Progress Report on the Analysis of the Potential Impact of Mid-Frequency Active Sonar on Whales

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MPL TECHNICAL MEMORANDUM # 612
March 2017

Suggested Citation:

Širović, A., Baumann-Pickering, S., Hildebrand, J.A., Trickey, J.S., Meyer-Löbbecke, A., Rice, A.C., and Wiggins, S.M. (2017) “Progress Report on the Analysis of the Potential Impact of Mid-Frequency Active Sonar on Whales.” Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, MPL Technical Memorandum #612 under Cooperative Ecosystems Study Unit Cooperative Agreement N62473-16-2-012 for U.S. Navy, U.S. Pacific Fleet, Pearl Harbor, HI.

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Executive Summary

Passive acoustic monitoring (PAM) provides extensive datasets to examine the behavioral response of cetaceans to anthropogenic sound. Broadband passive acoustic monitoring permits the recording of the full range of cetacean sounds as well as signals produced by the Navy and other anthropogenic sources. We have been collecting broadband PAM data in southern California since 2006. Within this dataset are many instances of anthropogenic sound as well as cetacean presence at the locations of naval training.

We present a progress report on the development of methods to investigate the potential impacts of sonar and other anthropogenic activities on calling animals. The basis for this effort is previously collected PAM data from four sites in the years 2006 to 2015. Recording effort at these sites varied between 674 and 2,284 days per site, resulting in a total of 19 years of continuous acoustic recordings during 79 instrument deployments and 227 TB of acoustic data. As part of the work in this progress report, automated routines have been established and/or modified to detect and classify acoustic signals of blue whales (*Balaenoptera musculus*) and Cuvier's beaked whales (*Ziphius cavirostris*) as well as Mid-Frequency Active (MFA) sonar pings and explosions. This has the advantage of minimizing bias known to occur when multiple human analysts annotate acoustic data manually. It will also allow a finer granularity of acoustic detections with analysis based on individual calls or events: B and D blue whale calls, beaked whale clicks, MFA sonar pings, and explosions. With this level of granularity, we will be able to compute detailed signal parameter descriptions for a subsequent multivariate statistical analysis. The complete data preparation requires a total of ~1,100 days of computing time and ~300 person-days of manual editing. We are currently approximately 95% of the way through this process.

After this preparatory process is completed, future analysis will address source to receiver range ambiguity. Beaked whales have a narrow detection range of <2 km around the sensor yet blue whales can be heard over several tens of km. We will reduce detection range for blue whales to a range similar to beaked whales by selecting for high received level calls of animals near the sensor. Range of the MFA sonar source can be estimated assuming a nominal source level of 235 dB_{rms} re 1 μPa @ 1 m. In the case of a sonar detection, which tends to be much farther away from the recorder than the animal, the received level at the recorder can be used as a proxy for the received level at the animal when detections are constrained to be close to the recorder. We are in the process of determining appropriate thresholds for received levels to define and reduce this range and received level discrepancy between the levels at the animal and recorder.

Several multivariate statistical approaches will be explored to account for natural temporal and spatial variability in call densities, *e.g.*, caused by species or population level variability in seasonality, habitat preference, behavioral context of calling, and individual variability. Equally, a statistical framework to document and quantify potential changes in the acoustic behavior due to MFA sonar needs to incorporate potential impact of other anthropogenic signals, such as explosions and ship noise.

I. INTRODUCTION

The potential for anthropogenic sound, such as Mid-Frequency Active (MFA) sonar, to disrupt activities of marine mammals is an issue of concern to the Navy (NRC, 2003). Early studies of anthropogenic impact have relied on visual methods, documenting disturbance by observing an absence of whales near a sound source, whales travelling away from a sound source, or whales acting in an unusual manner while exposed to a man-made sound. More recently, attaching acoustic tags to the animals during controlled exposure experiments (CEE) has allowed more detailed measures of individual's reaction to disturbance (Tyack *et al.*, 2011; DeRuiter *et al.*, 2013; Goldbogen *et al.*, 2013).

Passive acoustic monitoring (PAM) is an alternative approach to examine the behavioral response of marine mammals to anthropogenic sound. Acoustic recorders are used to document both the production of sound by the animals, and the presence of the potentially disturbing anthropogenic sound. PAM data overcome several of the limitations of CEE, such as the availability of realistic sound sources, the relatively small sample sizes on a limited range of species, and the specter of possible research effects.

