

## Enhancing NOAA's Ability to Characterize Aquatic Soundscapes

### INTRODUCTION—SOUNDSCAPES AND THE SOUNDS THAT COMPRISE THEM

A soundscape can be thought of as the aggregate collection of all of the sounds (both natural and anthropogenic) that occur or are received at a particular location making up the total acoustics of a place (Chapter 2). Sounds that occur within a soundscape can be of either natural or anthropogenic origin, with natural sources of sound further divided into biotic (biological) and abiotic (physical) sources. Collectively, these three categories of sound sources, the biophony (natural biological), geophony (natural physical), and anthrophony (man-made) (Pijanowski et al., 2011), comprise the soundscape of a particular location.

In marine and freshwater environments, natural sounds comprising the biophony include those produced by animals that reside underwater, and can range in frequency from a deep, low-pitched 10 Hz to extraordinarily high pitched, ultrasonic sounds over 200 kHz. In marine soundscapes, these sources include fish, seabirds, marine mammals, and invertebrates which use sound to perform critical life functions. Natural abiotic sounds comprising the geophony are produced by the physical environment. These sound sources include weather-generated sounds from rain, lightning strikes, wind, and breaking waves on the water's surface, movement of ice, water, or sediments, tectonic or geo-seismic activity like volcanic eruptions or earthquakes, and any other naturally occurring abiotic process which creates sound within the marine environment.

Anthropogenic sounds comprising the anthrophony, on the other hand, are sounds from human activities introduced into the natural environment. Anthropogenic sounds in underwater soundscapes include noise from transportation and vessels, oil and gas exploration, drilling and production, construction and dredging activities, fishing activity, echosounders, geophysical surveys, military activities including sonar, explosions, and many other human activities. In the aquatic realm this category of underwater noise did not exist prior to the advent of the industrial age. By their very nature, therefore, the introduction of these man-made sources of sound into the aquatic environment alters soundscapes from their natural and historical states.

### THE NEED TO UNDERSTAND AND CHARACTERIZE SOUNDSCAPES

The ocean is an inherently noisy place. Historically, it has been filled with the cacophony of sounds, including those produced by animals, wind, rain, ice, and geologic activity among the many other sources noted above. These natural sounds have been present throughout long evolutionary time scales; over millions of years, animals have existed, evolved, and adapted to the natural underwater acoustic environment. Unlike other potential means of communication (e.g., visual, chemical, tactile), in the ocean sound propagates with great speed to great distances (e.g., Munk et al. (1994) demonstrated low frequency sounds can travel across and between multiple ocean basins in a matter of hours). The production and reception of sound is an incredibly efficient means of communicating over distance. Marine animals, therefore, have evolved over millions of years to rely on sound as a primary means of communication, and gaining information about and interacting with the environment in order to be able to survive and reproduce.

### ***Importance to NOAA's Understanding of Species and Places***

The soundscapes in a particular location, and the acoustic habitats (Chapter 2) of the animals inhabiting it, vary temporally, over both short- and long-time intervals, with tidal, diel, seasonal, and annual cycles in signals present, and also across frequencies with sounds from different sources occupying different portions of the acoustic spectrum (Figure 3-1). Soundscapes and acoustic habitats may also vary greatly geographically. Between nearby locations, the lower frequency (i.e., deeper pitch) portion of the soundscapes may be similar due to the greater ability of low-frequency sound to travel long distances, while the higher frequency portion may be distinctly different, since these sounds are attenuated much more quickly and are therefore more site-specific. Between two distant locations, or locations in different environments (e.g., open water vs. enclosed bay), the soundscapes may be entirely different across the frequency spectrum. Soundscapes may even vary with depth due to the sound propagating characteristics of the water column. In order to understand how soundscapes and acoustic habitats vary in different environments, locations, and depths, how animals' utilize sound to carry out critical life functions, and the variety and levels of sounds an animal may experience and respond to throughout the world's ocean, accurate characterization of the underwater soundscape is essential.

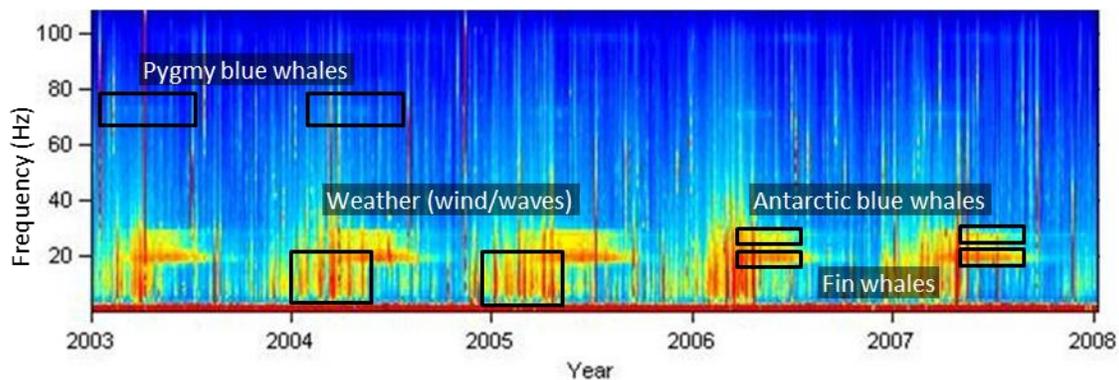


Figure 3-1. Long-term spectrogram (5 years) illustrating repetitive seasonal changes in the soundscape, due to weather, and singing Antarctic and pygmy blue, and fin whale populations south of Australia. Data is from the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) passive hydroacoustic monitoring station off Cape Leeuwin, Australia.

