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# Calibrating passive acoustic monitoring: Correcting humpback whale call detections for site-specific and time-dependent environmental characteristics

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**Abstract:** This paper demonstrates the importance of accounting for environmental effects on passive underwater acoustic monitoring results. The situation considered is the reduction in shipping off the California coast between 2008–2010 due to the recession and environmental legislation. The resulting variations in ocean noise change the probability of detecting marine mammal vocalizations. An acoustic model was used to calculate the time-varying probability of detecting humpback whale vocalizations under best-guess environmental conditions and varying noise. The uncorrected call counts suggest a diel pattern and an increase in calling over a two-year period; the corrected call counts show minimal evidence of these features.

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## 1. Introduction

Passive acoustic monitoring is an important tool for understanding marine mammal ecology and behavior. When studying an acoustic record containing marine mammal vocalizations, the received signal can be greatly influenced by the environment in which the sound is transmitted. The ocean bottom properties, bathymetry, and temporally varying sound speed act to distort and reduce the energy of the original waveform produced by the marine mammal. In addition, constantly varying ocean noise further influences the detectability of the calls. This ever-changing acoustic environment creates difficulties when comparing marine mammal recordings between sensors, or at the same sensor over time.

One way to correct for temporal and spatial variations in detectability due to environmental effects can be obtained from the expression for estimating the spatial density of marine mammals from passive acoustic recordings: Eq. (3) of Marques *et al.*<sup>1</sup> The corrected call counts in Eq. (3) are

$$\hat{N}_c \equiv n_c \frac{1-\hat{c}}{\hat{P}},\tag{1}$$

where  $n_c$  is the number of detections (uncorrected call count) in the data,  $\hat{c}$  is the probability of false detection, and  $\hat{P}$  is the probability of detection. In the case where human analysts scan the detection outputs generated by an automated detection algorithm to eliminate false detections (i.e.,  $\hat{c} = 0$ ) as is done with the data presented in this paper, the calibration factor is the estimated probability of detection,  $\hat{P}$ . Helble *et al.*<sup>2</sup> demonstrated that  $\hat{P}$  can change by factors >10 between sensors at different

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locations or at the same sensor over time. At some sites,  $\hat{P}$  has an exponential dependence on ocean noise level and, hence, a seemingly modest change in noise, itself insignificant in the high dynamic range spectrograms commonly used to detect vocalizations, can nonetheless greatly skew the counts of calling activity. To illustrate the influence that the ocean environment has on the detection of marine mammal vocalizations, two single hydrophone datasets simultaneously recorded over a two-year period using high-frequency acoustic recording packages (HARP)<sup>3</sup> were analyzed for humpback whale (Megaptera novaeangliae) vocalizations. Humpback vocalizations consist of a sequence of discrete sound elements called units that are separated by silence.<sup>4</sup> The recorded detection counts (number of detected units) were corrected to account for the influence of environmental properties using the numerically derived probability of detection. The resulting environmentally calibrated datasets provide a more valid approach to examining both short-term and long-term calling trends of the biological sources themselves. The two sites are located off the coast of California as shown in Fig. 1, which also illustrates shipping traffic for the region using the ship Automatic Identification System (AIS).<sup>5</sup> Site SBC (34.2754°, -120.0238°) is located in the center of the Santa Barbara Channel, and site SR (36.3127°, -122.3926°) is located on Sur Ridge, a bathymetric feature 45 km southwest of Monterey. Data recording covers the period from January 2008 to January 2010, during which a decrease in shipping noise occurred at both locations due to a downturn in the world economy, coupled with the implementation of an air-quality improvement rule on 1 July 2009, by the California Air Resources Board (CARB). McKenna et al.<sup>6</sup> discovered that these events in combination reduced the monthly average ocean noise level by 12 dB re 1  $\mu$ Pa<sup>2</sup>/Hz in the 1-Hz wide band at 40 Hz and by 9 dB re 1  $\mu$ Pa<sup>2</sup>/Hz in the 1-Hz wide band at 90 Hz over a period from 2007 to 2010 at site SBC. Additionally, shipping traffic creates variability in the recorded noise levels at both sites on daily time scales. Ship AIS data has been used in combination with ocean noise recordings to reveal a correlation in shipping density with ocean noise, which peaks during the morning and evening hours, and remains lowest during nighttime hours at site SBC.<sup>7</sup> The changing ocean noise characteristics at these two sites create significant changes in  $\hat{P}$  on both short-term and long-term time scales.

