High-frequency modulated signals of killer whales (*Orcinus orca*) in the North Pacific

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Abstract: Killer whales in the North Pacific, similar to Atlantic populations, produce high-frequency modulated signals, based on acoustic recordings from ship-based hydrophone arrays and autonomous recorders at multiple locations. The median peak frequency of these signals ranged from 19.6–36.1 kHz and median duration ranged from 50–163 ms. Source levels were 185–193 dB peak-to-peak re: 1 μPa at 1 m. These uniform, repetitive, down-swept signals are similar to bat echolocation signals and possibly could have echolocation functionality. A large geographic range of occurrence suggests that different killer whale ecotypes may utilize these signals.

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1. Introduction

Killer whales (*Orcinus orca*) produce a variety of acoustic signals including echolocation clicks for foraging and pulsed calls and whistles for communicative purposes (Ford, 1989). Killer whale echolocation clicks and pulsed calls have distinct characteristics, which together allow for the discrimination to species level (Au *et al.*, 2004; Barrett-Lennard, 1996). North Pacific killer whales are known to produce whistles from 1–18 kHz (Thomsen *et al.*, 2001; Ford, 1989). Samarra *et al.* (2010) recently reported on Norwegian and Icelandic killer whales that use a high-frequency whistle type with observed fundamental frequencies ranging from 16.9–74.7 kHz.

Within the North Pacific, killer whales are divided into different ecotypes (residents, transients, and offshores) based on morphological, behavioral, and genetic differences. Acoustic behavior varies considerably between ecotypes. Resident populations are highly vocal and use stable, acoustic repertoires of discrete pulsed calls that define familial groups (Ford and Fisher, 1983). Both offshore killer whales and residents have been shown to have similar echolocation and communication behavior while foraging (Dahlheim *et al.*, 2008). Mammal-eating transient killer whales produce clicks and whistles infrequently, likely a stealth tactic as a result of their prey's ability to detect these sounds (Barrett-Lennard, 1996).

Here we describe high-frequency modulated (HFM) killer whale signals, similar, but not identical to those reported in the Atlantic by Samarra *et al.* (2010). These HFM signals are produced across a broad region of the North Pacific.

2. Methods

To search for the presence of killer whale HFM signals, we examined acoustic recordings from the North Pacific at the following locations: Gulf of California, Washington

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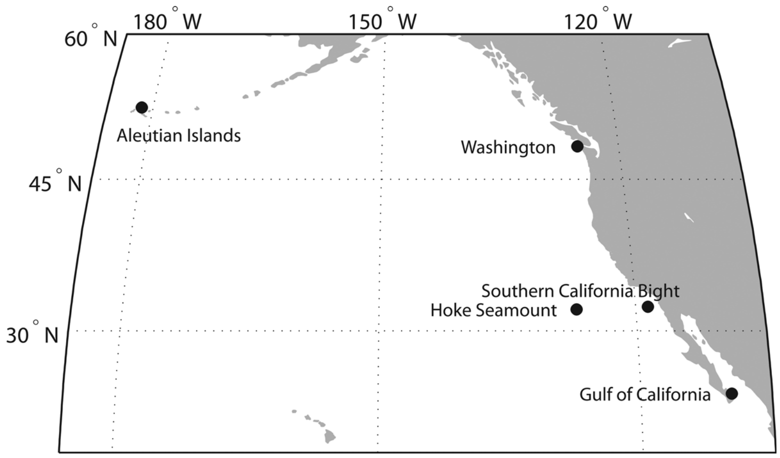

Fig. 1. Map of killer whale high-frequency modulated (HFM) signal recording locations in the North Pacific.

coast, Hoke Seamount (between California and Hawaii), near Kiska Island in the Aleutian Islands, and in the Southern California Bight (SCB) (Fig. 1). Instrumentation included autonomous bottom-moored high-frequency acoustic recording packages (HARPs, Wiggins and Hildebrand, 2007), towed hydrophone arrays, and hydrophone arrays deployed from the Research Platform FLIP (Gassmann *et al.*, 2011); all hydrophones had at least 96 kHz bandwidth (Table 1).

Long-term spectral averages (LTSAs, Wiggins and Hildebrand, 2007) were evaluated by an analyst (Anne E. Simonis) to identify the HFM signals, as well as killer whale whistles, echolocation clicks, and pulsed calls. LTSAs average 500 discrete Fourier transform spectra from non-overlapping 10 ms Hann-windowed frames, arranged sequentially to create a spectrogram with a resolution of 100 Hz for every 5 s. When HFM signal sequences were detected in the LTSAs, the corresponding original time series and fine-scale spectrograms were inspected more closely.

