Submitted in support of the U.S. Navy's 2019 Annual Marine Species Monitoring Report for the Pacific

Comparison of Fisheries and Naval Explosions in the SOCAL Range Complex

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Table of Contents

List of Tables

List of Figures

Executive Summary

Over the past decade, underwater explosive sounds have been recorded in the U.S. Navy's Southern California Range Complex. The majority of these events are related to the use of seal bombs by the fishing industry as a deterrent to depredation. In addition, a smaller number of explosions are from Navy ordnance use during training exercises, especially in the Southern California Anti-submarine Warfare (ASW) Range (SOAR).

Navy-supplied periods of missile ordnance use on SOAR reveal explosions with different signal characteristics than those measured for seal bombs. The characteristic difference between Navy missile explosions and seal bombs is that seal bombs included multiple bubble pulses following a primary pulse versus the Navy ordnances that consisted of only a primary pulse. These differences suggest a straightforward approach for separation of these two types of explosions based on the presence or absence of multiple bubble pulses. However, further investigation revealed that acoustic propagation can greatly alter recorded waveforms such that signal type differentiation is difficult and may need more sophisticated methods than visual examination by a trained analyst.

Background

The U.S. Navy's Southern California (SOCAL) Range Complex is located in the Southern California Bight and the adjacent deep waters to the west. In January 2009, an acoustic monitoring effort was initiated within the SOCAL Range Complex with support from the U.S. Pacific Fleet. Large numbers of explosions were detected in underwater recordings in the SOCAL region. The majority of the explosions have been shown to co-occur with the squid fishery and are related to use of seal deterrent devices known as "seal bombs" (Meyer-Löbbecke *et al.*, 2016; Meyer-Löbbecke *et al.*, 2017). The region is also used by the Navy for training exercises, including activities that use explosives. This report evaluates recorded explosion activity in the SOCAL Range Complex near San Clemente Island with the goal of identifying differentiating acoustic characteristics between fisheries and military explosions so that future monitoring efforts may be able to separate these two types of explosions.

Methods

Passive Acoustic Monitoring Recorders

High-frequency Acoustic Recording Packages (HARPs - Wiggins and Hildebrand, 2007) were used to record marine mammal, ambient, and anthropogenic sounds in the SOCAL Range Complex. HARPs are autonomous, battery-operated instruments capable of recording underwater sounds from 10 Hz to 100 kHz continuously over long periods (up to ~1 year) to provide a comprehensive time series of the marine soundscape. HARPs are configurable into standard oceanographic-style moorings or seafloor mounted instrument frames, all of which use a releasable ballast-weight anchor to secure the instrument to the sea floor until planned recovery. A combination of these configurations were used in the SOCAL Range Complex, and were chosen depending on deployment and site requirements.

To capture underwater sounds, HARPs use hydrophones tethered and buoyed above the seafloor approximately 10 – 30 m. The hydrophones typically used were constructed with two channels, one for low-frequency sounds (<2 kHz) and the other for mid- and high-frequency signals (>2 kHz) with lead-zirconium-titanate (PZT) ceramic elements and different preamplifier, filter, and signal conditioning electronics for each channel. Each hydrophone's electronic circuit board was calibrated in the laboratory at Scripps Institution of Oceanography and representative data loggers with complete hydrophones were full-system calibrated at the U.S. Navy's Transducer Evaluation Center in San Diego, CA to provide the full-band frequency response of the system so that accurate sound pressure levels can be measured from the recordings.

Acoustic data were recorded to an array of standard laptop computer style 2.5" hard disk drives in a compressed format. Upon instrument recovery, batteries and disk drives were replaced along with a new ballast-weight anchor to ready the HARP for the next deployment.

Data Acquisition

The SOCAL long-term recordings reported here span three years from summer 2016 to spring 2019 and occurred at three locations west and south of San Clemente Island: sites E, H, and N (Figure 1; Tables 1 – 3).During this period, Naval exercises were conducted with known ordnance use in the Southern California Anti-submarine Warfare (ASW) Range (SOAR). Also, a controlled experiment to characterize seal bomb explosion source signatures was conducted in the spring of 2017 at site SBE (32° 51.4'N, 117° 32.8'W, 870 m deep) east of San Clemente Island, ~20 km offshore of La Jolla, California (Figure 1) and was used for comparison to the long-term recordings in which the source and location of explosion events was not known.

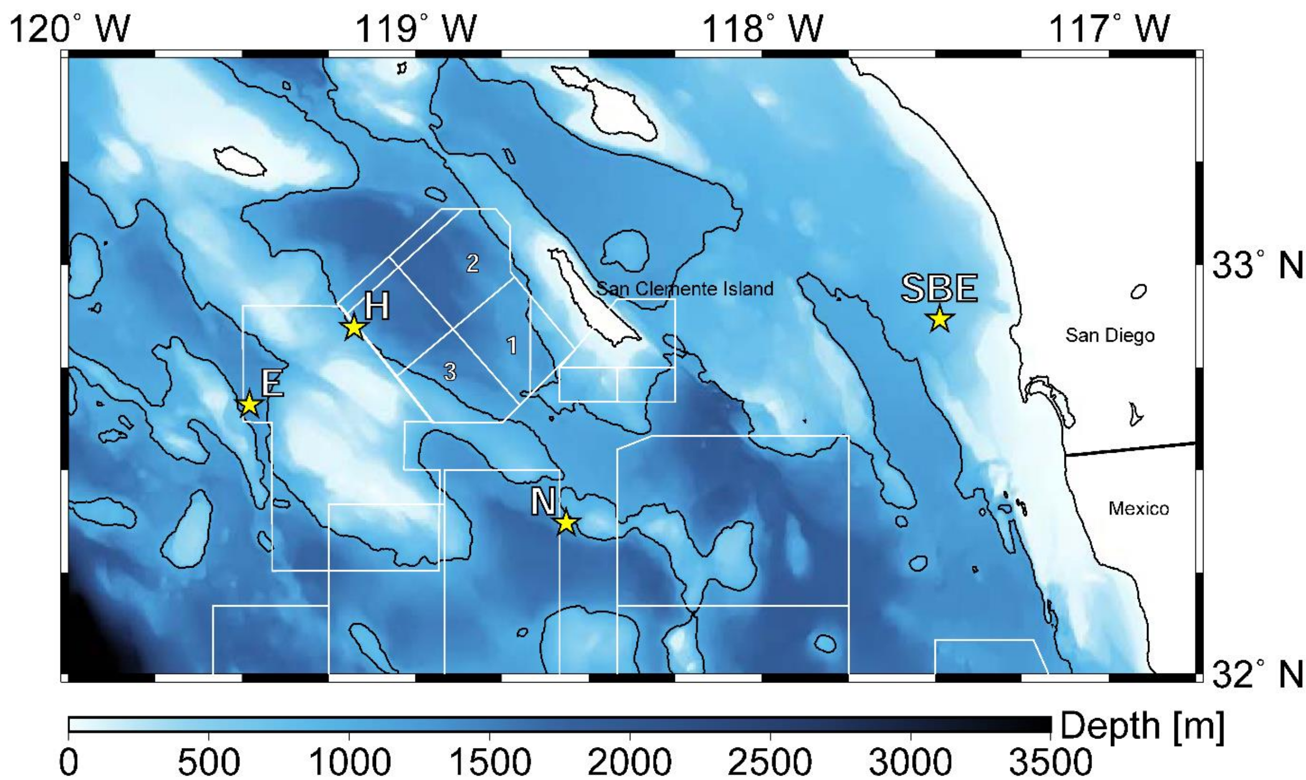

Figure 1. SOCAL Range Complex acoustic recorder site locations and bathymetric map. *Acoustic recorder locations are shown as yellow stars at sites E, H, and N; and the seal bomb experiment site SBE. White polygons are Navy operational areas with SOAR subareas numbered 1, 2 and 3. Black contours are coastlines and 1,000 m depths, colors designate bathymetric depths.*

Table 1. SOCAL Range Complex site E acoustic recorder deployments.
Deployment name, locations, analysis periods, and number of days analyzed.