To date, we have barely scratched the surface of the PAM data that are available for behavioral response research. Melcon *et al.* (2012) analyzed data from one species (blue whale, *Balaenoptera musculus*), one call type (D call) at one site in southern California (site M; Figure 1), covering a single season over a period of two years; their results suggest that naval sonar may suppress blue whale vocal activity at received levels of >120-130 dB re: 1μPa.

The purpose of this effort is to expand the analysis of behavioral impact of sonar using PAM data collected in the Navy's Southern California (SOCAL) Range Complex at four strategic sites where there are long-term recordings and different historic levels of MFA sonar detections. A major advantage of these long-term data sets is the large sample size for signals of interest. There have been 100,000s of sonar pings recorded during these deployments. Their received levels at the recorders range from 100 dB re: 1μPa up to 165 dB re: 1 μPa, thus providing a broad range of intensities to assess sonar impacts opening the possibility for the development of dose response curves.

The goal of this study is to examine existing PAM data for acoustic behavioral response of blue whales and Cuvier's beaked whales (*Ziphius cavirostris*) to sonar operations in an area of frequent naval activity. We will develop models to investigate the interplay between acoustic behavior and sonar parameters such as duration of sonar event, sound exposure level (SEL), and maximum received sonar sound pressure level (SPL). In this report, we document the progress made during the second year of work on data preparation, defining signal parameters to be used in analysis, and likely statistical approaches we will be testing soon.

II. METHODS

A. Acoustic data collection

Since 2006, high-frequency acoustic recording packages (HARPs) have been deployed across the Southern California Bight, the continental shelf region between Point Conception and the Mexican border. This area includes the SOCAL Range Complex, a zone of frequent naval training exercises, with San Clemente Island as a focal point for much of this activity. HARPs recorded underwater sounds from 10 Hz up to 100 kHz, covering all cetacean and anthropogenic signals of interest. Four sites (designated E, H, M, and N) were chosen for the MFA sonar impact analysis (Figure 1) because of their high (H, N), medium (M), or low (E) numbers of MFA sonar detections and intensities (*e.g.*, Debich *et al.*, 2015). Previous ONR-funded work showed that blue whale calls are regularly detected at these sites using PAM (Širović *et al.*, 2015) and they are within primary habitat for Cuvier's beaked whales in southern California (Baumann-Pickering *et al.*, in prep.).

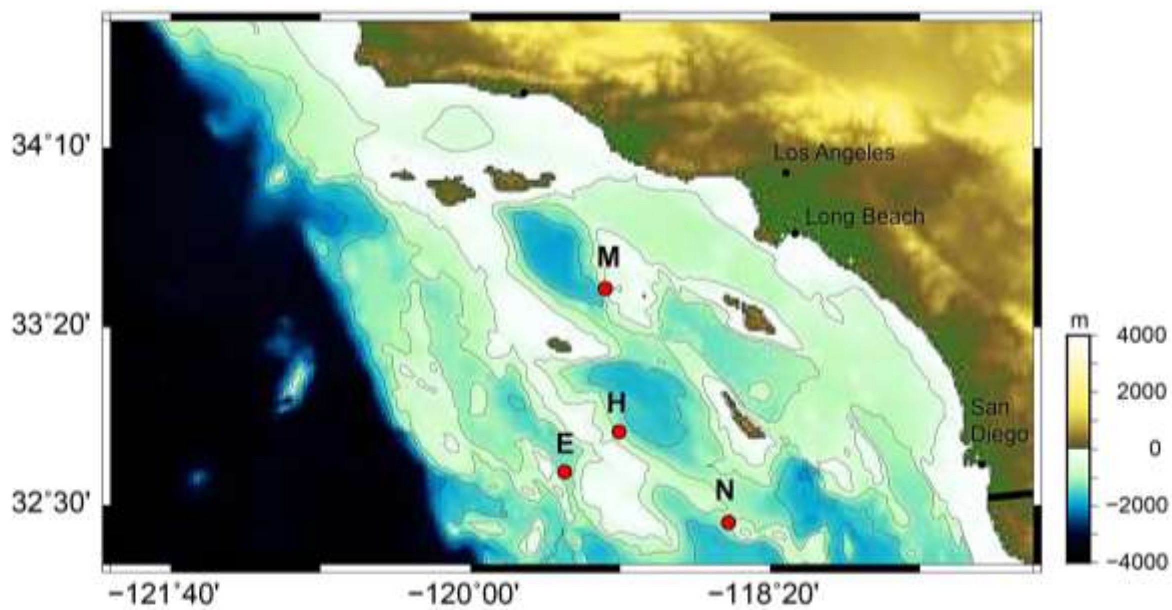

Figure 1. Locations of acoustic recorder deployments off Southern California used in this study.