When HFM signals were detected, their contours were traced with custom software (*Selena*, Department of Animal Physiology, University of Tübingen) and viewed using a colored spectrogram [2 s window and 2048 sample fast Fourier transform (FFT)]. Spectrograms were calculated with 41% overlap, resulting in 97 Hz frequency resolution and 6.04 ms temporal resolution. The frequency-time contour of each signal was tracked automatically and overlaid on the spectrogram, verified visually and corrected manually, if necessary. Time, frequency, and amplitude values for each pixel were exported to a spreadsheet. The following parameters were calculated based on the contours identified: minimum frequency, maximum frequency, start frequency, end frequency, frequency at halfway point in time, peak-amplitude frequency, bandwidth, duration, sweep rate, intersignal interval, and number of inflection points. To account for a variety of signal-to-noise ratios, analyses were restricted to within -10 dB of the peak-amplitude along each contour. Signals that did not have at least 10 dB of signal-to-noise were discarded.

Source levels were obtained by localizing HFM signals using calibrated hydrophone arrays deployed from FLIP and a transmission loss model as described by Gassmann *et al.* (2011). We report source levels as both root-mean-square (rms) and peak-to-peak re: 1 uPa at 1 m over the bandwidth of the signal.

3. Results

HFM signals from killer whales were characterized at study areas ranging from the Aleutian Islands to the Gulf of California in both coastal and offshore habitats (Fig. 1). In addition to these sites, HFM signals were detected in the Pacific Islands region, at Pearl and Hermes Atoll, and near Kauai, Hawaii (authors' unpublished data).

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Table 1. Location and specifications of recordings containing killer whale high-frequency modulated signals.

Location	**Latitude**	**Longitude**	**Recording Type**	**Sample Rate (kSamples s^{-1})**	**Depth (m)**	**Date**
Southern California Bight (HARP)	32° 22.19'N	118° 33.89'W	HARP	200	912	4-Oct-2009
Hoke Seamount	32° 06.37'N	126° 54.58'W	HARP	200	770	11-Dec-2008
Aleutian Islands	52° 19.01'N	178° 31.24'E	HARP	200	783	05, 11-Aug 2010
Gulf of California	23° 49.45'N	109° 37.67'W	ship-based hydrophone array	192	20	31-May-2006
Washington Coast	48° 20.25'N	125° 12.52'W	ship-based hydrophone array	192	20	7-Jul-2006
Southern California Bight (FLIP)	33° 02.44'N	118° 41.00'W	ship-based hydrophone array	200	122	11-Nov-2008

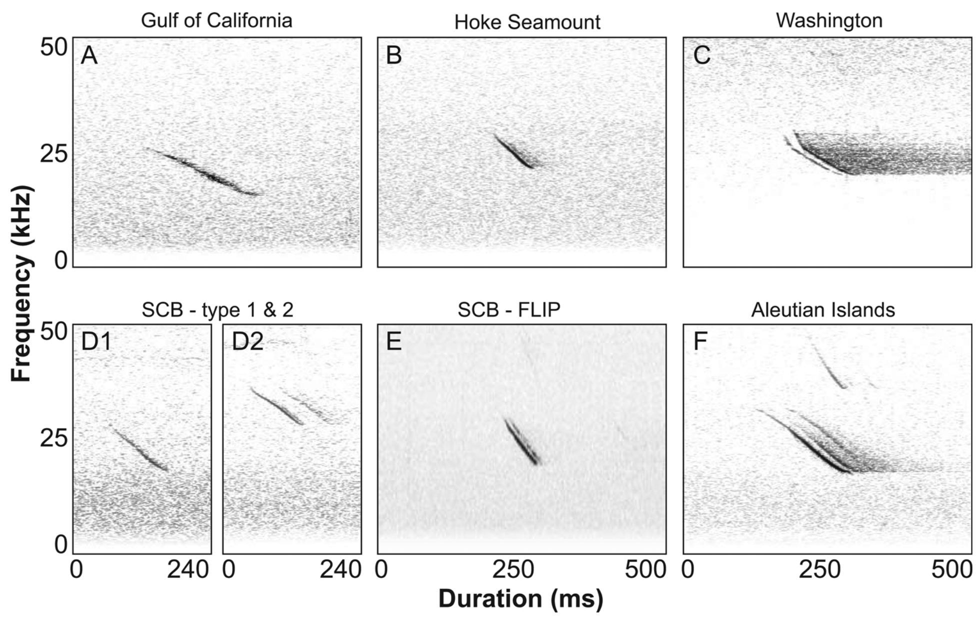

Fig. 2. Killer whale HFM signal spectrograms for five regions in the North Pacific (512-point FFT, 41% overlap, high-pass filter with corner frequency at 4 kHz).