Deployment Name	Lat N	Lon W	Depth [m]	Analysis Period	Effort Days
SOCAL_E_61	32° 39.5'	119° 28.7'	1,331	03/05/17 – 07/10/17	128
SOCAL_E_62	32° 39.5'	119° 28.8'	1,312	07/11/17 – 02/10/18	215
SOCAL_ES_63	32° 39.2'	119° 29.1'	1,330	03/15/18 – 07/11/18	119
SOCAL_E_64	32° 39.5'	119° 28.6'	1,300	07/12/18 – 11/28/18	140
SOCAL_E_65	32° 39.4'	119° 28.4'	1,338	11/28/18 – 05/07/19	128
					Total 730

Table 2. SOCAL Range Complex site H acoustic recorder deployments.
Deployment name, locations, analysis periods, and number of days analyzed

Deployment Name	Lat N	Lon W	Depth [m]	Analysis Period	Effort Days
SOCAL_H_59	32° 50.7'	119° 10.6'	1,000	07/06/16 – 11/09/16	126
SOCAL_H_61	32° 50.8'	119° 10.5'	1,000	02/22/17 – 06/06/17	105
SOCAL_H_62	32° 50.8'	119° 10.5'	1,000	06/07/17 – 10/04/17	120
SOCAL_H_63	32° 50.8'	119° 10.5'	1,000	10/05/17 – 11/08/17	34
SOCAL_H_65	32° 50.8'	119° 10.2'	1,000	07/09/18 – 11/29/18	142
SOCAL_H_66	32° 50.8'	119° 10.0'	1,013	11/29/18 – 05/05/19	158
					Total 685

Table 3. SOCAL Range Complex site N acoustic recorder deployments.
Deployment name, locations, analysis periods, and number of days analyzed.

Deployment Name	Lat N	Lon W	Depth [m]	Analysis Period	Effort Days
SOCAL_N_59	32° 22.3'	118° 33.9'	1,260	07/07/16 – 11/08/16	125
SOCAL_N_60	32° 22.2'	118° 33.9'	1,260	11/09/16 – 02/21/17	104
SOCAL_N_61	32° 22.3'	118° 33.9'	1,300	02/21/17 – 06/07/17	105
SOCAL_N_62	32° 22.3'	118° 33.9'	1,300	06/07/17 – 12/21/17	197
SOCAL_N_63	32° 22.3'	118° 33.9'	1,296	02/04/18 – 07/09/18	155
SOCAL_N_64	32° 22.1'	118° 33.9'	1,290	07/09/18 – 11/28/18	142
SOCAL_N_65	32° 22.2'	118° 33.7'	1,240	11/29/18 – 05/05/19	157
					Total 985

Data Processing

The standard HARP sampling rate is 200 kHz with 16-bit samples typically compressed by a factor of two. This results in about one terabyte (TB) of HARP disk usage for every two months of recording. Upon uncompressing the HARP recordings, over 12 TBs per instrument-year are generated for analysis, which typically are processed in about 2 – 4 weeks.

During the data processing procedure, three sets of wav files are created: full-band up to 100 kHz; decimated mid-frequency up to 5 kHz; and decimated low-frequency up to 1 kHz. Decimation is accomplished by application of a low-pass filter to the data both forward and backwards to prevent time shifts and resampling at a lower rate. Decimation allows for more efficient data analysis of signals at low frequencies compared to the full-band recordings. For each of the three data sets, long-term spectral averages (LTSAs) are constructed from 5 s window spectral averages and arranged sequentially as long-duration spectrograms. These long spectrograms allow for easily identifying sound events of interest and for data quality evaluation over hours to days. The LTSAs also provide a means of quickly opening and evaluating the fine-detail wav files through a graphical index scheme, which allows an analyst to click a mouse cursor on an event of interest in the LTSA display to open the related wav file (Wiggins and Hildebrand, 2007). Automatic detection and additional spectral analyses can be performed directly on the relatively small LTSA files without needing the large number of source wav files.

Data Analysis

Explosive sound sources in the ocean include military ordnance, seismic exploration airguns, naturally occurring earthquakes, and seal bombs used by the fishing industry as deterrents. Since the onset of an explosion is relatively rapid, it appears as a vertical spike in an LTSA that, when expanded to a finer detailed spectrogram, shows the sharp onset decaying over time often into a reverberant signal. Explosions have energy as low as 10 Hz and often extend up to 2,000 Hz or higher, and can last for a few seconds including the reverberation.

Explosions were detected automatically over the three years and at three sites using a matched filter detector on recordings decimated to 10 kHz sampling rate. The acoustic time series was filtered with a 10^{th} order Butterworth bandpass filter between 200 Hz and 2 kHz. Cross correlation was computed between 75 seconds of the envelope of the filtered time series and the envelope of a filtered composite set of previously recorded example explosions (Figure 2) as the matched filter signal. The cross correlation was squared to 'sharpen' peaks of explosion detections. A floating threshold was calculated by taking the median cross correlation value over the current 75 seconds of data to account for detecting explosions within noise, such as shipping. A cross correlation threshold above the median was set. When the correlation coefficient met or exceeded the threshold, the event was considered a potential detection and a spectrogram of the detection was inspected more closely as described below.

Consecutive explosions were required to have a minimum time distance of 0.5 seconds to be detected. A 300-points (0.03 s) floating average energy across the detection was computed. The start and end of the detection above threshold was determined when the energy rose by more than 2 dB above the median energy across the detection. Peak-to-peak (pp) and root-mean-square (rms) received levels (RLs) were computed over the potential detection period and over the length of the template window before and after the detection. The potential detection was classified as false and deleted if: 1) the dB difference for the pp and rms levels between the signal detection period and the period after the detection was less than 4 dB or 1.5 dB, respectively; 2) the dB difference for pp and rms levels between signal detection period and period before the signal was less than 3 dB or 1 dB, respectively; and 3) the detection was shorter than 0.03 or longer than 0.55 seconds of duration. The thresholds were evaluated based on the distribution of histograms of manually verified true and false detections. A trained analyst subsequently viewed concatenated spectrograms (1 s duration) of the remaining detections for verification based on the temporal-frequency character of energy present.