B. Automated detection of acoustic signals

We are in the final stages of the process of detecting and classifying the acoustic signals needed to perform the analysis on the impact of mid-frequency active sonar on blue whale and beaked whale calling behavior. The use of automated routines allows us to minimize the bias known to occur when multiple human analysts annotate acoustic data manually. This processing will allow a very fine granularity of acoustic detections including individual clicks for beaked whales, single calls for blue whales, and single ping events for MFA, providing detailed signal parameter descriptions to be computed, in addition to allowing the evaluation of impact at a variety of time scales.

1. Cetacean signals

Blue whale B calls (Širović *et al.*, 2015) and Cuvier's beaked whale echolocation click encounters (Baumann-Pickering *et al.*, in prep.) recorded through the end of 2012 were processed previously under ONR grants. Additional years of data were analyzed as a part of this project's effort and for Cuvier's beaked whale density estimation effort also supported by U.S. Pacific Fleet (Hildebrand *et al.*, 2016).

Blue whale B and D calls

Blue whale B calls were automatically detected using spectrogram correlation (Mellinger and Clark, 2000). This method cross-correlates a time-frequency kernel representation of a call with a spectrogram of the recording; a detection event occurs when the correlation value exceeds the specified threshold for a specified duration, in the case of this detector, 5 s. The performance of the automatic detector is affected by seasonal and inter-annual shifts in call frequency (McDonald *et al.*, 2009) and seasonal changes in call abundance (Širović, 2016). To account for these changes and keep rates of missed and false calls as consistent as possible, multiple kernels and thresholds were used for each year and site. In general, the average recall of the detector was above 80% across all sites.

To achieve a more complete view of blue whale calling behavior, an effort to detect blue whale D calls was also expended for this project. To automatically detect these, a generalized power-law (GPL) detector (Helble *et al.*, 2012) was adapted by modifying the detection parameters including the frequency space over which the detector operates. A unique feature of the GPL detector is that it performs well on non-stereotypical calls, such as D calls. The detector was fine-tuned to perform at less than 9% missed call rate. However, all detections had to be verified to identify any false detections. The verification was performed using a graphical user interface tool that enables the analyst to review time-condensed spectrograms containing the detections and to accept or reject each detection. Through this process, only true calls remain in the dataset for subsequent analysis.

Cuvier's beaked whale FM pulses

Beaked whales are known to produce frequency-modulated (FM) echolocation pulses that are distinguishable to the species or FM pulse type level (Baumann-Pickering *et al.,* 2013). Beaked whale encounters (start and end times of acoustic FM pulse bouts separated by one hour or more) were initially automatically detected and then classified to the species or signal type with an analyst-assisted software (Baumann-Pickering *et al.*, 2013), eliminating false encounters. The rate of missed encounters for this detector has been shown to be approximately 5% in southern California recordings. All Cuvier's beaked whale acoustic encounters were reviewed in a second analysis stage to remove false detections of individual FM pulses and provide a consistent detection threshold. FM pulse detections occurred when the signal in a 10 – 100 kHz band exceeded a detection threshold of 121 dB pp re: 1μPa. FM pulses within the acoustic encounters were manually reviewed using comparative panels showing long-term spectral average, received level, and inter-pulse interval of individual FM pulses over time, as well as spectral and waveform plots of selected individual signals. Within each encounter, false detections were removed by manual editing, for instance, when spectral amplitude, inter-click interval, or waveform indicated the detections were from vessels, sonars, sperm whales or delphinids. In addition, this step provided another check on beaked whale species classification, and remaining misidentified or false encounters were corrected or removed.