### ***Understanding of Anthropogenic Changes to Soundscapes***

The introduction of anthropogenic noise into the ocean effectively began with the advent of the industrial age less than 200 years ago, with the most rapid increase in noise-producing human activities occurring over just the last 50-75 years. From steam engines and the development of propeller-driven ships, to massive levels of shipping, oil and gas exploration, and industrial activity, man's acoustic footprint in the ocean has become more and more widespread. Even in relatively pristine oceanic habitats like the Southern Ocean surrounding Antarctica, the sounds of man's distant activities can often be heard.

Such a rapid change in the underwater acoustic environment and animals' acoustic habitats, an instant on evolutionary time scales, has the potential to affect ecosystems and animals in a multitude of complex ways that we are only just beginning to appreciate. The effects of introduced noise may manifest themselves through a range of acute, chronic, and cumulative effects of multiple noise sources and other stressors (See Chapters 1 and 2, Appendix A). The consequences of these potential impacts include those that are immediate and obvious (e.g., masking leading to missed detection and avoidance of a predator), to more incremental and cryptic effects (e.g., increased stress levels, missed feeding or

breeding opportunities). The accumulation of cryptic effects over long periods may ultimately result in detrimental effects on the individual, which can impact the recovery, growth, or stability of a population, or ecosystems that they inhabit. In both cases, an ability to accurately characterize the contributions of natural and human sources to soundscapes is an essential step to understanding the ways that aquatic animals utilize sound and how man-made noise may potentially impact them.

### **CHARACTERIZING MARINE SOUNDSCAPES**

Marine soundscapes can be characterized by sampling the acoustic environment from hydrophone sensors (underwater microphones) attached to a variety of fixed and mobile instrument platforms. Analysis of this empirical data can then reveal how the soundscape varies over time, from place to place, and across the frequency spectrum. In addition, in recent years, there has been increased effort to conduct computer-based predictive soundscape modeling of anthropogenic contributions to soundscapes, based on the physical characteristics of the environment and the distribution and density of human activities.

#### ***Data Collection—Fixed Platforms***

Fixed platforms include autonomous hydrophone instruments, which are typically battery-powered devices capable of recording sound for periods ranging from a few days to multiple years. A large variety of these devices have been developed by many different research groups and companies (see Sousa-Lima et al., 2013). Important features of these instruments include recording duration (which may be extendable via duty-cycling the recording), frequency response (sensitivity), sampling rate, depth limit, instrument self-noise, dynamic range, ease of deployment, and cost. Instruments may be deployed in a variety of manners (see Dudzinski et al., 2011). Most commonly the moorings are entirely beneath the ocean's surface which is usually quieter, and less prone to ship strikes and fishing gear interactions. Gaining wider use in recent years are moorings with a surface component allowing for access to solar power, and communication over line-of-sight radio, satellite, or cell phone networks (e.g., Cornell Laboratory of Ornithology 2013, Marine Instrumentation Ltd. 2013). Some systems include software for detection of events of interest, such as vocalizations of a certain species. These detections may be used either to turn on recording (e.g., Tregenza 1999) or for real-time transmission of detected signals to shore.

Another form of fixed sensor is the cabled hydrophone or hydrophone array. These systems have been built by academic, private, and military groups; they feature real-time sound streaming from one or more hydrophones at each site. The U.S. Navy, for example, has long operated the large-scale Sound Surveillance System (SOSUS), and since the early 1990s has made it available to researchers with a security clearance (Nishimura & Conlon 1994). More recently, a number of cabled systems have been, or are being, installed for scientific research off the coasts of the U.S., Canada, Japan, Australia, and Italy, often in conjunction with other sensors following the concept of ocean observatories (e.g., Isern & Clark, 2003). Also, private researchers have installed hydrophones short distances offshore in a number of places around the world.

#### ***Data Collection—Mobile Platforms***

Mobile hydrophone platforms have long included vessel-deployed hydrophones, typically towed in an array behind the vessel or dangled overboard. These are still widely used for marine mammal surveys, by NOAA and many other researchers around the world. More recently, a variety of additional mobile platforms have come into use including hydrophone-equipped autonomous vehicles and drifting buoys. Autonomous vehicles include ocean gliders, which can use buoyancy changes and wings to “fly” forward

through the ocean or wave energy to propel themselves forward, and propeller-driven vehicles, which travel faster than gliders but often have higher noise levels. Drifting buoys are untethered and drift freely with currents, may be either surface- or subsurface-deployed, and may be either expendable or recoverable. In addition, acoustic recording tags have been developed to be placed on individual animals as part of broader behavioral studies. These tags may record the animals' vocalizations and other sounds the animal may hear, simultaneous with other parameters such as acceleration, pitch, roll, and yaw. These animal-borne tags, while requiring careful ethical consideration in their use, can provide previously unobtainable data on animal responses to sound through 3-dimensional reconstructions of animal movement and behavior underwater, in the presence of natural and human sound sources.