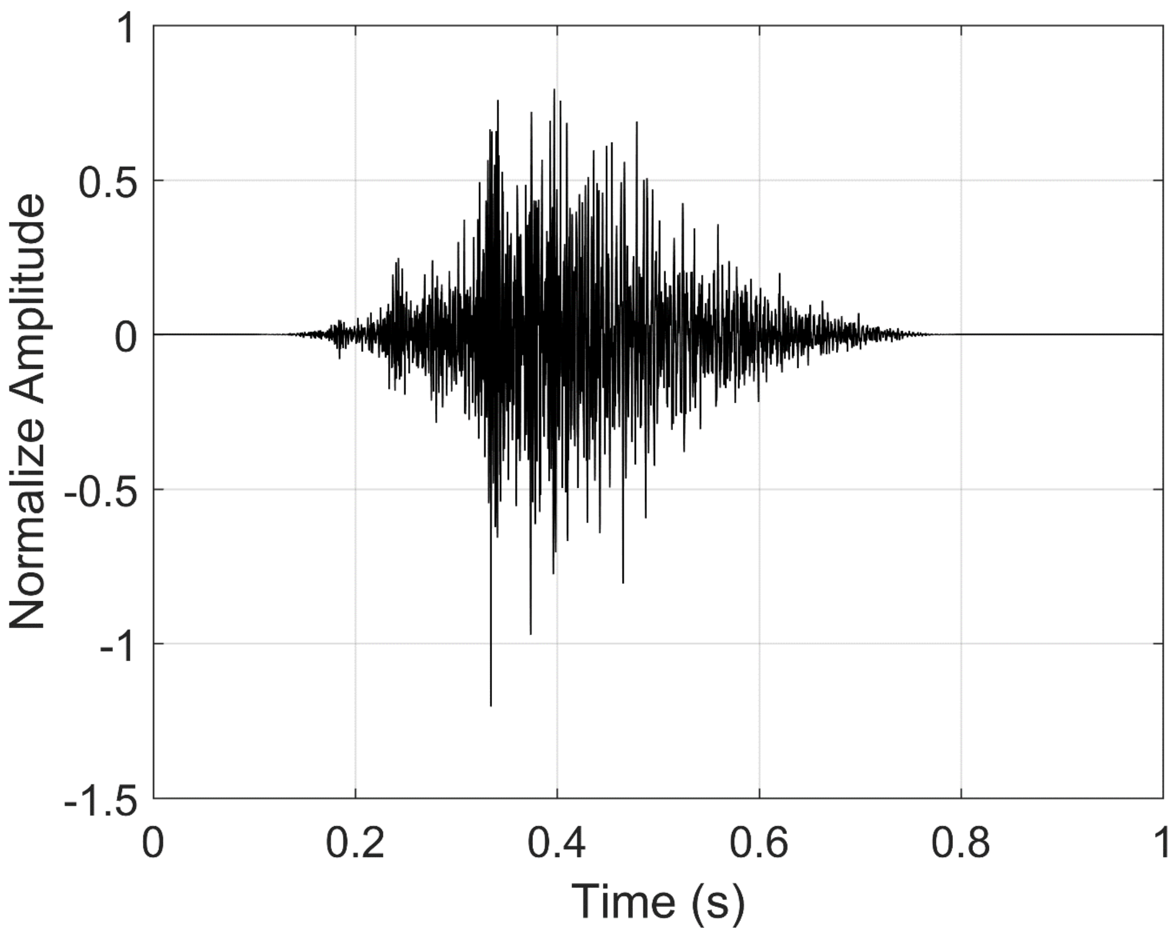

Figure 2. Explosion detector matched filter template.
Amplitude normalized waveform time series template for explosion detector is a 10th order Butterworth bandpass filtered (200 Hz to 2 kHz) composite set of previously recorded example explosions.

Seal Bomb Experiment

During late spring 2017, over 600 seal bombs were exploded underwater and offshore of La Jolla, California (Figure 1 – site SBE) to characterize their source signature (Wiggins *et al.*, 2019). High signal-to-noise ratio (SNR) recordings of explosions were made away from the sea surface and seafloor reflecting boundaries using a HARP with a low sensitivity hydrophone suspended 265 m beneath the sea surface (~600 m above the seafloor). Peak source level for the 2.3 g seal bomb charges was found to be high at 234 dB re 1 µPa m as was sound exposure level (SEL: 197 dB re 1 $\mu Pa^2 m^2 s$) and pressure impulse (208 Pa m s). Received sound pressure waveforms were found to be much different than those used for the automatic explosion detector (Figure 2), with much shorter signal duration and discrete positive and negative pulses (Figure 3). Differences between these two signals are attributed to differences in signal propagation, as will be discussed below.

The short-range, direct, unobstructed first arrival from a seal bomb explosion was a positive pulse lasting ~1 ms duration and followed ~4 ms later by a negative pulse of similar duration (Figure 3 a). Seal bombs contain silica so that they will sink to an explosion depth of ~3 m upon deployment, resulting in a secondary negative pulse (i.e. reflection off of the sea surface). Successive positive pulses (b – d) are from bubbles that form and collapse beneath the sea surface after the initial explosion, and the subsequent negative pulses are the sea surface reflections of these bubble pulses.

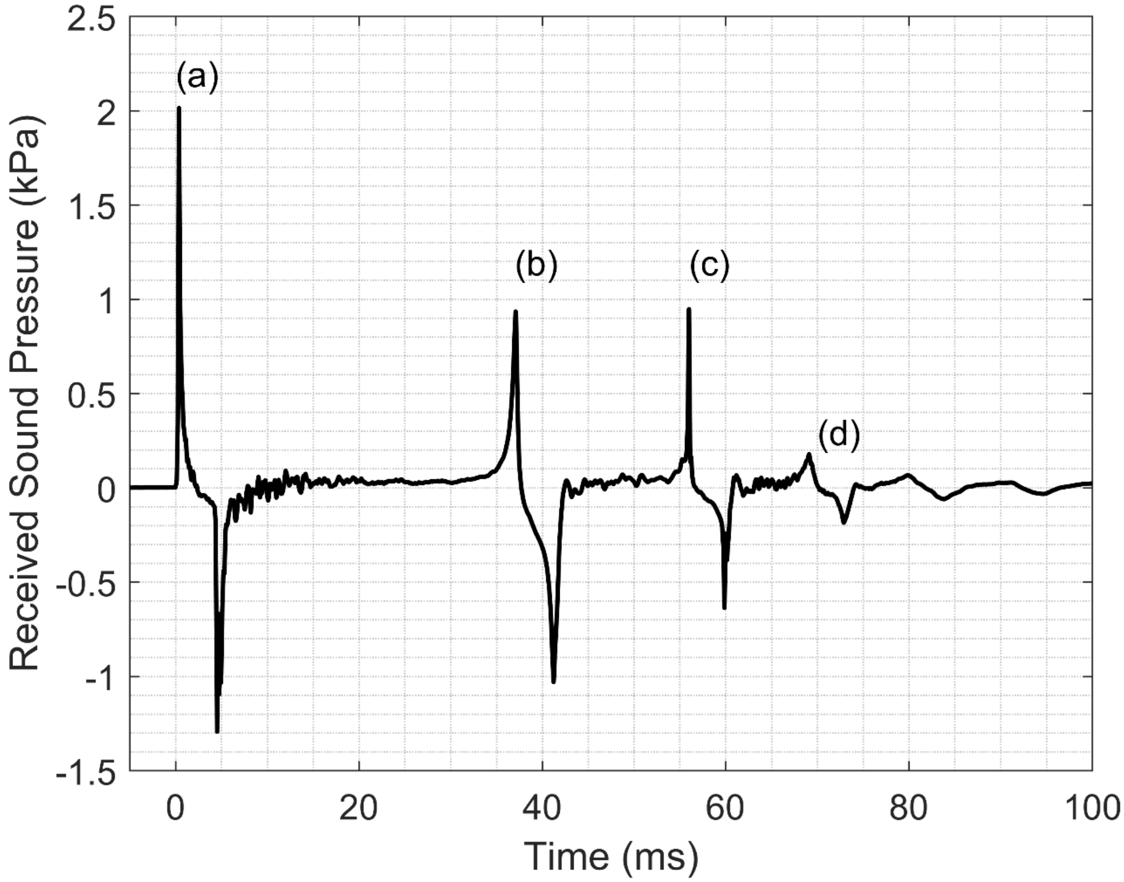

Figure 3. Seal bomb received sound pressure waveform for close (262 m) range.
The first positive pulse (a) is from the seal bomb explosion; whereas, positive pulses (b – d) are subsequent bubble pulses. Following each positive pulse by ~4 ms is a negative pulse from the reflection off of the sea surface of the preceding positive pulse, indicating the source explosion depth was ~3 m (assuming 1500 ms^{-1} sound speed).

