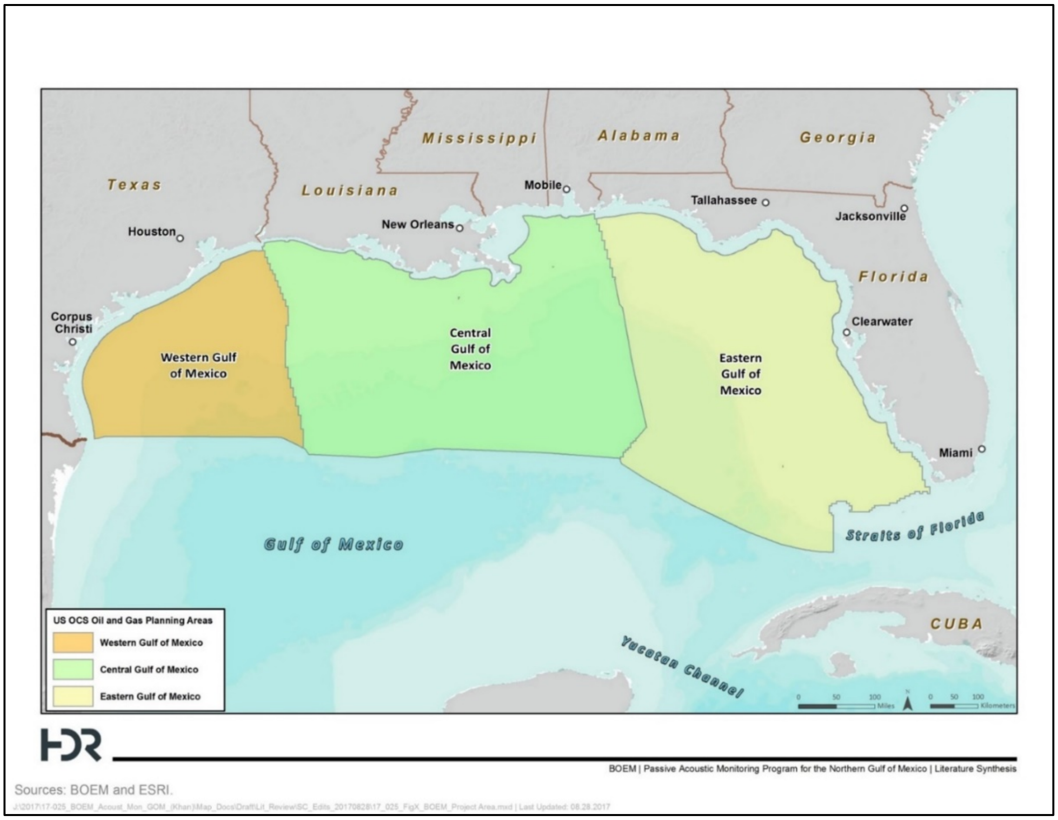
The Western Planning Area lies 17 kilometers (9 nautical miles) offshore of Texas and extends to the United States (US) Exclusive Economic Zone (EEZ), which is the jurisdictional limit over the continental shelf. The EEZ limit is 370 kilometers (200 nautical miles) from the US. The Central Planning Area lies offshore of Alabama, Mississippi, and Louisiana from 6 kilometers (3 nautical miles) to the US EEZ. The Eastern Planning Area lies 17 kilometers (9 nautical miles) offshore of the Gulf Coast of Florida and extends to the EEZ. The water depths in the Western, Eastern, and Central Planning Areas extend up to approximately 3,346 meters (10,978 feet) (BOEM 2013).

2.1.1 Oceanographic and Other Features of the Study Area

In addition to a sound source characteristics, propagation of underwater sound depends upon many environmental factors, such as water depth, bathymetry, currents, salinity, temperature, and sediment composition. All have a part in the transmission of sound and formation of soundscapes. Therefore, a short description of the relevant features of the GOM is provided in the following paragraphs. It also is important to keep in mind that the GOM adjoins North America, which is one of the most industrially developed continents in the world. Thus, there is high magnitude and extent of anthropogenic underwater noise in the GOM.

The GOM is distinguished by an enormous river delta, limestone islands, expansive and relatively flat continental-shelf areas, submarine canyons, steep escarpments, sea fans, and a central deep, flat basin where bottom depths exceed 3,700 meters (12,139 feet). Bottom depths in the GOM range from <10 meters (<33 feet) in the Florida Keys to the maximum depth (3,700 meters [12,139 feet]) over the Sigsbee Abyssal Plain. In the GOM, continental shelf waters (i.e., less than 200 meters (656 feet) in depth) make up approximately 35 percent of the Gulf. Sediments here are made up of sand, silt, and clay. The shelf is quite broad in some places (e.g., offshore west Florida, Texas-Louisiana coast, and Campeche) and narrowly restricted in other places (such as near the mouth of the Mississippi River and offshore eastern Mexico).

The area in the US where deep water in the GOM comes closest to shore is off the Mississippi River Delta where deep waters are within 10 kilometers (5.4 nautical miles) of shore. Deep oceanic waters include only 25 percent of the GOM and are located mostly in the mid-western GOM. At the shelf break, the seafloor begins to slope steeply towards the abyssal plain of the deep GOM, often terminating in a near-vertical scarp or cliff-like formation that extends on down to the bottom. This region is called the continental slope and includes waters in the 200 to 3,000-meter (656- to 9,843-foot) range and covers 40 percent of the ocean basin. The area slopes steeply, and contains deep canyons, knolls and banks particularly in the western portion of the region. Sediments are generally calcareous here and came from shells of marine organisms.



Sources: BOEM and ESRI.

Figure 1. Study area for BOEM literature review of passive acoustic monitoring (PAM) work in the Gulf of Mexico.

Two major rivers discharge freshwater into the GOM: the Mississippi River in the southern US and the Rio Grande on the Mexico-US border. Warm, tropical water enters the GOM through the Yucatan Strait, circulates as the Loop Current, and then exits through the Florida Strait eventually forming the Gulf Stream. Portions of the Loop Current often break away forming eddies (also referred to as “rings” or “gyres”) which affect regional current patterns. The Loop Current and associated eddies (both anticyclonic and cyclonic) dominate the upper-layer circulation.

Seasonal variations in sea surface temperature (SST) occur uniformly across the GOM with maximum temperatures occurring in summer (July through September) and minimum temperatures occurring in mid-winter (February through March). Temperature differences between the eastern and western GOM are attributed to the influx of warm Caribbean waters through the Yucatan Channel, which dominates the SST in the Eastern GOM. Sea surface salinities in the Northern Gulf vary seasonally and are heavily influenced by outflow from the Mississippi River. In months with little freshwater input, the salinities along the coast range from 29 to 32 practical salinity units (psu or parts per thousand [ppt]). During the spring and summer when the freshwater input volume from the Mississippi and other rivers is high, a strong salinity gradient forms with salinities typically less than 20 psu (or ppt) in shelf waters. The mixed layer in the central, open GOM extends from 100 to 150 meters (328 to 492 feet) with salinities between 36.0 and 36.5 psu (or ppt).

Sound propagation in the marine environment is influenced by a variety of physical properties of the ocean, including temperature, salinity, sediment type, and pressure. Influences on sound in the GOM include, but are not limited to, the following:

- Surface sound ducts, or channels, occur when the sound speed increases with depth below the surface, leading to a positive sound speed gradient, forming the local minimum of the sound speed near the surface. This can occur in the mixed layer when surface waters are cooler than underlying waters. Sounds propagating in these channels are refracted upward and can become partially trapped near the surface, leading to enhanced sound propagation and higher near-surface sound levels. A weak surface sound channel is present during some months of the year in the GOM, with variations in the gradient and depth of the surface channel based on the month and zone (Zeddies et al. 2015). Acoustic tags placed on sperm whales (*Physeter macrocephalus*) in the GOM, that were part of controlled exposure experiments (CEEs), received peak pressures and sound exposure levels (SELs) that did not necessarily decrease monotonically as the distance between the whale and the seismic array increased (DeRuiter et al. 2013). The authors identified that selective high-frequency content (>500 Hz) was trapped near the surface when a surface duct occurred.

- As noted by Snyder (2007), energy from distant ships located in shallow water (e.g., shelf regions) may be able to travel long distances with little attenuation if the energy is trapped in the deep sound channel (or the deep ocean region where speed of sound decreases to a minimum value based on depth and then speed of sound increases due to pressure). The amount of noise received will depend on a variety of factors, including the slope of the shelf, the bottom properties of the slope, and the near-surface characteristics of the shelf waters.
- Noise enhancement can occur in frontal regions, such as across the Loop Current (refer to Urick 1984). The SST is warmer to the north of the Loop Current and colder to the south, which causes the surface sound speed to be higher to the north.
- Variations in oceanographic features may lead to changes in travel time and propagation paths for sounds produced underwater (e.g., Mellberg et al. 1990, 1991). For example, Rankin (1999) reported that preliminary studies of changes in the sound speed across the hydrographic features present in the GOMreport, “Cetaceans, sea turtles and seabirds in the Northern Gulf of Mexico: distribution, abundance and habitat associations” (GulfCet) II, (Davis et al. 2000) study area suggest that warm core rings may essentially offer a “shadowing effect” for sound created outside of the feature. In cold core rings, animals at depth and in surface waters may be exposed to increased levels of sound, while animals in a warm core ring may realize a lowered overall intensity level.

There are a number of significant features and important regions in the GOM. For instance, De Soto Canyon lies on the relatively flat continental slope. This canyon starts in approximately 450 meters (1,476 feet) of water and ends in approximately 950 meters (3,117 feet); it is a transition area where the sediments of the Mississippi River Delta meet the calcareous deposits of the easternmost GOM. De Soto Canyon is an area with a significant amount of hardbottom area. As relevant to this report, the area has been identified as important to marine mammals. National Oceanic and Atmospheric Administration (NOAA)’s Cetaceans and Sound Mapping (CetSound[2]) working group was formed to evaluate the impacts of anthropogenic noise on cetacean species and to develop geospatial tools to understand the long-term human activities that contribute to underwater noise throughout US waters (NOAA n.d.). Biologically Important Areas (BIAs) have been developed through this working group; CetSound identified one BIA that directly overlaps with the study area. The BIA identified for Bryde’s whales (*Balaenoptera edeni*) has an area of 23,559 square kilometers (9,096 square miles) (LaBrecque et al. 2015) and extends along the northern reaches of the West Florida Escarpment. The Bryde’s whale BIA begins near the De Soto Canyon area offshore from Pensacola, Florida, in the 100-meter (328-foot) depth range, and it extends into the 400-meter (1,312-foot) depth to offshore areas of Tampa, Florida. The area supports a small resident population of Bryde’s whales (Rosel et al. 2016), that was listed in May 2019 as endangered under the Endangered Species Act (84 Federal Register 15446-15488).

Mississippi Canyon is another feature that is well-studied and known in the GOM. The Mississippi Canyon begins at the 200-meter (656-foot) isobaths and is located at the tip of the Mississippi Fan. This location has been a productive area for oil and gas exploration.

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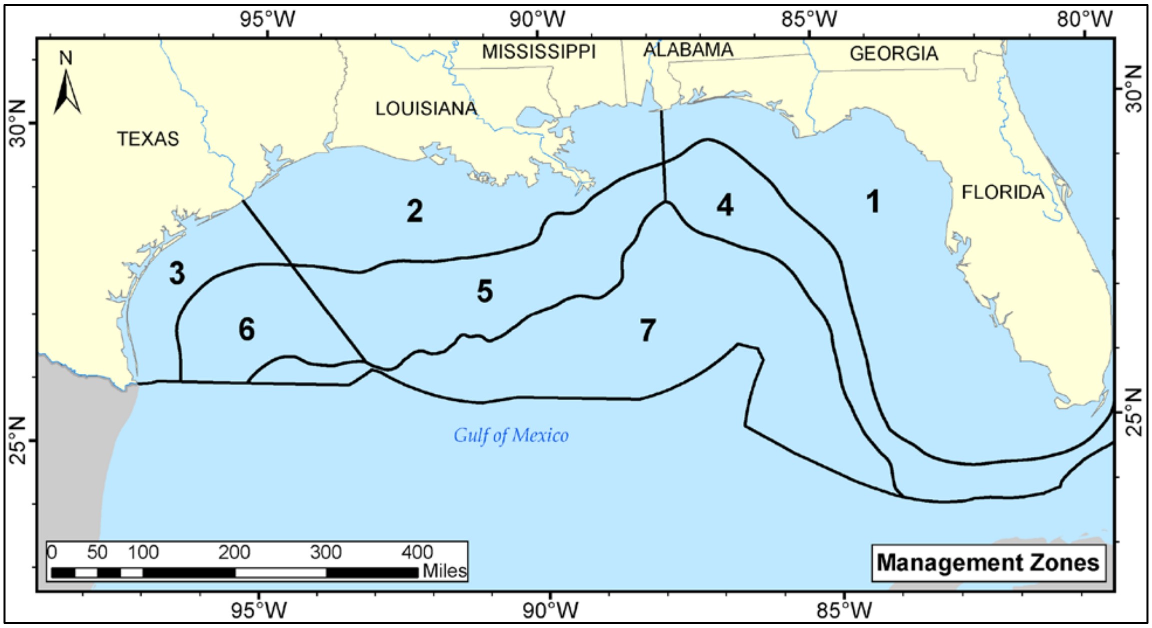
[2] NOAA’s CetSound: http://cetsound.noaa.gov/cetsound

Flower Garden Banks is located offshore of Texas and Louisiana. Designated to protect the unique coral reef system that occurs here, Flower Garden Banks includes East Flower Garden Bank, West Flower Garden Bank, and Stetson Bank. The area includes salt domes. The area is the only known site that supports species of *Acropora* in the GOM.

2.1.2 Study Area Acoustic Zones

Recently, the Northern GOM was partitioned into seven acoustic zones (**Figure 2**) for the purposes of preparing "take" estimates for the annual marine mammal acoustic exposure caused by introduction of underwater noise from geological and geophysical exploration activity in the GOM for years 2016 to 2025 (see BOEM 2016a). The selected zone boundaries, patterned to conform to BOEM's planning areas where possible, considered geospatial dependence of acoustic fields (i.e., sound propagation conditions as affected by physical properties of the project area) and marine mammal species distribution to create regions of optimized uniformity in both acoustic environment and animal density. This resulted in three shelf zones, 1–3, (25 to 200 meters [82 to 656 feet]); three slope zones, 4–6, (200 to 2,000 meters [656 to 6,562 feet]); and 1 deep zone, 7, (> 2,000 meters [>6,562 feet]).

Zeddies et al. (2015) noted that the size and shape of acoustic footprints from exploration surveys in the GOM are influenced by many parameters, with the strongest being bottom depth and seabed slope. Bottom depth influences marine mammal species distribution in the GOM in that there are distinctions from Shelf to Slope and from Slope to Deep. Maps in Appendix A of Zeddies et al. (2015) depict marine mammal distribution information from the Marine Geospatial Ecology Laboratory (Duke University) model (Roberts et al. 2016) and the subdivision depth boundary contours.



Source: BOEM (2016a)

Figure 2. Seven acoustic regions and representative model sites (zones) in the Gulf of Mexico.

2.2 Literature and Database Search Methods

The authors collected data through online databases and literature and the World Wide Web to gather information characterizing PAM projects in the GOM. The search focused on gathering a variety of literature types on biological and physical ambient noise levels in the GOM, on PAM projects focused upon marine mammals in the GOM, and on anthropogenic sound sources in the region. The authors focused on collecting information from the last 15 years of studies.

The following commercial databases, search tools, and email list servers were used in the search for data on PAM projects in the GOM: the Acoustical Society of America’s meeting abstracts database, BOEM’s Environmental Studies Program Information System, DataCite, Defense Technical Information Center, Google Scholar, MARMAM (Marine Mammals Research and Conservation Discussion) email list, and NOAA Central Library. Authors of this report also accessed private electronic libraries of HDR, Inc. and Azura, Limited Liability Company (LLC) staff members. Key search terms and phrases were used to conduct methodical queries of databases and the World Wide Web. The search included terms in all fields (title, abstract, etc.) referencing noise and/or sound, research method, marine mammal species of interest, specific BOEM planning areas and GOM features of interest, and/or specific researchers/institutions, funding sources, and monitoring programs.

This collaboration ensured a more complete list of terms was developed to capture all data and literature available on GOM PAM projects and sound sources. Examples of simple terms and phrases used in the search include the following:

“acoustic,” “ambient noise/sound,” “anthropogenic noise/sound,” “biological sound sources,” “detection,” “passive acoustic monitoring,” “Central Planning Area,” Eastern Planning Area,” “Western Planning Area,” “Deepwater Horizon,” “beaked whales,” “Bryde’s whales,” “cetaceans,” “dolphins,” “marine mammals,” “Risso’s dolphins,” “sperm whales,” and “whales.”

Authors of this report searched for information from a number of researchers and funders, including those individuals comprising the “Center for the Integrated Modeling and Analysis of the Gulf Ecosystem (C-IMAGE) institutions,” “CetSound,” “GOM Research Initiative,” “Littoral Acoustic Demonstration Center –Gulf Ecological Monitoring and Modeling (LADC GEMM),” “Natural Resource Damage Assessment partners,” and “Scripps Institution of Oceanography.”

This list merely is meant to provide examples of search terms and key words. Appendix 1 contains a comprehensive list of keywords.

Studies generally pertained specifically to PAM studies in the GOM. Some references on research methods and PAM studies that were consulted occurred outside the region because similar studies may be lacking for the GOM, but may be useful either to characterize PAM work in general and/or to provide suggestions on the future BOEM plan for PAM in the GOM. The literature search focused on published, peer-reviewed studies written in English and indexed in scientific databases. Relevant government and industry technical reports, websites, presentations, and conference proceedings were also reviewed. Individuals involved in PAM projects were contacted when necessary and requests were made for particular references and recent publications.

Online shared databases are becoming more common and more advanced with improvements in web applications and online storage capacities. However, the integration of PAM data into existing databases is challenging due to the large volume of data storage required for long-term, high-frequency recordings. Additional challenges include the extensive data processing required for raw PAM data, the metadata standards required to document information about PAM data collection, and the difficulties in determining the meaning of a PAM record compared to a visual sighting record, for example (Fujioka et al. 2014). Despite these challenges, several online databases made successful attempts to integrate PAM data, so that researchers can store, manage, and disseminate their data to the public. During the literature search, the authors conducted a concurrent search of data online and examined the availability of PAM data in large, publicly accessible databases.

3. Current and Past Passive Acoustic Monitoring (PAM) Projects in the Gulf of Mexico and Related Research Approaches

3.1 Basic Underwater Acoustic Terminology and Metrics

A variety of metrics are used to describe sounds, and these different metrics are not directly comparable. The most common term used to define underwater sound is sound pressure, which in underwater acoustics is expressed as a basic unit in Pascals. This measurement is easily measured with a hydrophone and expresses the pressure, velocity, amplitude and direction of particle movement when the sound wave propagates away from the source. The most common unit used to express sound pressure is the microPascal (μPa).

The frequency of sound is the number of waves that pass a given point per second, which is measured in hertz (Hz). Frequency is often expressed as low (less than 1 kilohertz [kHz]), medium (1 kHz to 10 kHz), and high (greater than 10 kHz).

Sounds are generally impulsive or non-impulsive. Impulsive sounds include those sounds related to the use of explosives, seismic airguns, and pile-driving strikes. Non-impulsive sounds or pure tone generally include examples such as sonar pings, vessel noise, and drilling noise.

Sound pressure (referenced as 1 μPa) is often used to characterize continuous sounds in term of risk of damage to marine animals, such as fish, turtles, and mammals. The root-mean-square (rms) sound pressure and peak sound pressure are the most commonly used sound pressure level (SPL) metrics (Popper et al. 2014). Peak sound pressure is often used to characterize impulsive sounds and is measured as the maximum absolute value of an instantaneous sound pressure during a specific time period. The sound exposure level (SEL) metric is an index of the total energy in a sound and is usually expressed in dB re 1 $\mu Pa^2 \cdot s$. This metric can be used to assess risk from exposure to multiple sound sources; therefore, it is also an index for accumulated sound energy (Popper et al. 2014).

To assess the exposure of marine mammals to anthropogenic sounds, the National Oceanic and Atmospheric Administration's (NOAA's) National Marine Fisheries Service (NMFS) recommends specific metrics for establishing acoustic thresholds and predicting impacts of sound sources on marine mammal hearing (NMFS 2016; NMFS 2018). NMFS includes both the Cumulative Sound Exposure Level (SEL_{cum}) and Peak Sound Pressure Level (PK) metrics in their recent technical guidance recommendations for determining permanent threshold shift (PTS) onset acoustic thresholds. The SEL_{cum} metric is typically normalized to a single sound exposure of one second and takes into account both received level and duration of exposure. This metric is applied to a single source to estimate impacts of exposure to an animal but is not considered appropriate for assessing exposures resulting from multiple activities/sources occurring within the same area or over the same time period (NMFS 2016).

In addition, the SEL_{cum} metric is not appropriate for assessing effects of impulsive sounds (e.g., seismic airguns, impact pile drivers) of short duration and high amplitude which can cause greater risk to the inner ear compared to non-impulsive sounds (e.g., tactical sonar, vibratory pile drivers). Therefore, NMFS recommends the use of the PK metric for impulsive sounds with PK thresholds considered unweighted and/or flat-weighted within the frequency band of a hearing group. Because NMFS considers dual metric acoustic thresholds for impulsive sounds, the onset of PTS is assumed to occur when either the SEL_{cum} or PK metric is exceeded (NMFS 2016). See Popper et al. (2014) for more information on frequency weighting and additional metrics.

3.2 Field Methods to Measure and Assess Ambient and Anthropogenic Underwater Noise Levels in the Gulf of Mexico

3.2.1 Autonomous Acoustic Instruments

PAM of ambient noise in the GOM has been ongoing since 1996, when the first generation of Naval Oceanographic Office Environmental Acoustic Recording System (EARS) buoys was deployed (Snyder 2007). In 2001, the Littoral Acoustic Demonstration Center (LADC), which currently operates as the Littoral Acoustic Demonstration Center–Gulf Ecological Monitoring and Modeling (LADC-GEMM) consortium, was formed to make environmental measurements, particularly on ambient noise and marine mammals, using these EARS buoys (Ioup et al. 2016).

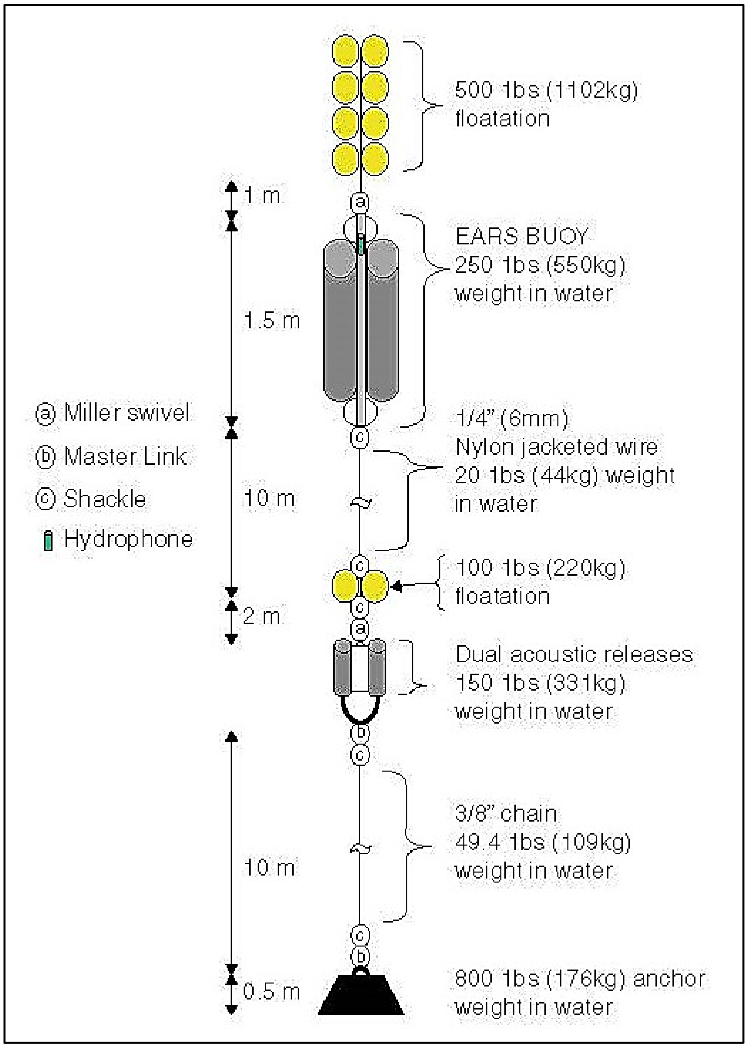
This consortium of scientists from universities and the US Navy has included representatives from the University of New Orleans, the University of Southern Mississippi, and the Naval Research Laboratory-Stennis Space Center; and the University of Louisiana at Lafayette, the Applied Research Laboratories at the University of Texas at Austin, and Oregon State University (Ioup et al. 2016). The consortium also collaborates with businesses such as Proteus Technologies, Limited Liability Company (LLC); R2Sonic, LLC; ASV; and Seiche Measurements Limited (Sidorovskaia and Li 2017). The LADC studies and additional monitoring and recording of ambient and anthropogenic noise in the GOM are summarized below.

3.2.1.1 Environmental Acoustic Recording System (EARS): Littoral Acoustic Demonstration Center (LADC) ambient noise studies in Mississippi Valley-Canyon region, 2001–2017

The LADC used EARS buoys to measure ambient noise and marine mammal sounds in the GOM in 2001, 2002, 2007, 2010, and 2015. They also used EARS to characterize seismic airgun array sounds in 2003 and 2007 in the Western GOM. Brief descriptions of these studies are provided below. EARS buoys were specifically developed for long-term recordings of ambient noise. The current Generation 2 EARS buoys can record one channel to 100 kHz or 4 channels to 25 kHz and are capable of sampling at rates up to 200 kHz (Ioup et al. 2016). The deployment design usually differs from other studies described here and allows receiving hydrophones to be placed in the water column at the pre-defined depths relevant to survey purporses. Each mooring consists of flotations, the EARS buoys, dual acoustic releases, and an anchor (**Figure 3**).

In 2001 (LADC 01), the LADC deployed three bottom-mounted EARS buoys in the Northern GOM in water depths of 600, 800, and 1,000 meters (1,969, 2,625, and 3,281 feet) along the continental slope (Newcomb et al. 2002). The hydrophones were placed 50 meters (164 feet) above the seafloor (Ioup et al. 2016). The EARS sampled at a rate of approximately 12 kHz and was capable of capturing sperm whale vocalizations (Newcomb et al. 2002; Paulos 2007). The 36 days of the deployment period, which was 18 July and 29 August 2001 overlapped with the Sperm Whale Acoustic Monitoring Program (SWAMP) shipboard surveys.

