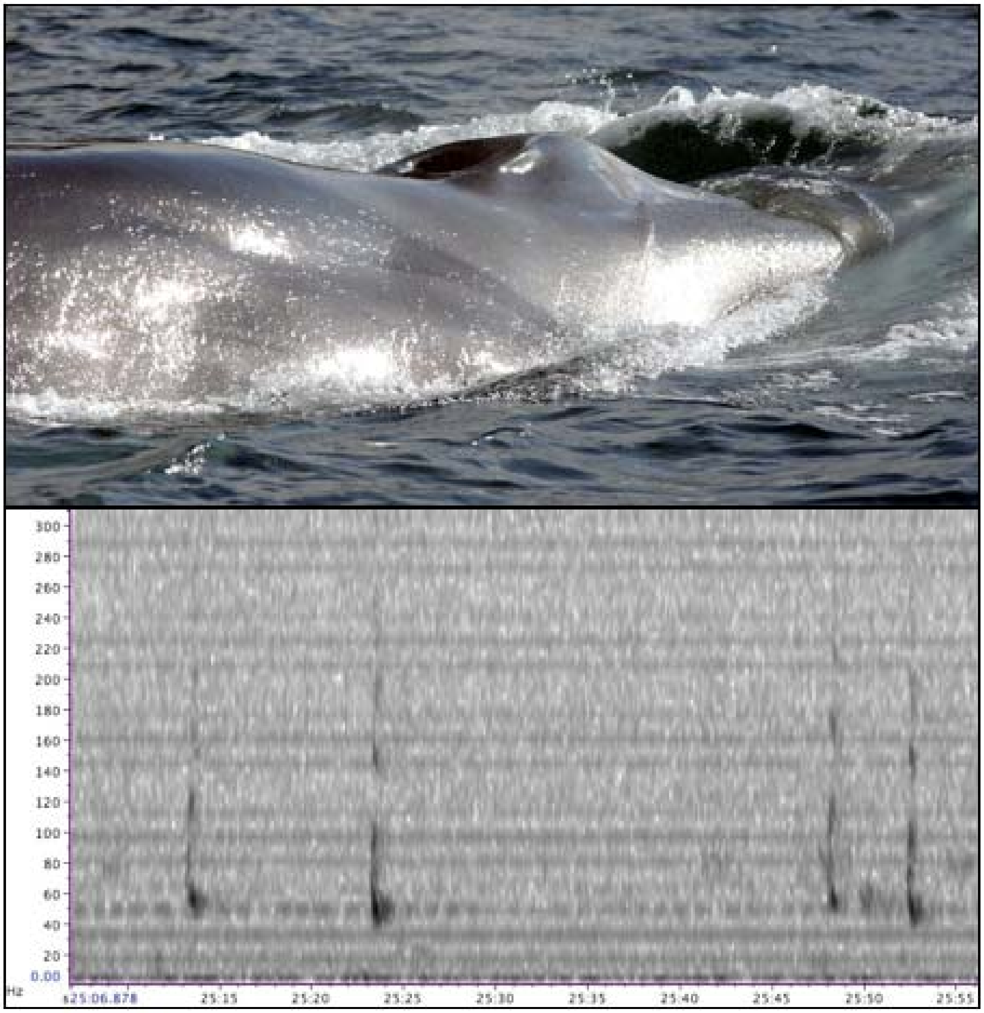
Passive Acoustic Monitoring (PAM) Sound Catalogue: Approach for NW Atlantic Additions



Report Produced For

Environmental Studies Research Funds
National Energy Board
444 - 7th Avenue, S.W.
Calgary, Alberta T2P 0X8

24 March, 2010

Tara Stevens[1,2]
Dr. Jack Lawson[1]

[1] Marine Mammal Section, Fisheries and Oceans, Canada, St. John's, NL
[2] Cognitive and Behavioural Ecology, Memorial University of Newfoundland, St. John's, NL

Executive Summary

Passive acoustic monitoring (PAM) can be used to assess the presence of marine animals when they are producing sounds. This is useful in mitigating the potentially negative effects of anthropogenic sounds on marine mammals. PAM technology lacks error-proof, automated detection algorithms; sound samples for species of interest are needed to “train” such software. This project is limited to sounds in the northwest Atlantic. For some species, data in the public domain is limited or non-existent. This ESRF-funded project expands on previous work to collect underwater sound data and build an easily accessible and well-documented digital cetacean sound catalogue for the northwest Atlantic. Such a catalogue will be useful for research and industry applications of PAM and other detection systems. All cetacean species found in the northwest Atlantic were assessed for the existence of vocalization recordings and whether those data could be accessed for this project. Of the 25 species identified, we have been able to acquire audio recordings of 19 from the northwest Atlantic and two from neighbouring Atlantic regions. The ESRF catalogue includes recordings of representative whale calls and echolocation examples in WAVE format, and is supplemented with non-cetacean sounds that might evoke false positives in a PAM system.

Sommaire

La surveillance acoustique passive (SAP) peut être utilisée pour évaluer la présence d’animaux marins lorsqu’ils produisent des sons. Elle est utile pour atténuer les effets négatifs potentiels des sons anthropogéniques sur les mammifères marins. La technologie SAP est déficiente sur le plan des algorithmes de détection automatisée sans erreurs et des échantillons de son des espèces visées sont requis pour le « perfectionnement de » ce logiciel. Ces sons se limitent au Nord-Ouest de l’Atlantique et, dans le cas de certaines espèces, peu de données sont disponibles dans le domaine public, voir aucune. Le projet, financé par le Fonds pour l’étude de l’environnement (FEE), est la continuation de travaux précédents et vise à recueillir des données sur les sons subaquatiques et à produire un catalogue numérique des sons de cétacés, facilement accessible et bien documenté, pour le Nord-Ouest de l’Atlantique. Il sera utile pour les applications de recherche et les applications industrielles du SAP et autres systèmes de détection. Toutes les espèces de cétacés du Nord-Ouest de l’Atlantique ont été évaluées pour déterminer si des enregistrements de vocalisations existaient et si ces données pouvaient être évaluées dans le cadre du projet. Des 25 espèces désignées, 19 enregistrements audio du Nord-Ouest de l’Atlantique et 2 des régions atlantiques avoisinantes ont été obtenus. Le catalogue du FEE comporte des enregistrements de chants représentatifs de baleines ainsi que des exemples d’écholocation en format WAVE. On y a aussi ajouté des sons ne provenant pas de cétacés qui pourraient mener à une fausse interprétation lors de l’utilisation du système PAM.