During the seal bomb experiment, HARPs with high sensitivity hydrophones suspended several meters above the seafloor were used to record the explosions. Seal bombs were deployed every 30 s while transiting ~11 km h^{-1} along ~10 km track lines from the HARP locations. Arranging and scaling received waveforms as a function of slant range from the receiver shows how nearly identical source conditions can result in different recorded signals. For example, the record section from a near-seafloor HARP (Figure 4) shows the time between explosion arrivals (1 – 5) decreased with increasing range, resulting in characteristically different waveforms.

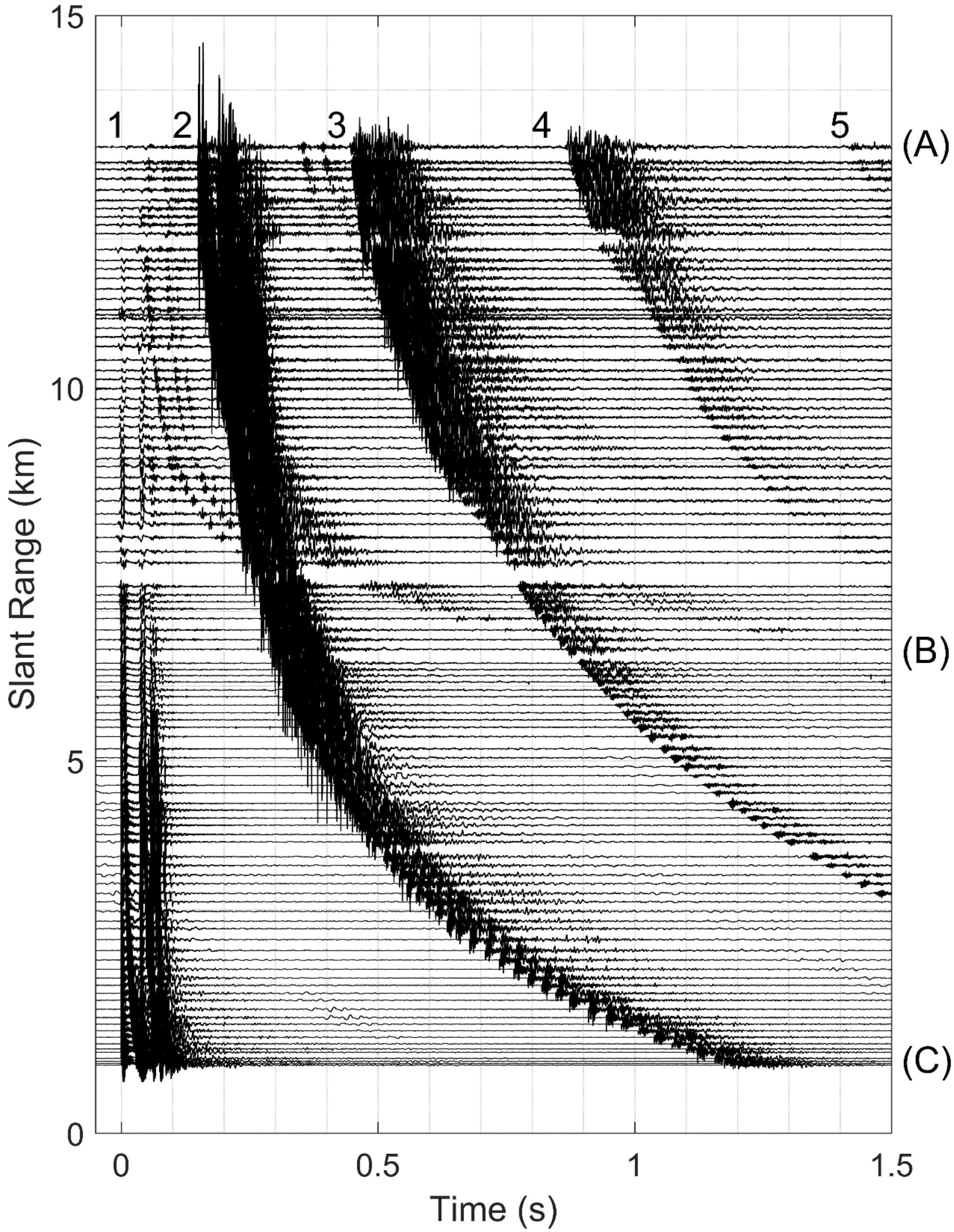

Figure 4. Seal bomb record section.
Received waveforms are offset and amplitude scaled based on slant range between seal bomb source and HARP receiver. Waveforms aligned with leading edge of the first arrival at 0 s. Arrivals are numbered (1–5); example waveforms shown in Figures 5 and 6 are taken from far (A), mid (B), and close (C) ranges.