In 2002 LADC returned to the 2001 deployment area and re-deployed three EARS buoys in the Northern GOM in water depths ranging from 645 to 1,034 meters (2,116 to 3,392 feet) between 28 August and 23 October 2002 (Ioup et al. 2009, Newcomb et al. 2007). Buoys were moored 50 meters (164 feet) above the seafloor (Ioup et al. 2016). The sampling rate was approximately 12 kHz (Newcomb et al. 2007). This deployment overlapped with the second leg of sperm whale seismic studies (SWSS) that took place between 19 August and 15 September 2002, referred to as the “DTAG experiment” after the digital-recording acoustic tags (DTAGs) were used to obtain data on the movements and physiology of sperm whales.



Source: Ioup et al. (2016).

Figure 3. Schematic of components of an environmental acoustic recording system (EARS) mooring.

The goal of these multiple deployments has been to quantify short-term and long-term changes in broadband baseline noise levels in the Mississippi Canyon region in order to direct future mitigation measures to decrease potential impacts of anthropogenic acoustic pollution (Sidorovskaia and Li 2017) and study the impacts of oil spills on deep-diving marine mammals using PAM methods. In addition to bottom-mounted EARS buoys, the 2015 and 2017 (to be conducted) acoustic data were collected using autonomous surface vehicles (ASVs) with towed hydrophone arrays and gliders. The LADC deployed the first set of EARS (LADC 07) between July 6 and 16, 2007 (active recording period was July 6 through 14), in deep waters (approximately 1,500 meters [4,921 feet]) (Ackleh et al. 2012; Sidorovskaia and Li 2017). These two sites were only 17 and 37 kilometers (9 and 20 nautical miles) from what would become, in April 2010, the *Deepwater Horizon* oil spill site.

The hydrophones of the EARS were positioned approximately 500 meters (1,640 feet) above the seafloor to target feeding depth of beaked whales and recorded continuously for 12 days at a sampling rate of 192 kHz (Ackleh et al. 2012; Sidorovskaia and Li 2017). The LADC 2007 dataset also provided first acoustic recordings of the GOM beaked whales. After the spill, the LADC deployed the second set of EARS (LADC 10) at the same sites, and they recorded between 10 and 24 September 2010. The third set of EARS were also deployed at the same sites and recorded between 26 June and 22 October 2015. LADC-GEMM is scheduled to operate three platforms in the region during summer-fall 2017.

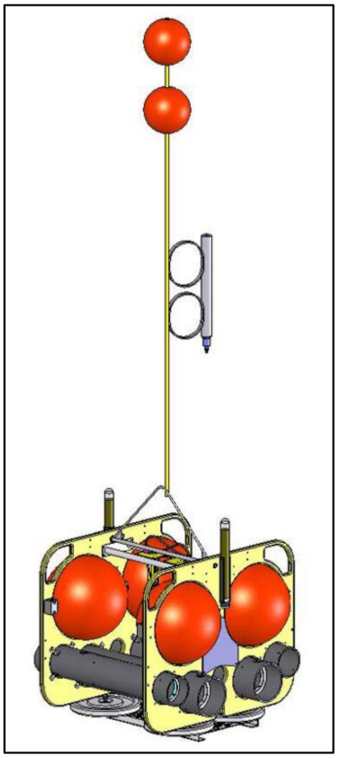
3.2.1.2 High-frequency acoustic recording package (HARP): ambient noise in the Gulf of Mexico, 2010–2013

To assess the ambient noise in the GOM during and after the *Deepwater Horizon* oil spill, bottom-mounted high-frequency recording packages (HARPs) were deployed in the Northern and Eastern GOM between May 2010 and October 2013 (Wiggins et al. 2016).

Similar to EARS, a HARP was developed in response to the need for an instrument capable of recording long-term, high bandwidth acoustic data by researchers from Scripps Institution of Oceanography (Wiggins and Hildebrand 2007). These acoustic recorders consist of a hydrophone, data logger, battery power supply, ballast weight, acoustic release system, and flotation and have sampling rates up to 200 kHz. HARPs can be mounted to the seafloor or attached to devices such as Wave Gliders (see **Section 3.2.2**). The hydrophone is suspended 10 meters (33 feet) from the seafloor (Hildebrand et al. 2015b, Merkens 2013) (**Figure 4**).

The maximum deployment depth is approximately 7,000 meters (22,966 feet) (Sousa-Lima et al. 2013). Bottom-mounted HARPs use EdgeTech acoustic releases which contain an electronic board and International Transducer Corporation transducer to receive acoustic commands from a support ship and then power a motor-activated release of the ballast weights. Because the HARP system is capable of recording mid- to high-frequency sound, it can record acoustic data from a variety of sources such as baleen and toothed whales, pinnipeds, sirenians, fish, vessels, seismic surveys, wind, and rain (Wiggins and Hildebrand 2007).

The GOM HARPs single deployment periods were for 2 to 9 months and sampled continuously at 200 kHz. The five deployment locations included three deep-water sites and two shallow-water sites. The deep sites ranged from 980 to 1,300 meters (3,215 to 4,265 feet) and were located in Green Canyon, Mississippi Canyon, and De Soto Canyon. The shallow sites were in Main Pass and Dry Tortugas at 90 and 260 meters (295 and 853 feet), respectively. Ambient noise recordings were calibrated and processed to produce monthly average noise spectral levels time series (Wiggins et al. 2016)[3].



Source: Merkens (2013).

Figure 4. Schematic of a high-frequency acoustic recording package (HARP).

3.2.1.3 Marine autonomous recording units (MARUs): anthropogenic noise across the Northeastern Gulf of Mexico shelf ecosystem, 2010–2012

Cornell conducted this post *Deepwater Horizon* oil spill study to record ambient noise in the northeastern GOM and identify major anthropogenic and abiotic noise contributors (Estabrook et al. 2016). Between western Louisiana and the West Florida shelf break, researchers deployed bottom-mounted marine autonomous recording units (MARUs) (Calupca et al. 2000) at seven sites between 39 and 461 kilometers [21 and 249 nautical miles] apart and ranging in depth from 250 to 1,370 meters (820 to 4,495 feet). Near year-round deployments allowed for acoustic coverage between July 2010 and February 2012, resulting in 79,440 hours of recordings. Most of the MARUs recorded using duty-cycles with sampling rates of 8 and 20 kilohertz (kHz); one low-frequency MARU was deployed three times and recorded continuously at sampling rates of 2 and 5 kHz (Estabrook et al. 2016).

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[3] These spectral data are available for download at: https://data.gulfresearchinitiative.org/data/R4.x267.180:0009.

MARUs, also known as “pop-ups,” are bottom-mounted autonomous recording buoys developed in the late 1990s by the Bioacoustics Research Program at the Cornell Laboratory of Ornithology (Calupca et al. 2000, **Figure 5**). MARUs used in this study consisted of a hydrophone, an 80-gigabyte hard drive, and a microprocessor.[4] They are battery-powered and float a few feet above the seafloor by a cable attached to an anchor. MARUs include an acoustic communication system which allows researchers to beam an acoustic signal into the water when they are ready to retrieve the unit.

The MARU hears the signal, severs its attachment to the anchor, and pops up to the surface for retrieval (Calupca et al. 2000). MARUs can be set for low or high frequency recordings are a capable of a maximum sampling rate of 64 kHz. They also can be set to operate continuously or on a set schedule (duty cycle). Maximum deployment depth is between 2,500 meters (8,202 feet) (acoustic release dependent) and 6,000 meters (19,685 feet) (on moorings) (Sousa-Lima et al. 2013).

Source: Rice et al. (2014b).

Figure 5. External and internal views of a marine autonomous recording unit (MARU).

3.2.1.4 EARS: source characterization study, 2007

From 2 September through 22 September 2007, LADC conducted this study to characterize the full three-dimensional acoustic field of the seimic airgun array in the northwestern GOM (Newcomb et al. 2009). Acoustic recording equipment for this study consisted of EARS moored array with Generation 2 four-channel EARS buoys (each channel measuring up to 25 kHz) and a total of 48 hydrophones with 16 hydrophones on the mid-water column bottom-moored array and 8 on the deeper (1,500-meter [4,921-foot]) bottom-moored array (Newcomb et al. 2009).

3.2.1.5 EARS: long-term ambient noise statistics in the Gulf of Mexico, 2004–2005

This study involved deployments of bottom-moored EARS buoys approximately 294 kilometers (159 nautical miles) south of Panama City, Florida, near a major shipping lane (Snyder 2007). The Naval Oceanographic Office deployed a total of seven buoys in water depths of 3,200 meters (10,499 feet) such that each hydrophone was positioned 265 meters (869 feet) above the sea floor. Sampling rate was 2,500 Hz with a useful bandwidth of 10 to 1,000 Hz (Snyder 2007, 2009) for ambient noise characterization.

3.2.1.6 Noise level effects on manatee habitat use, 2003–2004

To assess the affects of ambient and anthropogenic noise on West Indian manatee (*Trichechus manatus*) use of foraging habitat, PAM was conducted in two manatee habitats (grassbeds and dredged habitats) in Sarasota Bay, Florida, from April to September in 2003 and 2004 (Miksis-Olds et al. 2007b). Two different PAM methods were used. In 2003, recordings were made using a HTI-99-HF hydrophone with built-in preamplifier. The sampling rate was 200 kHz for all recordings. In 2004, ambient noise was recorded using a passive acoustic listening (PAL) buoy deployed for 3 to 4 days at each site in order to

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[4] The Cornell Lab of Ornithology: http://www.listenforwhales.org/page.aspx?pid=456

provide better sampling of diurnal noise patterns. This bottom-mounted system was duty-cycled at 10-minute intervals and had a low-noise broadband hydrophone (100 Hz to 50 kHz) (Miksis-Olds et al. 2007b).

3.2.1.7 EARS: source characterization study, 2003

The LADC conducted an acoustic characterization study for a 21-element marine seismic exploration airgun array to investigate the potential impacts on marine mammals and fish and predict the exposure levels for future seismic surveys in other areas (Tashmukhambetov et al. 2008). The LADC deployed two single-channel EARS (25-kHz bandwidth) near Green Canyon during June 2003. The hydrophones were approximately 250 meters (820 feet) from the seafloor in a water depth of approximately 990 meters (3,248 feet).

3.2.1.8 PAM studies to detect, localize, and characterize marine mammals in the Gulf of Mexico

A variety of methods have been used to detect, localize, and characterize marine mammal sounds in the GOM. These methods have included the use of data collected by fixed acoustic recorders and/or systems and by mobile recorders that may be remotely controlled or towed. Mobile platforms have not been proven to be suitable for studying baseline ambient noise levels but have been successfully used to study marine mammals in the GOM. Relevant mobile platforms are described in this section (the bottom-moored platforms were introduced in **Section 3.1**) along with brief summaries of the study objectives.

3.2.2 Fixed Autonomous Acoustic Recording Devices

3.2.2.1 High-frequency acoustic recording package

3.2.2.1.1 HARP population densities, 2010–present

The Scripps Institution of Oceanography team used PAM data recorded from HARPs in the Northern and Eastern GOM to assess marine mammal populations after the *Deepwater Horizon* oil spill (Baumann-Pickering et al. 2013, Frasier 2015, Frasier et al. 2016, Hildebrand et al. 2015b). Three HARPs were deployed between 980 and 1,320 meters (3,215 and 4,331 feet) depths in Green Canyon and Mississippi Canyon in the Northern GOM and near the Dry Tortugas in the Eastern GOM (Hildebrand et al. 2015b). Two HARPs were deployed on the continental shelf in shallow waters near Main Pass and De Soto Canyon. At each site, the HARPs recorded continuously at a sampling rate of 200 kHz for two to nine months per deployment since 16 May 2010 (Hildebrand et al. 2015b). Continuous acoustic sampling is ongoing at five sites in the GOM as of the time of finalization for this report[5]. See **Section 3.2** for more information on methods used to measure and assess ambient and anthropogenic underwater noise levels. See **Section 4.2** for a summary of beaked whale and delphinid density estimates generated from these PAM data.

3.2.2.1.2 Assessing impacts of *Deepwater Horizon* on large whale species, 2010–2012

As part of the *Deepwater Horizon* oil spill assessment, 22 MARUs were deployed in the northeastern GOM between 16 June and 15 October 2010 and from 15 November 2011 to 29 February 2012 along the continental slope from Louisiana to Florida (Clark 2015, Rice et al. 2014a, Rice et al. 2015, Rice et al. 2014b). MARUs were deployed in the same area where previous visual surveys had observed Bryde's whales and sperm whales. MARUs were anchored at depths between 231 and 1,370 meters (757 and 4,494 feet), and the 22 deployment sites were 39 to 241 kilometers (21 to 130 NM) apart (Rice et al. 2014b). Most of the MARUs were set to record high frequencies; the high-frequency MARUs sampling rate was 8 or 20 kHz, while the low-frequency sampling rate was set to 2,000 Hz. To aid in density estimations of sperm and Bryde's whales, the last deployment included two arrays, each deployed in an area with high probability of sperm whale or Bryde's whale occurrence. The sperm whale array consisted of four high-frequency MARUs recording from 14 November 2011 through 13 December 2011. The

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[5] Dr. John Hildebrand, Scripps Institution of Oceanography, confirmed the HARP study in GOM is ongoing.

Bryde’s whale array included four low-frequency MARUs and recorded from 15 November 2011 through 29 February 2012 (Rice et al. 2014b).

3.2.2.1.3 HARP Bryde’s whale study, 2010–2011

To identify Bryde’s whale calls in the GOM, HARPs were used in conjunction with vessel-based recordings via a towed array and sonobuoys during the 2011 NMFS Southeast Fisheries Science Center’s (SEFSC’s) Atlantic Marine Assessment Program for Protected Species (AMAPPS) survey (NEFSC and SEFSC 2012, Širović et al. 2014). The sonobuoys and array were deployed from the NOAA Ship *Gordon Gunter* during this line transect survey following the 200-meter (656-foot) isobath from the southeastern edge of the GOM to Pascagoula, Mississippi between 28 July and 1 August 2011 (Širović et al. 2014).

Three HARPs provided long-term recordings in the Northern and Southeastern GOM: (1) Main Pass HARP (north-central GOM) deployed 29 June to 29 August 2010, 2 November 2010 to 19 February 2011, 20 March to 14 April 2011, and 2 May to 21 June 2011; (2) De Soto Canyon HARP (Northeastern GOM) deployed from 21 October 2010 to 17 January 2011 and 21 March to 6 July 2011; and (3) Dry Tortugas HARP (Southeastern GOM) deployed 20 July to 26 October 2010, 3 March to 15 May 2011, and 12 July to 14 November 2011. Depths ranged from 90 meters (295 feet) at Main Pass to 1,320 meters (4,331 feet) at Dry Tortugas. The sampling rate of all HARPs was 200 kHz, but the data were decimated to a 2-kHz rate for analysis (Širović et al. 2014).

3.2.2.2 Digital spectrogram recorders

Digital spectrogram (DSG) recorders are a type of autonomous acoustic recorder designed and manufactured by Loggerhead Instruments (Sarasota, Florida; **Figure 6**). Specifically referred to as the DSG-ST, these recorders are designed for long-term deployments of hundreds of days depending on the desired duty cycle and sampling rate (up to 288 kHz). They are also said to be the lowest power acoustic recorder on the market. The housings are rated from 300 meters (984 feet) depths (polyvinyl chloride) to 3,000 meters (9,843 feet) depths (aluminum).[6]

Figure 6. Image of a digital spectrogram recorder.

(Loggerhead Instruments, DSC-ST).

3.2.2.2.1 Dolphin distribution on the West Florida Shelf, 2008–2010

DSG recorders (DSG recorders, Loggerhead Instruments, Sarasota, Florida) were used in conjunction with visual surveys to determine the seasonal and spatial distribution of dolphins on the West Florida Shelf (Simard 2012, Simard et al. 2015). These recorders were deployed at 19 sites from June through September 2008. Spaced 25 kilometers (13.5 nautical miles) apart, the recorders formed a grid pattern between the shoreline and the 30-meter (98-foot) isobath.

During the second deployment from June 2009 through June 2010, the recorders were deployed at 63 stations in a grid pattern with 20-kilometer (11-nautical mile) spacing out to the 100-meter (328-foot) isobath. The sampling rate was set to 50 kHz for the first deployment and 37 kHz for the second deployment. Because this study was targeting high-frequency sounds (e.g., dolphin echolocation clicks above 130 kHz), the chosen sampling rates and duty cycles were a balance between sufficient recordings of high-frequency sounds and the digital memory constraints during long deployments (Simard et al. 2015).

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[6] Loggerhead Instruments, DSG-ST Specification Sheet: https://static1.squarespace.com/static/57cf673c414fb5a80f7adf1c/t/5845d15be4fcb5c4ed91593e/1480970594125/DSG-ST-SPEC-SHEET.pdf

3.2.3 Mobile Acoustic Recording Systems

Mobile acoustic recording systems move through the water column or along the surface and may be autonomous or towed.

3.2.3.1 Gliders

Marine gliders equipped with acoustic equipment offer a low-cost approach to studying marine mammal sounds (Mellinger 2015). They can cover large areas over long periods of time and can simultaneously record environmental data, including temperature, salinity, dissolved oxygen, nutrients, and currents. They are relatively easy to deploy and can send data when at the surface. They are also capable of near-real-time detections of marine mammal species of interest when equipped with a glider-resident detection and/or classification system (Mellinger 2015).

A hybrid sea-surface and underwater autonomous vehicle, the Wave Glider uses wave energy for propulsion and solar energy via panels to continuously charge the batteries used for powering control, navigation, communication, and scientific instrumentation payloads (Manley and Willcox 2010). A Wave Glider consists of a submerged glider and a surface float which is equipped with real-time communications that allow remote control of its path. It can accommodate a variety of payloads, including an acoustic Doppler current profiler (ADCP), acoustic modems, and HARP systems (Manley and Willcox 2010).

The Seaglider™ is trademarked by Konsberg Maritime AS; the Slocum is built by Webb Research Corporation, as discussed in their respective descriptions. Each glider is described in the following respective paragraphs and there may be overlapping information since they are based on the same type of technology.

A deep-diving autonomous vehicle, the Seaglider™, currently produced by Kongsberg Maritime AS, was developed in the 1990s by Applied Physics Laboratory at University of Washington and the University of Washington's School of Oceanography with funding from the US Navy's Office of Naval Research (**Figure 7**).[7] The Seaglider™ controls its buoyancy via an external "bladder," can control pitch and roll, and is capable of moving forward and steering without a propeller or movable rudder. When it surfaces, it connects to a remote base station via an iridium router based unique device identifier connectivity solution connection. The Seaglider™, used in the GOM, recorded at a sampling rate of 125 kHz (Sidorovskaia et al. 2015a).

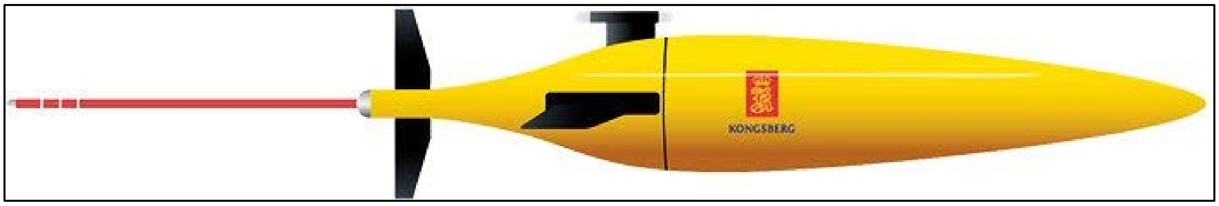

Figure 7. Seaglider™ autonomous underwater vehicle.

Another type of glider that has been used in PAM studies in the GOM is the Slocum glider (manufactured by Webb Research Corp) (**Figure 8**). This class of glider includes buoyancy-driven electric autonomous underwater vehicles (AUVs), 1.8 meters (5.9 feet) in length and shaped like a winged torpedo. Slocum gliders move horizontally and vertically and have long range and duration capabilities. The Slocum glider

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[7] Autonomous underwater vehicle, Seaglider: https://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/EC2FF8B58CA491A4C1257B870048C78C?OpenDocument

uses a pump that transfers mineral oil back and forth between the external and internal bladders. This changes the center of buoyancy of the instrument by which it either glides up or down.

The Slocum gliders then control the pitch and roll by shifting battery packs around. At the end of each dive the gliders come to the surface and transmit compressed science and/or engineering via Iridium calls. They can be deployed up to 18 months and can move horizontally up to 2 knots in speed. Slocum gliders can be outfitted with over 40 different types of sensors for sampling a wide variety of ocean conditions. Their operating depth range extends to 1,000 meters (3,280 feet).[8]

Figure 8. Slocum glider.

Image from http://www.teledynemarine.com/slocum-glider/ .

3.2.3.1.1 Littoral Acoustic Demonstration Center–Gulf Ecological Monitoring and Modeling (LADC-GEMM) glider studies in Mississippi Canyon, 2015

The LADC-GEMM (see **Section 3.2.1**) first deployed a Seaglider™ to record marine mammal sounds (Sidorovskaia et al. 2015a) and compare its performance in detecting different species with bottom-moored buoys and autonomous surface vehicles (ASVs). This study also included the simultaneous use of ASVs and EARS buoys (see **Sections 3.2.2**). The glider was programmed to move in a sawtooth pattern, diving down to 1,000 meters (3,280 feet) in depth and moving 4 kilometers per hour (~2 nautical miles per hour) horizontally.

Once deployed on 24 June 2015, it moved in a continuous clockwise triangle pattern around three waypoints (Sidorovskaia et al. 2015a). Attempts to recover the Seaglider™ on 4 August 2015 were unsuccessful; therefore, a Slocum Glider with two acoustic recording units was deployed on 12 October 2015 to collect relevant data for comparison over a 10-day period and complete the originally planned glider-portion of the study (Sidorovskaia et al. 2015b).

3.2.3.1.2 Wave Glider HARPs, 2011

In 2011, HARP electronics were installed in the surface floats of two Wave Gliders, and the hydrophones were towed behind each subsurface glider unit at approximately 8 meters (26 feet) in depth and used two sensors covering the band 10 Hz to 100 kHz (Hildebrand et al. 2013, Collins 1993).

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[8] Slocum G3 Glider: http://www.teledynemarine.com/slocum-glider/

3.2.3.2 Autonomous surface vehicles and/or unoccupied underwater vehicles (with towed arrays)

ASVs (**Figure 9**) have been used to collect marine mammal PAM data throughout the GOM. ASV Global specifically designs ASVs as low impact vehicles for marine observations and data collection.[9] For example, the C-Enduro class of ASV can effectively gather data from the marine environment while also generating power via solar panels and wind turbines (**Figures 9 and 10**). They can also be outfitted with a diesel generator or fuel cell if longer missions are required. In addition to PAM, ASVs are capable of water quality monitoring, water sampling, wave monitoring, acoustic transponder tracking (fish), current profiling, meteorological monitoring, and more.[9]

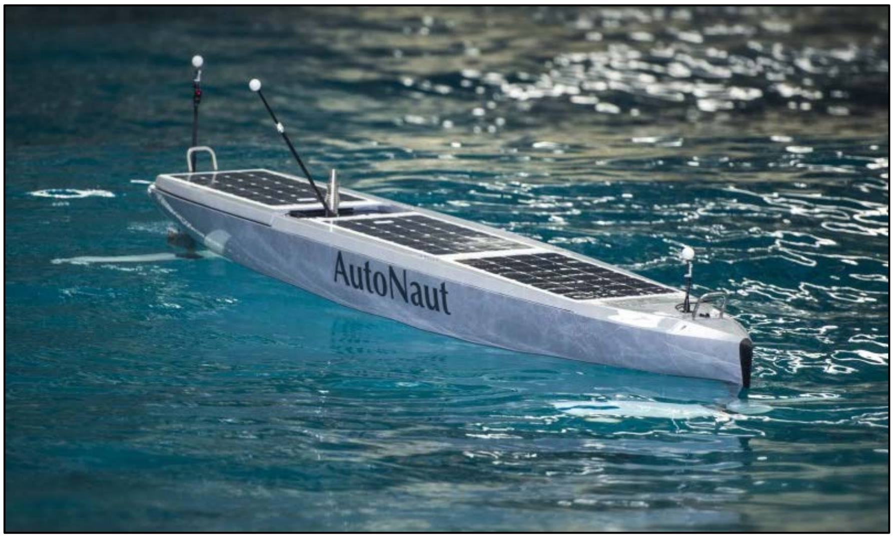

Figure 9. AutoNaut® with towed array–wave propelled autonomous surface vehicle.

Source: Sidorovskaia et al. (2015a).

Figure 10. ASVs C-Worker (left) and C-Enduro (right).

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[9] ASV Unmanned Marine Systems: https://www.asvglobal.com/marine-science/

With low self-noise ASVs coming to the market, they could potentially offer a low-cost solution for measuring soundscapes in real time. An ASV that could be deployed in the BOEM PAM Program for the Northern GOM is the recently developed AutoNaut® (**Figure 9**). This is a wave propelled unit and performs equally well on all headings including directly into wind and waves. The unit has zero emissions, and can roam the oceans for very long periods, transmitting data by satellite to shore. This extreme endurance coupled with a unique solution to the speed-payload-power balance for unmanned surface vessels (USVs) offers great new potential to all engaged in oceanic monitoring and surveillance.

3.3.2.1 ASV-towed arrays, LADC-GEMM PAM studies in Mississippi Canyon, 2015

As part of the LADC-GEMM consortium studies on the long-term impact of the *Deepwater Horizon* oil spill on deep-diving marine mammal populations, Autonomous Surface Vehicles, LLC provided two ASVs fitted with towed hydrophone arrays to record marine mammal sounds in the vicinity of the spill between 23 June and 2 July 2015 (Dyer et al. 2015; Sidorovskaia et al. 2015a; Ziegwied et al. 2016). The ASV C-Enduro™ is a 4.2-meter (13.8-foot) catamaran that is powered via solar panels, a wind turbine, and a diesel generator with two electric engines. It can cruise at 3 knots and be deployed up to 90 days. During this study, the C-Enduro™ towed a 55-meter (180-foot) two-element array.

The ASV C-Worker™ is 6 meter (20 feet) long, has an average speed of 4 knots, and can be deployed up to 30 days. It houses a fully redundant power propulsion and communication system and can integrate multiple offshore payloads. For this study, the C-Worker™ towed a 220-meter (722-foot), two-element array. Acoustic data were recorded as the ASVs were under autonomous power. Data were collected at a sampling rate of 500 kHz along with concurrent conductivity-temperature-depth and global positioning system data. The PAM systems were configured to detect a variety of species with vocalizations ranging from 20 to 160 kHz (Dyer et al. 2015, Ziegwied et al. 2016)[10].

3.2.3.3 PAM arrays towed from vessels

3.2.3.3.1 NMFS-SEFSC Shipboard Surveys, 2012–2016

As noted earlier, NMFS-SEFSC has conducted several recent shipboard surveys in the GOM aboard the NOAA Ship *Gordon Gunter*. These surveys include visual observations and PAM via a towed hydrophone array.