#### Systems standardization and documentation

While the use of identical hardware systems is ideal for making comparative measurements, in the absence of this, *standardization and/or careful documentation of system characteristics are essential to make results of soundscape surveys comparable over time or geographic regions*. Beyond basic information on deployments such as location (latitude/longitude, sensor/water depth), sampling rate, and recording start and end times, thorough documentation on the equipment configuration should include information on the frequency response, sensitivity, and self-noise of the hydrophone and recording system, directivity of the hydrophone, temporal drift and/or calibration of the recording system, and configuration of the deployment system (especially any compensation to reduce vibration and strum) including sensor depth. Also important are environmental characteristics: water depth, vertical sound speed profile (or at least temperature profile), wind speed, wave height, and bottom characteristics if available.

#### **Data Analysis**

Acoustic data analyses can be carried out on with a wide variety of programs designed specifically for sound analyses. Both readily available, off-the-shelf programs and software (e.g., Ishmael, Avisoft, Raven, to name a few), as well as custom-written scripts in programming languages like MatLab or R, can perform a range of acoustic analyses on the recorded data to describe its features, including the spectral (frequency) and temporal composition, and received levels of sound in the datasets.

In the first instance, specific sound types of biological, abiotic, or anthropogenic origin can be extracted by browsing the data for the sounds of interest (Figure 3-2). These analyses can be conducted manually, by reviewing spectrograms visually and aurally, or by using automated detectors for specific signals. Calls of a species of interest (mammal, fish, snapping shrimp, etc.) may be extracted for studies of seasonal and spatial animal distributions, response to anthropogenic activities, behavior, acoustic repertoires, levels at which animals produce sound, and most recently, for population density and absolute abundance estimation using cutting edge techniques that are rapidly being developed (for a review see Marques et al., 2013). If data is sampled from multiple time-synchronized hydrophones, a sound source can often be localized and its movement tracked. With a known source location, either through acoustic localization or with another data source (e.g., Automatic Information System vessel tracking systems or known locations of human activity), the source level and frequency signature can be determined. *Determining accurate source features on a variety of human activities (e.g. seismic airguns, vessel traffic, pile driving) is an essential component in assessing potential impacts of sound on marine life and their acoustic habitats, and contributions to the broader oceanic soundscape.*

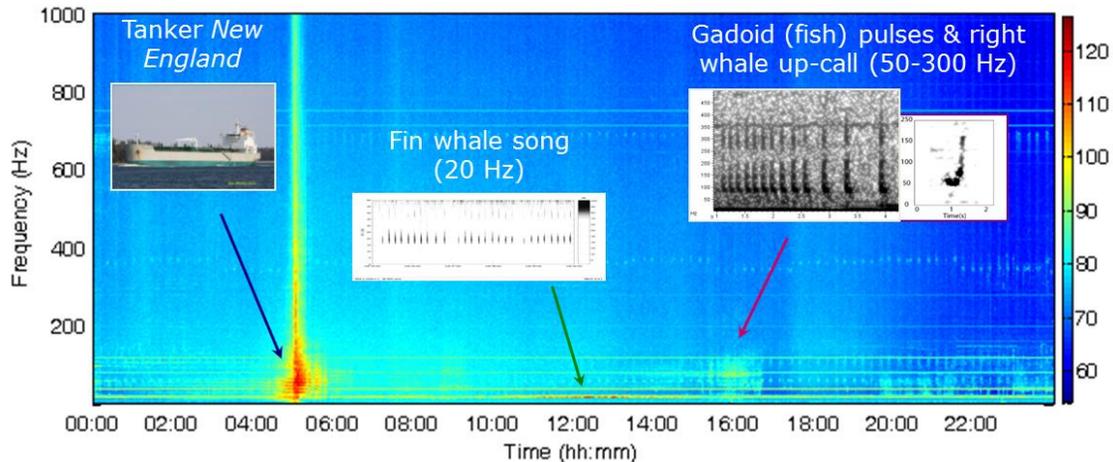


Figure 3-2. An example of a 24 hour soundscape with component noise sources illustrated. Recording is from a NOAA Northeast Fisheries Science Center and Stellwagen Bank National Marine Sanctuary collaboration with Cornell University.

When characterizing the soundscape of a place, it is often most valuable to look at longer time frames and the variability of the soundscape's characteristics over that time. The *temporal variation* of noise levels will describe changes in the sound pressure levels over time. The *spectral variation* of noise describes the variation in different frequency components present. And a combination of both domains describes the variability in both temporal and frequency components of the recorded soundscape. Figure 3-3 is an example of this type of analysis, illustrating how spectral content can be analyzed and displayed using a *noise level percentile distribution*, which, for each frequency band, shows the percentage of time that various noise levels are exceeded. For instance, the 90th-percentile value is a high sound level that is only exceeded 10% of the time. Such a percentile spectrum is useful when noise levels vary over time, as it can reveal very quiet periods or very loud events which, while being at significantly higher or lower levels than average, would only be present a very small percentage of the time. The noise level percentile spectrum is one of many ways (e.g., spectral probability density plots described in Merchant et al., 2013) to *quantify over long time frames the essential components of a soundscape of a place, illustrating variability in sound levels and frequency content of the soundscape.*