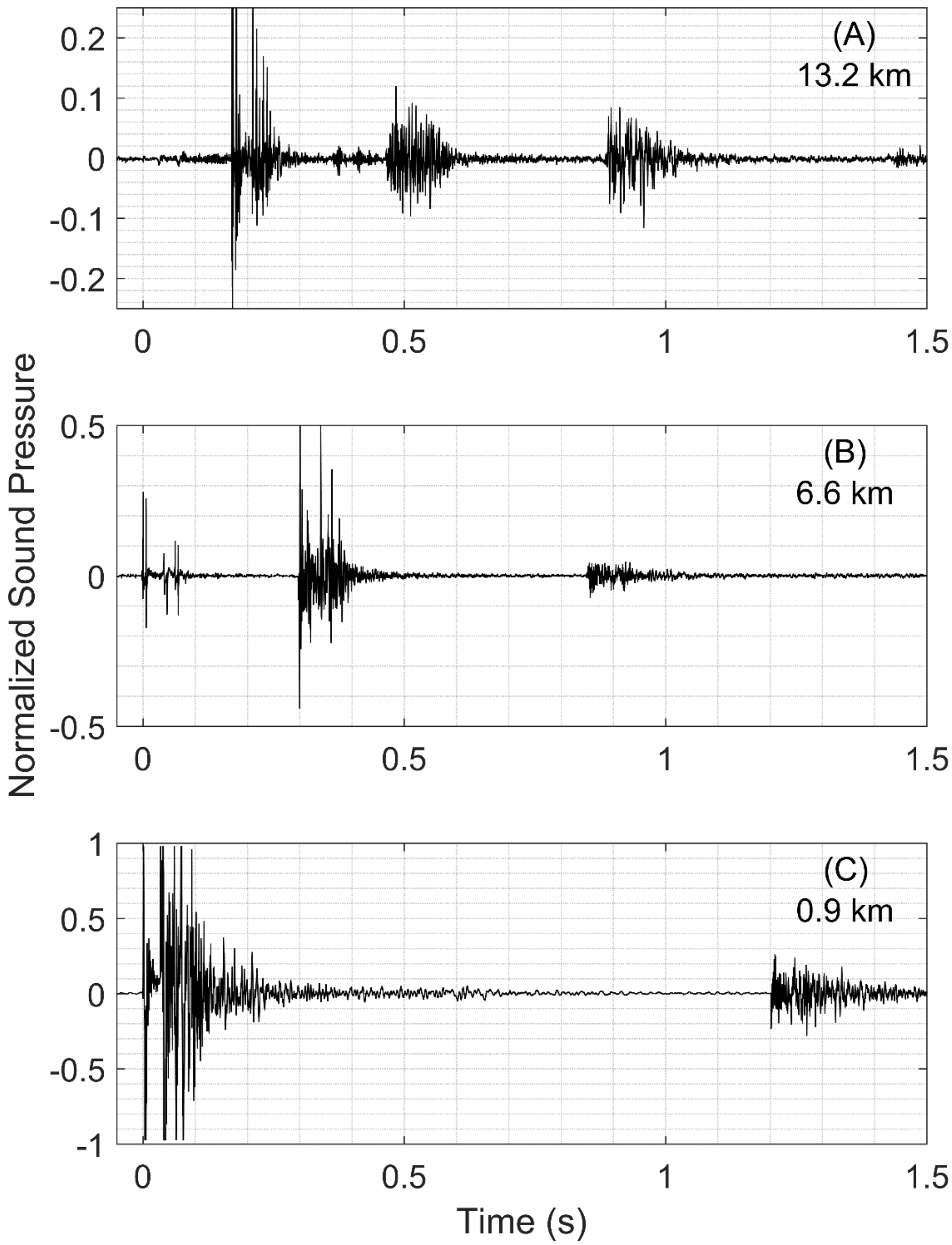

Figure 5. Seal bomb 1.5 s received waveforms at three discrete ranges.
(A) At far range (13.3 km), the direct path arrival is heavily attenuated due to refraction and additional arrivals occur close in time. (B) At midrange (6.6 km), the second arrival has larger amplitude than the first, and additional nearby seafloor reflections are noticeable in the first two arrivals (see Figure 6). (C) At close range (0.9 km), where source is directly above the receiver, the first arrival is clipped and the second arrival reflection from the seafloor and sea surface indicate the water depth was ~900m. All waveforms are temporally aligned with the leading edge of the direct arrival at 0 s. Amplitudes are normalized to the system clipping level.

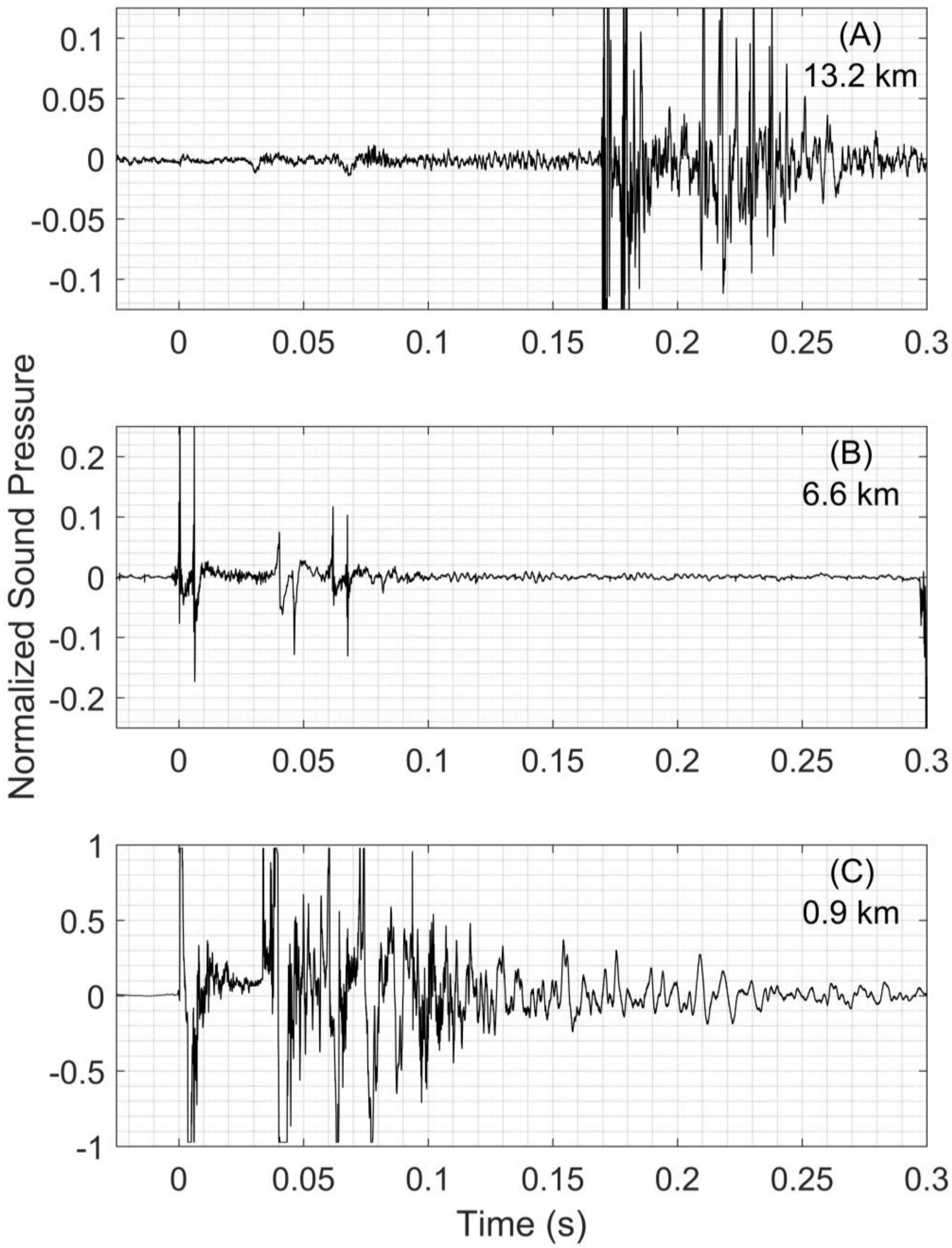

Figure 6. Seal bomb 0.3 s received waveforms at three discrete ranges.
(A) At far range (13.3 km), the direct path arrival is heavily attenuated due to refraction and second arrival shows discrete nearby seafloor reflections. (B) At midrange (6.6 km), the first arrival shows the direct pulse and bubble pulses, and additional pulses trailing ~10 ms were from the seafloor reflections ~7.5 m beneath the hydrophone. (C) At close range (0.9 km), where source is directly above the receiver, the direct and bubble pulses, including complications from associated sea surface source reflection and sea floor to hydrophone reflections, are clipped. All waveforms are temporally aligned with the leading edge of the direct path arrival at 0 s. Amplitudes are normalized to the system clipping level.

Separately comparing explosions from far (A 13.2 km), mid (B 6.6 km), and close (C 0.9 km) ranges along the track line further illustrates how received waveforms are affected by the acoustic propagation environment (Figure 5 and 6). At close ranges, the direct path arrival (1) had high SNR, but at far ranges it was heavily attenuated due to refraction caused by a strong temperature/sound speed vertical gradient (see Wiggins et al., 2019). The following arrivals (2 – 5) were due to reflections off the seafloor and sea surface with the second arrival becoming the largest amplitude arrival at far ranges. At farther ranges than shown here, the arrivals become closer in time, and with additional reflections. With more complicated bathymetry and shallower depths, arrivals from seal bomb explosions can overlap, span longer durations, and become increasingly complex as shown with the composite signals used for the explosion detector template (Figure 2).

Navy Ordnance

Periods of military exercises were provided by the Navy with specified missile ordnances used in one of three subareas of SOAR (Table 4; Figure 1). The Naval exercise periods were concurrent with HARP recording periods presented in this report and provided examples of missile explosions for analysis and comparison to recordings of seal bomb explosions.

Two air-to-ground missile (AGM) type ordnances occurred between August 2016 and September 2017: AGM-114M Hellfire missile with ~9 kg (~20 lbs) net equivalent weight (NEW) explosive charge, and AGM-64 Maverick missile with ~27 – 36 kg (~60 – 80 lbs) NEW explosive charge.

Table 4. Naval missile ordnance use on SOAR.
All times are GMT. SOAR subareas shown in Figure 1.