### 2. Methods

The methods presented in this paper rely heavily on the modeling results and analysis methods described in Helble et al.<sup>2</sup> The paper describes how values of  $\hat{P}$  were determined for both site SBC and site SR over a range of potential environmental conditions including ocean noise levels, sound speed profiles, bathymetry, and ocean bottom characteristics. Additionally, the uncertainties in  $\hat{P}$  over a range of likely environmental conditions were determined, and the results were validated by means of model/data comparisons. The approach in Helble et  $al^2$  uses a full wavefield acoustic propagation model ["CRAM," based on the range-dependent acoustic model (RAM)<sup>8</sup>] to simulate the propagation of humpback call units from source to receiver, in amplitude and phase as a function of frequency. The model simulated calls originating from geographical locations evenly spaced on a lattice with 20 arc-sec spacing, bounded by a 20 km radial distance from the HARP, at 20 m depth. The simulated received humpback units for each site were added to time-varying noise recorded from each site and the generalized power-law detector<sup>9</sup> was used to process the combined waveform. Resulting probability of detection maps were created as a function of latitude and longitude for the areas surrounding each HARP. From these maps, the average probability of detection for a 20 km radial area was determined for a full range of noise conditions, yielding probability of detection versus noise curves for both site SBC and site SR.

Sound speed profiles were obtained from oceanographic casts taken near the HARP recording packages. Monthly variations in sound speed profiles changed estimates in  $\hat{P}$  by no more than 20% for site SBC and 10% at site SR. In contrast, changes in sound speed profile that occur between summer and winter profile types can lead to significantly greater changes in  $\hat{P}$  at site SBC (only slightly higher than 10%)

change at site SR).<sup>2</sup> Therefore, updating the input sound speed profile twice annually captured this seasonal variability in the modeling.

Values of  $\hat{P}$  were then used to normalize the counts of real humpback detections  $(n_c)$  recorded on the HARP sensors at site SBC and site SR for 2008 and 2009. This normalization yielded the estimated number of call units that actually occurred within the 20 km radial area surrounding the HARP  $(\hat{N}_c)$ , assuming a uniform distribution of calling animals in the area monitored. In order to satisfy this assumption, detected units were tabulated in weekly increments. Model/data comparisons from Helble *et al.*<sup>2</sup> indicate this assumption likely is true at least on monthly time scales for both sites SR and SBC. The resulting normalized call counts were provided in number of units per km<sup>2</sup> per week. On shorter time scales, the calling animals cannot be assumed to be uniformly distributed. However, comparing unnormalized call counts with variations in  $\hat{P}$  on shorter time scales is important to gain an understanding of the correlation between detection counts and variations in ocean noise levels, and this analysis was carried through for site SBC (discussed in Sec. 3).

#### 3. Results

Ocean noise levels (in units of dB re  $1 \mu Pa^2$ ) were obtained by integrating the spectral density (in units of dB re  $1 \mu Pa^2/Hz$ ) over the 150–1800 Hz bands. Time periods with detected humpback vocalizations or other obvious biological sources were omitted from the noise measurements. Ocean noise levels averaged over consecutive 75-s periods between 2008–2009 varied by up to 35 dB at both locations (Fig. 2 and 75–110 dB re 1  $\mu$ Pa<sup>2</sup> in the 150–1800 Hz band). The seven-day running means of the noise (green curves) are better able to reveal long-term changes in the noise. The decrease at SBC of  $\sim 5 \, \text{dB}$  in the integrated spectral density of the 150–1800 Hz band over the course of the deployment is consistent with the downward trend described by McKenna et al.<sup>6</sup> at 50 Hz and at 90 Hz. The decrease in ocean noise occurs with the onset of the Great Recession, which significantly reduced maritime trade.<sup>6</sup> An additional reduction in ocean noise at SBC occurred in the 150-1800 Hz band after July 1, 2009, with the enforcement of the CARB air quality improvement rule, again consistent with the results at 40 Hz and 90 Hz. It resulted in a diversion of much of the shipping traffic to transit lanes outside of the channel. Similar results can be seen for site SR; a significant drop occurs in both ocean noise levels and in the variance of ocean noise when