2. Anthropogenic signals

Mid-Frequency Active (MFA) Sonar

Automatic detection of MFA sonar was implemented using a modified version of the *silbido* detection system (Roch *et al.*, 2011) designed for characterizing toothed whale whistles. The algorithm identifies peaks in time-frequency distributions (*e.g.* spectrogram) and determines which peaks should be linked into a graph structure based on heuristic rules that include examining the trajectory of existing peaks, tracking intersections between time-frequency trajectories, and allowing for brief signal drop-outs or interfering signals. Detection graphs are then examined to identify individual tonal contours looking at trajectories from both sides of time-frequency intersection points. ONR-funded modifications to the published system consisted of a noise regime change detection system, and statistical analyses of graphs and tonal contours for characteristics that removed 57% of the false positives with negligible impact on detected calls (MacFadden, 2015; MacFadden and Roch, in prep.).

For MFA sonar detection, parameters in *silbido* were adjusted to detect tonal contours ≥ 2 kHz (in data decimated to a 10 kHz sample rate) with a signal to noise ratio ≥ 5 dB and contour durations > 200 ms with a frequency resolution of 100 Hz (Figure 2). The primary MFA sonar in use by the United States Navy, the AN/SQS-53C, is operated on surface ships and generates tones and sweeps having typical durations of 0.5 to 2 s with frequencies near 3.5 kHz, at nominal root-mean-square (rms) source levels of 235 dB_{rms} re 1 µPa @ 1 m)(United States Navy, 2013, Vol. 1). This type of sonar dominates the data set used in this study; however, the filtering process and signal data rate in this detection process excluded a number of lower or higher frequency MFA sonar signals.

In the frequency range between 2 and 4.5 kHz, the detector frequently triggered on noise produced by instrument disk writes that occurred at 75 s intervals. Over several months, disk write detections dominated the detections, but they were eliminated using an outlier test. Histograms of the detection start times, modulo the disk write period, were constructed and outliers, as identified by a non-parametric outlier test (Emerson and Strenio, 1983), were discarded. This removes some valid detections that occurred during disk writes, but as the disk writes and sonar signals are uncorrelated, this process is expected to only have a minor impact on analysis. As the detector did not distinguish between sonar and other tonal signals within the operating band, analysts manually examined detection output. The manual examination was performed using a graphic user interface that displayed 30-min panels showing long-term spectral average, received level, and inter-detection interval of individual detections. Analysts would accept or reject contiguous sets of detections based on those displayed characteristics.

Detections were compiled into MFA sonar events, defined as MFA sonar detections separated by more than 5 min. For each event, start, stop, minimum, maximum, start and end frequencies were saved, as well as peak-to-peak (pp) received level (RL, in dB) and sound exposure level (SEL). Additionally, cumulative sound exposure level (CSEL) is calculated for each ping over the entire duration of the MFA sonar event. All of these parameters may be relevant in the context of multivariate statistical modeling as they each contain information of different granularity that may be explanatory for a potential acoustic response of blue or Cuvier’s beaked whales to sonar events.