ESRF Project Rationale and Description

Applicability to Passive Acoustic Monitoring Systems

Passive acoustic monitoring (PAM) is a powerful method employed to detect the presence of marine animals that are producing sounds such as calls, whistles, or echolocation clicks by using either moored or towed hydrophones. By allowing operators to detect and localize marine mammals, the PAM approach can be a useful tool to mitigate potential effects of anthropogenic sounds, such as from seismic and naval activities. PAM technology, particularly software, has been under development for more than a decade, yet still suffers from a lack of error-proof automated detection algorithms. This is a product of these systems relying on fully- or semi-automated sound classification methods that work best when the software and operators are "trained" using existing sound samples for species of interest. Availability and quality of these sounds are usually limited for the northwest Atlantic (see summary in Table 1).

An ESRF-Funded Cetacean Sound Catalogue

The ESRF Management Board approved funds to identify and collect what sound data exist for cetaceans of the northwest Atlantic in support of the "Statement of Canadian Practice with respect to the Mitigation of Seismic Sound in the Marine Environment". This Code of Practice has been adopted by the Offshore Petroleum Boards in an effort to mitigate the potential impacts of sounds produced during the conduct of offshore seismic surveys. Part of this Code of Practice provides for the use of passive acoustic monitoring for the detection of sound-producing cetaceans at night or during periods of poor visibility.

<u>Species of Interest For The Project</u>

All cetacean species found in the northwest Atlantic were assessed for the existence of vocalization recordings and whether that data was assessable for this project. Species found in Atlantic Canada and Species At Risk (SARA-listed) were given preference. Of the 25 species identified, recordings of 19 from the northwest Atlantic and two from neighbouring Atlantic regions were acquired. The number of recordings collected per species ranged widely based on a number of factors, including the degree of complexity of the species' call repertoire, the number of recordings that exist, the vocal behaviour of a particular species, and the occurrence of a species in this region. The catalogue is composed of relatively short recordings of representative whale calls, call sequences, song, and echolocation examples in WAVE format. WAVE was chosen because it is a standard, cross-platform, uncompressed audio file type.

Sounds from several pinniped (seal) species that have been recorded in the same times and locations as cetaceans in the NW Atlantic and Arctic Canada (e.g., bearded seal, *Erignathus barbatus* (Figure 1), walrus, *Odobenus rosmarus*, and harp seal, *Pagophilus groenlandicus*) are included in this catalogue. Furthermore, the catalogue is supplemented with non-mammal sounds, such as vessel, propeller, and other anthropogenic noises, fish sounds, environmental noise, etc. that might evoke false-positives in a PAM system. All recordings have associated metadata which provides critical context.

Project Benefits

This project expands on a variety of previous work by collecting underwater sound data and building an easily-accessible and well-documented digital marine mammal sound catalogue for the northwest Atlantic. This database of recordings and associated metadata will be useful to research and industry applications of PAM and other detection systems. It will also provide means for users and contributors to enhance the value of existing and future sound recordings by standardizing recording methodologies and metadata collection.

The catalogue primarily focuses on cetacean species found and recorded in the northwest Atlantic. Where recordings from this region were unavailable, recordings from other geographic areas were used to supplement the catalogue. Its benefit for future acoustic monitoring and mitigation programmes will give industry and regulatory agencies a better tool to mitigate the potential impacts of anthropogenic sounds by being better able to detect and locate sound-producing marine mammals and determine their identity more easily. Furthermore, researchers collecting sound recordings from autonomous moored hydrophone systems, which may include years of data, will be able to use this sound catalogue to develop more efficient data analysis methods. The outcomes of this project, therefore, will be of considerable use to industry and research for continued PAM development and support.

Project Goals

The goals of this ESRF project, then, were to:

(a) collect digital copies of existing marine mammal (primarily cetaceans) vocalization and echolocation sounds to be included in a digital sound catalogue to better ensure accurate species identifications,
(b) identify marine mammal species in the northwest Atlantic for which such sound recordings are lacking,
(c) collect digital copies of non-mammal sounds that might evoke “false positive” responses from existing PAM systems, and
(d) recommend appropriate follow-on research to collect needed data and further the advancement of PAM and PAM detection systems.

Digital Catalogue Of Cetacean Vocalization And Echolocation Sounds

The required acoustic recordings were extracted from existing digital collections of research institutions, government, military, and NGO researchers, and contractors. Most of the data that were originally recorded in analogue format had been transferred to digital media by the originating organization prior to inclusion in this catalogue; we digitized some older analogue-format data for humpback (*Megaptera novaeangliae*) and killer whales (*Orcinus orca*) from the Grand Banks that was stored on reel-to-reel tapes.

Acoustic recordings were only included in the study if they had associated metadata (e.g., detailed descriptions of the data and recording context). Metadata that was required before the audio file could be accepted were recording location, date, species identity, with degree of confidence for identification accuracy, and recordist and recorder information. See Table 2 for a list of metadata fields, some of which may remain blank for certain recordings as they were not documented at the time or remain unknown. The metadata, currently as an Excel spreadsheet, is structured in an open-ended format to accommodate the inclusion of additional sounds which may have fields that are currently undefined.

Recordings of cetacean species were the primary focus of this collection exercise. Twenty-five species were identified for the northwest Atlantic, including all baleen (mysticetes) and toothed (odontocetes) whales that are found in this region, at least during part of the year (Table 3). In addition to a large, multi-regional sightings database maintained by DFO, local knowledge and marine mammal text books and field guides were consulted to construct this species list. As expected, cetaceans exhibit a wide variety of vocal behaviours, most of which are species-specific. Additionally, different species have differently-sized call repertoires. Call frequency, call duration, call pattern, and inter-click interval are the most useful variables for determining the source of calls or echolocation clicks. For example, fin whales (*Balaenoptera physalus*) are a relatively common baleen whale that produce a stereotypic one to two second-long 20-hertz pulse, usually in a long repetitive sequence, or “song”. These calls are well-known (e.g., Desharnais and Collison, 2001; Simard and Roy, 2008) and easy to discriminate from ambient noise and from other species’ calls. Auto-detection algorithms are already relatively successful at identifying the fin whales’ 20-Hz calls. However, fin whales’ vocal repertoires are not limited to this type of call – they produce another call which exhibits a higher and more variable frequency and which are also more variable in duration. These calls are indistinguishable from those of the sei whale (*B. borealis*). The pattern (i.e., call repetition and the time between calls) of these less-familiar fin whale calls may be useful for species identification, but this remains unknown. Scenarios such as this, of indistinguishable calls, were common during this collection and highlight the usefulness of having multiple call samples per species and well-detailed metadata.