HFM signals were found throughout the year with no apparent seasonal trends. Repetitive bouts of uniform HFM signals were detected at all sites. The HFM signals were frequency down-swept (Fig. 2) with the majority (80–100%) having none or one inflection point (Table 2). Two different types of frequency down-swept HFM signals were observed. At most sites, HFM signals (type 1) swept from approximately 25–20 kHz (Table 2). In the SCB, a higher frequency down-sweep also was detected decreasing from 37– 32 kHz (type 2). The median −10 dB bandwidth was 4–10 kHz across all sites and call types. With median durations computed for each site ranging from 50–163 ms, the sweep rate ranged from 53–80 Hz/ms for type 1, and was 94 Hz/ms for the higher frequency signal, type 2.

Both HFM signal types 1 and 2 were found only in the SCB recording along with typical killer whale echolocation clicks and pulsed calls. During nearly 3.5 h, 57 type 1 and 16 type 2 signals were observed in three bouts lasting about 3 min each in which both types were concurrently recorded. The median inter-signal interval was 2.4 and 2.0 s for the types 1 and 2 HFM signal sequences, respectively. Type 2 signals were shorter in duration and bandwidth, had faster sweep rates, and were less prevalent than the lower-frequency type 1 (Table 2). Source levels of type 1 HFM signals recorded in the Southern California Bight were estimated to be between 18–193 dB peak-to-peak re: 1 μPa at 1 m while the corresponding rms source levels range from 173–178 dB re: 1 μPa rms (based on four signals).

In one of two Aleutian Islands recordings, as well as the SCB recordings, HFM signals were recorded in the presence of other killer whale sounds. In the other Aleutian Islands recording, HFM signals were ascribed to killer whales in the absence of other killer whale sounds, as the HFM signals across all sites were very uniform. In the case where HFM signals were recorded without the presence of other killer whale sounds, there were no other odontocete sounds recorded concurrently. Recordings from the Gulf of California and the Washington coast were made in the presence of visually detected groups of killer whales, such that we can ascribe the recorded signals to killer whales. In the Washington encounter, there were 9 individuals of the offshore ecotype, including 2 adult males and a sub-adult female. During both Gulf of California and

Table 2. Descriptive statistics of killer whale high-frequency modulated signal parameters given in median (**bold**) with 10th and 90th percentiles (brackets), compared to Samarra *et al.*, 2010; *n* values are shown as a fraction to indicate how many signals were used in the analysis (numerator) and how many were detected (denominator). ip = inflection points.

			Southern California Bight (HARP)					Samarra *et al.*, 2010				
Location	Gulf of California	Hoke Seamount	Type 1	Type 2	Southern California Bight (FLIP)	Washington Coast	Aleutian Islands	Iceland	Norway	Shetland	Iceland	Norway
n	7/7	32/46	46/57	9/16	25/25	33/34	88/179	548	234	8	22	23
Beginning frequency (kHz)	**24.3** [24.0 27.0]	**25.6** [22.3 27.0]	**25.6** [22.8 26.9]	**37.3** [36.5 37.6]	**24.7** [22.1 27.2]	**28.1** [25.3 30.4]	**26.6** [21.1 30.6]	31.3 ± 6.7	31.7 ± 6.1	22.6 ± 2.1	64.0 ± 2.7	64.3 ± 3.6
Frequency at 1/2 way point (kHz)	**19.6** [19.1 22.2]	**23.2** [20.6 24.3]	**21.7** [19.3 23.7]	**34.5** [34.0 35.6]	**20.5** [17.3 23.9]	**22.9** [19.4 24.8]	**21.6** [16.7 26.0]	32.5 ± 5.8	32.1 ± 5.8	23.6 ± 2.7	65.9 ± 2.3	59.2 ± 3.3
End frequency (kHz)	**16.3** [15.4 18.5]	**21.0** [19.2 22.7]	**18.1** [15.6 22.0]	**32.4** [30.2 33.6]	**17.9** [14.0 20.7]	**18.4** [15.1 21.5]	**17.6** [13.3 21.6]	37.0 ± 6.3	35.3 ± 6.4	28.0 ± 3.4	68.5 ± 3.2	58.1 ± 5.4
Minimum frequency (kHz)	**16.3** [15.4 18.5]	**21.0** [19.2 22.7]	**18.1** [15.5 22.0]	**32.4** [30.2 33.6]	**17.9** [14.0 20.7]	**18.4** [15.1 21.5]	**17.6** [13.3 21.6]	30.4 ± 5.9	30.7 ± 5.9	22.2 ± 2.3	63.1 ± 2.8	55.9 ± 4.0
Maximum frequency (kHz)	**24.3** [24.0 27.0]	**25.6** [22.3 27.0]	**25.6** [23.1 26.9]	**37.3** [36.5 37.6]	**24.7** [22.1 27.2]	**28.1** [25.3 30.4]	**26.6** [21.1 30.6]	37.2 ± 6.4	35.7 ± 6.0	28.0 ± 3.4	68.7 ± 3.0	65.1 ± 3.4
Peak frequency (kHz)	**19.6** [18.0 23.0]	**23.3** [21.0 24.7]	**22.6** [19.4 25.3]	**36.1** [33.3 36.8]	**21.3** [19.5 24.0]	**22.8** [19.4 25.4]	**22.3** [16.5 26.6]					
Bandwidth (kHz)	**8.6** [6.1 10.2]	**4.1** [2.2 6.2[]	**7.1** [3.8 9.8]	**5.1** [3.6 6.9]	**7.5** [4.0 10.2]	**9.8** [5.7 13.1]	**8.4** [3.4 15.8]	6.8 ± 3.7	5.0 ± 2.5	5.8 ± 2.1	5.6 ± 2.4	9.1 ± 4.1
Duration (ms)	**163.0** [108 241]	**50.0** [37 86]	**113.0** [50 182]	**56.0** [33 88]	**153.4** [94 270]	**113.0** [49 389]	**142.0** [78 300]	140 ± 140	170 ± 300	340 ± 130	40 ± 70	40 ± 30
Sweep Rate (Hz/ms)	**53.3** [40.6 56.4]	**79.9** [36.3 121.6]	**69.3** [38.0 116.1]	**93.8** [69.4 143.7]	**37.0** [20.1 66.6]	**86.7** [24.3 142.3]	**59.9** [27.6 97.2]					
Inter-signal interval (s)	**2.1** [2.0 2.38]	**1.9** [1.0 2.6]	**2.4** [1.1 4.7]	**2.0** [1.4 2.7]	**1.4** [1.3 2.3]	**2.9** [1.5 4.5]	**2.3** [1.3 4.3]					
% with 0 ip	88%	70%	84%	75%	100%	100%	73%					
% with $\leq$ 1 ip	**100%**	**89%**	**91%**	**94%**	**100%**	**100%**	**83%**	**98%**	**97%**	**88%**	**95%**	**100%**