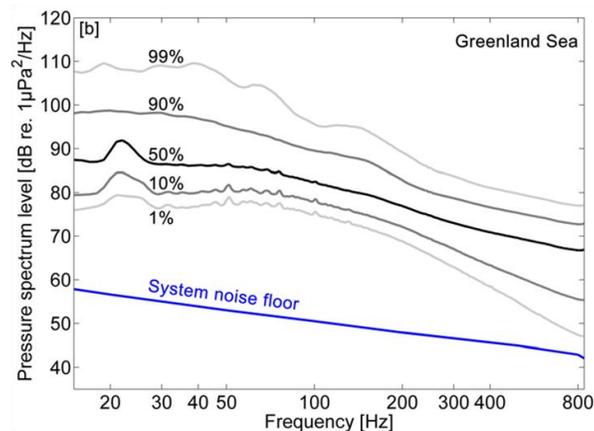


Figure 3-3. An example of a percentile noise spectrum. The 90th-percentile curve, for instance, is the level that is louder than ambient sound 90% of the time. Note the peak between 20-30Hz representing acoustic energy from fin whales. System noise floor represents the lowest levels that the instrumentation is capable of detecting. *Reproduced with permission from Klinck et al. (2012). Copyright 2012, Acoustical Society of America.*

Soundscape data can also be displayed in ways that reveal broad-scale temporal information, and also allow exploration of how a soundscape changes over varying time-scales (e.g., seconds, daily, seasonal, annual). One such method is the long-term spectral average (LTSA), which is essentially a day- to years-long visualization (i.e., spectrogram) of sound over this time. While individual sounds from animals, human activity, or abiotic noise sources are not typically distinguishable within these long term averages, when there is a relative abundance in calling individuals or sound sources, their acoustic energy is clearly visible along with any seasonal patterns (Figure 3-1). On the other end of the scale, high temporal resolution (e.g. <1s) displays and analyses can also be conducted to characterize short-term changes, and assess potential impacts from intermittent, time-varying, or duty-cycled sources on biologically relevant time-scales.

#### Value of long-term baseline data

Well-characterized long-term acoustic records from the same location spanning a decade or more are rare. *These long-term acoustic datasets are essential for establishing baseline conditions, assessing long-term trends in characteristics of interest like noise levels or animal presence and eventually abundance, and determining the contribution of human activities to changing soundscapes.* Examples of long-term acoustic datasets include sounds recorded by NOAA PMEL from the U.S. Navy's SOSUS arrays (Fox & Hammond, 1994), and sounds recorded by the Comprehensive Test Ban Treaty Organization (CTBTO) for monitoring nuclear explosions worldwide ([www.ctbto.org](http://www.ctbto.org)). Both of these systems sample only the very low frequency domain, which can be used for assessing the contributions of anthropogenic (container ships, seismic airguns) and many natural (baleen whales, storms, wave height, wind speed) sound sources to the ocean soundscape. Thus, these unique long-term archives of continuous passive acoustic data can permit analysis of both seasonal and multi-year variability in ambient sound levels at a multitude of temporal and spatial scales.

#### ***Predictive Sound Field Mapping***

An alternative to gathering empirical measurements of ocean noise that has been increasing in prevalence in recent years, is conducting large scale computer-based predictive sound modeling (NOAA, 2012; SC/65B/Rep03rev, 2014). This technique is particularly useful for assessing the potential contributions of human activities to the ocean soundscape over large geographic scales, and based on varying amounts of human activities. *With the necessary components of the density and distribution of sound sources, their spectral characteristics and source levels, and environmental data (e.g., bathymetry, vertical sound speed profile of the water column, sediments), sound propagation modeling can be conducted that can predict the sound-field resulting from multiple sources at a variety of locations.* One example of this was the recent NOAA-led CetSound—SoundMap effort (<http://cetsound.noaa.gov>) which conducted predictive sound field modeling to provide annual average sound levels throughout most of the U.S. Exclusive Economic Zone resulting from a range of anthropogenic activities (e.g., global shipping, passenger, fishing vessel traffic, and seismic survey activity). This predictive modeling capability can also be used over shorter time frames and/or geographic scales to predict the sounds resulting from any individual or particular set of activities (Figure 3-4).

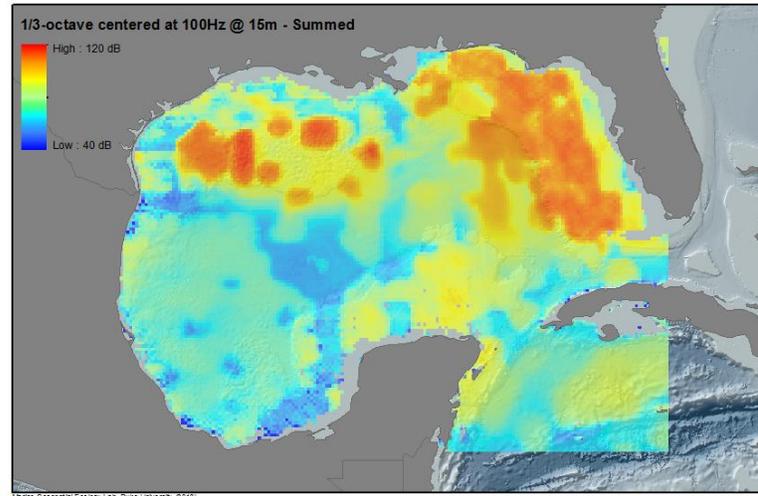


Figure 3-4. Gulf of Mexico predicted average annual noise levels (1/3 octave band centered at 100Hz, at 15m depth) summing contributions from (a) large commercial shipping, (b) passenger vessels, (c) seismic surveys, and (d) rig support vessel traffic. *Note—this figure is for illustrative purposes only, and as with any modeling output, is directly reflective of the underlying input data. For example, the modeled seismic survey activity was based on effort in 2009, which may not be representative of survey activity during other time frames.*