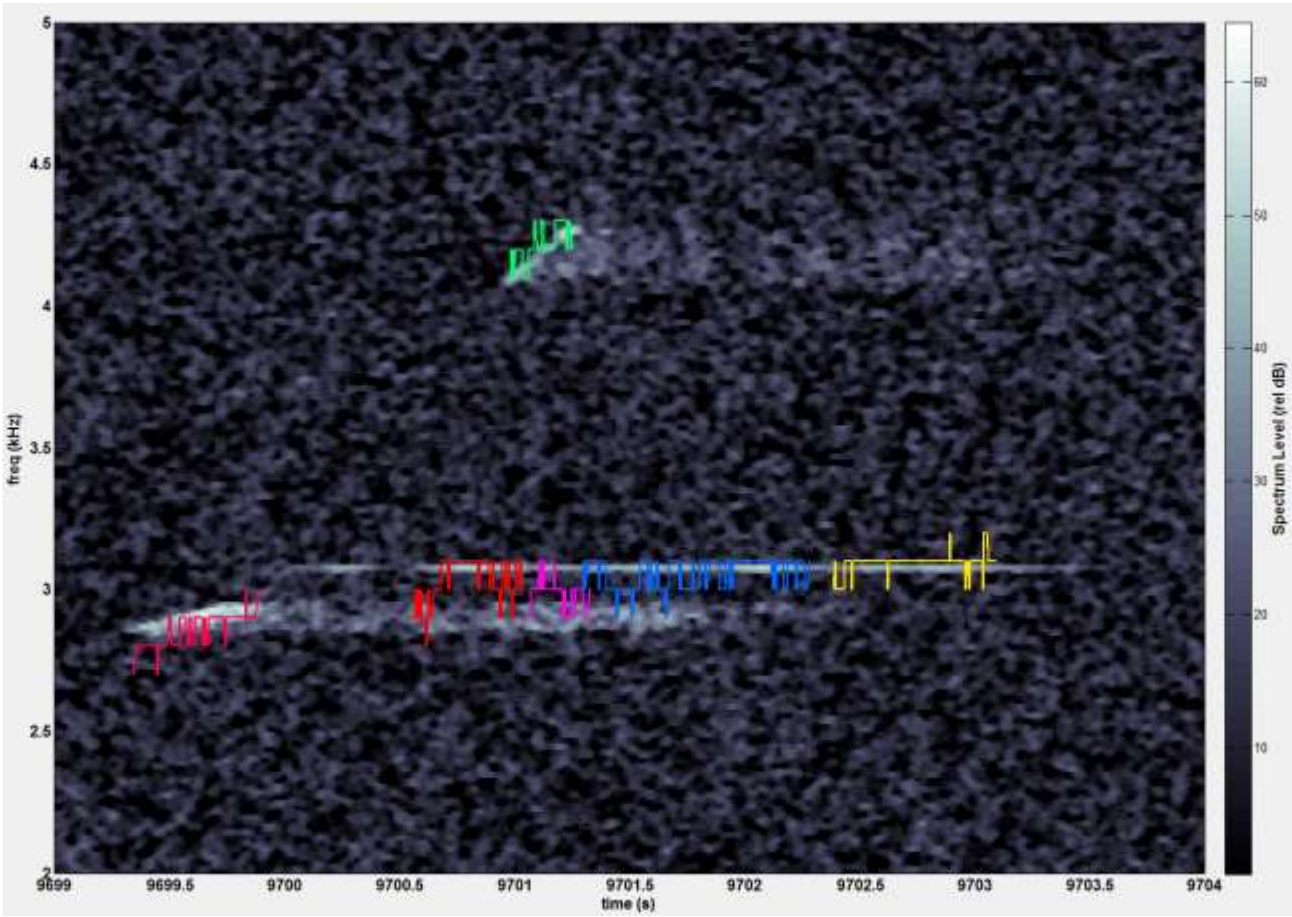

Figure 2. MFA sonar detections. Detections (colored lines) are shown over a gray scale spectrogram. Detector has a 100 Hz resolution, while spectrogram is plotted with 10 Hz resolution. The MFA sonar pings are in general well detected, however some are fragmented, for instance, with multiple segments covering the long ping.

Explosions

Effort was also directed toward finding explosive sounds in the data including military explosions, shots from sub-seafloor exploration, and seal bombs used by the fishing industry. Explosions were detected automatically using a matched filter detector on data decimated to 10 kHz sampling rate. Explosions have energy as low as 10 Hz and often extend up to 2,000 Hz or higher, lasting a few seconds with reverberation. The time series was filtered with a 10^{th} order Butterworth bandpass filter between 200 and 2,000 Hz. Cross correlation was computed between 75 seconds of the envelope of the filtered time series and the envelope of a filtered example explosion (0.7 s, Hann windowed) as the matched filter signal. The cross correlation was squared to 'sharpen' peaks of explosion detections. Regions containing candidates for detections are identified by a using a dynamic threshold of the cross correlation. The median cross correlation of 75 s data frames was computed and regions that exceed the median by 3×10^{-6} were identified for further analysis. Consecutive explosions had to be separated by at least 0.5 seconds to be detected. A 300-point (0.03 s) moving average energy across the detection was computed. The start and end defining the potential explosion were determined when the energy was more than 2 dB above the median energy across the detection. Peak-to-peak (pp) and rms RL were computed over the potential explosion period. To be classified as an explosion, the region had to be louder than the background noise before and after the detection region as well as meet constraints on the duration. Specifically, the explosion onset had to be 4 dB PP and 1.5 dB rms above the preceding region, offset had to be 4 dB PP and 1.5 dB rms, and the duration was required to be 0.03 to 0.55 seconds. The thresholds were evaluated based on the distribution of histograms of manually verified true and false detections. A trained analyst subsequently verified the remaining potential explosions for accuracy.