More recent PAM efforts by the NMFS SEFSC have targeted the Bryde’s whale population in the Northeastern GOM. For example, in September 2015 a female Bryde’s whale was tagged with an acoustic and kinematic data-logging, suction-cup tag in De Soto Canyon (Rosel et al. 2016). Also, with funding from NOAA Fisheries Office of Science and Technology Ocean Acoustics Program, in June 2016, NMFS SEFSC deployed five calibrated autonomous acoustic instruments along the 200-m isobath throughout the western GOM in predicted Bryde’s whale habitat. The objectives of this study are to collect passive acoustic data for use in investigations of 1) Bryde’s whale occurrence and distribution, and 2) ambient noise conditions in the western GOM. These units recorded through June 2017.

3.2.3.3.2 Airborne Mine Neutralization System Monitoring, 2011

HDR and Exploration and Production Environmental Services – RPS conducted monitoring surveys for protected species during an Airborne Mine Neutralization System live-inert explosives research, development, test, and evaluation event off the west coast of Florida (NSWC PCD 2012). Between 5 and 10 December 2011, the visual and acoustic monitoring efforts were conducted from a 50.3-meter (165-foot) research vessel within the Naval Surface Warfare Center Panama City Division (NSWC PCD) Study Area. The test area was approximately 22 kilometers (12 nautical miles) from shore in waters ranging from 20 to 40 meters (66 to 131 feet) in depth.

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[10] The data are available for download at: https://data.gulfresearchinitiative.org/data/R4.x261.233:0001.

Acoustic monitoring was conducted using a towed hydrophone array built by Seiche Measurements Limited, and PAMGUARD software (Gillespie 2008) was used during data collection and to initially classify recordings. The frequency range and sampling rate were 0 to 96 kHz and 48 to 192 kHz, respectively (NSWC PCD 2012). These acoustic detection data are available on Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP)[11] as part of the dataset "Acoustic Detections for Airborne Mine Neutralization System Passive Acoustic Monitoring in the NSWC PCD Study Area from December 2011."

3.2.3.3.3 NOAA *Pisces*: Protected Species Monitoring and Mitigation Measures during Trawling, 2011

Mid-water trawl sampling operations were conducted aboard the NOAA Ship *Pisces* during two cruises (21 June to 15 July and 7 to 29 September 2011) in the Northern GOM as part of NOAA's Natural Resource Damage Assessment following the *Deepwater Horizon* oil spill incident (Norris and Jacobsen 2015). Geo-Marine Inc. and Bio-Waves Inc. conducted visual observations and PAM during trawling operations to help researchers avoid potential capture and/or entanglement of marine mammals and sea turtles. PAM operations used a towed hydrophone array during the day and at night; the use of the array during nighttime was particularly important for data collection when visual observations were not possible.

3.2.3.3.4 Measuring Delphinid Whistle Characteristics and Source Levels on the West Florida Shelf, 2008–2009

As part of a larger study sponsored by the National Ocean Partnership Project conducted in cooperation with the University of South Florida, this study targeted bottlenose (*Tursiops truncatus*) and Atlantic spotted (*Stenella frontalis*) dolphins offshore of Sarasota, Florida (Frankel et al. 2014). A Transducers, Inc. ("squid") hydrophone array was towed from the Research Vessel (R/V) *Eugenie* during eight days in April 2008 and 11 days in April-May 2009. The main results obtained from the overall project included recordings of wild dolphins producing source level estimates of 164 and 161 dB re 1 µPa at 1 m for bottlenose and spotted dolphins. Marine Acoustics Incorporated also performed acoustic propagation predictions in order to estimate the detection range around individual bottom-mounted acoustic recorders. A total of approximately 33 hours of acoustic data were recorded during 11 days of effort in waters less than 50 meters (164 feet) in depth. The frequency response of the array system was limited to 32 kHz; the data were filtered at a sampling rate of 64 kHz (Frankel et al. 2014).

3.2.3.3.5 Low-frequency Sounds of Bottlenose Dolphins, 2003–2009

Acoustic data were recorded from bottlenose dolphins (*Tursiops truncatus*) at three sites in the Northeastern GOM: Mississippi Sound (May 2005 to June 2008); Tampa Bay, Florida (February 2006 to May 2008 and June 2008 to December 2009); and Sarasota Bay, Florida (July 2003) (Simard 2012, Simard et al. 2011). All sites were within 1 and 14 meters (3 and 46 feet) in depth. Acoustic recordings were collected continuously during boat-based visual surveys of bottlenose dolphins. A variety of acoustic recorders and hydrophones were used and were either towed or stationary. Recorder types included Fostex, Sony TCD-D8, NI-6062, M-Audio 24/96, M-Audio, TDT-RP2 A-D with sampling rates between 48 and 200 kHz (Simard 2012, Simard et al. 2011). Hydrophone types included Reson, Aquarian, and HTI-96-MIN. All recordings were analyzed for low-frequency narrow-band sounds which are thought to be correlated with dolphin socialization (Simard et al. 2011).

3.2.3.3.6 Assessing the Echolocation Pulse Rate of Bottlenose Dolphins, 2008

Visual and acoustic data on bottlenose dolphins were collected for the Dolphin Ecology Vocalizations and Oceanography Project and the Eckerd College Dolphin Project from April to September 2008 off west-central Florida (Simard et al. 2010). The survey area included Tampa Bay, Boca Ciega Bay, and Gulf waters extending 50 kilometers (27 nautical miles) offshore with bottom depths ranging from 1 to 30

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[11] See "Acoustic Detections for Airborne Mine Neutralization System Passive Acoustic Monitoring in the NSWC PCD Study Area from December 2011": http://seamap.env.duke.edu/.

meters (3 to 98 feet). Two acoustic recording systems were used: (1) a 16-element towed array (Innovative Transducers, Inc., Fort Worth, Texas) with a 64-kHz sampling rate and (2) a single HTI-96-MIN omnidirectional hydrophone with a 96-kHz sampling rate (Simard et al. 2010).

3.2.3.3.7 The Sperm Whale Seismic Study (SWSS) Program, 2002–2005

Sperm whale research in the GOM continued during this three-year study to establish the baseline behavior of sperm whales in the Northern GOM, characterize sperm whale habitat use in the Northern GOM, and determine possible changes in behavior of sperm whales when subjected to man-made noise, particularly from seismic airgun arrays (Jochens et al. 2008). The overall study area covered Northern GOM offshore waters between Galveston, Texas and De Soto Canyon, at depths ranging from 800 to 1,200 meters (2,624 to 3,937 feet). Cruises were conducted during the summers of 2002, 2003, 2004, and 2005 and included passive acoustic monitoring, and some included a test of three-dimensional passive acoustic tracking. Surveys generally took place between June and early September. The acoustic tagging component of this study is discussed in **Section 3.2.3**. Acoustic surveys used towed arrays, typically stereo-towed hydrophones with 3-meter (10-foot) separation between elements. Recording systems had a fairly flat response between 0.1 and 15 kHz (Jochens et al. 2008).

3.2.3.3.8 NMFS SEFSC Shipboard Visual Surveys, 2003–2004

NMFS SEFSC conducts the majority of all marine mammal shipboard surveys in the GOM. These surveys are designed to collect data to assess marine mammal stocks occurring in US waters. Therefore, these surveys are conducted using line transect distance sampling methods (Buckland et al. 2001). In addition to visual observation data, PAM data are also recorded to provide a more complete representation of cetacean occurrence. The first shipboard offshore marine mammal surveys in the GOM were conducted aboard the NOAA Ship *Oregon II* during spring 1990 (Mullin et al. 1991; Würsig et al. 2000). Since then, NMFS SEFSC has conducted numerous marine mammal shipboard surveys in the GOM. The NMFS SEFSC surveys during 2003 and 2004 were related to the SWSS Program. From 12 June through 18 August 2003, the NOAA Ship *Gordon Gunter* cruise GU-03-02 (023) was conducted to monitor cetaceans in oceanic waters (>200 meters [656 feet]) from Brownsville, Texas, to Key West, Florida. Methods included visual and acoustic surveys.

The PAM surveys used a five-element acoustic array towed approximately 600 meters (1,969 feet) behind the ship (NMFS SEFSC 2003). A similar array was used on the NOAA Ship *Gordon Gunter* cruise GU-04-02 (027) survey from 13 April through 11 June 2004 in EEZ waters between Brownsville, Texas, and the Florida Straits (NMFS-SEFSC 2004a). During the NOAA Ship *Gordon Gunter* cruise GU-04-03 (028) survey from 22 June through 19 August 2004 from the Maryland/Delaware border into southern Florida waters, a five-element broadband array was towed 450 meters (1,476 feet) behind the ship in waters deeper than 100 meters (328 feet). Digital audio tape recordings of signals of interest were made using multi-channel digital tape recorders and were limited to a bandwidth of 10 Hz to 24 kHz (NMFS-SEFSC 2004b).

3.2.3.3.9 The Sperm Whale Acoustic Monitoring Program (SWAMP), 2000–2001

The MMS (now BOEM) funded this study to assess the behavior of sperm whales in the Northern GOM and their responses to anthropogenic noise (e.g., seismic activity) (Jochens et al. 2006; Lang 2000). Research techniques included shipboard visual surveys, photo-identification, satellite and acoustic tagging, biopsy sampling, and acoustic monitoring. The acoustic tagging component of this study is discussed in **Section 3.2.3**.

The acoustic monitoring was conducted via a towed hydrophone array deployed during shipboard surveys on the NOAA Ship *Gordon Gunter* during 28 June through 26 July 2000, 16 March to 3 April 2001, and 17 July through 22 August 2001 (Burks et al. 2001, Mullin 2001). Two arrays were used: a five-element towed array with five hydrophones spaced 2 meters (7 feet) apart along a 100-meter (328-foot) long Kevlar-reinforced cable and a passive two-element array with a 8-meter (26-foot) polyurethane tube filled with Isopar M fluid and containing two Benthos AQ4 (mid-frequency) elements spaced 3 meters (10 feet) apart (Burks et al. 2001).

3.2.3.3.10 GulfCet II, 1996–1998

To continue the research from GulfCet I, GulfCet II shipboard and aerial surveys were conducted from the northwestern to the Northeastern GOM (Davis et al. 2000). Acoustic surveys were conducted via a towed hydrophone array in the Eastern Planning Area in late summer 1996 and mid-summer 1997 to identify and record cetacean and anthropogenic sounds. Similar to the array used in GulfCet I, the new array used in GulfCet II consisted of multiple hydrophone groups spaced along the cable. In contrast, this new array was spectrally flat (6 Hz to 18 kHz) and could be towed at faster speeds. Surveys ranged in depth from 50 to 3,000 meters (164 to 9,842 feet) (Davis et al. 2000).

3.2.3.3.11 GulfCet I, 1992–1994

Texas A&M University, operating under contract to the MMS (now BOEM) and the NMFS SEFSC, operating under an interagency cooperating agreement with MMS, conducted shipboard and aerial surveys to determine the distribution and abundance of cetaceans in the northwestern and north-central GOM (Davis and Fargion 1996). The 12 shipboard surveys, which were conducted seasonally between April 1992 and May 1994, included the use of towed hydrophone arrays to record marine mammal sounds, particularly sperm whale vocalizations. Developed by the Hubbs-Sea World Research Institute, the towed linear hydrophone array consisted of a 290-meter (951-foot) tow cable and a 235-meter (771-foot) wet section that contained 195 hydrophones in 16 groups. A combination of low-frequency hydrophones (Teledyne T-1) and high-frequency hydrophones (Benthos AQ 20) were used (Davis and Fargion 1996).

3.2.4 Tags

Data-logging tags include DTAGs that record acoustic data while being attached to the animal. Funded by the Office of Naval Research (ONR), the Woods Hole Oceanographic Institution developed the DTAG to reduce the size and increase the capabilities of acoustic recording tags in 1999 (Johnson and Tyack 2003). These tags use flash memory to record data and are encased in plastic. The maximum deployment depth is 2,000 meters (6,562 feet), and the audio sampling rate is 48 to 192 kHz.[12] The tags can record sounds, depth, temperature, and orientation (pitch, roll, heading) and can be attached to the animal via a long pole, gun, or crossbow (Johnson and Tyack 2003).

3.2.4.1 The Coastal Alabama Acoustic Monitoring Program, 2009–2017

Additional tagging efforts in the GOM are related to the Coastal Alabama Acoustic Monitoring Program (CAAMP) conducted by Dr. Sean Powers and the University of South Alabama Marine Sciences Department.[13] Although it does not target marine mammals, this program includes an array of 40 hydrophone stations deployed around Mobile Bay and Mississippi Sound to cover the entry and exit points of fish. Sonic devices (tags) are attached to several inshore fish so that the hydrophones will detect the locations of the fish to determine where and how much they travel during a year. Tagged fish include sharks, tarpon (*Megalops* sp.), sturgeon, red drum (redfish), and spotted seatrout (speckled trout; *Cynoscion nebulosus*).

3.2.4.2 The Sperm Whale Seismic Study (SWSS) Program, 2002–2003

As mentioned in **Section 3.2.2**, this three-year study was conducted to establish the baseline behavior of sperm whales in the Northern GOM, characterize sperm whale habitat use in the Northern GOM, and determine possible changes in behavior of sperm whales when subjected to man-made noise, particularly

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[12] DTAG: A Digital Acoustic Recording Tag: http://www.whoi.edu/page.do?pid=39337

[13] CAAMP Studies Redfish, Tarpon Movement: http://www.outdooralabama.com/caamp-studies-redfish-tarpon-movement

from seismic airgun arrays (Jochens et al. 2008). The tagging component of this study was part of a controlled experiment to test the responses of sperm whales to exposure to seismic airguns. Two types of DTAGs were used in the study. During 2002, DTAG1 tags were used and recorded audio at a sampling rate of 32 kHz. During 2003, both DTAG1 and DTAG2 tags were used, but only DTAG2 tags were analyzed. These tags recorded audio at a sampling rate of 96 kHz (DeRuiter et al. 2006).

3.2.4.3 The Sperm Whale Acoustic Monitoring Program (SWAMP), 2000–2001

As mentioned in **Section 3.2.2**, this MMS-funded study assessed the behavior of sperm whales in the Northern GOM and their responses to anthropogenic noise (e.g., seismic activity) (Jochens et al. 2006, Lang 2000). As part of this pilot study, suction cup multi-sensor DTAGs were successfully deployed on sperm whales 13 times in 2001. The tags were attached via a 12-meter (40-foot) carbon fiber pole. A total of 26 hours of DTAG data was recorded during NOAA Ship *Gordon Gunter* cruise GU-01-04 (13) from 17 July through 22 August 2001 (Mullin 2001). Additional DTAGs were successfully deployed on sperm whales during other surveys under this program (Thode et al. 2002).

3.2.5 Sonobuoys

Sonobuoys use a transducer and a communication radio transmitter to record and transmit underwater sounds. They can be dropped into the ocean from either an aircraft or a ship to record underwater sounds. There are three types of sonobuoys: (1) passive sonobuoys use a hydrophone to listen for sounds, (2) active sonobuoys use a transducer to send an acoustic signal and then listen for the return echo, and (3) special purpose buoys provide additional information about the environment such as water temperature and wave height.[14] The exact location of a target can be determined by deploying a pattern of sonobuoys.

One type of sonobuoy that has been used in marine mammal studies is the Directional Frequency Analysis and Recording (DIFAR) sonobuoy, which is a passive sonobuoy used by the US Navy to detect underwater submarines. DIFAR generally consists of a directional hydrophone that gives bearings to where the acoustic signal is originated; it can detect acoustic energy from 5 to 2,400 Hz, and can operate for up to 8 hours at depths of up to 305 meters (1,000 feet) (Holler 2014).

3.2.5.1 Bryde's whale sonobuoys, 2011

NMFS shipboard line transect surveys often include the use of sonobuoys to record marine mammal sounds in conjunction with a towed hydrophone array and visual observers. As mentioned previously in **Section 3.2.1**, the 2011 AMAPPS survey deployed sonobuoys as the ship followed the 200-meter (656-foot) isobath from the southeastern edge of the GOM to Pascagoula, Mississippi (NEFSC and SEFSC 2012, Širović et al. 2014). Between 30 July and 1 August 2011, NMFS deployed 13 DIFAR AN/SSQ-53E sonobuoys in arrays to confirm the characteristics of Bryde’s whale sounds (Hildebrand 2017, Širović et al. 2014). These sonobuoys consisted of a directional hydrophone with a bandwidth from 10 to 2,400 Hz, and the signals were transmitted to the ship-mounted antenna via a single radio carrier frequency. The sonobuoys automatically scuttled 8 hours after deployment (Širović et al. 2014).[15]

To determine the location of the whale calls, bearings to the same call were compiled from concurrent recordings from multiple sonobuoys in the array, and then the exact location of the call was estimated from the bearing crossings (Širović et al. 2014). During the sightings of three Bryde’s whale groups on 31 July 2011 in the Northeastern GOM in De Soto Canyon, three DIFAR sonobuoys were deployed in an array at 0, 11, and 42 minutes after the initial sighting.

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[14] Discovery of Sound in the Sea: http://www.dosits.org/galleries/technology/locatingobjectsbylisteningtotheirsounds/directionalfrequencyandrangingdifarsonobuoy/

[15] Sonobuoy deployment locations are available for download at: https://data.gulfresearchinitiative.org/data/R1.x135.120:0005#

3.2.5.2 The Department of the Navy *Empress II* Sonobuoys, 1991–1992

The Mississippi State University Research Center flew aerial surveys approximately 50 kilometers (27 nautical miles) south of Mobile, Alabama from November 1991 to June 1992 to determine the abundance of sea turtles and marine mammals in an area where the Department of the Navy was conducting *Empress II* ship shock trials (Esher et al. 1992). During these surveys, sonobuoys were deployed from the door of the survey aircraft to test the feasibility of using passive acoustics to locate and identify whales and dolphins in shallow coastal waters. A total of 32 AN/SSQ-41B sonobuoys were deployed between 11 November 1991 and 10 June 1992 and consisted of a subsurface hydrophone and preamplifier, a cable assembly, seawater battery pack, and surface electronics such as a VHF transmitter and antenna. The acoustic frequency range was 10 Hz to 10 kHz (Esher et al. 1992).

3.3 Analysis Methods for PAM Data

3.3.1 Using PAM Data for Estimation of Marine Mammal Densities

Density and population estimation is one of the primary techniques used for effective wildlife management and conservation. Reliable estimates of density and abundance are needed to monitor animal movements and population trends and to plan for mitigation of potential impacts from anthropogenic activities. The most common methods of generating density estimates of marine mammal species and populations use visual observation data and include some form of capture-recapture on marked or uniquely identifiable individuals or the use of line transect survey data collected following strict distance sampling protocols (Buckland 2001, Thomas et al. 2010). For example, this method includes shipboard line transect surveys during which the ship travels along randomly generated tracklines, and visual observers record the perpendicular distance between the ship and any marine mammals detected. It is assumed that all animals on the trackline are detected and that the probability of detection decreases with increasing distance from the trackline. The distribution of perpendicular distances between the animals and the trackline is used to estimate the proportion of animals detected within our observer strip which enables a researcher to estimate animal density and abundance (Thomas et al. 2010).

Animal density estimation using PAM data is new and may be the preferred method for species that are often not sighted at sea during shipboard or aerial surveys because they do not surface often and for regions where poor weather conditions limit regular visual survey coverage (Marques et al. 2012). The development of these new methods was initiated through the Density Estimation for Cetaceans from Acoustic Fixed Sensors project funded by the Exploration and Production Sound and Marine Life Joint Industry Program and NOAA under the National Oceanographic Partnership Program. Led by Dr. Len Thomas (St. Andrews University), the Density Estimation for Cetaceans from Acoustic Fixed Sensors team developed and promoted methods for estimating the density of cetacean species from fixed passive acoustic devices during this three-year project (2007–2010). Their methods are applicable to PAM data recorded from arrays of permanent, bottom-mounted sensors and single bottom-mounted or floating sensors (Küsel et al. 2015b, Marques et al. 2013, Thomas et al. 2009).

There are currently several approaches to estimate density from PAM data collected on fixed sensors (Marques et al. 2013). If distances between the detected animal(s) and the acoustic recorder can be obtained from single sensors or clusters of closely spaced sensors, each operating as a single unit, then census and/or strip transect and distance sampling methods are possible.

The census and/or strip transect method requires that all animals within a given area are detected, and the animals outside of that area can be excluded (Marques et al. 2013). For example, Moretti et al. (2010) used this method by counting dives of echolocating beaked whales that dive synchronously. They isolated dive starts using a bottom-mounted hydrophone array and assumed that all dive starts of the target beaked whale species within the study area were detected.

The distance sampling method requires that detected animal distances can be obtained and that the conventional distance sampling assumptions are met so that point transect using detections of animals and/or groups of animals or cue counting can be used (Marques et al. 2013). For example, Marques et al. (2009) used the cue counting method to estimate the density of a population of Blainville's beaked whales. This technique generally involves counting the number of detected acoustic cues for a known period of time and then scaling up this number to estimate animal density. They converted the number of detected cues into density by accounting for the probability of detecting cues, the estimated rate at which animals produce cues, and the proportion of false positive detections (Marques et al. 2011).

Another way to capture detection probability is through spatially explicit capture recapture. This method involves estimating acoustic counts using a subset of data to calculate probability of detection and then combine this probabilty to estimate density and variance (Martin et al. 2013). Similarly, Kyhn et al. (2012) used acoustic data loggers concurrently set up with visual tracking of harbor porpoises. Detection functions were estimated based on probability of detection from a mark-recapture approach using the acoustic data and point transect distance sampling. Density estimates for the Timing Porpoise Detector (T-POD) data were similar to visual densities (Kyhn et al. 2012). Marques et al. (2009) also used passive acoustic monitoring data to develop density estimates for marine mammals. The researchers specifically developed densities for Blainville's beaked whales after accounting for detection function, cue rate, and false positive detections in the US Navy's Atlantic Undersea Test and Evaluation Center range in the Bahamas (Marques et al. 2009).

Both the census and/or strip transect and distance sampling methods are based on estimates of the probability of detecting acoustic mammal sounds (e.g., calls) as functions of distance and require the use of receivers capable of localizing calls or tagging data (Küsel et al. 2011). When distance estimation is not possible, simulations can be used to estimate detection probabilities (Frasier et al. 2016). However, the assumptions used to implement the simulation models are not always met or the potential violation of the assumptions have unforeseen consequences. Therefore, methods based on empirical measurements instead of model-based methods are still preferred when estimating the detection function (Marques et al. 2013).

3.3.2 Habitat Modeling

Estimates of marine mammal density and distribution may be improved through the use of habitat models that can predict spatial distribution of density and/or abundance in relation to environmental variables. For example, density surface modeling is a type of habitat modeling method in which generalized additive models (GAMs) (Wood 2006) are used to estimate the spatial distribution of abundance and/or density or counts (the response variable) as a function of several geographical, physical, and environmental covariates (explanatory variables). Other methods such as species distribution models and density surface models may also be appropriate modeling methods.

For the GAMs example mentioned previously, after fitting GAMs to the survey data, the resulting density surface model (the chosen model) is applied to a prediction grid superimposed upon the area of interest so that animal abundance and/or density can be predicted for any portion of the area and related to specific covariates (Thomas et al. 2010). The covariates may include a variety of static and dynamic variables such as longitude, latitude, water depth, distance from shore, bathymetry, sea surface temperature (SST), and surface chlorophyll concentration. These habitat variables may be derived from in situ oceanographic data, remotely sensed data, or satellite-derived data (Redfern et al. 2006).

Habitat models may be built at finer spatial and temporal resolutions when using in situ data. However, these data are not always available at the required spatial and temporal scales need for a model, and the collection and processing of these data are labor intensive and costly. The ideal habitat models for cetaceans would be based on accurate quantitative measurements of data that characterize habitat variability, prey populations, and predator populations at a wide range of temporal and spatial scales and an understanding of the interactions of these variables and animal density (Redfern et al. 2006).

Roberts et al. (2016) used line transect survey data to develop habitat-based cetacean density models in the GOM for marine mammals based on species where possible. The researchers created models for seventeen species and for two guilds (or family groups), which included beaked whales and *Kogia*. Density was modeled in a two-step process by first determining detectability of each species and guild using data from line transect surveys and by applying this detection function to the survey transects to estimate abundance. Then, Roberts et al. (2016) used GAMs to model the abundance considering the environmental factors that are believed to correspond with distribution of cetaceans in the GOM. These factors included physiographic (i.e., depth, slope, distance to shore, canyons, seamounts, and isobaths), physical oceanographic (i.e., sea surface temperature [SST], distance to SST fronts, wind speed, total and eddy kinetic energies, and distance to geostrophic eddies), and biological (chlorophyll concentration, primary production, potential biomass and production of zooplankton and epipelagic micronekton) covariates (Roberts et al. 2016).

Most cetacean habitat models developed to date have relied on the use of line transect data from shipboard and aerial surveys (e.g., Becker et al. 2014, Forney et al. 2012). However, due to advances in statistical methods and technology, other data types, such as tagging and PAM data, are also now being used for habitat modeling (Redfern et al. 2006). PAM data may improve model accuracy and precision and provide a better representation of cetacean presence due to the increased temporal coverage that PAM can provide when compared to visual survey data (Soldevilla et al. 2011). Of course, using PAM data for cetacean habitat models does have limitations, including the ability to detect and localize mammal calls. As with density estimation, several factors such as sound propagation and acoustic masking can hinder detections. Sound propagation conditions can vary across sites and seasons and lead to variations in detection probability. Weather (wind, waves, rain), anthropogenic activities (sonar, vessels, seismic), and biologic (other marine animals) sounds can mask the marine mammal sounds that are the target of a study, thus minimizing the detections. Therefore, it may be important to develop methods for incorporating ambient noise metrics into future habitat models (Soldevilla et al. 2011). Before performing the habitat modeling, absolute abundance must be computed and this abundance must take into account sources of false negative and positive numbers. Additional advantages and limitations of using PAM for cetacean habitat modeling are discussed in Soldevilla et al. (2011) and Širović and Hildebrand (2015).

3.3.3 Acoustic Propagation Modeling

Underwater acoustic propagation refers to the movement of acoustic waves from one point to another (Lurton 2010). Propagation decreases the amplitude of the acoustic signal via geometrical spreading and absorption, which is based on the chemical propoerties of the seawater. As acoustic waves propagate, they lose their intensity. This propagation loss (also known as transmission loss, TL) is a key factor in PAM studies because it affects the ability of receiver to detect and classify sound source. Therefore, propogation loss must be evaluated when determining the performance of underwater acoustic systems (Lurton 2010).

To estimate TL from absorption and attenuation, acoustic propagation models[16] can be used in addition to direct field measurements. A variety of input parameters are often included in these models to reliably estimate TL. For example, inputs may include source frequency band and configuration, sound speed profile, bathymetry, bottom properties, and source and receiver geometry (Küsel et al. 2009). Acoustic propagation modeling has been applied to military operations, marine seismology, and physical oceanography and is more recently being used to address questions in regards to marine ecology, physics, and conservation (Tennessen and Parks 2016).