Humpback whale song is not only long and complex, but also varies from year to year as singers on breeding grounds progressively modify the song (e.g., Mattila *et al*. 1987). In general, however, humpbacks usually do not vocalize complete songs in northern feeding latitudes (i.e., off northeastern United States, and Atlantic and Arctic Canada) (Mattila *et al.* 1987), but do express highly variable call structures and frequencies, and even interspecific mimicry (D. Mellinger, pers. comm.). Other geographic and interannual variation and mimicry is evident in other whales such as killer whales (e.g., Ford, 2002; Simon *et al*., 2007; Shulezhko and Burkanov, 2008; Foote *et al*., 2008), bowhead whales (*Balaena mysticetus*), bottlenose dolphins (*Tursiops truncates*), and beluga whales (*Delphinapterus leucas*) (Rendell and Whitehead 2001). These types of variants make the development of autodetection algorithms and filters much more difficult.

Non-mammal Sounds

Recordings of non-mammalian sound sources were researched and gathered as well. These can provide a means to train PAM operators and neural network systems to better recognize “false positive” triggers. Sounds in this category include airgun or other seismic sounds, military sonars, low-flying aircraft, fish-finders, depth sounders, vessel and propeller noise, underwater pile driving, fish, environmental sounds (i.e., earthquakes, rain, lightening, etc.), and other types of ambient noise.

Catalogue structure

Data for inclusion in the catalogue were trimmed to contain only those signals of interest. In this respect, the catalogue serves to act as a training guide, providing concise examples of vocalizations, echolocations, and “false positive” sounds. A variety of calls were included, if possible, for species for which recordings could be secured. Figure 2 contains two spectrogram examples of whale songs from the catalogue. Clips contain the sounds of interest, plus several seconds of ambient noise on either side for context, when possible. While short clips are useful for identifying particular calls and easily exemplifying call variability, they are not necessarily suited for training auto-detection algorithms. For this, long clips (tens of minutes and longer) are needed to sample various recording environments and examine vocalization call pattern to ultimately provide in-context, annotated call records. A small number of in-context audio recordings were collected during this project, but most of these remain un-annotated.

The resulting collection of sounds are stored on replicate digital media, along with an electronic key (Excel spreadsheet) to their identity, source, and other metadata. This catalogue is present on external hard drives with a folder structure to facilitate ease of locating particular recordings that are listed in the accompanying spreadsheet. This catalogue is meant to be used by a variety of people with diverse backgrounds and levels of expertise in marine acoustics. It is useful for training and educational purposes and as such, is to be maintained as an open-source, easily-accessible database. The catalogue has been prepared for web access, housed initially on the DFO website, http://www.nfl.dfo-mpo.gc.ca/e0004341 (the exact web address remains to be determined), in order to facilitate distribution and increase practicality.

Cetacean Species Where Vocalization Data Remain Deficient

Of the 25 species identified for this study, recordings for all but four have been obtained. Vocalization recordings for Sowerby's (*Mesoplodon bidens*) and True's (*M. mirus*) beaked whales and dwarf (*Kogia sima*) and pygmy (*K. breviceps*) sperm whales have not been located. This is likely a function of their rarity and how difficult they are to identify at sea.

Of the species for which recordings were collected, not all are fully characterized. Beaked whales, in particular, fall into this category. As mentioned above in the context of Sowerby's and True's beaked whales, beaked whale species are uncommon or rare, difficult to locate, identify, and distinguish at sea, and exhibit long dive durations. This makes attributing recorded vocalizations to a particular species difficult and uncertain. Recordings from the three other beaked whales found in this region, Blainville's (*M. densirostris*), Cuvier's (*Ziphius cavirostris*), and northern bottlenose (*Hyperoodon ampullatus*), are included in this catalogue. However, only northern bottlenose whale recordings, and only the species' echolocation signals, were recorded in the northwest Atlantic – the remainder are from the eastern north Atlantic (Canary Islands), tropical Atlantic (Bahamas), and/or Mediterranean Sea. The latter were made with suction cup tags (D-Tags, Woods Hole Oceanographic Institution) either directly on the animals or while the tag was floating to the surface after it released from the animal. While this recording method has some caveats, such as recording off-axis vocalizations when the tag is on the animal, species certainty is usually higher and data quality is excellent.

Species that have variable calls are especially difficult to build a call catalogue for, given that a non-discrete repertoire often yields variability dependent upon behavioural state. Killer whales, long-finned pilot whales (*Globicephala melas*), and most dolphin species fit in this category. Bowhead and humpback whales, as mentioned above, also display variable song and calls. For most dolphins, it is difficult even with the aid of this catalogue to differentiate between species without visual confirmation. Vocalization (including pulsed calls, tonal whistles, and echolocation) structure, pattern, and frequency can be used to distinguish killer whales from pilot whales even without complete call coverage in this catalogue. This method, however, is not without exceptions and requires considerable experience and familiarity with these species' vocal behaviours. The same is true of beluga and narwhal (*Monodon monoceros*) vocalizations. Additionally, and as previously mentioned, species that mimic abiotic acoustic stimuli in their environment present a challenge. These include, but are not limited to, humpback, bowhead, and pilot whales.

Bottlenose, common (*Delphinus delphis*), white-beaked (*Lagenorhynchus albirostris*), and white-sided (*L. acutus*) dolphin recordings are limited in this catalogue because their vocalizations are often indistinguishable if the caller's identities are not confirmed visually. Risso's dolphin (*Grampus griseus*) recordings are of limited variety and quantity given that they are uncommon and are typically found offshore where there has been considerably less monitoring effort. Killer whale recordings are also limited as they are encountered relatively rarely in the northwest Atlantic (Lawson *et al*., 2007).

Some whale species exhibit site-specific vocalization repertoires. These may range from vocalizations that differ either subtly or considerably between ocean basins (i.e., blue whales, *B. musculus*), bordering regions (i.e., subpopulations such as Atlantic fin whales), or even sympatric populations (i.e., killer whales). It is unknown to what extent all species exhibit site-specific vocalization behaviour in the northwest Atlantic. As a result, users must refer to the metadata associated with the files in this catalogue to confirm exactly where the file was recorded. Unless noted above, such as for some beaked whale species, recordings originate from the north Atlantic.