III. PROGRESS UPDATE

Analysis this reporting period

The recording effort at sites E, H, M, and N from 2006 to 2015 varied between 674 and 2,284 days per site, cumulatively resulting in 19 years of recordings and 227 TB of acoustic data over 79 instrument deployments. Automatic detectors are being run on all deployments and output is being manually scrutinized as described above. All detectors have been well tested and are fully operational. The detection process generated millions of counts of acoustic signal detections to date. The complete data analysis requires a total of ~1,100 days of computing time and ~300 person-days of manual editing, not including the upkeep of computing infrastructure or potential trouble-shooting of computing irregularities.

To date, we have processed approximately 95% of the data needed for this analysis (Figure 3).

A potential advantage of controlled exposure experiments over PAM impact analysis approaches is the precise knowledge of the location of the source and the animal being studied. This can be addressed in a PAM impact analysis by using received sound level as a proxy for the range between the sensor and the sonar. If we assume a nominal source level of 235 dB_{rms} re 1 μPa @ 1 m (United States Navy, 2008 ,Vol. 2), sonar can be detected at a large distance (~20-50 km; Urick 1983). Likewise, it is possible to estimate the animal range from the sensor using received level and other call characteristics. The detection range to Cuvier's beaked whales is generally small based on the high-frequency content of the signal (<2 km, Hildebrand *et al.* 2015). In the case of blue whales, detection range can be restricted to calls with high RLs and hence animals close to the sensor within similar distances as beaked whales. By limiting the range to detected animals, we can limit the sonar-animal range ambiguity to a few kilometers. In the case of a sonar detection that is much farther away from the recorder than the animal, the RL at the recorder can be used as a proxy for the RL at the animal. We are currently in the process of extracting detections with appropriate RLs to reduce the detection range and minimize MFA RL ambiguity.