Propagation modeling is particularly important in PAM studies to assess marine mammal occurrence and ambient and anthropogenic noise affects on species and populations. For example, knowledge of acoustic propagation of seismic exploration signals is critical when predicting exposure levels and potential impacts to marine wildlife (Jochens et al. 2008). These types of anthropogenic noise propagation studies

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[16] The Ocean Acoustics library contains acoustic modeling software and data: http://oalib.hlsresearch.com/

have been conducted in the GOM to assess seismic airgun pulse exposure to cetaceans. As mentioned previously, sperm whales were tagged with acoustic devices during the SWSS Program in 2002 and 2003 (DeRuiter et al. 2006). These tagged whales were exposed to airgun pulses in a controlled experiment. Researchers calculated sound propagation paths of the pulses using ray trace and Fourier models. Results showed that whales near the surface may be exposed to high-frequency sounds (>500 Hz) when surface-ducting conditions are present. Therefore, cetaceans with even poor low-frequency hearing may be affected by airgun noise (DeRuiter et al. 2006).

In addition to examining the characteristics of anthropogenic noise and potential impacts on marine mammals, propagation modeling is used to localize and track individual sound sources. These models are particularly important when assessing the vocalization and/or phonation patterns of different animals and species and trying to discern acoustic sound of a specific individual (Sidorovskaia et al. 2004). For instance, the ability to discern spectral features of whale clicks from single hydrophone recordings based on surface- and bottom-reflected arrivals helps researchers develop algorithms for animal localization and tracking (Sidorovskaia et al. 2004; Tiemann et al. 2006).

Propagation modeling can also be included as part of the density estimation analyses discussed in the previous section. When the location of calling animals is not available and cannot be directly measured, propagation modeling can be used to determine the probability of detection at a single sensor (Marques et al. 2013). A common model used for for high-frequency vocalizations is the Bellhop ray-based propagation model. For example, Küsel et al. (2011) used the Bellhop model to model the high-frequency clicks of beaked whales in order to calculate sound TL values as a function of range and depth. These values are used to predict signal-to-noise ratios of received clicks, which are then used to predict the probability of detection as a function of signal-to-noise ratio. This detection function is combined with call rate and false positive rate to estimate density (Küsel et al. 2011).

Additional studies that include propagation modeling of marine mammal sounds and anthropogenic and/or ambient noise are as follows: Aroyan et al. (2000); DeRuiter et al. (2010); Frasier et al. (2016); Hermannsen et al. (2015); Hildebrand (2006); Küsel et al. (2009); LePage et al. (1996); Malme (1995); McCauley et al. (2000a); Mellinger et al. (2009); Mellinger et al. (2003); Shyu and Hillson (2002); Širović et al. (2007); and Tashmukhambetov et al. (2008). The methods used by these studies include acoustic modeling to further investigate how various species of marine mammals produce sound and use echolocation, as well as the way in which sound travels due to physical characteristics of the marine environment. The studies consider physical characteristics, such as environmental fluctuations, seafloor characteristics, and sound-speed profiles. Some of these studies also look at the characteristics of airgun pulses throughout the marine environment and use propagation loss modeling to explore how marine species respond to seismic survey equipment.

3.3.4 Assessing Behavioral Response and/or Vocal Response to Anthropogenic Sources

There is a growing concern about the effects of underwater anthropogenic sound on marine life. The continuing increase in anthropogenic sounds and sound sources in the marine environment requires a variety of methods to study the behavioral and acoustic responses of marine animals to specific acoustic exposures from sources such as military sonar, seismic exploration, shipping vessels, construction, and others. Tyack (2009) provides a thorough review of the methods to study the effects of these sounds on marine life, particularly marine mammals. These methods are divided into two main types: observational and experimental. Observational studies focus on observing the behavior of animals near the anthropogenic sound source to determine changes in behavior. Experimental studies use a controlled environment to test animal responses under a set of chosen stimuli. These controlled environment experiments (CEEs) provide the best method of proving that a particular sound stimulus causes a response because a specific known dose of sound is broadcast to an animal, and the acoustic exposure and behavioral responses can be directly measured (Tyack 2009).

3.3.5 Detectors and Classifiers

The detection and classification of marine mammal vocalizations is often a time consuming and tedious process when analyzing PAM data, particularly when analyzing data for multiple species. PAM systems are often deployed for long periods of time and can collect large volumes of data. In fact, when multiple recorders are deployed at the same time, years of data can be amassed in just a few months. Manually reviewing all of these data for detections requires excessive labor hours and cost. Researchers have been using several signal processing strategies to automate this process, including supervised and supervised machine learning algorithms. Although no single algorithm can be used to detect and classify all species which may be recorded, algorithms do exist for certain species and groups, and new algorithms are being developed (Bittle and Duncan 2013). For more information, refer to Mellinger et al. (2015), which summarizes detection and classification methods for marine animal sounds.

3.4 Data Availability

The primary databases that are currently used to archive PAM data collected in the GOM are described in the following subsections.

3.4.1 The *Deepwater Horizon*-GOM Research Initiative (GoMRI) and GoMRI Information and Data Cooperative (GRIIDC)

The Gulf of Mexico Research Initiative (GoMRI) was established by a Master Research Agreement between BP and the GOM Alliance. In accordance with this agreement, all data collected or generated under this agreement must be available to the public.[17] To fulfill this requirement, the GoMRI Information and Data Cooperative (GRIIDC) was formed. The GRIIDC is a group of researchers, data specialists, and computer system developers who work together to support the data management system which stores scientific data collected in the GOM. The mission of GRIIDC is to ensure that these data promote continual scientific discovery and public awareness of the GOM ecosystem.

Housed at the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi, the GRIIDC database includes over 1,000 datasets which focus primarily on GOM research and which include data from research awarded by the following: GoMRI, BP Gulf Science Data, and Florida RESTORE Act Centers of Excellence Program. The GoMRI research comprises of awards from the Florida Institute of Oceanography, Louisiana State University, the Alabama Marine Environmental Science Consortium, the Northern Gulf Institute, and others. Therefore, the database houses a variety of data types, such as oceanographic and water quality data (e.g., conductivity, temperature, and depth), toxicity data, light detection and ranging, and hyperspectral data, and PAM data (e.g., sonobuoy deployments, marine mammal acoustic detections, ambient noise).

In addition to guiding researchers through data management steps, the GRIIDC provides tools that help researchers manage their data throughout an entire study or project. The one-on-one support provided by GRIIDC is unique in that every data package contributed is reviewed for completeness, and the GRIIDC team works directly with the researchers to improve their data and metadata submissions and teach them about best management practices that they can apply to their current and future studies.

3.4.2 The Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP)

In collaboration with a consortium of international partners, Duke University researchers initiated the Spatial Ecological Analysis of Marine Megavertebrate Animal Populations (SEAMAP) initiative in 2002 to form a taxon-specific geo-informatics facility of the Ocean Biogeographic Information System (OBIS) for global marine mammal, sea turtle, seabird, ray, and shark data (Halpin et al. 2006). This project is a part of the Census of Marine Life. As the project has evolved the team is also working to quantify the

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[17] GoMRI and GRIIDC: https://data.gulfresearchinitiative.org/. Census of Marine Life: http://www.coml.org/about-census/ .

goals have expanded to include explaining global patterns of marine species distribution and biodiversity; standardize databases and sampling techniques; provide study status and impacts on threatened species; and support modeling of species distributions in response to environmental change.

Since its beginning, this OBIS-SEAMAP program has amassed a geo-referenced repository that includes 873 datasets (1935–2017) and over 5,550,000 records.[18] This spatially referenced online database is continuously expanding through contributions from data providers (Halpin et al. 2006). OBIS-SEAMAP is not only as a repository of data but it also contains tools for distributing and visualizing data. For instance, the web-based geographic information systems applications make datasets widely accessible to teachers and students, researchers, and other members of the general public, and anyone who may not have access to expensive desktop geographic information systems programs. The mapping interface allows users to map several layers of data. For example, one can map sampling effort (trackline data) along with animal observations to quickly find gaps in survey coverage and concentrations of sightings in a particular area of interest (Halpin et al. 2006).

The OBIS-SEAMAP system accommodates a wide variety of data types, such as sampling effort, telemetry tracking, sightings, strandings, bycatch records, and photo-identification catalogs. Contributors to OBIS-SEAMAP include academic, federal agency, non-governmental, and other private organizations and individuals that span the entire globe. As described in Fujioka et al. (2014), OBIS-SEAMAP has been expanded to accommodate PAM data. These data are distinguished from other data types via classification of a combination of count type and platform where count type is presence (animal was detected) or absence (no animal detected) and platform is stationary (e.g., bottom-mounted recorder) or mobile (e.g., towed array). Advanced features for PAM data include more visualization and analysis tools (e.g., diel plots of detections) and extended metadata. The goal is to provide a common framework to facilitate the wider use and sharing of PAM data (Fujioka et al. 2014).

3.4.3 Tethys

Developed by Scripps Institute of Oceanography, NOAA, and San Diego State University, Tethys is an open source temporal-spatial database for metadata related to acoustic recordings.[19] This acoustic metadata system was designed to enhance meta-analyses over large spatial and temporal scales and to provide a standard for representing detections, classifications, and localizations of biologic, ambient, and anthropogenic signals (Roch et al. 2013). The set of rules for structuring metadata is called Tethys, while the Tethys Metadata Workbench is the implementation of this framework and includes a server program and client libraries (Roch et al. 2016).

Through this workbench, researchers can manipulate their metadata and access additional data sources, such as geophysical, biological, and astronomical data sources (Roch et al. 2016). The Tethys interfaces allows the query and processing of publicly available biological and oceanographic data. However, the client-server framework requires users to work with the data in MATLAB, Java, or Python languages (Roch et al. 2013). The web-services-based server enables exchange of data between research groups. For example, summary data can be exported into OBIS-SEAMAP.

Although Tethys currently focuses on marine mammal, fish, and anthropogenic signals, the framework can be used in a variety of contexts. It has already been used to annotate and derive information from millions of cetacean, pinniped, fish, elephant, and anthropogenic acoustic detections from a decade of deployments across the globe. Tethys is well suited for research involving density and abundance estimates, long-term seasonal and diel patterns, and social network analyses (Roch et al. 2016).

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[18] OBIS SEAMAP: http://seamap.env.duke.edu

[19] Tethys: http://tethys.sdsu.edu/

4. The Current State of Knowledge

We identified 32 projects conducted in the Gulf of Mexico (GOM) using passive acoustic monitoring (PAM). **Table 1** provides a summary of the studies including the project title, survey dates, general location, methods used, water depth, sampling rate, data recorded, and literature source. Eight of the studies were designed specifically to gather data on ambient noise in the GOM; the other 24 studies were designed to gather information on marine mammals using PAM. **Figures 11 through 14** show deployment locations for PAM devices and tracklines for surveys involving PAM in the GOM. **Figure 11** provides a map for all three Bureau of Ocean Energy Management (BOEM) Planning Areas. **Figures 12**, **13**, **and 14** give a zoomed-in overview for the Eastern Central, and Western Planning Areas, respectively. The majority of studies occurred in only a portion of the GOM, focusing primarily on the Eastern and Central GOM. PAM surveys have tended to be in waters of the continental shelf and slope up to approximately 1,500 meters (4,921 feet) deep; only a couple of the surveys were in deeper waters extending to approximately 3,200 meters (10,499 feet).

4.1 Ambient and Anthropogenic Underwater Noise Levels in the Gulf of Mexico

Three sources of ambient noise exist—biological and physical (or collectively considered natural ambient noise) and anthropogenic ambient noise. Natural sources of sound include earthquakes, wind and/or waves, rainfall, bio-acoustic sound generation, and thermal agitation of the seawater. Anthropogenic sources include a variety of sounds generated from human activities, including noise related to the following:

- Engines, thrusters, civilian commercial sonar, and other equipment in commercial shipping
- Airguns, oil drilling and other equipment used in oil and gas exploration, development and production
- Sonar, communications, and explosives in military exercises and testing
- Commercial civilian sonars in commercial and recreational fishing and boating
- Acoustic deterrent and harassment devices in the fishing industry
- Airguns, sonar, telemetry, communications, and navigation used during research
- Equipment and vessel operation during construction activities

Noise in the ocean is growing in intensity and expanding across coastal regions, and into deeper habitats (Hildebrand 2009). Noise can be categorized into one of three types: low, medium, and high frequency.

Low-frequency noise generally includes sounds in the bandwidths between 10 and 500 Hz. This category is primarily anthropogenic sources, including commercial shipping followed by seismic sources. However, fish can generate low-frequency sound and make up a large part of this spectrum for natural ambient noise. The most common way fish produce these sounds is by grinding or strumming or by using muscles on or connected to bones around the swim bladder. Fish can chorus together and increase the amount of noise in the low-frequency band by as much as 30 decibels (dB) (Hildebrand 2009). Low-frequency sounds generally travel across ocean basins because they propagate over long ranges. Shipping noise has increased over 12 dB as shipping across the globe has expanded. Over the years, oil exploration and construction has expanded into deeper waters and increased the propagation of seismic sounds.

Medium-frequency noise generally includes sounds from 500 Hz to 25 kHz. This category generally include natural sources of sound, such as sea-surface agitation including break waves, spray, bubble formation and collapse, and rainfall. Heavy precipitation can increase noise levels in this range by as much as 20 dB. Biological sources in the medium-frequency range include snapping shrimp (*Alpheus* spp.). When snapping shrimp are present and actively producing sound, they can also increase the amount of noise by 20 dB. Medium-frequency sounds are more local or regional in nature, as they do not propagate over long distances. Military and mapping sonars and small vessels are in this medium range (see **Section 4.1.3**).

Table 1. Passive Acoustic Monitoring (PAM) Studies for Ambient Noise and Marine Mammals in the Gulf of Mexico

PAM Study	Dates	General Location	PAM Methods	Water Depth m (ft)	Sampling Rate (kHz)	Data Recorded (Marine mammal species; noise types)	Source
Marine Mammal Densities from HARP Studies	16 May 2010–Present	Northern GOM Eastern GOM	Seafloor HARPs	980–1,300 (3,215–4,265)	200	Beaked whales: Gervais' Cuvier's, Blainville's, unknown *Mesoplodon* sp.; *Kogia* spp.; sperm whale; bottlenose dolphin; Atlantic spotted dolphin; Risso's dolphin; pilot whales; oceanic stenellids	Hildebrand et al. 2015b
NMFS SEFSC Bryde's Whale Study	Jun 2016–May 2017	Eastern GOM	ARPs	200 (656)	2000 or 2500 kHz	Recordings in progress	NMFS-SEFSC (unpublished data)
LADC-GEMM Ambient Noise Studies in Mississippi Canyon, 2007–2015	26 Jun–22 Oct 2015; 10–23 Sep 2010; 6–16 Jul 2007;	Northern GOM	EARS, [ASVs with towed arrays, gliders in 2015]	1,000–1,500 (3,281–4,921)	192 kHz	Abiotic, seismic surveys, sperm whale, beaked whales, delphinids, shipping	Sidorovskaia and Li 2017
NMFS SEFSC Shipboard Surveys, 2014	Summer 2014	Eastern GOM	Towed hydrophone array	-	-		NMFS-SEFSC (unpublished data)
Ambient Noise in the GOM, 2010–2013	May 2010-Oct 2013	Northern GOM Eastern GOM	HARPs	90–1,300 (295–4,265)	200	Abiotic (hurricane and wind), anthropogenic (seismic surveys), sperm whale, beaked whales, delphinids	Wiggins et al. 2016
NMFS SEFSC Shipboard Surveys, 2012	Summer 2012	Eastern GOM	Towed hydrophone array	-	-		NMFS-SEFSC (unpublished data)
Assessing Impacts of *Deepwater Horizon* on Large Whale Species, 2010–2012	15 Nov 2011–29 Feb 2012; 16 Jun–15 Oct 2010	Northeastern GOM	MARUSs (22)	231–286 (758–938)	2-20	Potential Bryde's whales; sperm whale; seismic surveys	Rice et al. 2014b
Airborne Mine Neutralization System Monitoring	5–10 Dec 2011	Northeastern GOM	Towed hydrophone array	3.5 (11)	48–192	Bottlenose dolphin, Atlantic spotted dolphin	NSWC PCD 2012
NOAA *Pisces* - Protected Species Monitoring and Mitigation Measures for Mid-Water Trawl Sampling	7–29 Sep 2011; 21 Jun–15 Jul 2011	Northern GOM	Towed hydrophone array	Unknown	Unknown	Sperm whale, delphinids	Geo-Marine, Inc. (unpublished data)
Wave Glider HARPs (WGHs)	Feb–Aug 2011	Northern GOM	Wave Gliders (2) with HARPs	93–980 (305–3,215)	10–100	Sperm whale, delphinids	Hildebrand et al. 2013
HARP Bryde's Whale Study, 2010–2011	29 Jun 2010–14 Nov 2011	Northern and Southeastern GOM	3 HARPs	90–1,320 (295–4,331)	200		Širović et al. 2014

PAM Study	Dates	General Location	PAM Methods	Water Depth m (ft)	Sampling Rate (kHz)	Data Recorded (Marine mammal species; noise types)	Source
Bryde's Whale Sonobuoy	30 Jul–1 Aug 2011	Northeastern GOM	Sonobuoys (13)	NA	0–3.5	Bryde's whale	Hildebrand 2017
Dolphin Distribution on the West Florida Shelf, 2008-2010	Jun 2009–Jun 2010; Jun–Sep 2008	Eastern GOM	DSGs	0–100 (0–328)	37–50	Delphinids	Simard 2012
Measuring Delphinid Whistle Characteristics and Source Levels on West Florida Shelf, 2008-2009	Apr 2008–Apr-May 2009	Eastern GOM	Towed hydrophone array	~10–50 (~33–164)	64	Bottlenose dolphin, Atlantic spotted dolphin	Frankel et al. 2014[1]
Low-frequency Sounds of Bottlenose Dolphins, 2003–2009	2003–2009	Eastern GOM Central GOM	Hydrophones	1–14 (3-46)	48–200	Bottlenose dolphin	Simard et al. 2011[3]
Assessing Echolocation Pulse Rate of Bottlenose Dolphins, 2008	Apr–Sep 2008	Eastern GOM	Towed hydrophone array	1–30 (3–98)	64 and 96	Bottlenose dolphin	Simard et al. 2010[2]
Source Characterization Study, 2007	2–22 Sep 2007	North western GOM	EARS [moored array]	1,000 (3,281)	25 kHz	Seismic survey	Ioup et al. 2009
Ambient Noise Measurements, Gulfport Mississippi Harbor, 2005	Jun–Aug 2005	North central GOM	Stationary hydrophone	10 (33)	N/A	Small vessels, large ships, bottlenose dolphin	Stanic et al. 2007
Long-Term Ambient Noise Statistics in the GOM	3 Apr 2004–23 May 2005	Eastern GOM	EARS	3,200 (10,499)	2.5	Abiotic (weather and/or hurricanes), anthropogenic (shipping vessels)	Snyder 2007[4]
Mississippi Sound Bottlenose Dolphin Whistles	Apr 2004–Mar 2005	North central GOM	Towed hydrophone	-	-	Bottlenose dolphin	Hernandez et al. 2010
SWSS Program	2002–2005	Northern GOM	Towed array & DTAG	800–1,200 (2,625–3,937)	-	Sperm whale, seismic activity	Jochens et al. 2008
NOAA Ship *Gordon Gunter* Cruise GU-04-03 (028) 2004	22 Jun–19 Aug 2004	Eastern GOM	Towed array	-	-		NMFS-SEFSC 2004b
Noise Level Effects on Manatee Habitat Use, 2003–2004	Apr–Sep 2004; Apr–Sep 2003	Eastern GOM	Hydrophone	-	200	Boat noise, snapping shrimp	Miksis-Olds et al. 2007b
NOAA Ship *Gordon Gunter* Cruise GU-04-02 (027) 2004	13 Apr–11 Jun 2004	Northern GOM	Towed array	-	-		NMFS-SEFSC 2004a

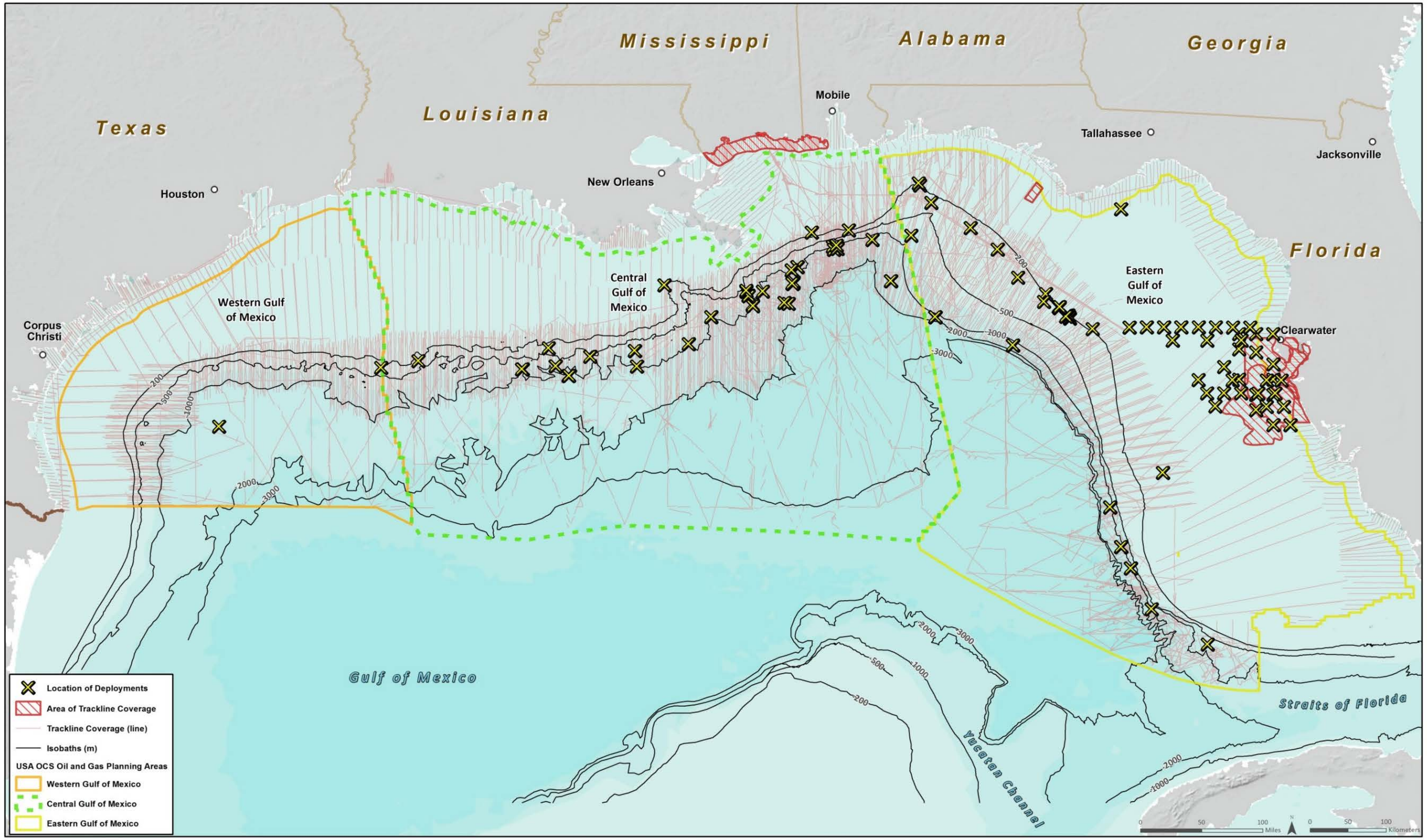
PAM Study	Dates	General Location	PAM Methods	Water Depth m (ft)	Sampling Rate (kHz)	Data Recorded (Marine mammal species; noise types)	Source
Source Characterization Study, 2003	Jun 2003	Northern GOM	EARS	990 (3,248)	25 kHz	Seismic surveys	Tashmukhambetov et al. 2008
NOAA Ship *Gordon Gunter* Cruise GU-03-02 (023) 2003	12 Jun–18 Aug 2003	Northern GOM	Towed array	-	-		NMFS-SEFSC 2003
LADC-GEMM Ambient Noise Studies in Mississippi Canyon, 2002	19 Aug–24 Oct 2002	Northern GOM	EARS	645–1,034 (2,116–3,392)	12	Weather (e.g., Tropical Storm Isidore, Hurricane Lili), marine mammals	Newcomb et al. 2007
LADC-GEMM Ambient Noise Studies in Mississippi Canyon, 2001	17 Jul–21 Aug 2001	Northern GOM	EARS	600–1,000 (1,969–3,281)	12	Sperm whale, vessels, seismic airguns, weather (e.g., Tropical Storm Barry)	Newcomb et al. 2002
SWAMP	17 Jul–22 Aug 2001; 16 Mar–3 Apr 2001; 28 Jun–26 Jul 2000;	Northern GOM	Towed array & DTAGs	-	-	Sperm whale, delphinids, seismic activity	Lang 2000; Jochens et al. 2008; Burks et al. 2001
GulfCet II	Late summer 1996; mid-summer 1997	Eastern GOM	Towed array	50–3,000 (164–9,843)	-	Sperm whale, delphinids, seismic activity	Davis et al. 2000
GulfCet I	Apr 1992–May 1994	Northwestern GOM North-central GOM	Towed array	-	-	Sperm whale, delphinids, *Kogia* spp., and a possible sei or Bryde's whale	Davis and Fargion 1996
DoN Empress II	11 Nov 1991–10 Jun 1992	Central GOM	Sonobuoys	-	-	Sperm whale, pilot whale, and *Stenella* spp.	Esher et al. 1992

[1] No tracklines available; georeferenced polygon from figure "Delphinid Whistles."

[2] Georeferenced polygon based on "echolocation."

[3] No tracklines provided; polygons derived based on study area descriptions: Mississippi Sound, Mississippi (30°16' N, 88°31' W); Tampa Bay, Florida (27°40' N, 82°42' W) and Sarasota Bay, Florida (27°30' N, 82°35' W).

[4] Georeferenced locations of EARS from figure "Long-Term Ambient Noise Stats" from Snyder 2007.