Fig. 1. Map of coastal California showing the two HARP locations: site SBC and site SR (stars). Ship traffic from the AIS is shown for the region. The color scale indicates the number of recorded unique transits within a 1 km<sup>2</sup> area from October 2009–October 2010. Yellow and orange regions indicate 76–500 total transits, red regions indicate 501–1250 total transits, and purple regions indicate greater than 1251 transits. Note that ship traffic is shown after the enforcement of CARB law, as indicated by greater shipping traffic outside the Santa Barbara Channel.

comparing the Aug–Dec 2008 levels with those of Aug–Dec 2009. The time period from Feb–Jul 2008 cannot be directly compared to Feb–Jul 2009 because the sensor during the former time period was located 10 km southwest of the ridge, in deeper water. The black curve for site SR in Fig. 2 indicates the seven-day average noise level when each noise estimate used in the average is made from the 75-s time period surrounding each detected humpback unit. When averaging the noise estimates this way, the resulting noise level generally falls below the running mean noise level for the same time period (i.e., the black curve generally falls below the green curve) because an increasing number of units is detected during periods of lower noise. This discrepancy indicates the need to obtain noise estimates during the periods of marine mammal vocalization detections; using a simple running-mean noise average does not properly represent the noise environment in which the calls are detected.

Figure 3 shows ocean noise levels for site SBC for a one week period in May 2008 (upper plot), the related values of  $\hat{P}$  (middle plot), and the uncorrected number of units detected per hour over the same period (lower plot). Examination of the lower plot by itself would indicate a strong diel cycle to the humpback calling activity, with significantly more calls occurring during nighttime. However, inspection of  $\hat{P}$  indicates a significant diel cycle in the likelihood of detecting humpback units. This change in  $\hat{P}$ could account for much of the diel signal found in the humpback calling pattern for this period. While nearby passages of ships are easily identified (short duration spikes in the upper plot), smaller noise variations centered near 80 dB re  $1 \mu Pa^2$  are difficult to notice if detections are manually marked from a spectrogram. When ocean noise levels at site SBC drop from 80 dB re 1  $\mu$ Pa<sup>2</sup> to 75 dB re 1  $\mu$ Pa<sup>2</sup>,  $\hat{P}$  increases from 0.1 to 0.65 (see Fig. 9 of Helble *et al.*<sup>2</sup>). The reason is that calls from a large area that were buried in noise at higher noise levels become detectible with the decrease in noise. This observation illustrates the importance of correcting for subtle variations in noise at this site (in contrast, large spikes in noise that occur in a high noise environment have little effect reducing  $\hat{P}$  because  $\hat{P}$  is already low). Changes of only a few decibels in noise level can have substantially different effects on the change in  $\hat{P}$  depending on



Fig. 2. Ocean noise levels in the 150–1800 Hz band over the 2008–2009 period at site SBC (upper) and SR (lower). The gray curves indicate the noise levels averaged over 75 s increments, the green curves are the running mean with a seven-day window, and the black curve (site SR only) is a plot of the average noise levels in a seven-day window measured at the times adjacent to each detected humpback unit. White spaces indicate periods with no data. The blue vertical lines mark the start of enforcement of CARB law.



Fig. 3. Ocean noise levels at site SBC in May 2008 (upper), probability of detecting a humpback unit ( $\hat{P}$ ) within a 20 km radius of site SBC in May 2008 (middle), and the number of humpback units detected in uncorrected form ( $n_c$ ) at site SBC for the same time period (lower). Shaded time periods indicates sunset to sunrise. The vertical grid lines indicate midnight local time.

the site specific bathymetric and environmental parameters. At site SBC,  $\hat{P}$  decreases exponentially with increasing noise, making changes in  $\hat{P}$  more dramatic over relatively small changes in noise at lower levels, whereas at site SR  $\hat{P}$  changes quadratically.<sup>2</sup>