### CURRENT NOAA ASSETS/CAPABILITIES TO CHARACTERIZE AQUATIC SOUNDSCAPES

Passive acoustic monitoring and research at NOAA are being conducted by researchers at the NOAA Fisheries (NMFS) Science Centers (FSC), the National Ocean Service—National Marine Sanctuaries (NOS-NMS) and National Centers for Coastal Ocean Science (NCCOS), and the NOAA Office of Oceanic and Atmospheric Research— Pacific Marine Environmental Laboratory (OAR-PMEL) Acoustics Program. Most passive acoustic research projects at the NMFS FSCs and NOS NMSs focus on investigating seasonal presence, distribution, movement, and behavior of marine animals, as well as characterizing anthropogenic noise and assessing its potential impacts. The acoustics components of the PMEL Acoustics Program also focus on monitoring to detect and localize small submarine earthquakes and volcanic activities.

#### **Acoustic Equipment**

Currently, a variety of fixed and mobile platforms are being utilized by NOAA to record acoustic data to study the ecology and behavior of marine animals, ambient ocean noise, geophysical events, as well as anthropogenic noise that could affect marine life. The fixed platforms used by NMFS, NOS and OAR-PMEL include AURALS (Autonomous Underwater Recorders for Acoustic Listening), EARs (Ecological Acoustic Recorder), HARPs (High-frequency Acoustic Recording Package), MARUs (Marine Autonomous Recording Unit), C-PODs (Cetacean and Porpoise Detectors), AMARs (Autonomous Multichannel Acoustic Recorder), SM3Ms (Song Meter SM3M Submersible), PMEL produced Autonomous Underwater Hydrophones (AUH) and several regional hydrophone network nodes deployed in the Washington inland waters. For mobile platforms, the equipment used includes towed hydrophones and/or hydrophone arrays, sonobuoys, free floating hydrophones, dipping hydrophones, and gliders currently being used at six of the NMFS FSCs (see Table 3-1, Figure 3-5). Although most of these projects focus on recording signals of biological origin, acoustic data obtained during the process can additionally be used to characterize and improve our knowledge of underwater soundscapes.



Figure 3-5. OAR-PMEL AUH being deployed, and a towed array on the deck of a ship.

Table 3-1. Passive Acoustic Monitoring Capacity across NOAA offices (as of 08/2016)

<b><u>NOAA Office</u></b>	<b><u>Current Equipment Holdings (leased or owned)</u></b>	<b><u>Approx. Data Holdings</u></b>	<b><u>Staff Acoustics Capacity*</u></b>	<b><u>Example Projects</u></b>
NMFS-AFSC	47 AURALs sonobuoys; towed array 3 EAR (lease) 14 CPOD 1 SM2M HF 1 DSG-Ocean 3 DSG-ST	Past : ~45TB Future: ~8TB/year	2 FTE ; 8 contractors;	ALTIMA (Arctic Long-Term Integrated Mooring Array); CHAOZ (Chukchi Sea Acoustics, Oceanography, and Zooplankton); CHAOZ-X (extension of CHAOZ); ARCWEST (Arctic Whale Ecology Study); High Arctic Passive Acoustics Study; CIBA (Cook Inlet Beluga Acoustics Project); Cook Inlet Anthropogenic Noise Study;
NMFS-NEFSC	37 MARUs 5 HARPs 6 Sound traps 2 Towed hydrophone arrays	Past: ~70TB FY16-17: >100 TB	2 FTE, 6 contractors, 3 short-term contractors/ interns/students.	Occurrence of fish, invertebrates, baleen whales & toothed whales in western N. Atlantic; Acoustic ecology of baleen whales; Soundscape comparisons among habitats; Acoustic abundance analyses of odontocetes
NMFS-NWFSC	17 EARS 3 CPODs 2 Towed arrays 96 Sonobuoys	Past: 28TB total Future: 4TB/year	2-FTEs	PODS (Pacific Orcinus Distribution Survey) Cruise Winter habitat of Southern Resident killer whales
NMFS-PIFSC	8 HARPs; multiple towed arrays; 9 miniHARPs	Past: ~130TB Future: collecting up to 20TB/yr	0.25 FTE, 3 contractors	Long-term monitoring across the central and western Pacific; acoustic monitoring of the Hawaii longline fishery; towed acoustics on abundance surveys
NMFS-SEFSC	3 HARPs 5 LARPs 3 towed arrays	Past: 100 TB Future: ~10 TB/year	½ FTE; 1 contractor	Right whale calving grounds project; Dry Tortugas sperm whale project