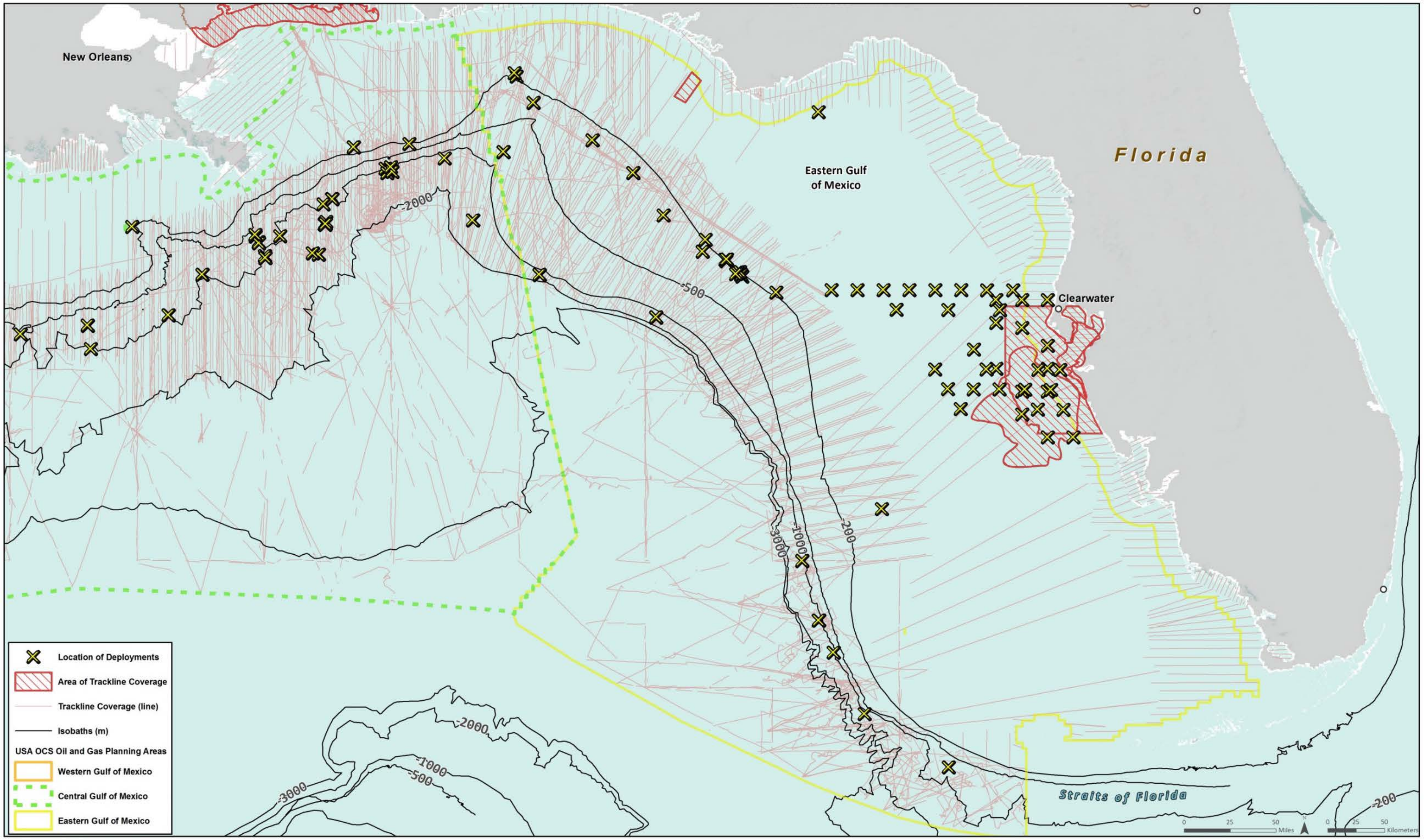


BOEM | Passive Acoustic Monitoring Program for the Northern Gulf of Mexico | Literature Synthesis

Sources: BOEM and ESRI.

J:\2017\17-025_BOEM_Acoust_Mon_GOM_(Khan)\Map_Docs\Draft\Lit_Review\SC_Edits_20170922\17_025_FigX_BOEM_Surveys_overview_imagery_11x172.mxd | Last Updated: 09.22.2017

Figure 11. Locations of PAM deployments and trackline coverage in the Gulf of Mexico.

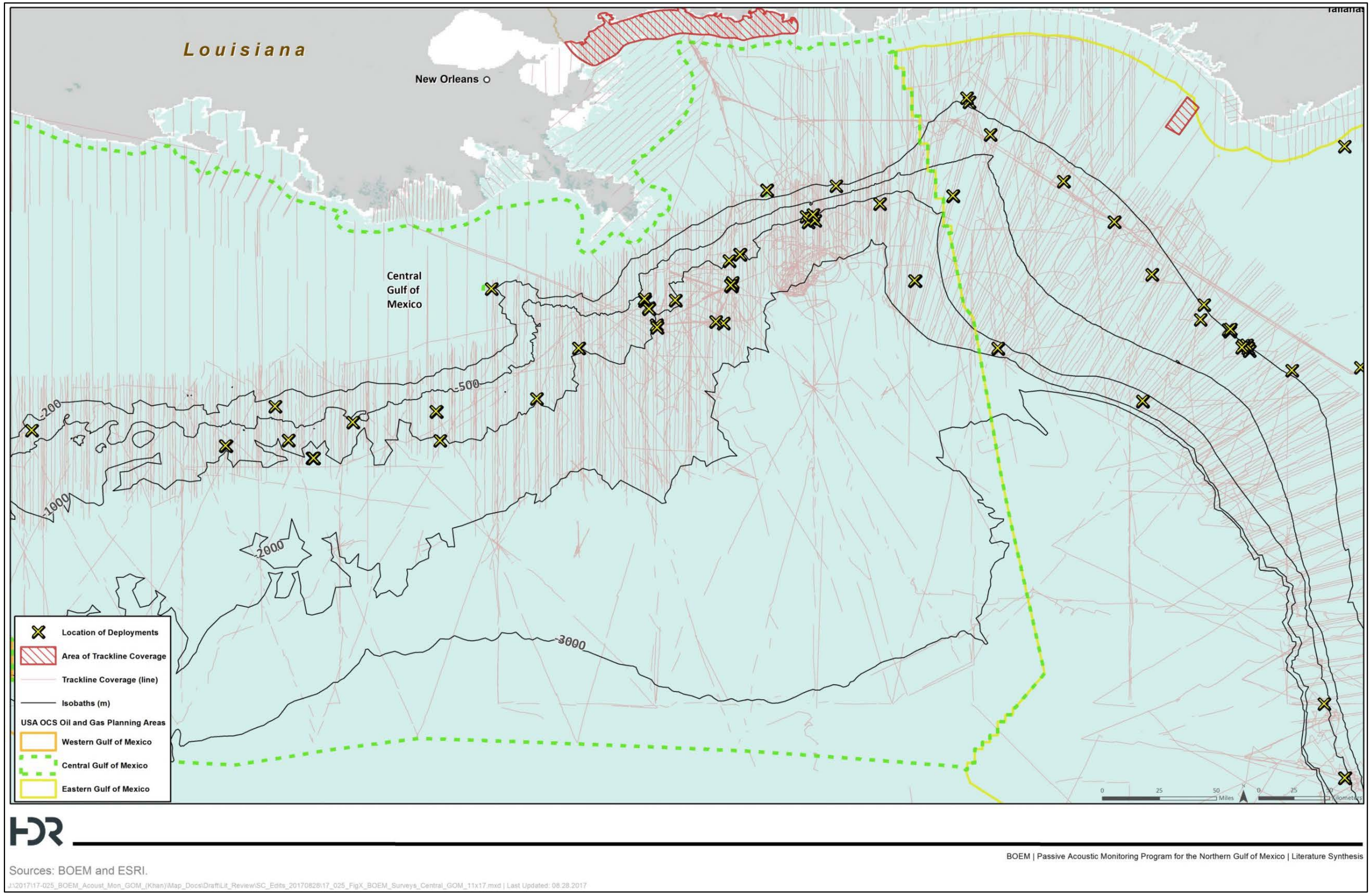


BOEM | Passive Acoustic Monitoring Program for the Northern Gulf of Mexico | Literature Synthesis

Sources: BOEM and ESRI.

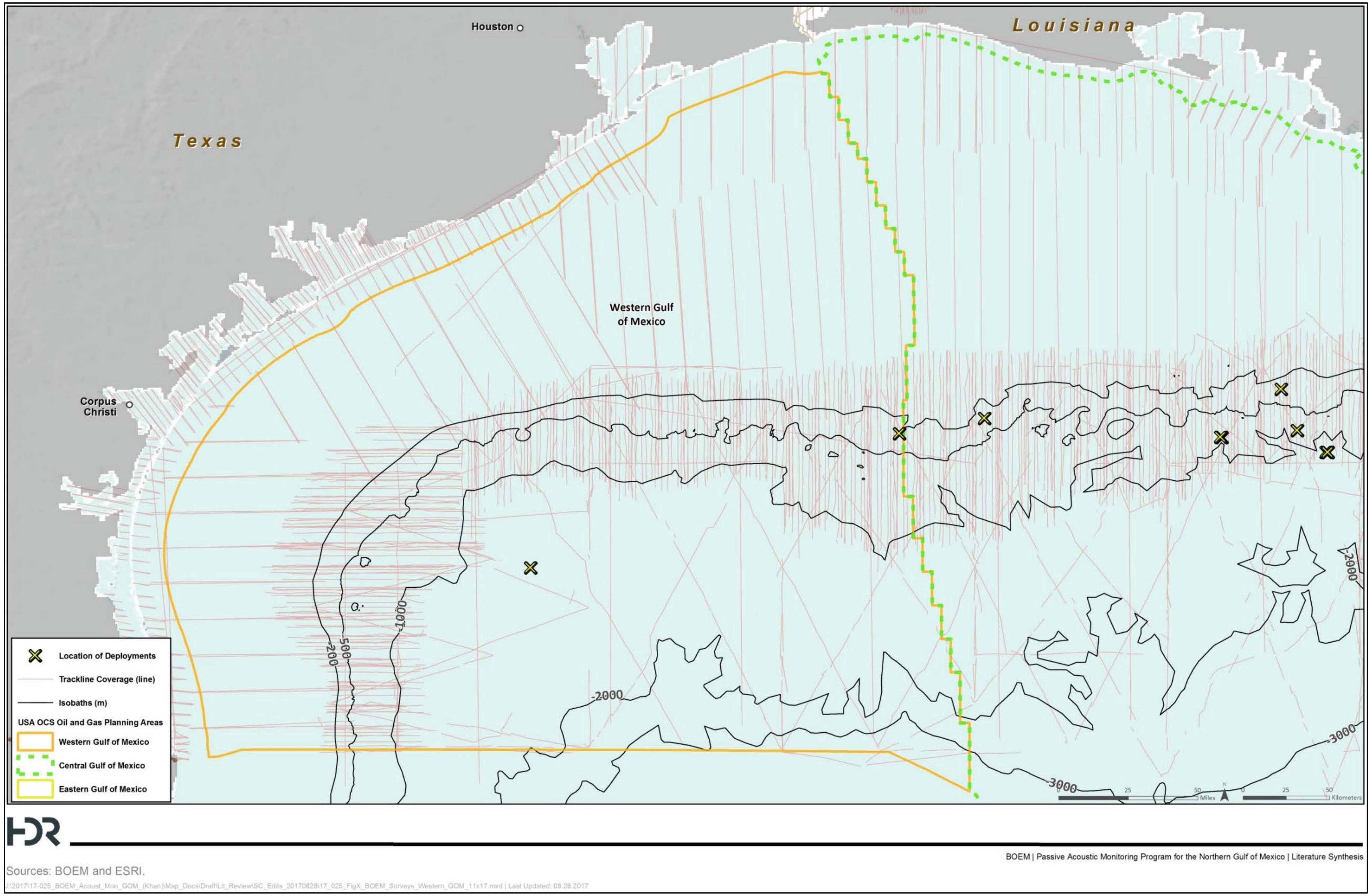
J:\2017\17-025_BOEM_Acoust_Mon_GOM_(Khan)\Map_Docs\Draft\Lit_Review\SC_Edits_20170828\17_025_FigX_BOEM_Surveys_Eastern_GOM_11x17.mxd | Last Updated: 08.28.2017

Figure 12. Locations of PAM deployments and trackline coverage in the Gulf of Mexico, Eastern Planning Area.



Sources: BOEM and ESRI.

Figure 13. Locations of PAM deployments and trackline coverage in the Gulf of Mexico, Central Planning Area.



Sources: BOEM and ESRI.

Figure 14. Locations of PAM deployments and trackline coverage in the Gulf of Mexico, Western Planning Area.

High-frequency generally includes sounds above 25 kHz and is generally located close to the receiver. Thermal noise, the result of particles moving close to the hydrophone for instance, is included in this category.

4.1.1 Natural Biological Sound Sources

In the Northern GOM, the Littoral Acoustic Demonstration Center-Gulf Ecological Monitoring and Modeling (LADC-GEMM)[20] research consortium has actively researched the sources of ambient noise and has conducted marine mammal measurement and analysis during the last decade. The consortium is led by the University of Louisiana at Lafayette with academic partners from the University of New Orleans, University of Southern Mississippi, and technical advisers from the Naval Research Laboratory and the Naval Oceanographic Office at Stennis Space Center. The aims of setting up the LADC and of their 2001 study were to measure and characterize the ambient noise baseline within the Northeastern GOM; measure and model noise propagation and examine the associated effects of fronts and eddies; measure and model TL; and determine placements for acoustic sensors and oceanographic equipment considering the incorporation of computer modeling to characterize the littoral environment. Recordings were made using bottom-mounted buoys (previously described as EARS buoys).

In early experiments (2001, 2002) the hydrophones were placed in an area with frequent visual sightings of sperm whales resident to the region. A large portion of the study was relevant to ambient noise, and aimed to achieve the following: detect classify, identify, and track sperm whales, and other marine mammals; coordinate the near-bottom measurements with other researchers conducting visual observation, surface acoustic measurements, and acoustic tag measurements in the region; investigate sperm whale behavior near airguns; and evaluate and modify automatic detection and characterization of marine mammal vocalizations received on near-bottom mounted hydrophones.

The 2001 recordings from three EARS buoys included sound measurements up to 6,000 Hz over 36 days. Recordings contained click and codas vocalizing sperm whales in addition to ships and airgun sounds. The researchers indicated an inverse relationship between the number of vocalizing sperm whales and the amount of geophysical prospecting (i.e., seismic surveys), and shipping activity (Newcomb et al. 2002).

Sidorovskaia and Li (2017) described changes in the baseline noise levels for the Northern GOM (Mississippi Valley-Canyon region) over a short-term seasonal scale and a long-term decadal scale. The field studies focused on the Mississippi Canyon area, where LADC-GEMM continued to deploy bottom-mounted hydrophones in 2007, 2010, and 2015. Recordings were analyzed and bio-sound sources were clearly distinguishable among baseline noise levels for marine mammal activities. Anomalies between 5 and 10 kHz indicate the presence of sperm whales; a 25 to 40 kHz variability indicates the presence of beaked whales and deep-water dolphins.

Sidorovskaia and Li (2017) emphasized that more analysis is required to confirm this hypothesis. The researchers also found high variability in ambient noise between two sites only 28 kilometers (15 nautical miles) apart. This variability in ambient noise could affect the local movement and regional migration patterns for marine mammals in the area. More study is being completed to examine these trends (Sidorovskaia and Li 2017). More information on marine mammal acoustics can be found in **Section 4.2**.

A small number of studies characterize ambient biological noise associated with fish species. Wall et al. (2014) used PAM to map red grouper (*Epinephelus morio*) vocalizations and investigate daily, seasonal, and spatial vocalization patterns on the West Florida Shelf. The University of South Florida researchers collected 11 months of data using fixed recorders and autonomous underwater vehicles (AUVs). The authors concluded that fish calling increased at sunrise and sunset. Although grouper calling was detected throughout the year, calling was highest in the late summer months of July and August and the early winter months of November and December. There was no difference comparing three phases of the lunar cycle. Trends in fish distribution were examined using AUV tracks and researchers found that red grouper

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[20] LADC-GEMM: http://www.ladcgemm.org/about/

vocalizations primarily were recorded in waters 15 to 93 meters (49 to 305 feet) deep with the majority occurring between 30 and 50 meters (98 and 164 feet). Vocalizations increased in hard bottom areas and within the Steamboat Lumps Marine Protected Area. These trends corresponded with known spawning habitat for grouper in Steamboat Lumps Marine Protected Area in particular and hard bottom areas in general (Wall et al. 2014). Nelson et al. (2011) found that red grouper vocalizations were dominant in the 50 to 180 Hz range on the West Florida Shelf.

Wall et al. (2012) investigated fish sounds collected from June to September 2008 using 23 autonomous, bottom-mounted acoustic recorders deployed in the Eastern GOM. The aim of the study was to determine the co-occurrence of vocalizations with presence of boats. A peak in sound production by fish was estimated at 500 to 1,500 Hz (Wall et. al 2012).

Finally, the Gulf Coast Research Laboratory has conducted studies using PAM to identify spotted sea trout habitat; however, the location of the study in estuaries and does not extend into BOEM's Planning Areas offshore in the GOM (Gulf Coast Research Laboratory 2017)[21].

4.1.2 Natural Physical Sound Sources

The work by the LADC-GEMM has revealed trends in the ambient noise characteristics for such physical sound sources as wind speed and wave height. For instance, as wind speed increases, associated ambient noise levels also increase (Newcomb et al. 2007). Researchers correlated a Beaufort Sea State 3 to 4 in 200 to 1,000 Hz band with tropical storm events (Newcomb et al. 2002). The studies also indicated a considerable decrease in marine mammal activity during hurricane passes. Sidorovskaia and Li (2017) also identified changes in short –term ambient noise levels with changes in weather conditions. Industrial and natural sources share the range of 200 to 25,000 Hz. In the fall, lower frequency soundscapes are predominantly associated with weather conditions due to low level of exploration activity in the GOM (Sidorovskaia and Li 2017).

In the Eastern Planning Area, the Office of Naval Research deployed EARS to measure ambient noise at approximately 294 kilometers (159 nautical miles) south of Panama City, Florida, in waters with a bottom depth of 3,200 meters (10,498 feet). Data were collected in intervals of 10 to 14 months in the vicinity of a major shipping lane. Sampling occurred at 2,500 Hz with a bandwidth of 10 to 1,000 Hz. The study found that events associated with extremely windy months, which include summer hurricanes and winter storms, have a major impact on ambient noise levels. Sounds from winds peaked at the higher frequencies (400 to 950 Hz) in this portion of the GOM during the summer of 2004, when four hurricanes were recorded. The high-frequency levels were also loud in November through January when wind speed is higher due to winter storms.

On the other hand, low frequencies were loudest in March 2005 and lowest in September 2004. Low-frequency is generally associated with shipping traffic; therefore, more loud noise associated with shipping is heard in periods where conditions are more favorable for ship traffic. The researcher detected a peak in the fluctuation spectrum of 25 Hz at a period of 8 hours, which occurred year round, but was particularly strong from November through February. This could not be attributed to shipping or weather; instead, it was suggested by Snyder (2007) that this is due perhaps to distant drilling operations to the west of the EARS location.

There was no significant difference in noise levels when comparing between daytime and nighttime periods (Snyder 2007). Snyder (2009) found that ambient noise levels also increased during a hurricane. Analysis of recordings made in 2004 during Hurricane Ivan shows an overall increase by 12 dB over the baseline conditions between 200 and 800 Hz (Snyder 2009). Unlike transient anthropogenic sources such as shipping, ambient noise related to weather like wind does not peak in time and tends to exhibit long-term smooth spectral level increase (Snyder and Orlin 2007).

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[21] See http://gcrl.usm.edu/research/spotted.seatrout.habitat.php .

4.1.3 Anthropogenic Underwater Noise Levels in the Gulf of Mexico

Whether intentionally or unintentionally introduced, anthropogenic noise in the marine environment is an important component of ocean noise (Richardson et al. 1995; Hildebrand 2009). **Table 2** and **Figure 15** include an overview in general of contributing acoustic sources in each frequency bandwidth.

Table 2. Example Representative Sound Sources by Frequency Level

Frequency Level	Representative Acoustic Sources
1–10 Hz	Ship propellers[1]; explosives
10–100 Hz band	Shipping activities[1]; explosives; seismic surveying sources[1]; construction activities; industrial activities; naval surveillance sonar systems
100–1,000 Hz	Shipping activities[1]; explosives; seismic surveying sources[1]; construction activities; industrial activities; naval surveillance sonar systems
1,000–10,000 Hz	Nearby shipping activities[1]; seismic airguns[1]; underwater communication; naval tactical sonars; seafloor profilers; depth sounders
10,000–100,000 Hz	Underwater communication; naval tactical sonars; seafloor profilers; depth sounders; mine-hunting sonars; fish finders; some oceanographic systems (e.g., acoustic Doppler current profilers)
Above 100,000 Hz	Mine hunting sonar; fish finders; high-resolution seafloor mapping devices (e.g., side-scan sonars, some depth sounders, some oceanographic sonars, and research sonars for small-scale oceanic features)

[1] These sources represent the major noise contributors in the GOM.

Sources: NRC (2003) and Hildebrand (2009).

Northern GOM soundscapes are characterized by a mix of industrial and natural sources across the 200 to 40,000 Hz band, as shown in Figure 15 (Sidorovskaia and Li 2017). Shipping activity and seismic surveys are the major noise contributors in the GOM (Shooter 1982; Newcomb et al. 2002, Snyder 2007; Snyder and Orlin 2007; Estabrook et al. 2016; Wiggins et al. 2016; Sidorovskaia and Li 2017). Analyses of long-term (i.e., multi-year) ambient noise recordings reveal pervasive activity from seismic surveys (Estabrook et al. 2016; Sidorovskaia and Li 2017; Wiggins et al. 2016), often detected across broad expanses of the GOM and ranges extending to at least 700 kilometers (378 nautical miles) (Rice et al. 2015; Estabrook et al. 2016).

Estabrook et al. (2016) noted that sound levels from shipping activity were not nearly as pronounced as those from the seismic surveys, which for the latter, in many cases, persisted for months at a time. In a review of multi-year GOM EARS data, scientists found no indication of an increasing baseline level of ambient noise (Sidorovskaia and Li 2017) below 1,000 Hz. However, Sidorovskaia and Li (2017) noted that high-frequency spectral levels showed an increase in more recent years (2010 and 2015) in the ambient soundscape of the Northern GOM. This increase may be attributed to anthropogenic activities including the increasing use of unmanned devices (sonars, AUVs, etc.) which use high-frequency bands for communication and exploration for seismic exploration.

Airguns and shipping activity are prevailing sources of anthropogenic noise in the GOM, and there were times in this report’s focus period with noticeable reductions in noise levels. For example, during hurricane and/or tropical storm passages, low-frequency noise levels decrease. This decrease is attributed to the absence and/or decrease of anthropogenic activity in the interest of human safety (Newcomb et al. 2002; Estabrook et al. 2016; Wiggins et al. 2017). Another time period of reduced anthropogenic baseline noise began on 21 September 2010. During May 2010, the U.S. Department of Interior enacted a moratorium on all deep-water drilling in U.S. waters of the GOM in the wake of the April 2010 explosion of the *Deepwater Horizon* drilling rig and resulting oil spill. The moratorium was lifted in October 2010; however, most oil exploration activity and all exploratory drilling activities in U.S. waters of the GOM were suspended until 2011. Sidorovskaia and Li (2017) noted that their 2010 EARS data provided a unique dataset of deep-water baseline ambient noise levels in the Northern GOM with reduced industrial operations, particularly for deep-water drilling.

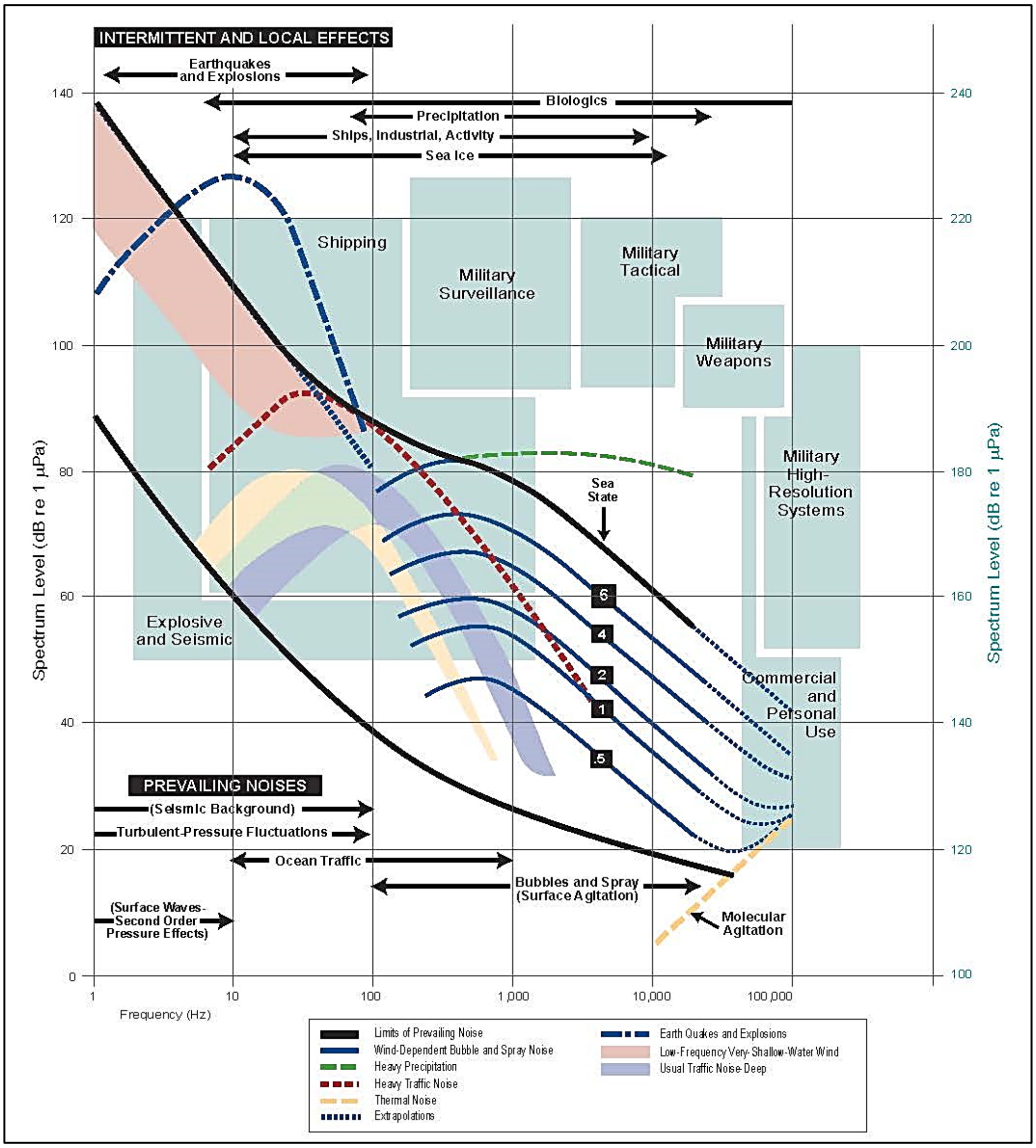

Figure 15. Sources of noise.

Shipping, military, commercial, and personal uses are shown in blue and use the blue spectrum level values on the right axis. These values are 100 dB greater than the values used on the left axis for intermittent, local effects, and prevailing noises (100 dB corresponds to five orders of magnitude). Source: Bradley and Stern 2008 [which was based on Wenz 1962; reprinted with permission, *Journal of the Acoustical Society of America*].

Seasonal variations in ambient noise levels due to industrial exploration are evident in various studies conducted in the GOM (Snyder 2007; Estabrook et al. 2016; Wiggins et al. 2016; Sidorovskaia and Li 2017). Anthropogenic noise sources showed considerable seasonal variability with the highest levels measured during the summer months (Sidorovskaia and Li 2017).

There also is regional variation in anthropogenic noise in the GOM. For example, the two Eastern GOM HARP sites showed high sound pressure spectrum level variability above 200 Hz associated with wind events in contrast to the three north-central GOM sites. (Wiggins et al. 2016). HARP measurements showed high average sound pressure spectrum levels (90 to 95 decibels referenced to 1 microPascal squared [dB re 1 μPa^2]) for deep (approximately 1,000 m) water sites below 50 Hz, caused by a high density of seismic exploration and shipping in the GOM.