Washington sightings, typical killer whale echolocation clicks, pulsed calls, and whistles were recorded with occasional HFM signals throughout the recordings (30 min from the Gulf of California, 3 h from Washington).

4. Discussion

Samarra *et al.* (2010) suggested that the signals were used for short-range communication. The HFM signals recorded in the Pacific could also have a communicative function; however, given that killer whales use lower frequency whistles and pulsed calls to communicate, it is curious that higher frequency HFM signals also would be for communication unless they are used in situations where high frequencies would not be detected by prey or competitive species.

Samarra *et al.* (2010) reported two different types of killer whale HFM signals with the two call types exhibiting similar structure, but with higher and lower frequency content. If the two signal types recorded in SCB were produced by different individuals, HFM signals could be used to identify individual group members or maintain group cohesion as described for discrete calls (Ford, 1989). The higher frequency content and lack of consistent down-sweeps of signals recorded in the Atlantic by Samarra *et al.* (2010) may be a consequence of the spatial separation and variable use of high frequency signals between the populations. Samarra did not identify any HFMs in the North Pacific where northern residents and west coast transients were recorded. As acoustic behavior is known to vary strongly between ecotypes, perhaps HFMs are not often utilized by these ecotypes or the groups recorded were not engaged in a behavior where HFM's would be utilized. These reasons and the reduced bandwidth of previous recordings may explain why HFM signals have gone unnoticed.

One possibility is that HFM signals may be used for echolocation similar to bats (Schnitzler, 2003). Most of the downswept signals from the Pacific recordings did not contain inflection points and are similar in frequency and shape to echolocation signals of some species of bats, albeit an order of magnitude longer in duration and inter-signal interval (Schnitzler, 2003). Beaked whale echolocation clicks also contain a frequency modulation sweep and stable inter-pulse interval (Zimmer *et al.*, 2005; Johnson *et al.*, 2004). Killer whales are reported to produce whistles and pulsed calls at source levels between 131–168 dB re 1 μPa at 1 m rms in the 1–20 kHz band (Miller, 2006); whereas, the higher source level of HFM signals detected in the SCB (185–193 dB peak-to-peak re 1 μPa at 1 m and 173–178 dB re 1 μPa rms) indicates that these signals may have a different function than typical whistles. Additionally, the wide bandwidth and long duration of HFM signals results in a large time-bandwidth product, which increases the processing gain of a signal (Au, 1993). As a result, HFM signals are more suitable than typical echolocation clicks for long range detection tasks. The structure of HFM signals indicates that they could potentially be used to identify prey items while foraging or to identify underwater features for orientation or navigation.

Our recordings, together with those of Samarra *et al.* (2010), indicate that several populations and ecotypes of killer whales use HFM signals. Additional visual sightings combined with passive acoustic monitoring could provide more insight into the associated behavior and ecotype of the killer whales utilizing these high frequency signals.

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