Ordnance Used	Start Window	End Window	SOAR subarea
Hellfire	8/3/2016 23:00	8/4/2016 2:00	2
Hellfire	8/4/2016 2:00	8/4/2016 5:00	2
Hellfire	8/29/2016 20:00	8/30/2016 0:00	2
Hellfire	9/1/2016 4:00	9/1/2016 6:00	1
Hellfire	9/10/2016 21:00	9/11/2016 1:00	SOAR
Hellfire	9/10/2016 21:00	9/11/2016 1:00	1
Hellfire	10/25/2016 15:00	10/25/2016 19:00	2
Hellfire	10/25/2016 19:00	10/25/2016 23:00	2
Hellfire	11/30/2016 21:00	12/1/2016 1:00	2
Hellfire	12/13/2016 21:00	12/14/2016 1:00	1
Hellfire	2/1/2017 2:00	2/1/2017 5:00	1
Hellfire	2/7/2017 17:00	2/7/2017 19:45	2
Hellfire	2/7/2017 17:00	2/7/2017 21:15	1
Hellfire	2/7/2017 21:00	2/8/2017 1:15	2
Hellfire	2/8/2017 15:30	2/8/2017 19:45	2
Hellfire	3/7/2017 18:00	3/7/2017 19:30	1
Hellfire	3/7/2017 20:00	3/8/2017 0:00	2
Hellfire	3/7/2017 21:00	3/7/2017 23:30	1
Hellfire	3/8/2017 18:00	3/8/2017 19:30	1
Hellfire	3/16/2017 17:00	3/16/2017 22:00	1
Hellfire	3/20/2017 20:00	3/21/2017 0:00	2
Hellfire	3/21/2017 15:00	3/21/2017 19:00	2
Hellfire	4/19/2017 15:00	4/19/2017 19:00	1
Hellfire	4/20/2017 15:00	4/20/2017 19:00	2
Hellfire	4/25/2017 15:00	4/25/2017 18:00	2
Hellfire	4/26/2017 15:00	4/26/2017 18:00	1
Hellfire	4/26/2017 18:00	4/26/2017 22:00	1
Hellfire	5/10/2017 23:00	5/11/2017 3:00	1
Hellfire	5/18/2017 13:30	5/18/2017 18:30	1
Hellfire	5/18/2017 18:30	5/18/2017 23:30	1
Maverick	7/20/2017 22:00	7/21/2017 0:00	3
Maverick	7/20/2017 22:00	7/21/2017 0:00	3
Maverick	7/21/2017 0:00	7/21/2017 3:00	3
Maverick	7/21/2017 0:00	7/21/2017 3:00	3
Maverick	8/16/2017 21:30	8/17/2017 1:30	3
Maverick	8/16/2017 21:30	8/17/2017 1:30	3
Maverick	9/13/2017 19:00	9/13/2017 23:00	3
Maverick	9/13/2017 19:00	9/13/2017 23:00	3
Maverick	9/18/2017 20:00	9/19/2017 0:00	3
Maverick	9/18/2017 20:00	9/19/2017 0:00	3

Results

Explosion detections

From summer 2016 to spring 2019, explosions were detected at all three sites: E, H, and N (Figure 1), with site E having the fewest number of detections and site H having the greatest (Table 5). The number of detections per week decreased at sites H and N, but increased at site E over the study period (Figure 7).

Grouping the detections into one-hour bins provides details on daily and weekly patterns. For the site with the most detections and best exposure to SOAR operations area (site H) over the period 6 July 2016 to 4 October 2017 with a total of 8,376 one-hour bins, 17,545 explosions were detected in 1,656 bins, with most of the explosions occurring at night (Figures 8 and 9).

In earlier SOCAL recordings, it was this diel pattern and accompanying weekday/weekend and seasonal patterns that were found to positively correlate with squid fishery activities, suggesting seal bombs were the main source of detected explosions (Meyer-Löbbecke *et al.*, 2016; Meyer-Löbbecke *et al.*, 2017).

Table 5. Detected explosions at sites E, H, and N.
Site name, period analyzed, number of detected explosions and number of detected explosions per year in the SOCAL Range Complex from July 2016 to May 2019.

Site	Period Analyzed Days (Years)	Number of Explosion Detections	Number of Explosion Detections per year
E	730 (2.00)	438	219
H	685 (1.88)	20,365	10,832
N	985 (2.70)	11,841	4,386

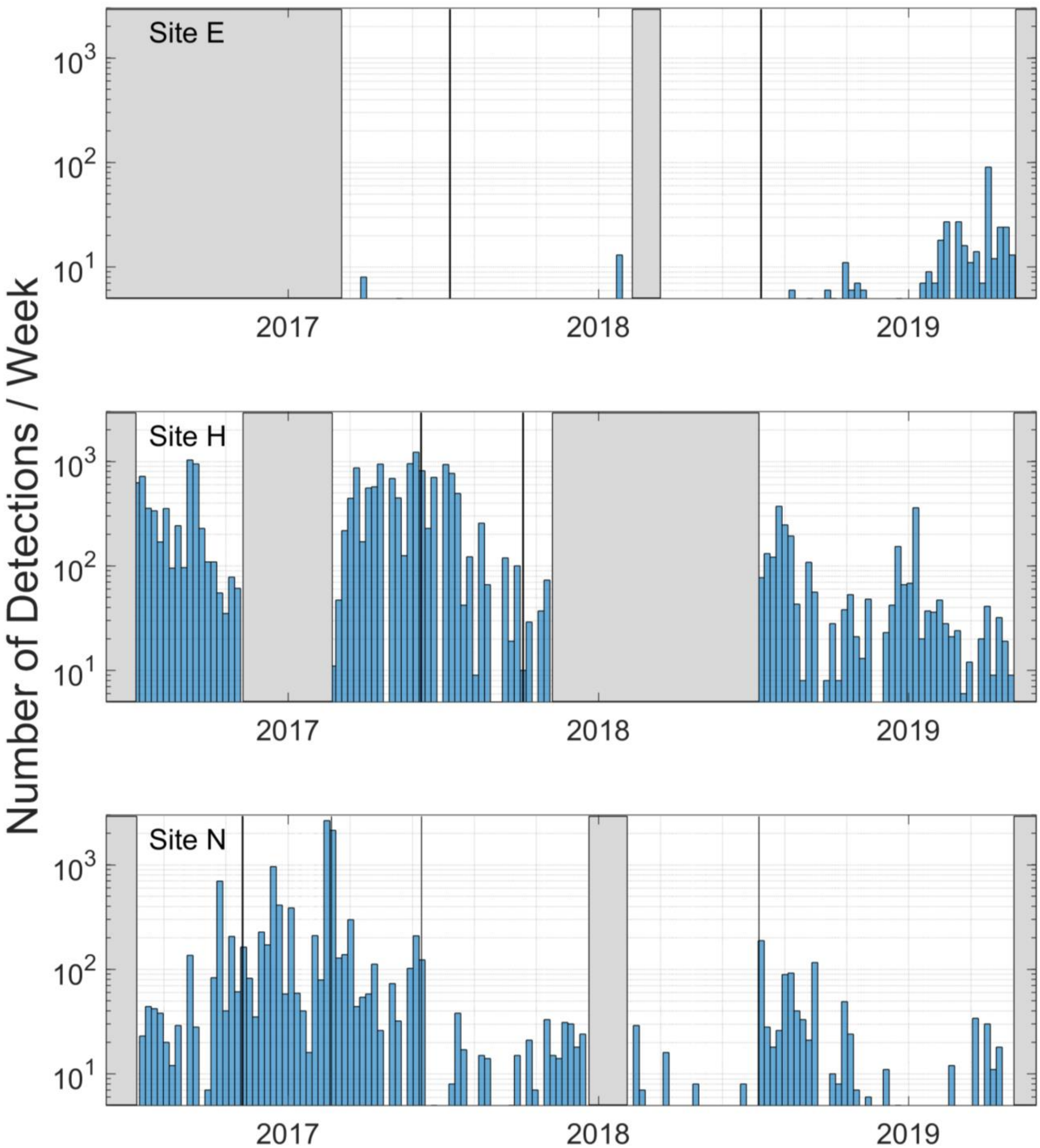

Figure 7. Explosion detections per week at sites E, H, and N.
Gray shading represents periods with no recording effort. Note vertical axis is logarithmic base-10 due to the wide range of weekly detections over the three year study period.