Finally, where recent recordings, such as within the past five to ten years, could not be found or were limited, recordings from earlier decades were acquired to supplement the catalogue. In general, these can still be used to evaluate call structure and frequency. However, as an example of a source of variation, it has been shown that blue whale song frequency (tonal) has decreased over time, a change that has occurred since the 1960s (McDonald *et al*. 2009). Right whales (*Eubalaena glacialis*), in contrary, produce a higher average fundamental frequency, a change observed within the lifetimes of whales today (Parks *et al.* 2007). As a result, "old" recordings or detectors developed years ago may not be effective with new recordings and such variation must be considered.

Non-mammal Sounds That Might Evoke "False Positive" Responses From Existing PAM Systems

A number of environmental, anthropogenic, and "false positive" sound types were identified in this study. These are sounds that might falsely appear as a cetacean vocalization or echolocation to an observer or are types of sounds that may trigger auto-detection algorithms. Identified non-mammal sounds can originate from a wide variety of sources (see above), but currently, only a limited number of these have been included in the catalogue and additional work will be needed to determine the sources that are most likely to trigger false positive responses from a PAM auto-detection system. In some instances, propeller noise, depth sounders, and other sonars might appear to be odontocete echolocation clicks on a spectrogram. To counter this, a catalogue with many examples of a particular species' echolocation is needed to fully characterize that species' pulse repetition rate and fundamental frequency. With these data, a better detector or classifier can be developed so as to reduce the rate of false positive triggers. As mentioned above, a limited number of candidate false positive samples were collected during this project.

All PAM detection algorithms will produce a non-zero rate of false positive detection. A rudimentary detector will yield more false detections; a learning-capable detector (e.g., a neural net system) exposed to more “training” by a well-described sample of signals encompassing the natural range of variation will provide a lower rate of false positives. The point of identifying false positives is to minimize the rate at which they are detected during PAM applications (thereby evoking mitigation actions such as seismic array shutdowns or source vessel course changes), while still recognizing that it will never be possible to eliminate them completely.

Recommendations For Follow-up Collections Of Needed Data

A fully comprehensive cetacean sound catalogue was far beyond the scope of this project due to the imposed time and funding restrictions. As a result, the focus of this project was for building the groundwork for a larger dataset, including establishing important relationships with acoustic labs, consolidating efforts for creating or augmenting existing vocalization datasets, learning what acoustic work other research groups are conducting and where different species recordings are located (partially documented by the source of sound files included in this project), and collecting an initial set of northwest Atlantic cetacean vocalizations, echolocations, and potential false-positive sounds.

As discussed above, some species were relatively easy to document. These include species that are well-researched, easily-accessible, and have easily-described vocal repertoires, such as north Atlantic right, sperm (*Physeter macrocephalus*), blue, and fin whales. Species that present highly-variable sound repertoires, such as humpback whales and most odontocetes, will usually be difficult to characterize. Clearly, further collection efforts will be needed for most cetacean species in order to better-characterize all possible acoustic behaviours for species in the NW Atlantic, which may differ from that in other regions. That repertoires may differ is important to consider for migrating species, such as baleen whales, and for those where data recorded in the NW Atlantic is lacking or non-existent, such as for most beaked whale species.

Continued work to better document sounds made by Species at Risk in Canada is essential for the most effective detection and protection through mitigation. These cetacean species include beluga, blue, bowhead, and right whales, northern bottlenose, Cuvier’s, and Sowerby’s beaked whales, and harbour porpoise. Difficulties arise when trying to monitor species that predominantly produce high-frequency echolocation or calls. Beaked whales produce short-duration ultrasonic echolocation clicks, typically with little energy below 20 kHz, and may be only produced at depth (Johnson *et al*. 2004); harbour porpoise produce high frequency echolocation clicks in the range of 130 – 145 kHz (Villadsgaard *et al*. 2007). At these frequencies, clicks are highly directional and also highly susceptible to masking, especially with towed arrays and associated flow noise, which may mean sounds from these species may be missed entirely by the hydrophone, recording system, and/or observers. As a result, there is a high chance that these species may go undetected, even if they are vocalizing within range of a system capable of their detection.

Seals are also highly vocal marine animals that produce a variety of sounds in the frequency range of most cetaceans. Some of their sounds are complex (e.g., bearded seals), and may be confused as cetacean vocalizations. An enhanced catalogue to document the vocal repertoire of seal species in this area (and the Arctic) is recommended.

Further work to identify anthropogenic or environmental sounds that could trigger false positive responses from a PAM auto-detection system is needed. See above, "Non-mammal Sounds That Might Evoke 'False Positive' Responses From Existing PAM Systems". Perhaps the most effective method for reducing the rate of false positive detections is to build more effective detection and classification algorithms that are more successful at finding signals of interest. For this, many long-duration, unedited audio files are needed (only a few are included in this ESRF-funded catalogue) that are used for annotating calls in the context of various ambient noise conditions. Call annotations, done on specialized software, consist most importantly of the start and end time and highest frequency of the call selected, although a number of other parameters are measured. Data from these annotations are exported in database form to develop the parameters for the detector. Call annotations are done by hand and take a considerable amount of expertise and time, as an analyst must go over many hours of recordings per species or group of species of interest. Once a particular detector has been developed, operating it with novel data is relatively fast. However, checking the detector, which means reviewing the sounds that triggered the detector and determining if they are positive or negative, is an essential step that must be repeated many times and with many sound samples to effectively tune the detection threshold. This step is typically much slower and can take months, depending on the species and thresholds of interest. There is often interplay between running a detector and checking the results, i.e., an operator runs a detector, finds that it is detecting a persistent signal not of interest (whether biological, anthropogenic, or mechanical), tunes the detector to ignore that noise, and then re-runs it for a new set of results. This process can require many passes and is why, for some species, developing a detector can take months or more.

Some cetacean species are more difficult to develop PAM detectors for than others. Right whales, for example, produce three types of distinctive calls: 'upsweep', 'gunshot', and 'scream' calls. Upsweep calls can be difficult to distinguish from some types of humpback vocalizations. Defining a detector for right whales while also eliminating humpback false-positives has proven to be especially difficult, and will require a lot of processing time to develop an optimal detectors. Meanwhile, detectors to discriminate dolphin species are not necessarily effective given that most small odontocete vocalizations are highly variable, consist of varying amounts of pulsed calls, tonal whistles, and echolocation clicks, overlap in frequency, and have similar inter-click intervals. Luckily, species discrimination is less crucial for most dolphin species than it is for Species at Risk, such as the right whale. A detector for dolphins, such as a tonal sound detector, does not necessarily have to be as precisely tuned and, therefore, would take considerably less time to develop. Finally, detectors for odontocete clicks that can be tuned to frequency (i.e., most beaked whales), such as an energy ratio mapping algorithm (ERMA) detector, have already been shown to be effective for some species.