NMFS-SWFSC	19 DASBRs; 7 Towed Hydrophone Arrays (1 tetrahedral, 2 inline, 4 End Arrays); 6 CPODs and 1 DSG	Past: 36 TB Future: 30Tb	2 FTE permanent; 1 FTE term,	PASCAL- Passive Acoustic Survey of Cetacean Abundance Levels in 2016; CalCurCEAS 2014 survey; SOCAL-BRS Surveys; many sea trials to develop and test equipment
OAR-PMEL	North Pacific SOSUS hydrophone archive; 48 AUHs (autonomous hydrophones); 3 acoustics capable profile floats 2 acoustic sea gliders 1 slocum glider 1 Acousonde 3B	Past:19TB, Future: 0.5 TB/yr  Past: 31 TB, Future: 5 TB/yr	1 FTE, 8 JI contractors	Long-term fin whale-ambient noise in N. Pacific  Ocean Noise Reference Station Network, Equatorial Atlantic
NOS-NCCOS	2 Soundtraps ( <a href="http://Oceaninstruments.com">Oceaninstruments.com</a> ), partnership with Duke University); 2 Remoras-Soundtraps packaged for gliders	Past: <100GB Future: 500 GB/year	1-FTE	Passive acoustic surveys for reef fish aggregations using ocean gliders; Soundscapes of temperate reefs; Fish and marine mammal responses to seismic surveys
NOS-NMS-Stellwagen	10 MARUs (through collaboration with NESFC and Cornell University) 2 Soundtraps	(included within NEFSC and NOAA-PMEL holdings)	1 FTE; 1 contractor (acoustic specialist); partial time from 1 FTE (GIS) & 1 contractor (GIS)	Occurrence and acoustic behavior of whales & fish in sanctuary; Sanctuary soundscapes; Vessel noise characterization; Sanctuary system noise monitoring (NRS collaboration)
NOS-NMS-Flower Garden Banks, Florida Keys and Gray's Reef	6 Soundtraps (through collaboration with NESFC)	Partial time from 4-6 FTEs (Conservation Science HQ staff & site Research Coordinators)	Partial time of 4-6 FTEs: Conservation Science HQ staff & site Research Coordinators	Sanctuary soundscapes

\*Staff positions typically funded via a range of office programs in lieu of dedicated acoustics funds

#### **Acronyms**

AUH: OAR PMEL Autonomous Underwater Hydrophone  
AURAL: Autonomous Underwater Recorders for Acoustic Listening  
DASBR: Drifting Autonomous Spar Buoy Recorders  
DSG: Loggerhead Ocean acoustic datalogger  
EAR: Ecological Acoustic Recorder  
HARP: High-frequency Acoustic Recording Package  
LARP: Low-frequency Acoustic Recording Package  
MARU: Marine Autonomous Recording Unit  
NRS: Ocean Noise Reference Station Network  
SM2M: Wildlife Acoustics Song Meter Submersible

**Data Holdings—NOAA**

Recording of passive acoustic data has been occurring throughout various NOAA offices at least sporadically for over 40 years. In the early 1990s, OAR-PMEL began archiving very low-frequency Navy SOSUS hydrophone array data, with more concentrated efforts utilizing their own capacity beginning later in the 1990s. In 2000, the AFSC set out its first long-term recorders in the SE Bering Sea to detect calls from endangered North Pacific Right Whales. Across NMFS, passive acoustic data collection ramped up between the early and mid-2000s (NMFS 2011). Currently, all the NMFS FSCs, many NOS NMS and NCCOS offices, and OAR-PMEL invest substantial efforts on passive acoustic research projects. Nearly all acoustic data being recorded currently are digitized (e.g., wav, mp3 formats), stored on hard drives, and therefore made accessible via a computer, although many recordings from early years (pre-2005) consist of either digital or analog data stored on magnetic media like DAT or HI-8 tape and retrieving these data can prove more challenging.

Due to the large sizes of digital acoustic files, data storage, archiving, and management at each facility and data sharing among NOAA research facilities is a challenging issue with estimates of over 100 TB per year of acoustic data accumulation for some FSCs. Passive acoustic data volume is continuing to grow across the agency. With such large raw data volumes being accumulated in various formats by offices throughout NOAA *a unified metadata and data archival capacity is sorely needed to support: proper documentation and long-term preservation of these data, as well as allowing for simplified querying and access to the data across NOAA.*

**Data and metadata archival system pilot study (2014-16)**

A pilot study between NEFSC, AFSC, and the National Centers for Environmental Information (NCEI) was recently implemented to develop archival system capacity for passive acoustics data. To begin, both AFSC and NEFSC have utilized Tethys, the metadata and spatial-temporal database developed by Dr. Marie Roch of San Diego State University for their own data holdings, and provided the data and metadata for NCEI to develop compatible data ingestion and management procedures. In parallel, IOOS, NMFS, and NCEI have been collaborating to develop an International Standards Organization (ISO) compliant metadata standard for passive acoustic datasets. Merging these projects, to provide a long term archival capacity, with ISO-compliant metadata is currently underway at NCEI and, if maintained, would be a great advance in NOAA's capacity to manage, utilize, and provide public access to passive acoustic data.

**Monitoring Data Resulting from Permitted Activities**

NMFS currently requires the collection of monitoring data in support of many of the activities it authorizes under numerous statutes (Chapter 1). These include 'sound source verification' (SSV) data, characterizing various source sound signatures arising from permitted activities (e.g., seismic airgun surveys, dynamic thrusters on vessels, pile driving), and also short- to long-term deployment of acoustic recorders associated with various projects. Thus for many years much of this information-rich data has been reported back to NOAA, but is not being accessed or utilized in any standardized fashion that would allow its value to be realized. *NOAA could expand its capability to more effectively utilize this data in adaptive management of permitted activities, as well as in broader scientific studies of species, special places, and anthropogenic activity impacts.*