Two shallow water HARP sites, one on the shelf and the other on the shelf break, show much different sound pressure spectrum levels compared to the deep water sites and compared to each other. The trends are primarily a function of proximity to anthropogenic activity. In their assessment of the evolution of the GOM soundscape over the past 15 years, Sidorovskaia and Li (2017) noted short-range spatial variability of the soundscapes within the vicinity of the Mississippi Canyon. The scientists noted that the analyses strongly suggest that the noise environment can significantly vary on a daily basis between two sites which are only 28 kilometers (15 nautical miles) apart (Sidorovskaia and Li 2017).

There has been minimal change in the eastern deepwater GOM ambient soundscape recently. Wiggins et al. (2016) compared data collected by HARPs during 2010–2013 to data collected by Snyder et al. (2007) with EARS in 2005. The authors found minimal change in the ambient soundscape of the eastern deepwater GOM over the six to eight years between the two measurements (1/3-octave levels from 2005 were within 1 to 2 dB of those measured in 2010–2013) (Wiggins et al. 2016).

The following subsections address anthropogenic noise contributors to the soundscapes of the Northern GOM.

4.1.3.1 Aircraft

Aircraft support the Outer Continental Shelf (OCS) oil and gas activities, and various research (i.e., aerial surveys) and tourism activities in the GOM. There have been no published measurements of underwater sound transmission and propagation from aircraft flying over the GOM. As noted by Wyatt (2008), little published primary source information is available for underwater noise produced by overflying fixed or rotary-wing aircraft associated with current oil and gas industry activities. Aircraft noise is generally short in duration and transient in nature, although it may ensonify large areas. Dominant tones in noise spectra from helicopters and fixed-wing aircraft are generally below 500 Hz with SPLs around 149 decibels referenced at 1 microPascal root mean square at 1 meter (dB re 1 μPa [rms] m) (Richardson et al. 1995). Underwater sound caused by an overhead airborne source will be highest at the surface and decrease with depth.

Marine mammals can receive both acoustic and visual cues (the aircraft and/or its shadow) from the circling aircraft, if they are located directly under the aircraft and/or well within Snell's predicted sound cone. Marine mammal responses to aircraft were discussed in Richardson et al. (1995) and Smultea et al. (2008). Snell's Law predicts a 26-degree sound cone from the vertical for the transmission of sound from air to smooth-surface water (Urick 1972, Richardson et al. 1995). The angle of the sound cone becomes greater in Beaufort wind force >2. In general, sounds emitted by aircraft are within the hearing range of most cetaceans, particularly those with good low- (<1 kHz) and mid-frequency (1 to 10 kHz) hearing abilities, such as whales and delphinids. The sound emitted from an aircraft varies with aircraft type (e.g., engine number and/or size, helicopter or fixed wing) and maneuvers performed (e.g., straight-line pass, tight or wide circles, speed or engine bursts, etc.) (see Smultea and Lomac-MacNair 2016).

4.1.3.2 Vessels

Shipping activity produces broadband noise as an unintended byproduct that contributes substantially to low-frequency (5 to 300 Hz) noise. Sound produced by motorized vessels contains a set of harmonically related tones caused by the cyclic properties of engine, shaft, and propeller rotation. The fundamental frequency of the tones, and the relative amplitudes at the harmonic frequencies are determined by the boat speed, engine type, propeller movement, and associated characteristics (Ogden 2010). Thus, a boat can be identified by the type of sound it introduces into the water. The noise created by recreational motorized vessels is high amplitude (e.g., typical peak narrowband source levels 150 to 165 dB re 1 μPa) and typically low frequency (e.g., peak frequency at high revolutions per minute approximately 300 to 450 Hz (Barlett and Wilson 2002 as cited in Simard et al. 2016).

Source levels of ships range between 140 and 195 decibels referenced 1 microPascal at 1 meter (dB re 1 μPa @ 1 m) (NRC 2003, Hildebrand 2009), depending upon factors such as ship type, load, and speed, and ship hull and propeller design. McKenna et al. (2012) measured underwater radiated noise for seven types of modern commercial ships during normal operating conditions in the Southern California Bight and found that a 54,000 gross tons container ship had the highest broadband source level at 188 dB re μPa@1m; a 26,000 gross tons chemical tanker had the lowest level at 177 dB re μPa@1m. Bulk carriers had higher source levels near 100 Hz, while container ship and tanker noise was predominantly below 40 Hz. Sound levels typically increase with increasing speed and vessel size (Allen et al. 2012; McKenna et al. 2013). Some energy also is detectable at much higher frequencies (up to 160 kHz) at close ranges (Hermannsen et al. 2014).

Though vessel-specific source levels are generally lower than many other anthropogenic noise sources, the large number of ships makes ship noise a major component of global rising ambient noise levels (e.g., Hatch et al. 2012). The US Department of Transportation Maritime Administration estimates that large vessel traffic (based on number and tonnage of vessels) is higher in the GOM than in other U.S. waters (US Department of Transportation Maritime Administration vessel port call statistics)[22]. A number of studies have been conducted in the GOM on sound associated with shipping and boating activities, including the following:

- Wiggins et al. (2016) collected HARP data that allows to examine contribution of shipping noise into the GOM soundscapes. The authors noted that the noise associated with a particular ship lasted less than 1 hour (due to the ship's movement past detection range of the acoustic recorder) and that shipping sounds were masked by airgun sounds at frequencies below 100 Hz.
- Researchers identified that MARU sites positioned nearest to high-density shipping lanes that lead to the Port of South Louisiana and the Port of Houston recorded the highest levels of 130 and 128 dB, respectively (Estabrook et al. 2016).
- In a study of boat visitation rates at natural and artificial reefs near Tampa Bay, Florida, acoustic data were collected between April 2013 and March 2015 (Simard et al. 2016). In the paper, the authors show a spectrogram of an outboard engine driven boat at high, with harmonics that extended upward to approximately 9,000 Hz. The detected boat sounds were of recreational boats traveling at high speeds based on the presence of higher frequency harmonics, not large commercial vessels which have lower fundamental frequencies.
- During a bottlenose dolphin study conducted on the West Florida Shelf from April to September 2008 and from April 2009 to June 2010, Simard et al. (2015) recorded harmonics from recreational boats extending into ultrasonic frequencies (>20 kHz). The authors also noted that boat noise was noticeably more common in coastal recordings than in offshore recordings; however, lesser variation was observed seasonally.
- From analyses of EARS data collected during 2004 and 2005 (Snyder and Orlin 2007), the average ship noise duration was 1.06 hours with a standard deviation of 1.08 hours. The average inter-arrival

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[22] See US Department of Transportation Maritime Administration vessel port call statistics.

time (time between ships) was 3.84 hours with a standard deviation of 3.73 hours. Shipping peaks dominated at levels between 25 and 400 Hz.

- During 2004–2005 in the GOM, Snyder (2007) recorded ambient noise in the 10 to 1,000 Hz band for over 1 year at a site approximately 300 kilometers (162 nautical miles) south of Panama City, Florida at about 3,000 meters (9,843 feet) depth, near local shipping lanes. Spectrum levels were computed in 1/3-octave bands from calibrated hydrophones. Mean sound pressure spectrum levels were approximately 90 decibels referenced 1 microPascal squared per Hz (dB re 1 μPa^2/Hz) at 25 to 50 Hz, approximately 80 dB re 1 μPa^2/ Hz at 100 Hz sloping down to about 60 dB re 1 lμPa^2/Hz near 1,000 Hz with highest variability at 25 Hz and at frequencies above approximately 200 Hz. At the lowest frequencies, these high levels are similar to sites with exposure to heavy commercial shipping, both distant and local (Andrew et al. 2002, Chapman and Price 2011), and at the higher frequencies variability was associated with local wind.

4.1.3.2.1 Echosounders

Commercial and scientific vessels use active sonars for detection, localization, and classification of underwater targets, including the seafloor, plankton, fish, and human divers (Hildebrand 2009). Source frequencies typically range from tens to hundreds of kHz. **Table 3** provides an overview of systems and their associated source levels. Commercial and scientific sonars have lower source levels than military sonars, and many source types are highly directional, such as seafloor mapping and echo-sounding sonars that are directed toward the ocean bottom.

Commercial and scientific sonars are more ubiquitous. For example, most large and small vessels are equipped with commercial sonars for water depth sounding that are operated continuously for aid in navigation (NRC 2003). Acoustic telemetry is becoming more common and is used for underwater communications, remote vehicle command and control, diver communications, underwater monitoring and data logging, trawl net monitoring, and other applications. Acoustic modems operate over distances up to 10 kilometers (5.4 nautical miles) and use signals with frequencies ranging from 7 to 45 kHz and source levels up to 190 dB re 1 μPa @ 1m (Hildebrand 2009).

Table 3. Commercial and Scientific Sonar Sources

Sonar Type (frequency width)	Maximum Source Levels (if known)
Multibeam (seafloor mapping; 12 kHz or 70 to 100 kHz)	245 dB re 1 μPa @ 1m
Sub-bottom profilers (3–7 kHz)	230 dB re 1 μPa @ 1m
Hydroacoustic sonars (20–1,000 kHz)	
Scanning sonars (85–100 kHz)	
Synthetic aperture sonars (85–100 kHz)	
Acoustic modems (7–45 kHz)	190 dB re 1 μPa @ 1m

Source of information: Hildebrand (2009).

Though echosounders may transmit at high source levels, the very short duration of their pulses and their high spatial directivity make them unlikely to cause damage to marine mammal auditory systems, according to current knowledge, based on a review by Lurton and DeRuiter (2011). Behavioral responses are of concern as well. Unlike nonlethal echosounders, effects of various types of sonar on marine mammals were reviewed by Richardson et al. (2010). Richardson et al. (2010) found that there have been few studies conducted on the responses of mysticetes to mid-frequency and high-frequency echosounders. When compared with naval tactical sonar, civilian and commercial echosounders generally produce sound at lower source levels, which translates to lower potential received levels for marine mammals. More information is available in Richardson et al. (2010).

4.1.3.3 Commercial fishing

Commercial fishing vessels radiate broadband noise over a wide range of frequencies. Diesel propulsion engines are typically found on most fishing vessels; these engines radiate energy into the water at low frequencies. These tonals are typically less than 500 Hz and are related to the rotational speed and the number of pistons on the diesel engine. The dominating noise at lower frequencies (below 20 Hz) is generated by sound produced through propeller cavitation (above approximately 1 kHz). Detailed features of the vessel noise spectrum depend on the type of machinery used, vessel speed, and propeller loading (Mitson and Dalen 2007). Much of the machinery on a vessel produces vibration in the frequency range of a few Hz to 1.5 kHz. This acts on the hull and radiates noise into the water.

The major commercial fishery in the Northern GOM is the shrimp fishery, which uses bottom trawl nets. Marine Mammal Organisation (MMO) (2015) reported a frequency range of 40–1,000 Hz with a peak of 100 Hz, and source level of 147 dB re 1 μPa m for an operating trawler. In the case of shrimp trawlers, sound is generated both by the towing vessel and by the fishing gear being dragged across the seabed (Chapman and Hawkins 1969; Normandeau Associates, Inc. 2012). Bottom trawls are fitted with chains, rollers, and metal bobbins that generate irregular sounds as they come into contact with one another and with the seabed. As noted by Normandeau Associates, Inc. (2012), there are also low-frequency (below 100 Hz) sounds from the warps or cables connecting the trawl to the ship, the trawl doors, or spreading devices, and contact with the seabed. Only one published study measuring noise produced by fishing vessels in the GOM was located:

- Newcomb et al. (2008) recorded noise levels at frequencies less than 10 kHz that were generated by a shrimp trawler in Mississippi Sound. The levels due to the shrimp boat were greater than 60 dB at the lowest frequencies. Additional higher frequency spikes were detected at the 30 to 35 kHz and 40 to 50 kHz ranges; these frequencies were attributed to the processing equipment operating on board the trawler. Newcomb et al. (2008) also showed spectrograms with power supply switching transients.

4.1.3.4 The oil and gas industry

Underwater noise associated with offshore petroleum-related operations may be generated by many types of sources and may have a wide variety of acoustic characteristics. The following subsections summarize what is known about noise associated with seismic surveys, operating platforms, and structure removal.

4.1.3.5 The seismic industry (seismic surveys)

Seismic surveys commonly are used not just by the oil and natural gas industry, but also by the US Geological Survey, the National Science Foundation, and in other locales, the offshore wind industry.

Geophysical surveys are conducted to achieve the following goals:

1. Obtain data for hydrocarbon and mineral exploration and production
2. Aid in siting of oil and gas structures, facilities, and pipelines
3. Identify possible seafloor or shallow depth geologic hazards
4. Locate potential archaeological resources and benthic habitats that should be avoided

Geophysical survey types and their purposes are summarized in BOEM (2016b). Noise produced by geophysical seismic surveys includes sounds from airgun pulses, as well as the survey vessel and associated survey boats (Estabrook et al. 2016). In this section, we focus specifically on the contribution of airgun noise to the acoustic environment of the GOM.

Seismic surveys are conducted using an array of airgun releases that introduce compressed air into the water and creates a bubble that generates a pulse of sound sufficiently energetic to penetrate deep beneath the seafloor. A seismic airgun array produces a single downward-directed high-energy impulse that is primarily directed downward to map the composition of the seafloor (Gisiner 2016). Unavoidably, some sound energy is emitted in directions away from vertical (BOEM 2016a). In many instances, the time between seismic pulse emissions by a seismic array is occupied by a series of multiple arrivals of the same reverberated pulse following or preceding the main pulse arrival at the receiver location (Rankin 1999, Estabrook et al. 2016, Guerra et al. 2016).

Sound energy is reverberated and reflected after propagation over many tens of kilometers or more (Guerra et al. 2016, Estabrook et al. 2016). In fact, Estabrook et al. (2016) determined that seismic airgun noise in the Northern GOM propagated over a large spatial scale of several hundred kilometers. One notable finding from this seismic survey occurred when airgun pulses estimated to originate within the Mississippi Canyon, propagated sound approximately 620 kilometers (335 nautical miles) to the Dry Tortugas, and 165 kilometers (89 nautical miles) southeast, spanning at least 700 kilometers (378 nautical miles) across the Mississippi Fan.

Airguns are broadband acoustic sources that generate energy over a wide range of frequencies, from less than 10 Hz to more than 5 kHz, with industry usable frequencies ranging between 5 and 500 Hz (BOEM 2016a). The acoustic output has its highest energy at relatively low frequencies of 10 to 200 Hz (Goold and Fish 1998). Airgun arrays may also produce significant high-frequency sound energy, up to 22 kHz within a few km of the source (Goold and Fish 1998). Airguns create intense sound impulses with a short rise time and very high peak SPL source levels in the region of 220 to 248 dB re 1 µPa @ 1 m), which are repeated around every 10 to 20 seconds and can travel large distances in the water column. In addition to reporting on airguns, Crocker and Fratantonio (2016) reported on characteristics of radiated sound measured for 18 distinct geophysical survey systems.

Research efforts that have provided information on seismic survey acoustic characterization in the GOM include the following:

- From 2010 to 2017, HARPs deployed by Scripps Institution of Oceanography have monitored the soundscape of three deep and two shallow water sites in the GOM over 10 to 3,300 Hz. Average sound pressure spectrum levels were high, >90 dB re 1 µPa2/Hz at <40 Hz for the deep water sites and were associated with noise from airguns. More moderate SPLs, <55 dB re 1 µPa2/Hz at >700 Hz, were present at a shallow water site in the Northeastern GOM, removed from the zone of industrial development and bathymetrically shielded from deep water anthropogenic sound sources. The study is continuing to date.
- Between July 2010 and February 2012, MARUs deployed by Cornell University collected acoustic data at 7 sites in the Northeastern GOM (Estabrook et al. 2016). Seismic survey and shipping noise dominated the ambient noise environment and chronically elevated noise levels across the Northern GOM ecosystem below 500 Hz throughout the multi-year study (Estabrook et al. 2016). Anthropogenic noise sources significantly contributed to the ambient noise environment; however, seismic survey noise dominated the noise environment and chronically elevated noise levels across several important marine habitats (Estabrook et al. 2016). The 1⁄3-octave band spectrograms illustrated persistent shipping and seismic survey activities throughout the Northern GOM during the study. Seismic and shipping noise appeared to temporarily decrease or stop due to Tropical Storm Lee between 1 and 6 September 2011 (Estabrook et al. 2016). During this time period noise levels above 1 kHz at each site increased and noise below 500 Hz decreased, suggesting a temporary decrease in anthropogenic activity. Seismic surveys occurred persistently during this time period of July 2010 through February 2012 within the De Soto Canyon and Lloyd Ridge areas throughout this study (Estabrook et al. 2016).
- In 2007–2008, two short cruises were conducted to calibrate seismic sources on the R/V *Marcus Langseth* (Diebold et al. 2010). These findings were compared with the 2003 calibration of the seismic sources on the R/V *Maurice Ewing* in the GOM (Tolstoy et al. 2004). The 2007–2008 cruises were moved westward in comparison to the 2003 cruises. This relocation was incorporated to avoid drifting from shallow sites.
- In September 2007, the LADC conducted an experiment in the northwestern GOM to measure the calibrated three-dimensional acoustic field of the primary arrival from a seismic airgun array–the 3D Seismic Source Characterization Project (Newcomb et al. 2009). Twenty paired sensitive and

desensitized hydrophones were deployed at a range of depths on three separate moorings. Special positioning equipment was used to locate these moorings continuously in three dimensions. EARS buoys recorded the wide bandwidth data from the industrial seismic airgun array for a full range of vertical and horizontal arrival angles and broad range of distances between source and receiver. The data were acquired with sufficient shot records to establish a statistically valid sample of SPLs and spectral characteristics in over 1,000 angular bins at frequencies up to 25 kHz.

- In the summer of 2003, the LADC conducted the first GOM acoustic characterization experiment for a 21-element marine seismic exploration airgun array of total volume of 0.0588 cubic meters (3,590 cubic inches). Two EARs buoys, one with a desensitized hydrophone, were deployed at a depth of 758 meters (2,487 feet) in waters with a bottom depth of 990 meters (3,248 feet), near Green Canyon (Tashmukhambetov et al. 2008). The researchers collected data on pressures, which could be used in testing models of the sound propagation from use of seismic equipment. This modeling can be useful in predicting sound exposure levels for marine mammals, which is useful in turn in planning future seismic surveys.
- As part of the Minerals Management Service (MMS, now BOEM)-funded Sperm Whale Seismic Study (SWSS), during 2002 and 2003, tagged sperm whales (*Physeter macrocephalus*) were experimentally exposed to airgun pulses in the GOM, with the multi-sensor, acoustic recording tags (e.g., DTAGs; Johnson and Tyack 2003) providing acoustic recordings at measured ranges and depths (Madsen et al. 2006). Madsen et al. (2006) quantified the sounds exposure levels (SELs) recorded on acoustic tags attached to eight sperm whales at ranges of 1.4 to 12.6 kilometers (0.8 to 6.8 nautical miles) from controlled airgun array sources operated. Madsen et al. (2006) discovered that in the GOM received levels can be as high at a distance of 12 kilometers (6.5 nautical miles) from a seismic survey as they are at 2 kilometers (1.1 nautical miles) (in both cases >160 dB peak-to-peak pressure level). Received levels, as determined from acoustic tags on sperm whales, generally fell at distances of 1.4 to 6 to 8 kilometers (0.8 to 3.2 to 4.3 nautical miles) from the seismic survey, only to increase again at greater distances (Madsen et al. 2006). Due to multi-path propagation, the animals were exposed to multiple sound pulses during each firing of the array with received levels of analyzed pulses falling between 131 to 167 dB re 1 μPa (peak pressure level) [111 to 147 dB re1 μPa (rms pressure level) and 100 to 135 dB re 1 μPa^2 s (SEL) after compensation for hearing sensitivity using the *M*-weighting. Received levels varied widely with range and depth of the exposed animal; when whales were close to the surface, the first arrivals of air-gun pulses contained most energy between 0.3 and 3 kHz, a frequency range well beyond the normal frequencies of interest in seismic exploration. Some arrivals recorded near the surface in 2002 had energy predominantly above 500 Hz; a surface duct in the 2002 sound speed profile helps explain this effect (DeRuiter et al. 2006). Findings indicated that airguns sometimes expose animals to measurable sound energy above 250 Hz, and demonstrated the influences of source and environmental parameters on characteristics of received airgun pulses (DeRuiter et al. 2006).
- In summer 2001, Newcomb et al. (2002) used EARS for approximately one month to record ambient noise. Data clearly revealed seismic airguns. Newcomb et al. (2002) captured similar sound pressure spectrum levels by using similar equipment to Snyder (2007). However, the Newcomb et al. (2002) study was conducted at shallower depths of 600 to 1,000 meters (1,968 to 3,280 feet) on the continental slope as compared with the Snyder (2007) study, which captured data at deeper depths of 3,200 meters (10,499 feet).

Although the following survey falls outside of the 2002–2017 period focused on in this report for the literature review, we have included the following significant and relevant findings for the GOM because the study's emphasis included collection of acoustic information:

- In surveys of the US waters of the Northern GOM, the MMS-sponsored GOM cetacean studies (GulfCet I and II) included using passive acoustical techniques throughout the 1990s (1992–1997) to determine seasonal variability in the occurrence and distribution of marine mammals (Davis and Fargion 1996; Davis et al. 2000). Rankin (1999) studied the potential effects of sounds from seismic exploration on the distribution of cetaceans. She determined that the overall average intensity level

> was 8.4 dB re 1 μPa (above ambient), with a maximum of 13. 1 dB at 613.5 Hz and a minimum of 4.3 dB at 26.7 Hz. High-frequencies were measured up to 2,426 Hz for cruise 4 (12 February–27 February 1993) of GulfCet I. The overall average peak was at 81.7 Hz, with a high at 106.9 Hz and low at 35 Hz. Seismic sounds were concentrated in petroleum exploration areas on the upper and middle continental slope.
>
> The airgun pulses recorded within the cold core rings and ring peripheries were generally higher in intensity than those recorded in other hydrographic features. The presence of more intense seismic exploration sounds in these regions appear to be due to the tendency of the cold core ring features to occur in more shallow regions, where oil exploration and production are greater. The confluence zones and the warm core rings were located in deeper waters. Although they contained a large percentage of time with seismic exploration sounds (34 and 31 percent, respectively), the intensities in these habitats were considerably lower.
>
> It is likely that the source of the seismic pulses recorded in the warm core rings were along the continental slope and Rankin's focal study area, where the cold core rings were located. The regions bordering the cold core rings also contained a great deal of time with lower intensity seismic exploration sounds. The Eastern Planning Area was characterized as having little active seismic exploration surveys and, therefore, a low presence of noise from oil and gas exploration.

Summaries of documented behavioral impacts on marine mammals from seismic surveys can be found in a variety of resources including McCauley et al. (2000b), Bain and Williams (2006), Nowacek et al. (2015), BOEM (2016a, 2016b), and Estabrook et al. (2016).Operational Noise from Platforms Drilling and production platforms generate a continuous type sound through the transmission of the vibrations of the machinery and drilling equipment such as pumps, compressors, and generators that are operating on the platform. Noise resulting from the drilling operation may include the following:

1. Machinery noise, such as that from the drill's drive machinery, including drilling noise, engine and exhaust noise, and from the generators and other hotel plant used on the rig;
2. Noise and vibration from the grinding of rock in the seabed, which can either radiate directly from the drill bit through the rock into the water, or can conduct upwards through the drill shaft, radiating into the surrounding water;
3. Noise from communication and positioning systems, such as submarine warning beacons and Doppler type flow meters;
4. In the case of drill ships, noise from dynamic positioning (DP) thrusters (Nedwell and Edwards 2004, Genesis 2011). Drill ships and some types of semi-submersible maintain position using dynamically-positioned thrusters. Where the drilling rig or production platform is reliant on support and supply from other standby and supply vessels, these are often equipped with DP thrusters and powerful engines and therefore contribute to the overall noise level of drilling and production activities.

Noise from conventional metal-legged structures and semisubmersibles is not particularly intense and is strongest at low frequencies, averaging 119 to 127 dB re 1 μPa @1 m levels at 5 Hz and 154 dB re 1 μPa-m in the 10 to 500 Hz band, respectively (Richardson et al. 1995). Noise from drilling is continuous and occurs at low-frequency levels, generally closest to 5 Hz (Nedwell and Edwards 2004) made measurements of the noise radiated during drilling from the *Jack Bates* semi-submersible rig while drilling in deep water northwest of the Shetlands Islands in Scotland, United Kingdom, during September 2000. Measurements were made from the drill rig both during drilling, and when the drill was not in use.

Nedwell and Edwards (2004) noted that tonals could be seen at several unrelated frequencies ranging from approximately 20 to 600 Hz and suggested that they correspond to machinery noise. During drilling, the level of sound in the band from 20 Hz up to 1 kHz was significantly elevated over that for no drilling, and displayed tonal components which were approximately 20 to 30 dB higher than the level with no drilling. These tonals might have corresponded to natural frequencies of the drill shaft, excited by the drilling machinery on the rig or by the action of cutting at the seabed. Drillships are presumed to be the noisiest way of drilling in water, primarily because the hull has good coupling with the water and thus, facilitates underwater sound radiation (Kyhn et al. 2015). Other types, such as jack-ups and semi-submersible rigs have most machinery well above the water line and therefore, less noise is transmitted to the surrounding water.

Drilling-related noise from semi-submersible platforms in deep waters are between 10 and 40,000 Hz. BOEM estimated sound source levels for semi-submersible platforms at 154 dB re1µPa-m (BOEM 2017). Noise levels on semi-submersibles are typically lower than drillships (BOEM 2017).

As noted by Antunes and Gordon (2008), long periods of monitoring in conjunction with detailed information about rig and platform operations will be required to fully characterize noise output associated with different activities.

Information on drilling noise in the GOM is sparse. However, the following information was found to characterize this type of anthropogenic noise:

- Wiggins et al. (2016) recorded tones in the GOM in the 100–200 Hz band, found that they were common in recordings from deep-water HARP sites, and suggested that they may be related to petroleum extraction or exploration activities.
- During BOEM-funded GOM sperm whale studies in the early- to mid-2000s, 12 recording sessions were conducted in the GOM in the vicinity of drilling rigs and production platforms not drilling at the time in the GOM (Antunes and Gordon 2008). Of particular interest was a recording made at a range of around 9 kilometers (5 nautical miles) from an unidentified drilling rig in 2003; there was a pronounced and constant tonal at 260 Hz that was not pinpointed to a source.
- Antunes and Gordon (2008) noted that they recorded significant noise during two encounters with drilling rigs. On one occasion, during the approach to the *Ocean Lexington* rig on 29 June 2004, noise was heard coming from the drilling rig. A recording was made using the towed hydrophone system. However, the noise ceased before the vessel came within range and the calibrated system could be deployed, so it was not possible to measure absolute SPLs. The noise consisted of pulses lasting for approximately 4 seconds with approximately 1.5 seconds between pulses. Noise was broadband with a band of emphasized frequency at around 8 kHz.