Given the timeframe and budget constraints of this project, collecting sufficient sound records for development of a complete suite of PAM detection algorithms for cetacean species in the northwest Atlantic was impossible. For such a task, specialized computers, software programmes, and personnel are needed; Dr. D. Mellinger (david.k.mellinger@noaa.gov) and his research group at the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL) Ocean Environment Research Division are especially recommended for this particular work. They are among the leading marine mammal acoustic researchers and have considerable experience particularly in this field. This group has a number of detectors already developed:

- Blue whale A-B calls – spectrogram correlation detector
- Fin 20-Hz pulses – long-term spectra
- Minke pulse trains – although these may not occur at latitudes north of ~42°N
- Right whale upsweeps – spectrogram correlation detector
- Humpback units – tonal sound detector
- Odontocete clicks that can be tuned to frequency – ERMA detector
- Odontocete whistles – tonal sound detector

Although most of these detectors would need to be tuned to particular north Atlantic vocalizations (which may differ for some species) and ambient noise conditions (including recorder and hydrophone self noise), a considerable amount of ground work has been completed for these species at least. With this experience, Dr. Mellinger's lab would be best-suited to develop additional PAM detectors for other north Atlantic species of interest, such as bowhead (another difficult species to vocally characterize) and beaked whales. These detectors run on software developed by the Mellinger lab, called Ishmael (a stand-alone programme for signal and detection processing), Osprey (MatLab-based for annotating sound files), and Check Detectors (MatLab-based for validating false or negative detections), which link together well and are easy to use.

It is very important to store sound records and associated metadata in an easily-accessible and organized format. Currently, sound files for this catalogue are stored and backed up on external hard drives, and metadata is found in an Excel spreadsheet. For this work to be useful to a wide range of people, and to make sharing data easy, it has also been prepared for web access on the DFO Newfoundland and Labrador website, initially. In addition, consolidating metadata fields to a useful research or industry standard, and maintained as an actual database (versus the existing Excel spreadsheet), is very important. Consultations on this topic with researchers supplying data for this project have been initiated, but have not been completed to the degree that is needed for a functioning and encompassing database. Standardized metadata fields associated with acoustic sound records are important to establish and maintain in an open-ended format that allows for the inclusion of data fields not yet needed. See Table 2 for a preliminary list of such metadata fields.

In general, feedback from researchers visited during this project was positive and much support, data, and advice were received. With the increasing number of acoustic or seismic surveys being conducted, and with more data recorded on autonomous recorders than ever before, nearly all those surveyed agreed that there is need for a collection such as this and especially for further work on auto-detection PAM algorithms.

Summary of Recommendations

A complete, comprehensive catalogue fully describing the acoustic repertoires of all marine mammal species in the northwest Atlantic was far beyond the scope of this project. This ESRF-funded catalogue builds the groundwork for a more comprehensive catalogue and database; perhaps one of the most useful results from the work carried out are the recommendations for follow-on efforts, as detailed above:

- Complete vocal repertoire for SARA-listed northwest Atlantic cetacean species
- Complete vocal repertoire for abundant cetacean species and beaked whales
- Complete collections of sounds of seals and less abundant cetacean species
- Complete collections of false-positive sound samples
- Collection of long-duration in-context recordings for training and tuning detectors
- Develop functional detectors and train operators with these
- Establish industry or research standards for metadata fields and database formats

Travel For Data Collection and Discussions During The Project

Data and additional information were collected for this project from a variety of researchers across Canada and the United States. Dedicated trips were conducted to meet with acoustic researchers to facilitate collection of digital and analogue acoustic data and to gather information on cetacean acoustic signal processing. Research groups visited include:

DFO (Québec), Biennial Marine Mammal Conference (Québec City, PQ)

- visited 12-16 October, 2009
- obtained beluga whale recordings

Dalhousie University (Halifax, NS)

- visited 26-28 August, and 25-27 November, 2009
- obtained killer whale, northern bottlenose and pilot whale recordings

Defence Research and Development, Canada (DRDC) (Halifax, NS)

- visited 23-25 November, 2009
- obtained digital recordings of many cetacean species, including beaked whales, and false positive data

Akoostix, Inc.; JASCO Research, Ltd. (Halifax, NS)

- visited 23-27 November, 2009
- data analysis processes and software advice from both companies

NOAA/PMEL (Newport, OR)

- visited 29 November-4 December, 2009
- obtained digital recordings of many cetacean species
- data processing techniques, software, and information about detection algorithms
- discussions on metadata fields and format

Woods Hole Oceanographic Institute (Woods Hole, MA.)

- visited 8-12 December, 2009
- obtained digital recordings of many cetacean species, including beaked whales
- discussions on metadata fields and format

NOAA/NMFS Laboratory (Woods Hole, MA.)

- visited 8-12 December, 2009
- obtained digital recordings of humpback, fin, minke and right whales, plus possible fish sounds

Bioacoustics Research Program, Cornell University (Ithaca, NY)

- visited 13-18 December, 2009
- discussions on catalogue format and accessibility

Macaulay Library, Cornell Lab of Ornithology, Cornell University (Ithaca, NY)

- visited 13-18 December, 2009
- obtained digital recordings of many cetacean and pinniped species
- discussions on catalogue format and accessibility

A number of researchers at other institutions not listed above could not be visited in person and were contacted via telephone and e-mail.

Acknowledgements

We are greatly indebted to the people that offered their time to provide advice, data, useful discussions, and recommendations for this project and for future work. In particular, we would like to acknowledge Joana Augusto (Dalhousie), Mark Baumgartner (WHOI), Greg Budney (Macaulay Library, Cornell), Chris Clark (Bioacoustics Research Program, Cornell), Sara Heimlich (NOAA), Joe Hood (Akoostix), Mark Johnson (WHOI), Dave Mellinger (NOAA), Hilary Moors (Dalhousie), Sharon Nieukirk (NOAA), Denise Risch (NOAA), Jim Theriault (DRDC), and Mike Webster (Macaulay Library, Cornell).