### TANGIBLE OUTCOMES APPLICABLE TO NOAA'S OCEAN NOISE STRATEGY MISSION

The highest priorities for increased NOAA capacity to monitor and characterize soundscapes will be in locations of significance for acoustically sensitive species (Chapter 1, Appendix A), designated habitats of importance (e.g., special places or sanctuaries as described in Chapter 2), or locations of significance undergoing rapid and large scale environmental or human use changes. With increased capacity, the following tangible benefits will be realized:

#### ***Quantification of Spatial, Spectral, and Temporal Variability of Ambient Noise Conditions***

As noted earlier (Figures 3-1 to 3-3), ambient noise conditions naturally vary over time, among locations, and in the frequency composition of the sounds that comprise them. Quantifying soundscapes and their variability will improve understanding of the various ambient noise conditions animals naturally encounter, and the changing contributions of various sources of noise in the marine environment. This will provide context to understand how animals might cope with wide ranging noise conditions and the compensation mechanisms they may employ (e.g., Parks et al., 2007) and assess the impact of future activities that generate underwater sound.

Example: Contribution of geo-seismic activity to soundscapes— Global seafloor earthquake patterns show that ocean basin seismic activity tends to be narrowly focused along mid-ocean ridges and along subducting continental margins. Earthquakes at these locations typically have shallow origins and thus can couple efficiently into the water column and convert to acoustic energy. To illustrate this, during the past 20 years of seafloor seismic monitoring in the northeast Pacific Ocean, nearly 50,000 earthquakes were detected over a 1km x 105 km area of seafloor. Seismic energy can thus be a significant, albeit sporadic contribution to the naturally occurring low-frequency ocean soundscape.

#### ***Increased Understanding of Anthropogenic Sound Sources, Their Contributions to Soundscapes, and Changing Human Use Patterns***

Human use of the marine environment is continuing to expand to more locations with greater intensity worldwide. An increased capacity to characterize soundscapes will allow NOAA to obtain a more detailed understanding and quantification of the characteristics of human noise sources and how they contribute to oceanic soundscapes. In addition, increased monitoring and predictive capacity will allow NOAA to assess how future changes in human use and activities may alter soundscapes in the future.

Example: Climate change effects on soundscapes—Climate change has altered the extent of sea ice coverage, sea temperatures, ocean acidity, and oceanographic currents, which is expected to lead to changes in species composition, abundance, and distribution at multiple trophic levels. These alterations to the natural environment will include a changing soundscape as the occurrence and distribution of biotic and abiotic sound sources will be modified. With current predictions now estimating that the Arctic could be ice-free in the summer within twenty years (Overland & Wang, 2013), the opening of new maritime transportation lanes, and expansion of oil and gas-related exploration and development and tourism into previously closed seasons and localities will likely result. This combination of increasing human activities, and changes in range distributions of marine animals, and in oceanographic and atmospheric dynamics, will lead to large-scale alterations of the Arctic soundscape.

***Improving Understanding of Behavior and Biology of Marine Life***

Much of NOAA's current passive acoustics research focuses on gathering information on the distribution, seasonal presence, and behavior of vocally active species, which are essential inputs to NMFS stock assessments. In recent years, increasing effort has led to advances in the use of passive acoustics to assess the relative abundance or density of vocal species (Marques et al., 2013). With further development and the addition of essential information on a species' vocal behavior and the variability in sound production among individuals (e.g., vocalization rate, demographics, seasonality) and local sound field characteristics (e.g., detection range, frequency-specific propagation conditions, ambient noise levels), these techniques should ultimately lead to a greater ability to use passive acoustics to refine absolute abundance estimates which can then feed directly into stock assessments.

***Assessments of Effectiveness of Noise Mitigation Strategies***

As attention to noise related impacts to marine life continues to increase, mitigation strategies are increasingly likely to be employed. These include measures like shifting of shipping lanes, vessel speed restrictions, and use of noise reduction technologies. A greater ability to characterize the soundscape will allow NOAA to assess the effectiveness of these measures by quantifying the resulting changes in surrounding soundscapes.

***Increased Accuracy of Predictive Sound Field Modeling***

With increasing use of predictive sound field mapping tools (NOAA, 2012; SC/65B/Rep03rev, 2014) there is a clear need to quantify the uncertainty in and verify accuracy of the predicted sound levels through comparison with empirical measurements. Empirical data are also essential to help characterize difficult-to-model environments (e.g., shallow coastal waters). In addition, as noted above, obtaining characterizations (source level, frequency composition, directivity) of specific anthropogenic sound sources is essential information to increase the accuracy of modeling efforts predicting sound fields resulting from human activities.

**FUTURE DIRECTIONS**

As NOAA begins to implement an agency-wide Ocean Noise Strategy, there are a range of actions that can be taken to work towards the goals of this strategy. Of perhaps the greatest importance, is the overarching need to coordinate activities among the various NOAA line offices and to prioritize the development of NOAA's assets in ways that can address priority research and management needs of species and habitats (Chapters 1 and 2). With a more coordinated approach to passive acoustic sampling, archiving of data and metadata in an accessible database, as well as of processing and analysis routines, NOAA will take great strides towards enhancing its capability to characterize, understand, and assess soundscapes and the variety of sounds that comprise them. The following actions, while not a comprehensive or exhaustive list, are concrete steps related to soundscape characterization that are particularly well suited to cross-agency coordination.