  The drilling rig was contacted by VHF radio, and the research team was informed that it was not drilling, but was engaged in “vibrating cold tubing.” During the recording on 2 August 2004 in the vicinity of the *Discovery Enterprise* drill ship, some machinery noise was recorded (Antunes and Gordon 2008). From radio contact with the bridge, scientists found out that the ship was running powerful pumps, and this operation was the likely cause of noise. The noise was continuous with peak levels at approximately 600 Hz and 3 kHz. Many emphasized frequency bands were evident at a spacing of approximately 250 Hz.

Because of the lack of information, we conducted a short review of literature available before the 2002–2017 period that focused on topics relevant to this report. We have included the following findings for the GOM:

- Duggan et al. (1980) reported on two joint-industry research projects conducted in the late 1970s which investigated the feasibility of using ambient surface vibrational measurements to evaluate the structural integrity of three steel template platforms in the GOM. Recordings were taken with signal conditioning filters set at 5, 15, and 30 Hz. The data taken on Gulf South Pass 62B (SP62B) was completely dominated by noise in the region 2.5 to 30 Hz. Scientists attributed the noise to drilling activity. The data from Shell Ship Shoal 274A (SS274A) appeared to be dominated by machinery from 5 to 30 Hz. The gas compressor and diesel generators were responsible for the peaks of greatest amplitude. The data from Conoco Main Pass 296A (MP296A) was, by comparison, relatively free of machinery noise in the region from 0 to 15 Hz.

4.1.3.4.1 Explosives used in rig removal

When oil and gas platforms become obsolete, they go through a decommissioning process. This process may include partial removal (from the surface to 26 meters [85 feet] depth) or complete removal of the platform structure. During the decommissioning of a hydrocarbon production platform in the GOM, all the bottom severance detonations produced a direct shock wave pulse and a pulse from the bubble oscillations; the peak overpressure of the direct shock wave was between 2–10 times greater than the bubble pulse (Connor 1990). The initial wave front contains much of the high-frequency energy of the blast wave, and consequently has a much higher acoustic pressure. The secondary pulses produce a longer duration waveform with significant low-frequency energy components.

Explosions generate low frequencies of 2 to 1,000 Hz with the main energy between 6 and 21 Hz and have very rapid durations <1 ms to 10 ms (Richardson et al. 1995, NRC 2005). The source levels from explosive detonations are some of the largest sounds generated by anthropogenic activities and can produce source levels of 272 to 287 dB re1µPa@1m (0-peak), or greater (Genesis 2011). The objective of the Barkaszi et al. (2016) study was to quantitatively measure the underwater pressure waves and acoustic proprieties generated by the detonation of explosives used for severance during offshore structure removal operations in the GOM. The researchers completed in situ measurements for 8 conductor shots and 11 pile shots and incorporated them into a model that provides a more accurate and conservative prediction of impact criteria.

Potential impacts to marine mammals from the detonation of explosives include lethal and injurious incidental take, as well as physical or acoustic harassment (CSA 2004). Injury to the lungs and intestines and/or auditory system can occur. Harassment of marine mammals as a result of a non-injurious physiological response to the explosion-generated shock wave and to the acoustic signature of the detonation is also possible. Marine mammal injury is not expected from explosive structure removal operations, provided that existing BOEM and BSEE guidelines and conditions of approval requirements are followed.

4.1.3.6 The military

As noted in BOEM (2017), there are multiple US Navy and US Air Force facilities along the US Gulf Coast. Noise sources used during military training and testing activities include aircraft use (including helicopters), live fire air-to-air and air-to-ground missile training, mine warfare training and testing, airborne laser mine detection systems, towed underwater sensors, surface and subsurface training, and shakedown cruises for newly built ships. Military training and exercises use active sonar sources and explosives as part of their operations and each of these sources have the potential to impact marine mammals, which is this the focus of this section.

4.1.3.5.1 Sonar

The US Navy uses mid-frequency active sonars for detecting submarines at ranges less than 10 kilometers (5.4 nautical miles). These systems produce frequency-modulated pulses in the 1 to 5 kHz band (DoN 2018), with signal durations of 1 to 2 seconds, 40-degree vertical beam width, and source levels of 235 dB re 1 µPa @ 1 m or higher (specific to AN/SQS-53C sonar) (Hildebrand 2009). The Atlantic Fleet Training and Testing (AFTT) Environmental Impact Statement (EIS) lists non-impulsive acoustic sources used in the AFTT Study Area, which includes the GOM (Table 2.3-1 in DoN 2018).

4.1.3.5.2 Explosives

The primary military missions involving detonations in the GOM include Naval Explosive Ordnance Disposal School missions. These activities involve underwater detonations of small (e.g., up to 5 kilograms [10 pounds]), live explosive charges adjacent to inert mines. Detonations are conducted on the sea floor, adjacent to an inert mine, at a depth of approximately 18.3 meters (60.0 feet). No acoustic measurements are available for the GOM; however, recent noise measurements were made off Virginia Beach, Virginia and in the Silver Strand Complex near San Diego, California.

Key findings for the California measurements included that measurements of peak (absolute value) acoustic pressure levels ranged from a minimum of 209 dB re 1µPa recorded at 1,651 meters (5,417 feet) to a maximum of 222 dB re 1 µPa recorded at 358 meters (1,175 feet) (Soloway and Dahl 2015). Measurements of (SEL ranged from a minimum of 184 dB re 1 µPa^{2}s recorded at 1,651 meters (5,417 feet) to a maximum of 191 dB re 1 µPa^{2}s recorded at 358 meters (1,175 feet). In terms of frequency content, it was found that 90 percent of the underwater-detonation energy is contained in the frequency range from 50 to 2,500 Hz. The AFTT EIS lists explosive sources used in the AFTT Study Area, which includes the GOM (Table 2.3-2 in DoN 2013).

4.1.3.7 Construction

Construction activities involve placing some form of equipment or structure onto the seabed and installing topside equipment, such as platforms. There are many different activities associated with construction. The main types are piling of structures, dredging, and trenching (Genesis 2011). Invariably, offshore construction involves a variety of different types of vessels including heavy lift, barges, pipe lay, anchor handling and support vessels. The study area for this literature review generally excludes coastal waters immediately adjacent to the shoreline where a large part of construction in the marine environment occurs.

However, construction projects have taken place offshore in the GOM and activities beyond the coastal zone primarily include construction of deepwater ports, which is the focus of this discussion of construction. Noise introduced into the water related to this type of construction generally includes pipeline and port construction activities. There are currently five active liquefied natural gas (LNG) terminals in the GOM, located off Texas and Louisiana, with additional terminals approved and applications pending (for locations in the same before-mentioned states).

A marine autonomous recording unit (MARU) array was deployed by Cornell University two months before construction; analyses of the recorded data revealed that construction noise was significant on recorders near the pipeline corridor, but was highly localized, and other areas around the array were much less noisy (see Bingham 2011). The major sources of noise introduced into the water column from LNG terminal construction would be from pile driving and Energy Bridge™ Regasification Vessel (EBRV) thrusters, which are addressed in the following subsections.

4.1.3.7.1 Pile driving

Piling is required to fix subsea structures into the seabed. Offshore pile driving includes impact hammering or in some cases, vibratory driving (i.e., vibro-hammering). Impact pile driving has three subcategories: drop weight, diesel, and hydraulic. Pile driving produces noise at low frequencies and high source levels. The noise generated by impact pile driving ranges from 10 Hz to 120 kHz (Wyatt 2008), with most of the energy in the frequency range of 100 to 500 Hz. Examples of peak underwater SPLs measured from impact pile driving are on the order of 220 dB re 1 µPa at a range of approximately 10 meters (33 feet) from 0.75-meter- (2.5-foot)-diameter and on the order of 200 dB re 1 µPa at a range of 300 meters (984 feet) from piles that are 5 meters (16 feet) in diameter (Dahl et al. 2015). The actual peak SPLs vary substantially and depend on numerous factors such as pile diameter, hammer size, and substrate. A vibratory pile driver is usually hydraulically powered although some electrically driven units are available. The majority of vibrators operate at frequencies between 20 and 40 Hz.

4.1.3.7.2 Vessels (including dynamic thrusters [i.e., barges])

A DP vessel maintains its position (fixed location or predetermined track) by means of active thrusters. Typical DP vessels include survey vessels, drilling ships, work boats, semi-submersible floating rigs, diving support vessels, cable layers, pipe-laying vessels, shuttle tankers, trenching and dredging vessels, supply vessels, and floating, production, storage and offloading vessels. These operations may generate higher levels of sound than drilling from fixed platforms (Hildebrand 2009), with a frequency range of 50 to 3,200 Hz and a source level of 121 to 197 dB re µPa at 1 meter (MMO 2015). The use of the DP thrusters, and their associated cavitation noise, causes a significant elevation of low-frequency sound from 3 to 30 Hz (Nedwell and Edwards 2004, Genesis 2011).

Measurements collected in the GOM include the following:

- Measurements were collected in August 2006 from the *Excelsior* EBRV while it was moored at the operational Gulf Gateway Deepwater Port located 116 miles offshore of Louisiana (Tetra Tech 2011). The objective of the measurements collected at the Gulf Gateway Deepwater Port was to quantify the underwater noise levels generated by an EBRV as it participated in typical docking maneuvers, onboard closed loop regasification activities, and vessel transiting. The overall purpose of this survey was to verify measurements completed during the first sound survey completed March 2005 when *Excelsior* first visited the Port and to further document sound levels during additional operational and EBRV maneuvering conditions, including the use of stern and bow thrusters required for DP during coupling. Sound levels during closed-loop regasification ranged from 104 to 110 dB re 1 µPA at 1m. Maximum levels during steady state operations were 108 dB re 1 µPA at 1m. Sound levels during coupling operations were dominated by the periodic use of the bow and stern thrusters and ranged from 160 to 170 dB re 1 µPA at 1m.

4.1.3.8 Unoccupied aerial vehicles

The use of unoccupied aerial vehicles (UAVs) is rapidly increasing as technology advances. As noted by Christiansen et al. (2016), UAVs are becoming an increasingly popular tool in wildlife research and monitoring. Christiansen et al. (2016) recorded noise characteristic of two commonly used multi-rotor UAVs, SwellPro Splashdrone and the DJI Inspire 1 Pro. The Splashdrone and Inspire UAVs produced broad-band in-air source levels of 80 dB re 20 µPa and 81 dB re 20 µPa (RMS), with fundamental frequencies centered at 60 and 150 Hz.

The noise of the UAVs coupled poorly into the water, and could be quantified only above background noise of the recording sites at 1 meter (3 feet) depth when flying at altitudes of 5 and 10 meters (16 and 33 feet), resulting in broad-band received levels around 95 dB re µPa rms for the Splashdrone and around 101 dB re µPa rms for the Inspire. The 1/3-octave levels of the underwater UAV noise profiles are close to ambient noise levels in many shallow water habitats. The sound levels are largely below the hearing thresholds at low frequencies of toothed whales, but are likely above the hearing thresholds of baleen whales.

4.1.3.9 Underwater gliders

Underwater gliders are autonomous vehicles that profile vertically by controlling buoyancy and move horizontally on wings. Underwater gliders are being used for a variety of ocean monitoring and/or observation tasks (Meyer 2016). A few types of gliders, including Seagliders, Slocum gliders and Wave Gliders, have been used in the GOM.

Dassatti et al. (2011) reported mean sound levels of 109 dB, with noise peaks (approximately 125 dB re 1µPa) in conjunction with the glider at the surface, due to splashing water or the hydrophone bouncing on the surface, and during engine operation.

A Wave Glider is an autonomous surface vehicle that has a surface float connected by cable to a submerged glider, using wave action for propulsion. The Wave Glider surface float is equipped with real-time communications allowing its track to be controlled remotely. Marine mammal bioacousticians have installed a HARP in the in the Wave Glider surface float, and a hydrophone for sensing underwater sound was connected to the submerged glider, providing a mobile instrument that records cetacean sounds (herein called a WGH).

Wiggins (2009) tested a WGH off the Big Island of Hawaii in October 2009, and as part of the assessment, reported a few observations of self-noise from the WGH that included broad-band pulses lasting two seconds throughout the recording; they presumed these to be glider-related (likely from energized servo motors used to adjust rudder headings) based on the consistent duration of the pulses.

There also were track direction-dependent, broad-band noise (20 to 70 kHz) periods that last around 30 minutes, which Wiggins (2009) speculated may be caused by breaking bubbles from the surface vehicle.

Some acoustic information for self-noise of gliders collected in the Gulf include:

- As noted by Wall et al. (2012) for their study of fish sounds on the West Florida Shelf using a Slocum Glider, the absence of a mechanical propulsion system allows the glider to produce significantly lower noise than a device with a motor. Fish sounds were identified manually because automated detection methods were hampered by the presence of noise from the gliders' altimeter, pump, rudder, and at-surface iridium satellite link.
- The performance of WGHs and seafloor HARPs was studied. Two WGHs were deployed for three sorties (i.e., flights) each for periods of one to two months per sortie in the Northern GOM, with operational periods during 2011 (Hildebrand et al. 2013) (see **Chapter 4** of this report). WGHs noise levels were sometimes, but not always, higher than seafloor HARP noise levels at low frequencies (<400 Hz). This may be due to the shallow depth (~8 meters [26 feet]) of the WGH hydrophone and the need for it to be towed by the Wave Glider. Likewise, the high frequency noise levels of the WGH hydrophone were somewhat higher than those of the seafloor HARP.

4.2 Marine Mammal Acoustics in the Gulf of Mexico

Marine mammals generally detected during the studies included sperm whales, beaked whales, *Kogia* spp., Bryde's whales, killer whales (*Orcinus orca*), and delphinids such as Risso's dolphins (*Grampus griseus*), bottlenose dolphins, Atlantic spotted dolphins, and short-finned pilot whales (*Globicephala macrorhynchus*). Although some study researchers did not report the vocalizing delphinid species, visual observers noted bottlenose dolphins, rough-toothed dolphins, and *Stenella* spp. including Atlantic spotted dolphins as present within the respective survey areas. Noteworthy results from the individual studies are highlighted in the following subsections.

4.2.1 Seagliders™, LADC Noise Studies in Mississippi Canyon, 2015

The Seaglider™ data was lost; therefore, trackline information was not available to be incorporated into this document.

4.2.2 ASV-Towed Arrays, LADC Noise Studies in Mississippi Canyon, 2015

Figures 11 and 13 include the trackline of the Slocum glider where data was collected. Sperm whales were recorded in three regions with some extensive aggregations near the *Deepwater Horizon* site. Additional marine mammal detections included whistles, pulsed calls, and echolocation click trains of delphinids (Dyer et al. 2015, Ziegwied et al. 2016)[23].

4.2.3 EARS Densities, 2007–2015

Figures 11 through 13 include the three EARS deployment locations focused on species in the Mississippi Canyon. Sperm whales, beaked whales, and Risso's dolphins were detected on all three sites. Among beaked whale species, Cuvier's beaked whales (*Ziphius cavirostris*) dominated at deeper sites with Gervais' preferring more shallow waters exhibiting some type of short-range habitat division between two species. Unknown species (signal) of *Mesoplodon* were also detected but less frequently similar to HARP reports (Hildebrand et al. 2015b). The comparison of regional abundance estimates among 2007, 2010, and 2015 deployments shows considerable decrease in sperm whale densities in 2010 (after the spill) as compared to 2007 with trends continued to persist in the 2015 data (Ackhleh et al. 2012). However the beaked whale abundance has increased in the vicinity of the spill site in 2015 as compared to 2007 and 2010 estimates.

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[23] The data are available for download: https://data.gulfresearchinitiative.org/data/R4.x261.233:0001

4.2.4 HARP Densities, 2010–2013

Figures 11 through 13 includes the HARP deployment locations for this study. Sperm whales, beaked whales, and *Kogia* spp. were detected at the deep-water sites (Hildebrand et al. 2015b; Merkens 2013). The most frequently detected beaked whale species was Gervais' (*Mesoplodon europaeus*) and Cuvier's (*Ziphius cavirostris*) beaked whales. Blainville's beaked whale (*Mesoplodon densirostris*) and an unknown species of *Mesoplodon* were also detected but less frequently (Hildebrand et al. 2015b). This unknown species could be the True's beaked whale (*Mesoplodon mirus*) based on known habitat associations; however, this species has never been sighted or stranded in the GOM. Therefore, the signals may be from a new species or a known species that produces multiple signal types (Baumann-Pickering et al. 2013).

The PAM data were used to estimate densities of Gervais' and Cuvier's beaked whales based on click and group counting methods (see **Section 4.2.3**) (Hildebrand et al. 2015b). The highest densities of beaked whales were in the Southern GOM in the southeast portion of the Eastern Planning Area near the Dry Tortugas, while the highest rates of sperm whale detections were found in the Northern GOM near the Mississippi Canyon area in the northeastern portion of the Central Planning Area (Hildebrand et al. 2015a). At the two Northern GOM sites, Gervais' beaked whales were detected throughout the project period; Cuvier's beaked whales were detected seasonally with low densities in the summer and higher densities in the winter. Both species had high densities throughout the project period at the Eastern GOM site (Hildebrand et al. 2015b).

Density estimates for delphinids were also generated from the PAM data using group counting and cue counting methods (Frasier 2015, Frasier et al. 2016). Seasonal increases in delphinid densities were evident at most of the deployment sites during the spring and summer (April–August). Since the *Deepwater Horizon* oil spill, the densities of *Stenella* spp. and pilot whales have increased at the site nearest the spill, while Risso's dolphin densities have remained fairly constant. Both stenellids and pilot whales exhibited long-term density increases at the sites east of the spill (Frasier 2015).

4.2.5 MARUs-Assessing Impacts of *Deepwater Horizon* on Large Whale Species, 2010–2012

Figures 11 through 13 include the PAM deployment locations for this study. Potential Bryde's whale detections were recorded on the West Florida Shelf. During the first deployment, researchers recorded three sound types associated with Bryde's whales: "down-sweep-sequences," "long-moans," and "tonal-sequences". The second deployment recorded down-sweep-sequences and long-moans; these sounds were primarily along a northwest to southeast bearing between the 200- and 300-meter (656- and 984-foot) isobaths (Rice et al. 2014a). The highest level of recordings of sperm whales was in the Mississippi Delta region (Clark 2015, Rice et al. 2015). Sperm whale detections decreased immediately after the oil spill but increased several months later. However, this pattern of occurrence was detected 10 more times, suggesting that other factors (e.g., prey availability) besides the oil spill may affect the distribution of this species in this region (Rice et al. 2015).

4.2.6 Wave Glider HARPs, 2011

Figures 11 through 13 include PAM deployment locations and glider tracks for this study. The WGHs recorded both delphinid and sperm whale vocalizations. When compared to the recordings from the seafloor HARPs when the gliders were nearby, the seafloor HARPs had higher detection rates for delphinid and sperm whale vocalizations on the shelf and in deep waters. It was expected that sperm whales would be recorded more often on the seafloor HARPs because they are known to be detected best by deep sensors.

4.2.7 The HARP Bryde's Whale Study, 2010–2011

Figures 11 through 13 includes the HARP deployment locations for this study. Three groups of Bryde's whales were observed by the *Gordon Gunter* visual survey team on 31 July 2011 along the West Florida shelf break; a sonobuoy recorded Bryde's whale Be9 calls on this day. Around the same time and area of this sighting, the HARP at De Soto Canyon recorded Be9 calls on 8 June 2011 and possible Bryde's whale calls on 24 June 2011. A total of 680 Bryde's whale Be9 calls were recorded from the De Soto Canyon HARP; these calls were consistent between March and July and again in October and January but were absent in November and December. No Bryde's whale vocalizations were recorded from the other two HARPs (Širović et al. 2014).

4.2.8 Dolphin Distribution on the West Florida Shelf, 2008–2010

Figures 11 and 12 include the PAM deployment locations for this study. A total of approximately 270 hours of data were recorded. Acoustic detections confirmed the presence of dolphins on the West Florida Shelf year-round; detection rates were higher in shallow waters and adjacent to Tampa Bay which was consistent with the visual sightings. Although detections were not identified to species, bottlenose dolphins, Atlantic spotted dolphins, and rough-toothed dolphins were sighted during the concurrent visual surveys (Simard et al. 2015).

4.2.9 Arrays Towed from Vessels

4.2.9.1 NMFS-SEFSC Shipboard Surveys, 2012–2016

Figures 11 and **12** include tracklines for this study.

4.2.9.2 The Airborne Mine Neutralization System Monitoring, 2011

Figures 11 and 12 include tracklines for this study. During a total of 29.5 hours of acoustic monitoring effort, three detections were recorded. These were associated with visual sightings and confirmed to be bottlenose dolphins and Atlantic spotted dolphins (NSWC PCD 2012).

4.2.9.3 The NOAA Ship *Pisces*: Protected Species Monitoring and Mitigation Measures during Trawling, 2011

Figures 11, 13, and 14 include tracklines for this study. Sperm whales and delphinids were recorded.

4.2.9.4 Measuring Delphinid Whistle Characteristics and Source Levels on West Florida Shelf, 2008–2009

Tracklines were not available for this study; however, we georeferenced a study area polygon based on figures available in Frankel et al. 2014. Therefore, **Figures 11 and 12** include the area for this study.

Bottlenose and spotted dolphins were observed during the surveys, and analysis of the acoustic recordings resulted in 1,695 bottlenose dolphin whistles and 1,273 spotted dolphin whistles with a high signal-to-noise ratio. In addition, ambient noise levels were recorded; median broadband ambient noise levels (2 to 40 kHz) in Florida were 101.1 dB re 1 µPa (Frankel et al. 2014).

4.2.9.5 Low-frequency Sounds of Bottlenose Dolphins, 2003–2009

Tracklines were not available for this study; however, descriptions of the study area provided in Simard 2012 and Simard et al. 2011 allowed us to create polygons for each study area. Therefore, **Figures 11 through 13** include the area for this study.

4.2.9.6 Assessing Echolocation Pulse Rate of Bottlenose Dolphins, 2008

Tracklines were not available for this study; however, descriptions of the study area provided in Simard et al. 2010 allowed us to create polygons for the study area. Therefore, **Figures 11 and 12** include the area for this study. This study included the first analysis of the echolocation pulse rate of multiple groups of free-ranging delphinids in relation to depth. Results indicate that dolphins alter the timing of their echolocation clicks in relation to depth which may be a function of navigation or foraging (Simard et al. 2010).

4.2.9.7 The Sperm Whale Seismic Study (SWSS) Program, 2002–2005

Tracklines were not available for this study; therefore, this survey is not included in the spatial analysis. Although spatially and seasonally limited, the surveys provided critical information on this sperm whale population and anthropogenic activity in this region (Jochens et al. 2008).

4.2.9.8 NMFS-SEFSC Shipboard Visual Surveys, 2003–2004

Figures 11 through 14 include tracklines for this study.

4.2.9.9 The Sperm Whale Acoustic Monitoring Program (SWAMP), 2000–2001

Figures 11 through 14 include tracklines for this study. Acoustic detections included sperm whales, delphinids, and seismic activity (Mullin et al. 2001).

4.2.9.10 GulfCet II, 1996–1998

Figures 11 and **12** include tracklines for this study. A total of 73 delphinid calls and 20 sperm whale calls were detected along with seismic exploration signals (Davis et al. 2000).

4.2.9.11 GulfCet I, 1992–1994

Figures 11, **13**, and **14** include tracklines for this study. A total of 1,055 hours of acoustic data were recorded, and analyses revealed 487 acoustic contacts from a variety of species including sperm whales, delphinids, *Kogia* spp., and a possible sei (*Balaenoptera borealis*) or Bryde’s whale (Davis and Fargion 1996).

4.2.10 Tags

4.2.10.1 The Coastal Alabama Acoustic Monitoring Program (CAAMP), 2009-2017

Data were not available for spatial analysis.

4.2.10.2 Bryde's Whale Sonobuoys, 2011

Figures 11 and 13 include the PAM deployment locations for this study. Using recordings from two sonobuoys, NMFS was able to identify a likely Bryde’s whale call consisting of pulse pairs; a total of 14 individual pulses (Be9 calls) were recorded.

4.2.10.3 The Sperm Whale Seismic Study (SWSS) Program, 2002–2003

Data were not available for spatial analysis. Researchers did not find any evidence of horizontal avoidance reactions to airgun sounds of <150 dB re 1 μPa (rms). Researchers did note that sperm whales in this portion of the GOM may be habituated to these anthropogenic noises and that studies are needed to test for avoidance at higher received levels (Jochens et al. 2008, Madsen et al. 2006, Miller et al. 2009).

4.2.10.4 The Sperm Whale Acoustic Monitoring Program (SWAMP), 2000–2001

Data were not available for spatial analysis.

4.2.10.5 The Department of the Navy *Empress II* Sonobuoys, 1991–1992

Figures 11 and 13 include tracklines for this study; sonobuoy locations were not available for spatial analysis. Acoustic detections were confirmed for sperm whales, pilot whales, and *Stenella* spp. (Esher et al. 1992).

4.2.11 Using PAM Data for Estimation of Marine Mammal Densities

As noted previously, the study “Assessing Impacts of *Deepwater Horizon* on Large Whale Species, 2010–2012” included use of MARU arrays to record PAM data for generating density estimates of Bryde’s and sperm whales in the Northeastern GOM. Rice et al. (2014b) used distance sampling methods for both species. For Bryde's whale PAM data, they modified point transect methods to apply conventional distance sampling to estimate Bryde's whale density based on the distance information derived from the location of Bryde's whales calls. The distance of each Bryde's whale call was determined by measuring the distance between the centroid of the low-frequency MARU array and the location of each call.

Using the long-moan calls, researchers estimated 0 to 10 individual Bryde's whales occurring within the detection range of a MARU with a mean daily estimate of 1 to 2 Bryde's whales across all of the low-frequency MARUs. Using the click-counting method, Rice et al. (2014b) generated sperm whale densities from the PAM data recorded from the high-frequency MARU array. The average density of sperm whales between 24 July 2010 and 23 February 2012 was 7.4684 sperm whales per 1,000 square kilometers (292 square nautical miles; coefficient of variation [CV] 58.52%).

Additional examples of studies in which PAM data were used to generate marine mammal density estimates in the GOM and recent studies to refine and further develop PAM density estimation can be found in the following: Ackleh et al. (2012), Frankel et al. (2014), Frasier (2015), Horrocks et al. (2011), Ioup et al. (2016), Kimura et al. (2010), Küsel et al. (2010), Küsel et al. (2015a), Küsel et al. (2015b), Kyhn et al. (2012), Marques et al. (2011), Marques et al. (2012), Martin et al. (2010), Mellinger et al. (2010), Moretti et al. (2010). These studies include a variety of methods to estimate marine mammal density, including the use of both stationary and mobile recording platforms, and the use of propagation modeling and tagging data to derive detection probability and spatial density. The researchers on this BOEM PAM program are considering appropriate study design approaches, including random sensor placement throughout the area of interest to obtain reliable results.

4.2.12 Habitat Modeling

To the best of our knowledge, no habitat models using only PAM data have been developed for marine mammals in the GOM. Most recently, Roberts et al. (2016) developed habitat-based cetacean models for 17 individual species and beaked whales and *Kogia* using line transect survey data. However, habitat models using passive acoustic monitoring data have been used to predict the distribution of vocalizing cetaceans in other regions.