Literature Cited

Desharnais, F., and Collison, N.E.B. 2001. An assessment of the noise field near the Sable Gully area. MTS/IEEE Conference and Exhibition, pp. 1348-1355.

Foote, A.D., Osborne, R.W., and Rus Hoelzel, A. 2008. Temporal and contextual patterns of killer whale (*Orcinus orca*) call type production. *Ethol*. **114**(**6**):599-606.

Ford, J.K.B. 2002. Dialects. *In* The Encyclopedia of Marine Mammals. W.F. Perrin, B. Würsig and H.G.M. Thewissen (Eds.). Academic Press, New York, NY. pp. 322-323.

Johnson, M., Madsen, P.T., Zimmer, W.M.X., Aguilar de Soto, N., and Tyack, P.L. 2004. Beaked whales echolocate on prey. *Proc. R. Soc. Lond. B*. (*Suppl*.) **271**:S383-S386.

Lawson, J.W., Stevens, T.S., and Snow, D. 2007. Killer whales of Atlantic Canada, with particular reference to the Newfoundland and Labrador Region. Res. Doc. 2007/062. CSAS, Dept. Fish. Oceans, Ottawa, ON.

Mattila, D.K., GuInee, L.N., and Mayo, C.A. 1987. Humpback whale songs on a North Atlantic feeding ground. *J. Mammal*. **68**:880-883.

McDonald, M.A., Hildebrand, J.A., and Mesnick, S. 2009. Worldwide decline in tonal frequencies of blue whale songs. *Endang. Species Res*. **9**:13-21.

Parks, S.E., Clark, C.W., and Tyack, P.L. 2007. Short- and long-term changes in right whale calling behavior: the potential effects of noise on acoustic communication. *J. Acoust. Soc. Am.* **122**(**6**):3725-3731.

Rendell, L., and Whitehead, H. 2001. Culture in whales and dolphins. *Behav*. *Brain* Sci. **24**:309-382.

Shulezhko, T.S., and Burkanov, V.N. 2008. Stereotyped acoustic signals of the killer whale *Orcinus orca* (Cetacea: Delphinidae) from the Northwestern Pacific. *Russian J. Marine Biol*. **34**(**2**): 18-125.

Simard, Y., and Roy, N. 2008. Detection and localization of blue and fin whales from large-aperture autonomous hydrophone arrays: a case study from the St. Lawrence estuary. *Can. Acoust*. **36**(**1**):104-110.

Simon, M., McGregor, P., and Ugarte, F. 2007. The relationship between the acoustic behaviour and surface activity of killer whales (*Orcinus orca*) that feed on herring (*Clupea harengus*). *Acta ethologica* **10**(**2**):47-53.

Villadsgaard, A., Wahlberg, M., and Tougaard, J. 2007. Echolocation signals of wild harbour porpoises, *Phocoena phocoena*. *J. Exp. Biol*. **210**:56-64.

Project Contacts

Dr. Jack Lawson, project leader and coordinator
Marine Mammal Section
Science Branch
Fisheries and Oceans Canada
Northwest Atlantic Fisheries Centre
P.O. Box 5667
St. John's, NL A1C 5X1
(709) 772-2285
Jack.Lawson@dfo-mpo.gc.ca

Tara Stevens, Ph.D. candidate (Memorial University of Newfoundland)
Marine Mammal Section
Science Branch
Fisheries and Oceans Canada
Northwest Atlantic Fisheries Centre
P.O. Box 5667
St. John's, NL A1C 5X1
(709) 772-4517
Tara.Stevens@dfo-mpo.gc.ca

Table 1. Northwest Atlantic cetacean species, their SARA status, reason(s) for inclusion, and sources of acoustic data.

Species	SARA Status	Reason for Inclusion	Types of Data Needed	Is There Canadian Data?	Data Source
Beaked whales (Sowerby's, Cuvier's, Blainville's, True's)	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	No	DRDC, WHOI
Beluga whale	Species at Risk	At Risk in Canada	Social calls, solitary calls, echolocation	Yes (Gulf)	DFO-PQ
Blue whale	Species at Risk	At Risk in Canada	Social calls, solitary calls	Yes (Gulf)	Cornell, DFO-PQ, DRDC, NMFS, WHOI
Bowhead whale	Species at Risk	At Risk, have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	Yes (Arctic)	DFO
Dolphins (White-beaked, white-sided, common, bottlenose)	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	Yes	Cornell, Dalhousie, DFO, DRDC, NMFS, WHOI
Dwarf and pygmy sperm whale	Species of Concern	Hearing sensitive in anthropogenic sound range	Social calls, solitary calls, echolocation	No	
Fin whale	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls	Yes (Scotian Shelf)	Cornell, Dalhousie, DFO, DRDC, NMFS, WHOI
Harbour porpoise	Species at Risk	At Risk; hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	Unknown	

Species	SARA Status	Reason for Inclusion	Types of Data Needed	Is There Canadian Data?	Data Source
Humpback whale	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	Yes	Cornell, Dalhousie, DFO, DRDC, NMFS, WHOI
Killer whale	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	Yes	Dalhousie, DFO
Minke whale	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls	No	Cornell, NMFS
Narwhal	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	Yes (Arctic)	DFO, DRDC
Northern bottlenose whale	Species at Risk	At Risk on Scotian Shelf, Canada	Social calls, solitary calls, echolocation	Yes (Scotian Shelf)	Dalhousie, DFO, DRDC
Long-finned pilot whale	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	Yes (Scotian Shelf)	Dalhousie, WHOI, DRDC
Right whale	Species at Risk	At Risk in Canada	Social calls, solitary calls	Yes (BoF, Scotian Shelf)	Cornell, DRDC, NMFS, WHOI
Sei whale	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls	Yes	Cornell, DRDC, DFO, WHOI
Sperm whale	Species of Concern	Hearing sensitive in anthropogenic sound range; have been seen near seismic and other anthropogenic activities	Social calls, solitary calls, echolocation	Yes (Scotian Shelf)	Cornell, Dalhousie, DFO, DRDC

Table 2. List of metadata fields associated with audio files in the ESRF sound catalogue.