The plots in Fig. 4 show the uncorrected number of units detected in weekly time bins at site SR from 2008–2009 (upper), the time-varying probability of detecting a humpback unit (middle), and the corrected, estimated number of humpback units occurring per unit area (lower) for the same time period. The weekly estimates of P were calculated by averaging the values of  $\hat{P}$  measured at each detected unit. The decrease in ocean noise due to the economic downturn and the enforcement of the CARB air-quality improvement rule creates an increase in  $\hat{P}$  for the Sep–Jan 2009 time period compared to Sep-Jan 2008. While substantially more units are detected in the Sep-Jan 2009 time frame (190% increase in the upper plot), the increase in detections during this period is not a biological effect, but rather is driven by the changing noise conditions. After the uncorrected call counts are "calibrated" by  $\hat{P}$ , the estimated number of units occurring between Sep-Jan 2009 is approximately equal to the number estimated for the same period in the previous year (8% decrease in the lower plot). The uncertainties associated with P due to environmental and source characteristics, the main sources of uncertainty in  $\hat{P}$ , are discussed in Helble et al.<sup>2</sup> A full analysis of all the uncertainties in  $\hat{P}$  is beyond the scope of this paper and is a subject of current research. Although the absolute numbers for  $N_c$  in the lower plot of Fig. 4 are uncertain, confidence in the temporal dependence of  $N_c$  at a given site is much greater since it is driven to a large extent by the temporal variability in the noise, which can be readily measured with the real data.

## 4. Discussion

The downturn in the world economy, combined with the enforcement of CARB airquality improvement rule provides a concrete example of how changing ocean noise conditions can skew the results of long-term marine mammal monitoring efforts. For site SR, lower noise during the fall of 2009 compared to the fall of 2008 resulted in an increase number of detections between these periods. After correcting for  $\hat{P}$  over the time period, values of  $N_c$  were roughly the same at site SR between the two seasons. While this change



Fig. 4. (Color online) Uncorrected number of humpback units detected ( $n_c$ ) in the 2008–2009 period at site SR (upper), estimated probability of detecting a humpback unit ( $\hat{P}$ ) within a 20 km radius of site SR (middle), and the corrected estimated number of units occurring per unit area ( $\hat{N}_c$ ) at site SR for the same time period (lower).

in economic conditions between 2008 and 2010 provides a convenient example for studying the influence of noise on  $\hat{P}$ , changing ocean noise conditions on these long time scales are by no means unique. For example, ocean noise levels have risen by an estimated 3 dB/ decade since the 1960s in some locations<sup>10,11</sup> due to an increase in global shipping. A more recent study by Andrew *et al.* analyzing ocean noise level trends over the past decade shows a leveling off of ocean noise levels in some locations, including a location near to the Sur Ridge HARP.<sup>12</sup> Results from Andrew *et al.*<sup>12</sup> thus demonstrate the need for detailed noise analyses, as changing noise conditions can have a profound effect on the probability of detecting marine mammals, even during times of relative stability. Additionally, changing economic conditions, ship traffic routes, ship propeller design, fluctuations in tourism, and changes in weather patterns can all create similar effects at various locations worldwide.<sup>13–20</sup> Short-term changes in ocean noise must also be accounted for because  $\hat{P}$  can rise and fall on time scales important for habitat and predator/prey studies. One such example can be seen at site SBC (Fig. 3), where a strong diel pattern in humpback acoustic detections is heavily influenced by shipping patterns in the region.

The influence of changing  $\hat{P}$  is even more pronounced when scientists attempt to assess the potential impact of noise on marine mammals<sup>20</sup> because the acoustic conditions under which the biological signals are recorded are heavily influenced by the noise. Correcting acoustic detections by  $\hat{P}$  removes these biases. Unfortunately, correcting shorttime series by  $\hat{P}$  becomes problematic if not enough calls are detected to satisfy the assumed homogeneous random distribution of animals in the study area. This assumption can be relaxed in cases where the passive monitoring systems provide localization capabilities, or multiple omni-directional sensors with overlapping coverage are deployed within a study area. However, understanding changes in  $\hat{P}$  on short time scales is still very useful; it indicates the degree to which the environment influences the acoustic detections.

In summary, if passive acoustic detections of marine mammal calls are to become an integral part of marine mammal monitoring, biological studies, and ecological assessments, estimates of the probability of detection, *P*, should become a standard approach to assessing animal presence and calibrating for environmental effects.

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