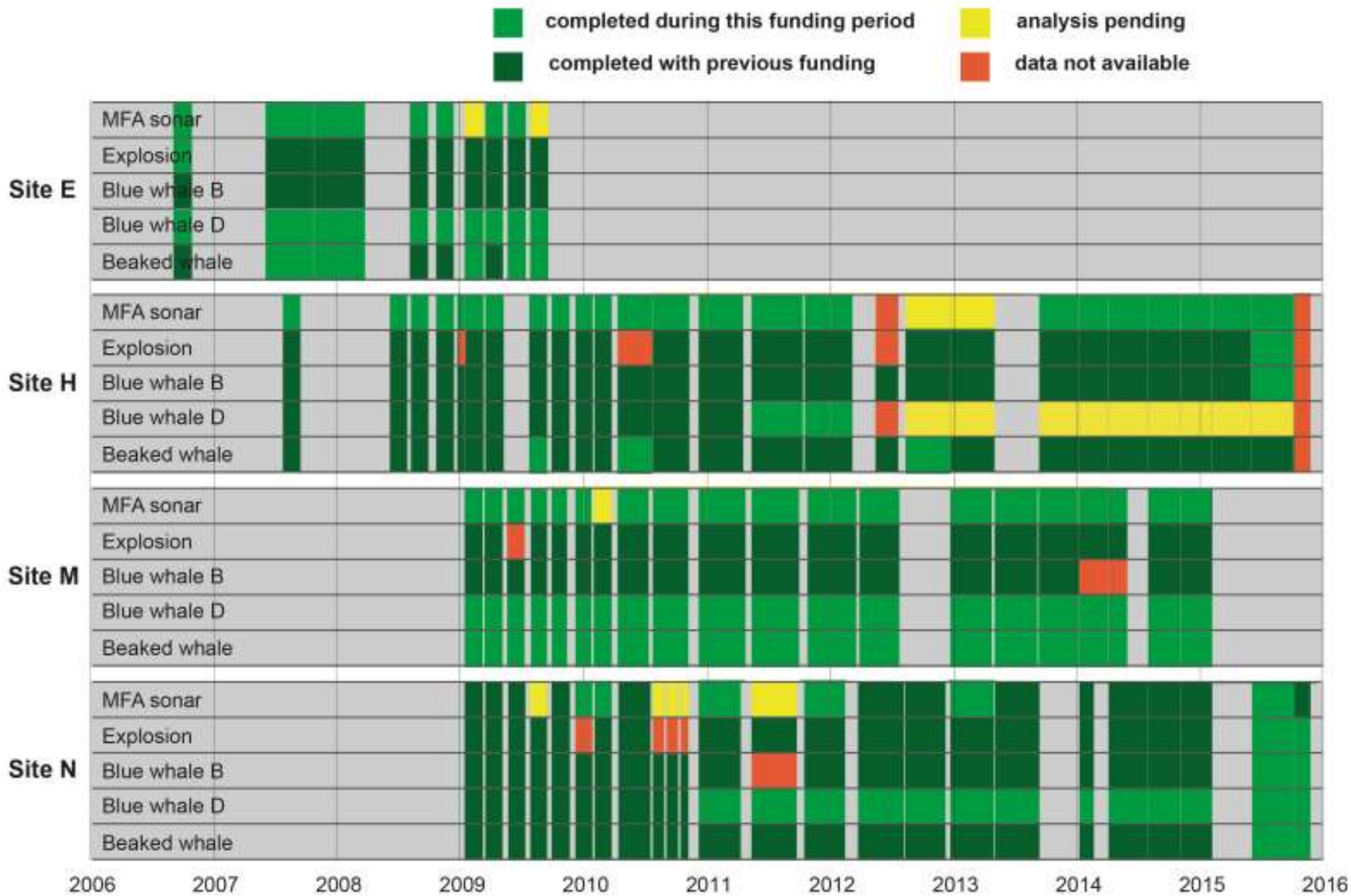

Figure 3. *Status of analyses for MFA sonar, explosions, blue whale B and D calls, and Cuvier's beaked whales* totaling over 19 years *of acoustic recordings, comprising 227 TB of data in 79 deployments at four sites. Colors denote current state of the analysis, as defined in the legend.*

Future Analysis

The relationship between MFA sonar and the acoustic behavior of whales is complex and requires inclusion of other potentially relevant variables, such as explosions and ship noise. Response to anthropogenic sounds by marine mammals is likely to be highly individual and variable, as well as based on the behavioral context of the exposure (Goldbogen *et al.* 2013; Southall *et al.* 2016). A multivariate statistical approach will be needed to account for natural temporal and spatial variability in call densities, *e.g.*, caused by species or population level variability in seasonality, habitat preference, behavioral context of calling, and individual variability.

After exploring different statistical frameworks, we decided to focus our analysis efforts on three different approaches to tests their applicability to this problem: generalized estimation equations (GEEs), hidden Markov models (HMMs), and multi-spatial convergent cross mapping. GEEs are used to estimate parameters of generalized linear models that have unknown correlations between outcomes. Their strength lies in the fact they can be used with repeated measurements over space and time and they provide the estimate of the average response of the population (Zeger *et al.* 1988). HMMs are based on stochastic temporal modelling, i.e. switching in time between different states, and how explanatory variables such as sonar affect the probability of switching (*e.g.*, Baum *et al.* 1970). Multi-spatial convergent cross mapping, an extension of convergent cross mapping, is a test for causal associations between pairs of processes represented by time series. It is based on non-linear state space reconstruction where causality can be distinguished from correlation even in the presence of process noise and observation error (Sugihara *et al.* 2012). This technique has shown to be useful for testing causality in systems where experiments are difficult (Clark *et al.* 2015) and thus seems ideally suited to this problem.

Once the data analysis has been completed, during 2017 we will perform preliminary analysis using data from one of the sites identified for the study to compare the performance and results of different multivariate statistical methods.

IV. CONCLUSION

Major progress has been achieved on standardized, automated detection of all acoustic signals of interest to generate an unbiased dataset with reproducible output. The data assembly is nearly complete and processing of the remaining data sets is underway. Relevant acoustic parameters for all signals have been defined and we are starting the exploration of multivariate statistical methods to test for impact of MFA sonar on the acoustic behavior of blue whales and Cuvier's beaked whales on a subset of the entire data set.

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