Contributing author
Contributing organization
Accessibility of data (can it be re-distributed, yes or no)
Original (or source) file name
Modified (or subset) file name
Geographic area name
Latitude
Longitude
Month of recording
Day of recording
Yea rof recording
Time of recording(UTC)
Local offset time value (from UTC, i.e., +2.5)
Recording equipment: hydrophone
Recording equipment: recorder
Recorder frequency sample rate
File format (i.e., .wav)
Depth of hydrophone(s) (metres)
Mobile hydrophone: position of recording start
Mobile hydrophone: position of recording end
Mobile hydrophone: course (bearing, true degrees)
Mobile hydrophone: speed (knots)
Bottom depth at sensor (metres)
Substrate characteristics (i.e., rock, sand, mud)
Sea state (Beaufort 1-10)
Species identification (may be more than one; visual sighting or based on signal analysis)
Degree of caller ID confidence

i. Low confidence – limited information and observer or analyst judgment
ii. Medium confidence – characteristics that are known to be related to the species from direct experience or published literature
iii. High confidence – multiple, well-known, or generally-accepted cues of the animal or signal origin
iv. Certain – known, direct confirmation of the animal or signal origin

Source of other noise and interfering sounds (observed, i.e., other marine mammals, vessel noise, etc.)
Minimum distance from recorded animals
Maximum distance from recorded animals
Minimum number of animals

Maximum number of animals
Behaviour of animals (i.e., travelling, feeding, socializing, resting)
Recording quality rating:

i. Poor – signals cannot be clearly distinguished even when filtered
ii. Fair/average – audible aural characteristics, may need filtering or amplification
iii. Good – easily-identified aural characteristics, background noise level generally does not interfere with signal identification
iv. Excellent – very clear aural characteristics; very high signal-to-noise ratio (SNR)

Other information/description
Date of latest modification of metadata

Table 3. Description of vocalization or echolocation data included in the ESRF catalogue for cetacean species likely to be found in the northwest Atlantic.

Species	Social calls	Solitary calls	Echolocation	Location(s)	Source
Beluga whale	Yes		Yes	Gulf of St. Lawrence	DFO-PQ
Blainville's beaked whale			Yes	NE Atlantic and Tropical Atlantic	Johnson (WHOI); DRDC
Blue whale	Yes	Yes		NW Atlantic	MobySound
Bottlenose dolphin	Yes		Yes	NW Atlantic	Macaulay Library (Cornell)
Bowhead whale	Yes			Atlantic Arctic	via Johnson (WHOI)
Common dolphin	Yes		Yes	Grand Banks	Whitehead (Dalhousie); Macaulay Library
Cuvier's beaked whale			Yes	NE Atlantic and Mediterranean Sea	Johnson (WHOI)
Dolphins, unspecified	Yes		Yes		Various
Dwarf sperm whale					
Fin whale		Yes		NE US, Atlantic Canada, offshore	Risch (NOAA); Macaulay Library
Harbour porpoise					Macaulay Library
Humpback whale	Yes	Yes		NE US, Atlantic Canada	Johnson (WHOI); Risch (NOAA); Macaulay Library
Killer whale	Yes		Yes	Grand Banks	Whitehead (Dalhousie)
Minke whale	Yes			NE US, Atlantic Canada	Risch (NOAA)
Narwhal	Yes		Yes	Atlantic Arctic	via Johnson (WHOI)
Northern bottlenose whale			Yes	Scotian Shelf	Moores (Dalhousie); Macaulay Library
Long-finned pilot whale	Yes		Yes	Cape Breton, NS	Augusto (Dalhousie); Macaulay Library
Pygmy sperm whale					
Right whale	Yes			Gulf of Maine, Scotian Shelf	Johnson (WHOI); Risch (NOAA)
Risso's dolphin					Macaulay Library
Sei whale		Yes		Eastern US, Atlantic Canada	Baumgartner (WHOI); Macaulay Library

Species	Social calls	Solitary calls	Echolocation	Location(s)	Source
Sowerby's beaked whale					
Sperm whale	Yes		Yes	Scotian Shelf	Moores (Dalhousie); Johnson (WHOI)
True's beaked whale					
White-beaked dolphin	Yes		Yes	Newfoundland	DFO-NL; Macaulay Library
White-sided dolphin	Yes		Yes	NW Atlantic	Macaulay Library