For example, Soldevilla et al. (2011) conducted one of the first studies using PAM data to model delphinid habitat. They used hourly occurrence of Risso's and Pacific white-sided (*Lagenorhynchus obliquidens*) dolphin clicks recorded from HARPs at six sites in the Southern California Bight. GAMs was used to model dolphin acoustic activity as a function of sea surface temperature (SST), SST spatial variability (SST CV [coefficient of variation]), sea surface chlorophyll concentration and CV, upwelling indices, and solar and lunar temporal indices. Model results indicated that mean SST and low SST CV were important predictors of acoustic activity for all dolphins, seasonal variability was an important predictor for Pacific white-sided dolphins, and chlorophyll abundance and variability were important predictors for Risso's dolphins (Soldevilla et al. 2011).

In comparison, several habitat models have investigated the habitat preferences of calling blue whales (*Balaenoptera musculus*) in the Southern Ocean (Širović and Hildebrand 2011) and calling blue and fin whales in the Southern California Bight (Širović and Hildebrand 2015). In the Southern Ocean, visual sightings are rare, so PAM provides insight into blue whale distribution and mesoscale habitat use. In this study, researchers found that blue whale calls were positively correlated with water depth and SST and negatively correlated with mean zooplankton abundance (101 to 300 meters [331 to 984 feet]) and mean krill biomass (<100 meters [328 feet]) although the negative correlation with zooplankton could occur if blue whales do not produce calls when feeding (Širović and Hildebrand 2011).

In the Southern California Bight study, spatially-explicit habitat models for calling blue and fin whales were developed to help the US Navy predict the year-round occurrence of these species. They found that the habitat models built with PAM data provided a much finer and longer temporal resolution than the models derived from visual survey data in this same region (Širović and Hildebrand 2015).

4.2.13 Acoustic Propagation Modeling

The SWSS digital acoustic recording tag (D-TAG) data were used to assess the ability of acoustic propagation models to accurately predict the sound field received by the sperm whales when exposed to airgun noise (Madsen et al. 2006). Researchers were able to quantify the SELs from the D-TAG recordings. These received levels varied greatly with range and depth of the exposed whale. Researchers concluded that the simple geometric spreading propagation models did not obtain accurate predictions of received levels and should not be used to establish impact zones when assessing potential impacts to cetaceans in deep waters. They recommend the use of complex multipath acoustic propagation models (Madsen et al. 2006).

4.2.14 Assessing Behavioral Response and/or Vocal Response to Anthropogenic Sources

Both observation studies and CEEs have been applied to several different marine mammal species to investigate their responses to a variety of sound sources, including seismic exploration, military sonar, and vessels across the globe. For example, studies on responses to seismic exploration have measured the behavioral response of migrating humpback whales (*Megaptera novaeangliae*) to airguns (Dunlop et al. 2015; Dunlop et al. 2016), the effects of airguns on bowhead whale calling rates (Blackwell et al. 2015) and behavior (Ellison et al. 2016), acoustic and behavioral changes of fin whales in response to airgun noise as well as shipping (Castellote et al. 2012), acoustic communication changes of blue whales in response to airguns (Di Iorio and Clark 2010), auditory effects of multiple underwater airgun impulses to the hearing thresholds of bottlenose dolphins (Finneran et al. 2015), and toothed whale reactions to seismic noise (Stone 2003; Tyack et al. 2006).

Many studies have focused on the response of gray whales (*Eschrichtius robustus*) to seismic activity off Sakhalin Island, Russia in the western North Pacific, which is a primary area of seismic exploration (Gailey et al. 2007; Yazvenko et al. 2007). Gordon et al. (2004) provides a summary of observations of behavioral changes in toothed whales, baleen whales, and pinnipeds in response to air guns and seismic surveys.The Department of Fisheries and Oceans Canada (2004) reviews the impacts of seismic sounds on marine mammals, sea turtles, fish, and invertebrates.

A recent long-term study on the behavioral responses of marine mammals to US Navy sonar was initiated in southern California in 2010. The main objective of this behavioral response study was to understand the behavior and responses of different marine mammal species to military sonar signals to inform management decisions about its use (Southall et al. 2012). Researchers used acoustic and/or movement tags on marine mammals, particularly beaked whales, and projected a scaled sound source that simulates military sonar signals. Using this experimental approach, researchers were able to measure calibrated received sound levels and behavioral responses (Southall et al. 2012). Other studies on the response of military activities have been conducted with long-finned pilot whales (*Globicephala melas*) (Antunes et al. 2014) and Blainville's beaked whales (Moretti et al. 2014).

Some of the main anthropogenic sources in the GOM include seismic exploration, shipping, drilling, platform installation, and construction (Azzara 2012, Azzara et al. 2013). Several studies have been conducted in the GOM to assess marine mammal response to anthropogenic noise sources, particularly seismic exploration. The SWSS Program (2002–2005) was an MMS program dedicated to conducting research on GOM sperm whales and their behavioral responses to seismic airguns (DeRuiter et al. 2006, Jochens et al. 2008, Madsen et al. 2006; Miller et al. 2009).

To study sperm whale responses, researchers conducted controlled exposure testing using seismic airgun arrays and tagged sperm whales. The D-TAGs attached to the sperm whales sampled the sounds and behavior of the whales. They were used to measure the acoustic exposures to the whales while also measuring the animal's behavioral responses (e.g., fluke strokes and animal orientation). They did not find any evidence of horizontal avoidance reactions to airgun sound levels of <150 dB re 1 μPa (rms). Also, opportunistic studies of S-tagged sperm whales and seismic activity detected no apparent horizontal avoidance or displacement of whales associated with operational seismic surveys. Researchers did note that sperm whales in this portion of the GOM may be habituated to these anthropogenic noises and that studies are needed to test for avoidance at higher received levels (DeRuiter et al. 2006, Jochens et al. 2008, Madsen et al. 2006, Miller et al. 2009).

Other examples of studies of marine mammal responses to anthropogenic noise in the GOM include observational studies. For instance, Miksis-Olds et al. (2007b) examined manatee use of foraging habitat in relation to ambient noise in Sarasota Bay, Florida. Ambient noise in the bay is dominated by snapping shrimp and vessels, and researchers found that the presence of vessel noise in the morning may affect manatee use of foraging habitat on a daily time scale. Additional studies on manatee responses to vessel noise have used playback experiments in which prerecorded watercraft sounds were played and manatee swim speed, behavioral state changes, and respiration rates were assessed. The most pronounced manatee responses were in reaction to personal watercraft (Miksis-Olds et al. 2007a). Another study in Sarasota Bay investigated the observed changes in dolphin density and occurrence before, during, and after bridge construction and demolition (Buckstaff et al. 2013). Compared to during construction, dolphin density in the vicinity of the bridge was significantly higher after construction was completed.

4.2.15 Detectors and Classifiers

Bittle and Duncan (2013) provides a fairly recent review of current marine mammal detection and classification algorithms for PAM. Some of these algorithms are actually included in the PAM systems so they are capable of automatically detecting certain marine mammal vocalizations at the source of the recording. These systems are mostly limited to detections of porpoise click trains (e.g., T-POD, C-POD).

Additional real-time automated systems have been developed to detect and classify delphinid vocalizations which typically consist of echolocation clicks, burst pulse sounds, and whistles. Known as Real-time Odontocete Call Classification Algorithm (ROCCA), this MATLAB-based tool (i.e., ROCCA) automatically extracts 10 variables and uses classification and regression tree analysis and discriminant function analysis to identify whistles from spinner, striped, pantropical spotted, long-beaked common, short-beaked common, rough-toothed and bottlenose dolphins, as well as short-finned pilot and killer whales (Oswald et al. 2007). Although the overall percentage of correct classifications is low for some of these species, ROCCA was added to the PAMGUARD software suite in 2011 for improved automated detection and classification (Bittle and Duncan 2013; Oswald et al. 2011).

In addition to ROCCA, other detectors that may be useful for identifying and classifying marine mammal species that occur in the GOM include Listening to the Deep Ocean Environment (LIDO), energy ratio mapping algorithm (ERMA), and Gaussian mixture models (GMMs). LIDO is capable of extracting low-frequency and high-frequency impulses; it uses spectral and temporal features to detect ultrasonic cetacean clicks, such as those from beaked whales and delphinids, sperm whale clicks, and impulsive ship noise (André et al. 2011). ERMA is able to detect clicks of Blainville's beaked whales while rejecting echolocation clicks of Risso's dolphins and pilot whales (Klinck and Mellinger 2011).

GMMs may be used as the second stage of processing to complement ERMA. Compared to other detection methods, GMMs have a high correct detection rate for beaked whales (Bittle and Duncan 2013). GMM development has continued and recent tests resulted in echolocation click detections of bottlenose, short-beaked common, long-beaked common, Pacific white-sided, Risso’s dolphins, and Cuvier’s beaked whales (Roch et al. 2011). General consensus among researchers is that the GOM will require regionally tuned delphinid classifiers which do not currently exist for the region.

4.3 Findings on Data Management

Three databases were identified as containing PAM data from the GOM. Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP), Gulf of Mexico Research Initiative GoMRI Information and Data Cooperative (GoMRI GRIIDC), and Tethys contained some information and data on PAM studies conducted in the GOM. However, all data were not available in the systems and some of the data only were available through requests to and direct communication with the various respective researchers.

5. Recommendations on the Experimental Design for the BOEM Passive Acoustic Monitoring Program for the Northern Gulf of Mexico

The figures and table in Chapter 4 provide a comprehensive review into the trends for data collected using passive acoustic monitoring (PAM) methods in the Gulf of Mexico (GOM). The Eastern and Central Planning Areas within the GOM have been extensively covered by PAM studies, compared with the Western Planning Area. A lack of data and emphasis exist on collecting information from the Western GOM (**Figures 11 through 14**). No stationary deployments have been made in the Western GOM (Western Planning Area) as compared with the 17 distinct sites in the Central Planning Area and over 50 distinct sites in the Eastern Planning Area where stationary PAM devices have been used to collect data. The Bureau of Ocean Energy Management (BOEM) PAM Program for the Northern GOM should consider the need for data collection in the Western Planning Area and include this area as a research emphasis.

Locations of PAM deployments and studies generally have covered the continental shelf and continental slope waters. Researchers have conducted the majority of PAM studies in the GOM in waters between 0 and 1,500 meters (0 and 4,921 feet) (**Table 1**). Only a few studies have focused upon the deep waters of the GOM, which include the abyssal plain. The BOEM PAM Program for the Northern GOM should focus upon this area due to the lack of data collected here, as well as the continuing expansion for a variety of oil and gas exploration activities into deeper waters.

Logistically, we found suggestions within the literature discussed above for PAM data collection methods. Glider use is expanding in marine research, and the types of data gliders can collect continue to be developed by the research community. The variety of information that researchers using gliders can collect includes a wide-spectrum of targeted studies including monitoring marine mammals, collecting ambient noise data, tracking currents and examining hydrographic features, assessing and tracking pollutants, and conducting oceanographic and environmental measurements (Waddell and Olson 2015).

Gliders can survey a large amount of area over a relatively short period of time and at various locations throughout the entire water column, whereas stationary PAM devices can be placed only at a particular location and a particular depth. Gliders can take measurements in the middle of the water column, not just at locations close to the seafloor or water surface. Given the breadth of coverage and types of data that could be collected, the BOEM PAM Program for the Northern GOM should explore the feasibility of mobile platforms fitted with a preferred PAM system to collect data relevant to baseline noise studies at least in selected frequency bands which are not overlapping with ones where the system self-noise is produced.

Gliders are limited to date by the depths at which they can travel; however, the capabilities are expanding. The suggested studies in deep waters may require use of stationary devices given glider limitations, depending on the explorations for the use of gliders as mentioned in the previous paragraph.

The BOEM PAM Program for the Northern GOM could investigate the use of oil and gas facilities such as platforms as locations of opportunistic deployments in deep water, as needed (Waddell and Olson 2015), particularly to address near-field noise levels from such facilities which are not well characterized. Furthermore, when stationary devices may be necessary, Snyder (2007) suggests that EARS should be deployed with weather buoys as possible in order to more accurately determine weather's influence on ambient noise (Snyder 2007). Therefore, researchers using stationary units should consider placing their PAM devices in the proximity of weather buoys[24].

Snyder (2007) concludes that assessing baseline ambient noise levels requires long-term continuous datasets. Longer, continuous monitoring would facilitate a more robust analysis of annual and seasonal variations in the ambient noise environment. Future work should include the continuous, long-term data collection using PAM even beyond the longest intervals in the Snyder (2007: 1 year), marine autonomous

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[24] See the website for NOAA's National Data Buoy Center at: http://www.ndbc.noaa.gov/

recording units (MARU) (Estabrook et al. 2016: 1.5 years), and high-frequency recording package (HARP) (Wiggins et al. 2016: 2.5 years) studies. The focus on long-term monitoring would also help track changes in the amount and type of noise being introduced into the GOM and to facilitate a better understanding of the sources contributing to future changes in underwater noise in the GOM (Hildebrand 2009).

There are inherent challenges in examining/comparing the information available on PAM projects. System calibration protocols, processing methods, statistical analysis, and metrics often either differ significantly among studies or are reported in different ways without sufficient details. Therefore, study results may not be comparable across the entire suite of projects available for review. Some PAM projects examining anthropogenic noise trends only include propagation modeling and do not include actual measured noise levels.

For example, studies involving pile-driving activities typically require modeling for “take” estimation of marine mammals; however, actual field measurements during test pile programs or construction periods are either not required or not reported in the literature. Thus, the findings are theoretical and may or may not represent the actual levels of sound introduced into the water column. Calibration is another area that may affect study findings. Some studies include calibration; in others either calibration is not always performed or not reported in the reports. An example of this challenge is often found in monitoring related to construction.

Researchers have identified data gaps concerning differences in sound propagation modeling predictions and field measurements. For instance, academic researchers have theorized that modeling sound propagation from seismic arrays may overestimate propagation losses (Kearns and West 2015). More information is needed to address whether there are discrepancies between modeled and actual propagation losses. As related to this finding, recently, BOEM conducted modeling to develop acoustic zones in the GOM for a Letter of Authorization permit request under the Marine Mammal Protection Act to conduct geological and geophysical exploration activity in the GOM.

In our literature review, we have found no effort to date to ground-truth the modeled acoustic zones with actual PAM data. We suggest that the BOEM PAM Program for the Northern GOM be designed to investigate these identified data gaps. For instance, a program should take into account these acoustic zones and gather information to determine whether the modeling is aligned with actual real-time field measurements.

Recently, BOEM awarded Continental Shelf Associates Inc. a contract to analyze all the visual and acoustic mitigation survey data collected during marine mammal monitoring of seismic operations in the GOM from 2009 through 2015 (CSA Ocean Sciences 2017). Before this effort, there had been no studies in the GOM on the effectiveness of PAM monitoring to assist mitigation efforts. As part of March 2015 webinars on a monitoring plan for marine mammals in the GOM, researchers noted that Arctic research has shown reactions of baleen whales to seismic activity and that the same type of information is needed for species of interest in the GOM, such as sperm whales (Kearns and West 2015).

For instance, research should address at what noise levels sperm whales would cease vocalizing and thereby PAM methods as mitigation and/or monitoring methods would no longer be successful (Kearns and West 2015). The BOEM PAM Program in the Northern GOM should incorporate findings and information available once the reports, publications, and presentations are available on this new contract. Additionally, participants in these 2015 webinars hosted by BOEM noted that there is a lack of information available on detection ranges in the GOM (Kearns and West 2015). Kearns and West (2015) also captured that academic and other researchers suggest the passive acoustic monitoring in the GOM should expand to include the development of a program to include localization capability. The incorporation of such a capability would further allow researchers to investigate population density of marine mammals.

Compared to the literature available on marine mammal species and PAM, there has been less emphasis on non-marine mammal species, such as fish and invertebrates. Kearns and West (2015) captured researchers' concern that the focus on marine mammals is too narrow. The BOEM PAM Program for the Northern GOM should consider a more ecosystem-based approach rather than relying solely on topics centered on marine mammals. Fish and invertebrates are important prey species and information; research should continue to expand upon the knowledge of all ambient biological noise in the GOM.

Similar Kearns and West (2015), we found inconsistencies in the availability of PAM data for the GOM. Some data can be found in the various databases–OBIS-SEAMAP, GoMRI GRIIDC, and/or Tethys–but none of these systems house all of the information available for the GOM. The BOEM PAM Program for the Northern GOM should work with GoMRI GRIIDC and the National Oceanic and Atmospheric Administration (NOAA) to ensure that all noise data from past efforts and from those going forward is available through the system. The data contained from mapping in this report is being consolidated and will be provided to BOEM with the final report deliverable. Future effort in time and funding should be invested to make sure all raw data are housed in single publically available database. Additionally, this future effort should focus on continuing to gather data not acquired under this effort and combine information with the rest of the data.

This report was a preliminary, cursory review of the available literature and data on ambient noise including biological, physical and/or environmental, and anthropogenic noise, particularly focused on the GOM. We were able to broadly characterize the available information and studies conducted. We recommend further effort and time be invested into a comprehensive review of the information available for the GOM. A number of stakeholders could benefit from such a comprehensive review.

Also, the baseline information and PAM data collection would benefit from input by a scientific advisory panel. Kearns and West (2015) captured federal agency comments, during a workshop on GOM research, that a scientific advisory group could help for vetting and managing information and leveraging resources. The US Navy has incorporated a scientific advisory group into its global marine species monitoring program and a similar framework could be used to discuss among stakeholders the current projects, suggested changes and adaptive management, and program goals, and track the evolving science behind the BOEM PAM Program for the Northern GOM.

A preliminary experimental design has been suggested for the proposed acoustic data collection under the BOEM PAM Program for the Northern GOM. This design includes deployment of a carefully selected suite of stationary and mobile data collection platforms at strategically identified locations within Mississippi and De Soto canyons in the Northern GOM. The suggested data collection area will include a 100-kilometer by 200-kilometer (54-nautical mile by 108-nautical mile) box within which data recorders will be placed as shown in **Figure 16**. Data will be collected using this proposed design over a 24-month period.

Based on the literature review findings, the following recommendations are made to improve the preliminary experimental design for the BOEM PAM Program for the Northern GOM:

- Focus the first two-year deployment effort in area of Mississippi Canyon and/or valley where many ambient noise sources are present and majority of previous baseline data collections were conducted. However, expand the sensor deployment to shallow water and abyssal plain.
- If possible, establish at least one stationary monitoring site in the BOEM Western and Eastern planning areas to understand the differences in soundscapes among regions over the first two years of deployment.
- Investigate use of mobile PAM platforms (gliders and autonomous surface vehicles) for ambient noise measurements, where consistent with study goals and objectives.
- Investigate the use of oil and gas facilities as opportunistic platforms for data collection, particularly to characterize near-field anthropogenic noise features of drilling and construction activities.

- Conduct comprehensive oceanographic data collection simultaneously with acoustic measurements to assure proper input into propagation models to study their effectiveness in predicting acoustic energy distribution from different sources.

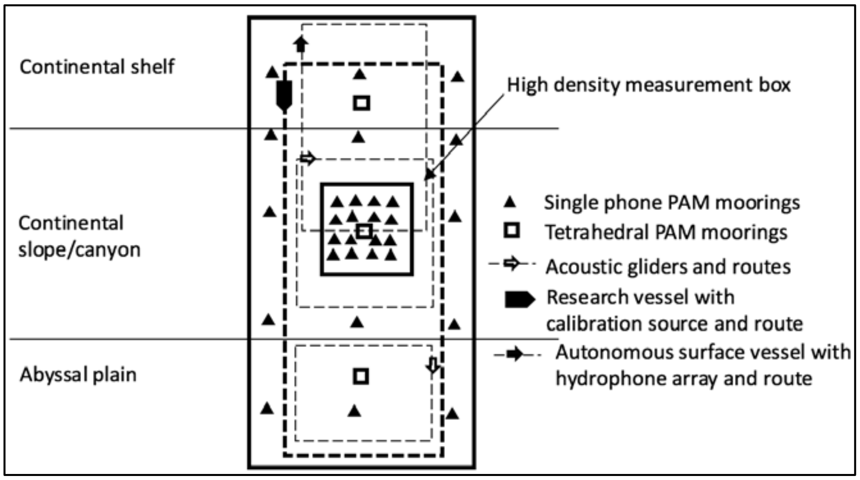

Figure 16. Suggested acoustic data recorder deployment scheme.

Note: The top of the area covers the continental shelf (<200 meters [>656 feet] deep), the middle area covers the continental slope (200 to 1,600 meters [656 to 5,249 feet] deep) and Mississippi Canyon and the bottom area covers the abyssal plain (>1600 meters [> 5,249 feet] deep). The black triangles represent locations of single hydrophone PAM moorings. The squares represent tetrahedral PAM moorings with localization capability. The small arrows represent notional tracks for acoustic gliders and autonomous surface vessel with hydrophone array. Last, a research vessel with a calibration source, denoted by the polygon, is proposed to transit the study area with a known source.

- Focus on long-term multi-year continuous calibrated PAM data collection over broad frequency range with understanding a need for designing special requirements for the systems that will be monitoring different frequency bands (hydrophone sensitivities and dynamic range, system response curves, etc.)
- Implement rigorous unified hydrophone and/or system pre-deployment calibration protocols across different PAM instruments to ensure quantitative data compatibility and comparability across different PAM platforms
- Develop common data processing workflows and reporting metrics across the program in consultation with BOEM.
- Incorporate goals to design experimental data collection in a way that would allow benchmarking modeling results for the GOM against newly collected data through the program for different propagation scenarios (range-independent, range-dependent, canyon propagation, etc.).
- Recommend appropriate PAM methodologies for different GOM regions (e.g., shallow water, continental slope, deep-water, industrially active) and for different study objectives (e.g., baseline noise measurements, anthropogenic soundscapes, species abundance, habitat use, etc.). Consider an ecosystem-based approach to PAM data gathering that would allow biological soundscapes relevant to species that have not been extensively studied in the GOM, such as fish and invertebrates.
- Make all data available to the stakeholders and public through NOAA, the GRIIDC, and other data-sharing databases.
- At a later date, support further effort into the comprehensive review of PAM information available for the GOM to include development and implementation of a scientific advisory group.
- Develop and implement protocols to determine acoustic detection ranges, false positive and negative rates within these ranges.
- Develop and implement protocols to determine acoustic sound production rates for species of interest.

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Appendix 1. Keywords for Literature Search

Monitoring and/or Research Keywords

Monitoring and/or Research
acoustic dataset
acoustic mapping
acoustic modeling
acoustic propagation
acoustic tag
aircraft noise
airgun (sound)
algorithm
ambient noise/sound
anthropogenic noise
ASVs
autonomous acoustic instrument
AUVs
Baseline noise
biological sound sources (ex. fish, invertebrates)
construction noise sources
Classification
Datalogging tag (DTAG)
DECAF (Density Estimation for Cetaceans from Passive Acoustic Fixed Sensors)
Density modeling
Detection
EARS
electronic tag data
explosives (platform removal)
explosives (military)
Gliders
HARPs
hydrophones
marine mammal observations
MARUs
natural sound sources (storm and/or hurricane; rain, rainfall, precipitation)
noise exposure criteria
noise level
noise statistics
ocean noise

Monitoring and/or Research
oceanographic
operational noise (oil and gas platforms)
passive acoustic monitoring
passive acoustic monitoring during seismic survey
pile driving
satellite-tracked radio tag (S-TAG)
signal processing
seismic sound
seismic airgun array
shipping noise
sonar
Song Meter SM3 acoustic recorder
Song Meter SM2 acoustic recorder
sound mapping
sound propagation
sound propagation, canyon
towed acoustic array
towed hydrophone array
UUVs
vessel (sound)
wave noise
weather noise
Wenz curves
wind noise

Regions and/or Events Keywords

Regions and/or Events
Biologically Important Areas (BIAs)
Central Planning Area
Desoto Canyon
Deepwater Horizon
Eastern Planning Area
Gulf of Mexico
Mississippi Canyon
Mississippi Valley
Outer Continental Shelf
Panama City

Regions and/or Events
Shelf
Shelf break
Slope
Western Planning Area

Focus Animals Keywords

Focus Animals
beaked whales
Bryde’s whales
cetaceans
dolphins
marine mammals
Risso’s dolphins
sperm whales
whales

Researchers, Funding Sources, Monitoring Programs Keywords

Researchers, Funding Sources, Monitoring Programs
Abadi
Ackleh
Benoit-Bird
Berchok
Biggs, Douglas
Bingham
Bio-Waves
BOEM
Center for the Integrated Modeling and Analysis of the Gulf Ecosystem (C-IMAGE) C-IMAGE Institutions: University of South Florida; Eckerd College; Florida State; Institute of Technology; Mote Marine Laboratory; Scripps; Pennsylvania State University; Hamburg University of Technology; Texas A&M University; Texas A&M University-Corpus Christi; University of Calgary; University of Miami; Universidad Nacional Autónoma de México; University of Florida; University of West Florida; Virginia Institute of Marine Sciences; University of Western Australia; NHL Stenden University of Applied Sciences, Terschelling [the Netherlands]; Woods Hole Oceanigraphic Institution; Mind Open Media; Florida Institute of Oceanography
CetSound (Researchers: Gedamke, Ferguson, Harrison, Hatch, Henderson, Porter, Southall, Van Parijs)
Cornell University
Cornish
Gordon
CREEM

Researchers, Funding Sources, Monitoring Programs
Dauphin Island
Dudzinski
Frasier
Gulf of Mexico Research Initiative
Howard, Matt
Hildebrand
Ioup
Industry Research Funding Coalition
Joint Industry Programme
Jochens, Ann
Johnson, Mark
Littoral Acoustic Demonstration Center-Gulf Ecological Monitoring and Modeling (LADC GEMM) Institutions: University of Louisiana at Lafayette; University of New Orleans; University of Southern Mississippi; Oregon State University; Proteus Technologies, LLC; R2Sonic, LLC; ASV Global; and Seiche Measurements Limited
Lang, Bill
Littoral Acoustic Demonstration Center
Mate
Mellinger
Merkens
MMS
Mullin, Keith
Naval Oceanographic office
NSF
Natural Resource Damage Assessment partners
Navy
Newcomb, Joal
NMFS
NOAA
Office of Naval Research
Olson
Pierpoint
Rice
Scripps
Sidorovskaia
Simard
Snyder, Mark
Southall

Researchers, Funding Sources, Monitoring Programs
SWAMP (Sperm Whale Acoustic Monitoring Program)
SWSS (Sperm Whale Seismic Study)
Texas A&M University
The Nature Conservancy
Tiemann
Thode
Tyack
University of Louisiana
University of St. Andrews, UK
USGS
Waddell
WHOI
Wiggins
Wildlife Acoustics
Wursig

March 3, 1849

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under US administration.

The Bureau of Ocean Energy Management

As a bureau of the Department of the Interior, the Bureau of Ocean Energy (BOEM) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS) in an environmentally sound and safe manner.

The BOEM Environmental Studies Program

The mission of the Environmental Studies Program (ESP) is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.