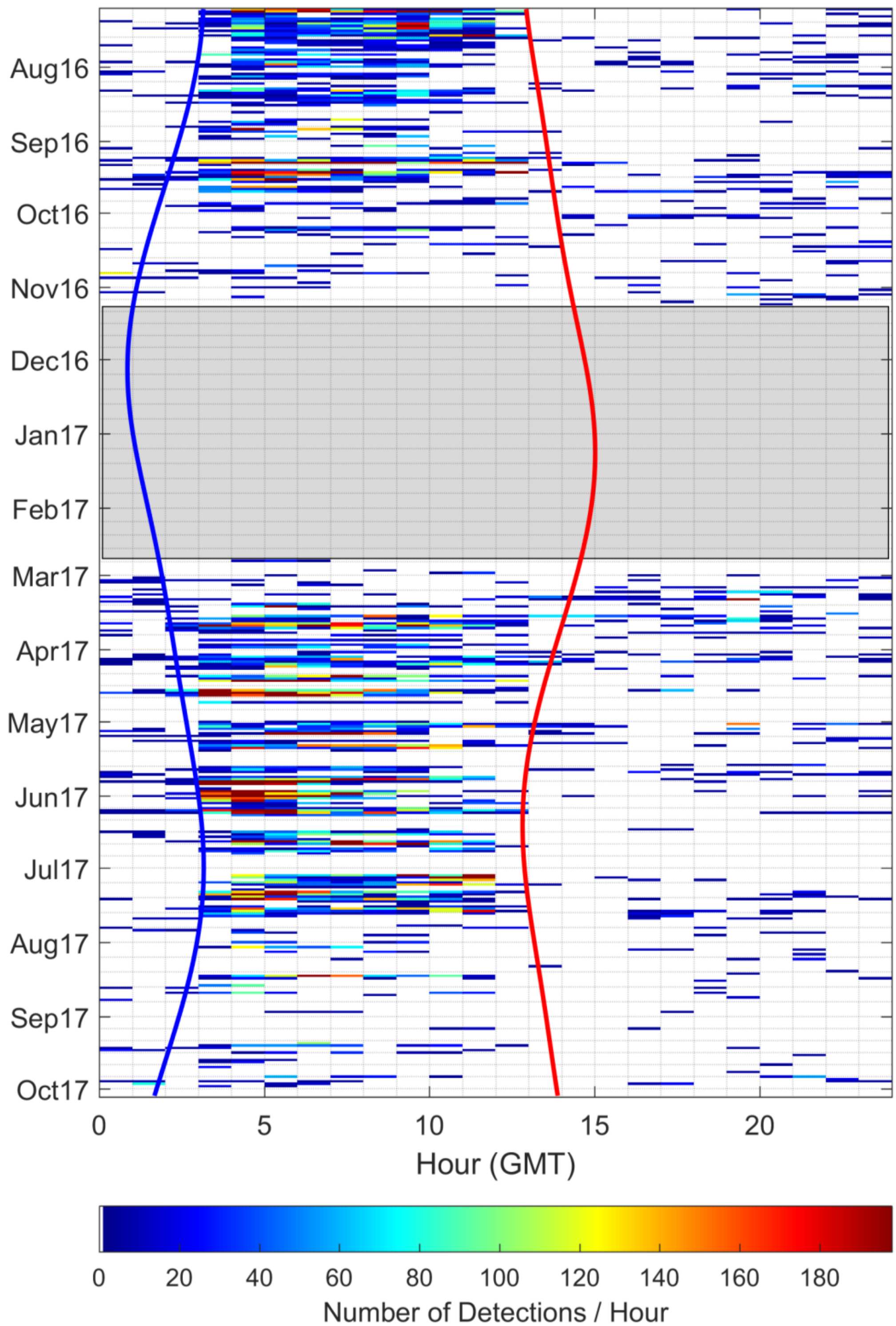

Figure 8. Site H detected explosion daily distribution.
Explosion detections in one-hour bins from 6 July 2016 to 4 October 2017. Bin color represents the number of explosions in each bin per the colorbar. The blue curve indicates sunset and the red curve indicates sunrise. Gray region had no recording effort.

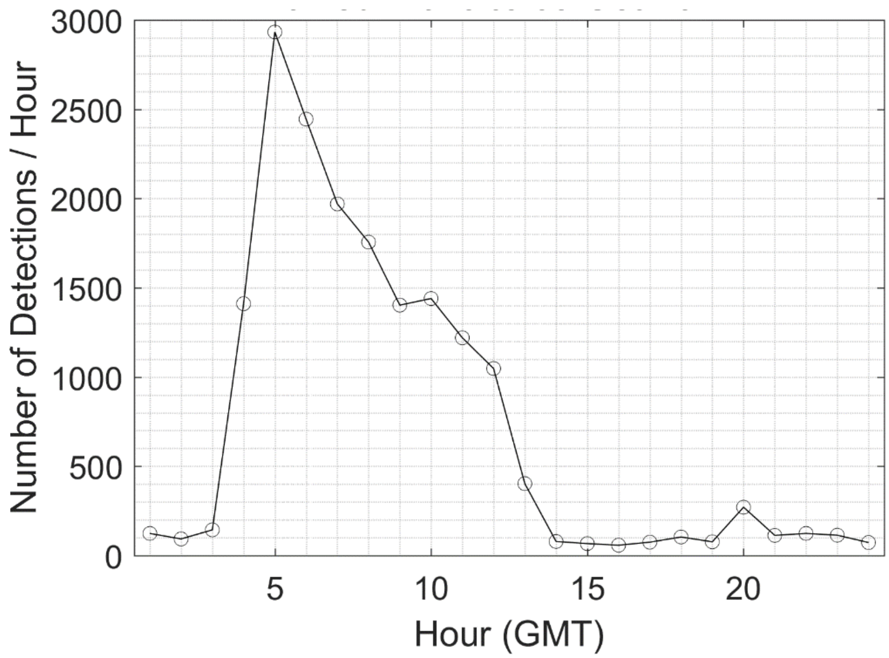

Figure 9. Site H total number of explosion detections per hour, displayed on a diel cycle. *Total number of explosion detections in each hour from 6 July 2016 to 4 October 2017. Sunset is ~0300 – 0400 GMT and sunrise is ~1300 – 1400 GMT (see Figure 8).*

Navy missile exercises

Most naval exercises were conducted during daylight hours, opposite of typical seal bomb activity. Periods from one hour before to one hour after Naval missile ordnance exercises on SOAR (Table 4) and the number of explosion detections in one-hour bins concurrent with these periods were plotted relative to the time of day (Figure 10). In addition, the number of explosion detections during these exercises was low. Out of the 8,376 one-hour bins evaluated, 186 were during Naval exercises of which 24 bins had a total of 170 detections, or about 1% of the total number of detected explosions over the July 2016 to October 2017 period.