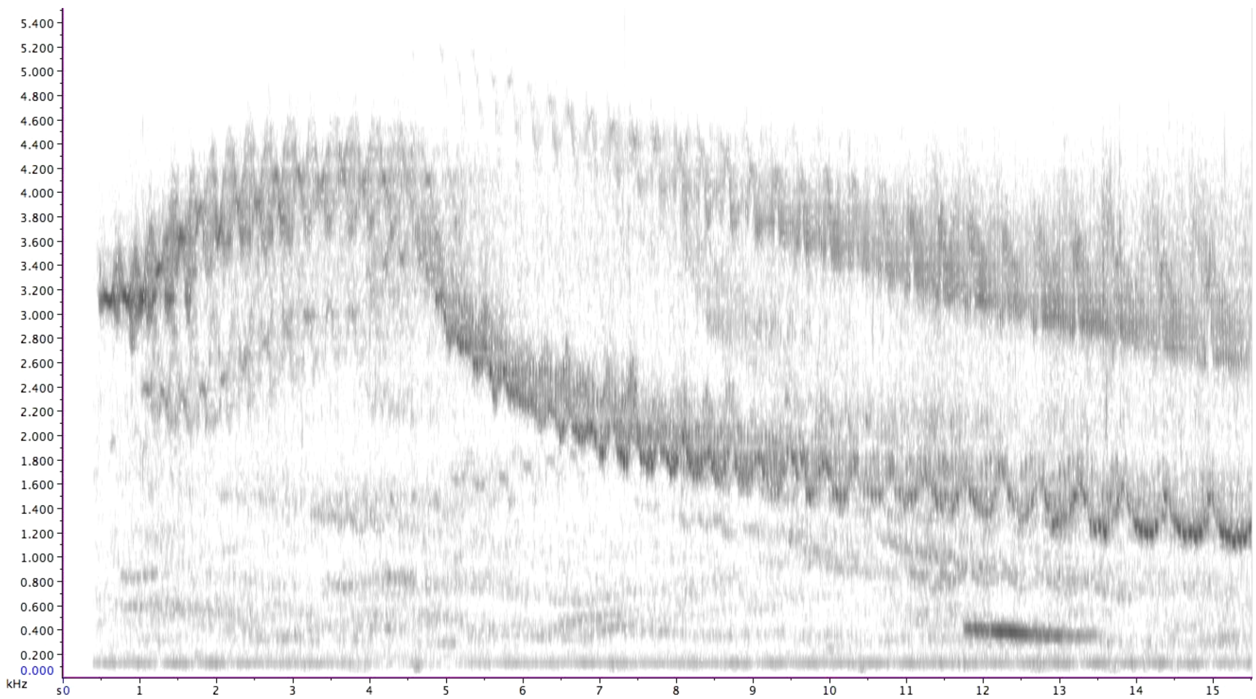
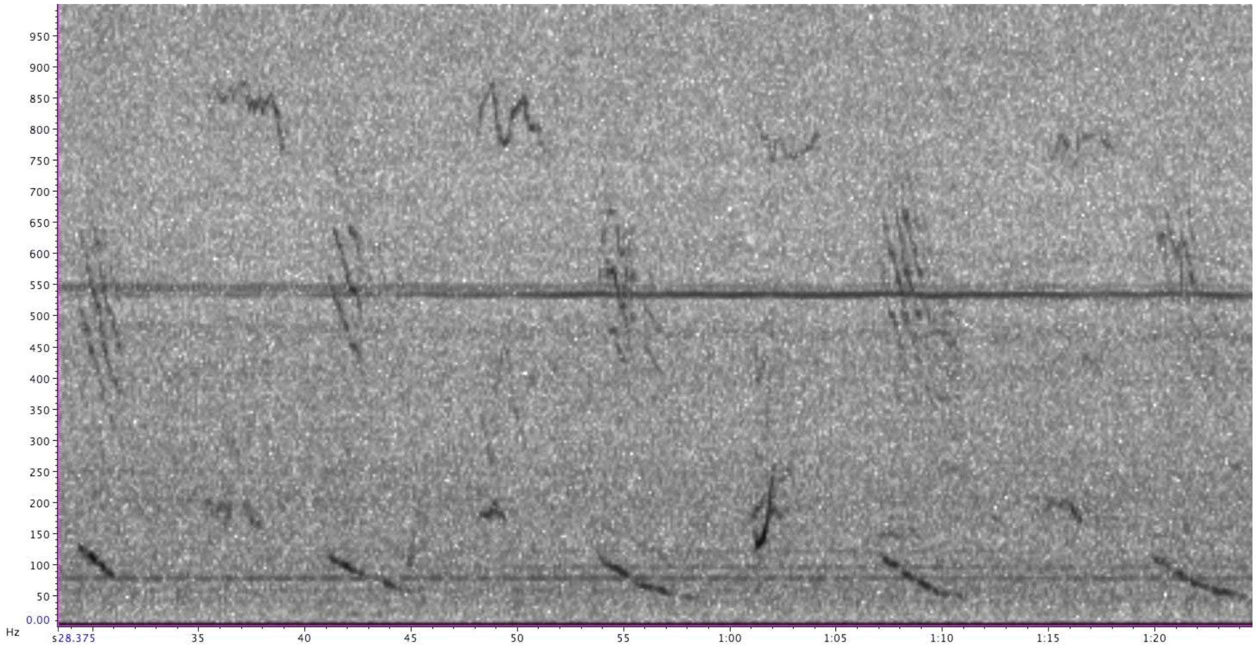


Figure 1. Spectrogram example of the complex songs of breeding bearded seals recorded in the Canadian Arctic.

a.



b.

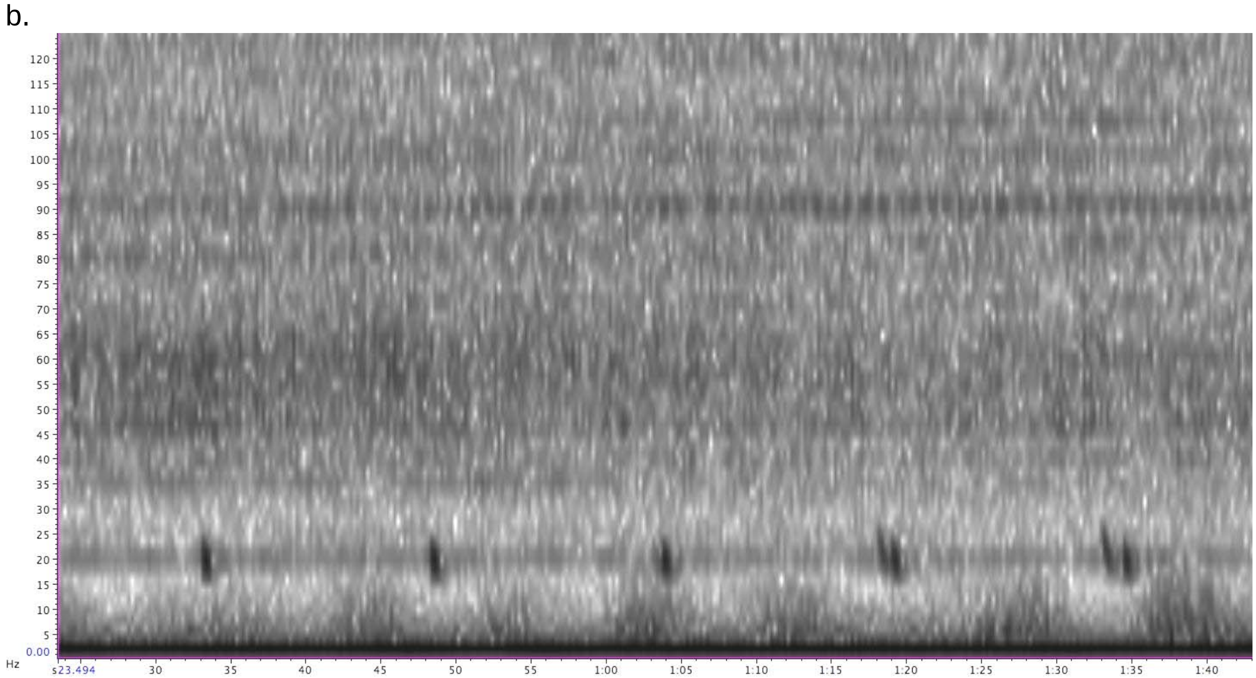


Figure 2. Spectrogram examples of a) a section of humpback whale song included in the ESRF catalogue, recorded by NOAA off Massachusetts, USA. The horizontal banding is machine noise from the recording equipment (1024 sampling rate, 512 FFT, Hann window), and b) a section of fin whale song included in the ESRF catalogue, recorded by NOAA off Massachusetts, USA (1024 sampling rate, 896 FFT, Hann window).