1. ***Establishment of NOAA-led, long-term, standardized passive acoustic research capacity across the agency***— While many offices across NOAA carry out passive acoustic research programs, they do so largely independently of others, often-times raising their own external funds to support the work. Key science needs would be met and knowledge gaps filled if NOAA committed to maintaining a long-term baseline monitoring capability that is coordinated across offices and standardized to the maximum extent feasible. An example of this is *the NOAA Ocean Noise Reference Station Network (NRS)*. The NRS is a collaborative effort, begun in 2014,

between OAR's Pacific Marine Environmental Laboratory (PMEL), NMFS Science Centers and the Office of Science and Technology, NOS National Marine Sanctuary Offices and the National Park Service. The objective of the project is to establish an initial NOAA-operated network of eleven ocean noise reference stations in U.S. waters to monitor long-term changes and trends in the underwater soundscape and acoustic habitats. By deploying identical and calibrated autonomous acoustic recording systems (PMEL's Autonomous Underwater Hydrophone packages) at each reference station, NOAA is recording consistent and comparable multi-year acoustic data sets covering the major regions of U.S. waters. Instruments are deployed for a nominal period of two years and record continuously over the 10-2500Hz frequency range, before being recovered and redeployed. Ultimately, upon successful completion of the pilot study and demonstration of its value, this network will be expanded to more locations, sample over a greater frequency range, and be maintained over decades to come. Notably, a recently formed Interagency Task Force on Ocean Noise and Marine Life (ITF-ONML) of the Subcommittee on Ocean Science and Technology (SOST) has highlighted this need across federal agencies. The ITF-ONML is now working towards aligning agency interests in establishing a long-term passive acoustic monitoring network, including the NRS system as a core component.

2. ***Standardization of basic data analysis routines and output metrics***—Beyond establishing a standardized metadata format and centralized passive acoustic database, a set of basic analysis routines should be applied to all appropriate datasets. Depending on the objectives of the data analysis (e.g., characterizing variation in ambient noise conditions, detection of animal calls, etc.), acoustic parameters should be carefully defined and standardized, to the extent possible, often requiring a combination of several metrics. One example of this is the current European Union effort to achieve or maintain a good environmental status by 2020 (Marine Strategy Framework Directive, European Commission, 2008), which requires documenting and characterizing underwater noise in all EU marine regions to evaluate if there is no adverse effect of energy inputs on any component of the marine environment. Under this directive, two indicators of underwater sound have been developed (European Commission, 2010):
  - a. Proportion of days and their temporal and spatial distribution per year over a grid in which low- and mid-frequency impulsive sounds (10 Hz – 10 kHz) exceed a specific threshold, measured in both Sound Exposure Level, SEL (dB re  $1\mu\text{Pa}^2\cdot\text{s}$ ) and peak level (dB re  $1\mu\text{Pa}_{\text{peak}}$ ).
  - b. Trends in the ambient noise level (in dB re  $1\mu\text{Pa}$  RMS) within the 1/3 octave bands 63 and 125 Hz measured as 1 full year averages (arithmetic mean).

A recent international soundscape mapping workshop worked to develop comprehensive recommendations (see workshop report SC/65B/Rep03rev, 2014) for soundscape analysis and characterization that were consistent with both the EU-MSFD recommendations and the predictive sound field mapping methodologies developed as part of NOAA's recent Cetacean and Sound Mapping effort (NOAA, 2012). Both of these efforts demonstrate the clear need for appropriate metrics to characterize and compare short and long term variability in noise across sites. Standardized analysis routines and metrics, developed in consultation with partners and stakeholders, and in consideration of national and international standards, will then allow for automated processing of datasets as well as detection of specific anthropogenic noise events, and occurrence of marine animals and/or abiotic events.

3. ***Archiving of passive acoustic meta and raw data***—Currently, while particular projects result from collaborations between different NOAA line offices (e.g., above NRS pilot study being initiated), each office that records passive acoustic data does so largely independently of others.

Data from such efforts are typically stored locally on hard drives and/or servers, and there is no current metadata standard that effectively describes the passive acoustic datasets from various platforms. A standardized metadata format (as described above) to accompany all NOAA passive acoustic datasets should be adopted across the agency. In addition, there is a strong need for a centralized data archival capability to improve access to and utility of current holdings, and sustainably preserve these data. Recognizing this need, the SOST's ITF-ONML (noted in recommendation 1) is similarly working to align federal agency interests in a centralized archive of passive acoustic data. This effort will likely build upon recent discussions with NOAA's National Centers for Environmental Information (NCEI) about providing this capability. A pilot study is being conducted between NMFS and NCEI to establish and test, with a small subset of data, the methodology for maintaining, archiving, and disseminating NMFS' existing and future passive acoustic data. With the successful demonstration of this capability, the effort should ultimately be expanded to include passive acoustic data sampled NOAA-wide, metadata describing the raw data, and the results of the standardized analysis routines.

4. **Developing NOAA 'in-house' predictive sound field capacity**—While NOAA led and coordinated the CetSound-SoundMap effort (<http://cetsound.noaa.gov>), the computationally intensive sound propagation modeling was carried out by external collaborators. Moving forward, NOAA needs to develop and establish an internal capability to conduct this sound field modeling for a variety of circumstances. This will provide the ability to: predict resulting sound-fields from (a) individual activities that are seeking authorization under various NOAA statutory authorities in order to assess potential species level impacts; (b) multiple human activities that are necessary in order to conduct place-based management of acoustic habitat; and (c) address NOAA's increasing need to more effectively assess cumulative impacts of human activities on species and habitats.

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