Manual analysis of the recordings revealed that of the 40 Naval exercise periods (Table 4), all but four contained noticeable explosions at site H, although not all of these explosions were detected by the automatic detector and analyst review process. Mid-Frequency Active Sonar (MFAS) signals often were present during the ordnance exercise periods. During other periods, which were not defined by the Navy to include ordnance use, but in which MFAS was present, only few explosions were observed.

Explosions during the defined Naval ordnance exercises were less frequent and had lower sound pressure level at site N because its location was farther from the SOAR range than site H, in addition to the bathymetric complexities of the acoustic propagation path between SOAR and site N (Figure 1).

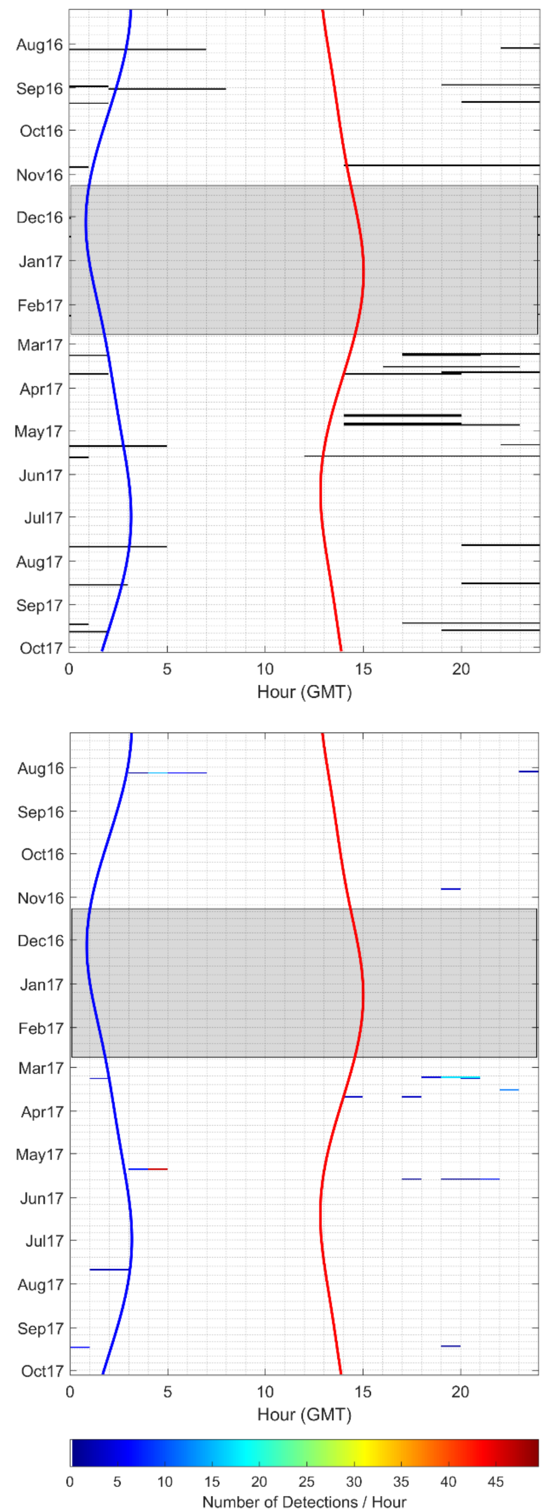

Figure 10. Site H Navy ordnance activity on SOAR.
(Top) Navy missile exercise periods 1 h before to 1 h after those in Table 4 in one-hour bins from 6 July 2016 to 4 October 2017. (Bottom) explosion detections during Navy missile exercises. Colors represent number of detections during one-hour bins. The blue curve indicates sunset and the red curve indicates sunrise. Gray region had no recording effort.

Navy ordnance waveforms

Both types of missiles, AGM-114M Hellfire and AGM-64 Maverick, were detected at site H during defined Naval exercise operations in SOAR with the smaller charge Hellfire explosions prior to July 2017 and the larger charge Maverick explosions from July to September 2017 (Table 4; Figure 10).

Long duration (1.5 s) waveforms from these two types of missiles show multipath arrivals similar to seal bombs; however, in short duration (110 ms) waveforms, the multiple bubble pulses as recorded during the seal bomb experiment were not apparent, suggesting missile explosions were not beneath the sea surface at depth (Figures 11 and 12).

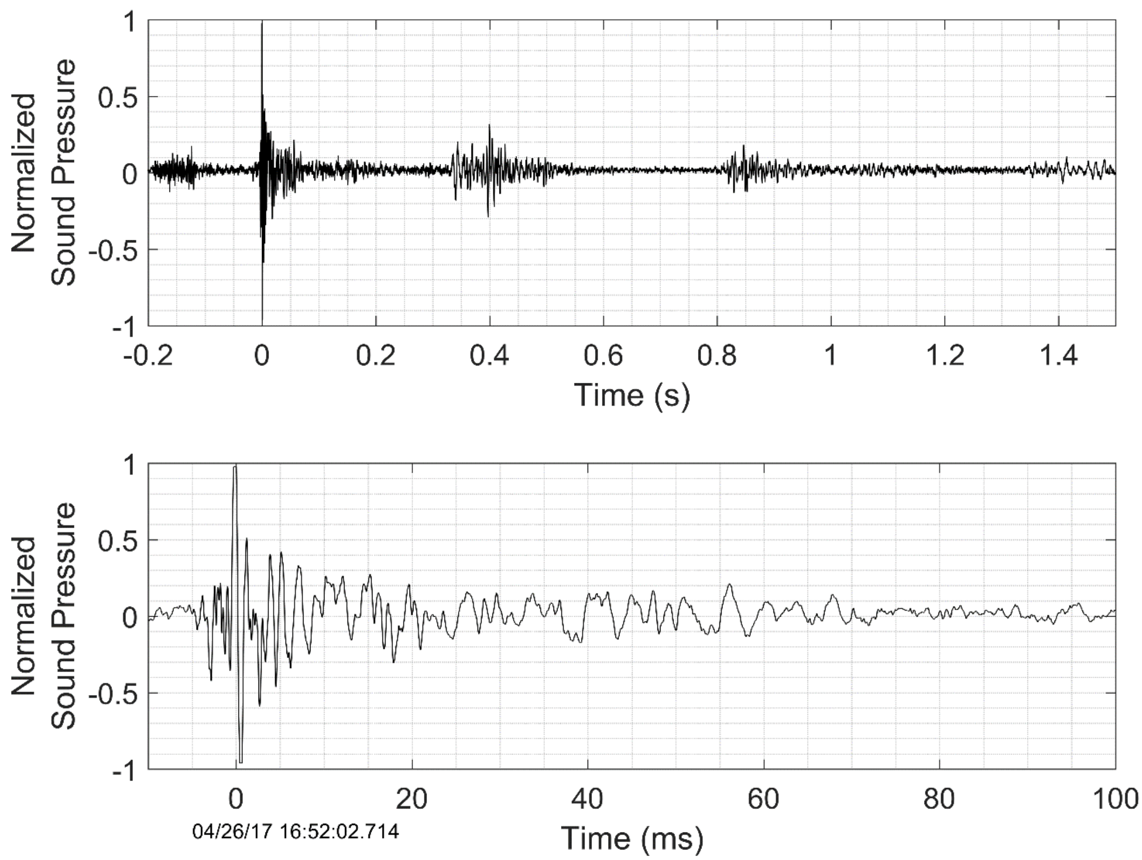

Figure 11. AGM-114M Hellfire normalized sound pressure waveforms.
Explosion recorded at site H during exercise on SOAR subarea 1. (Top) Long (1.5 s) time series shows 5 arrivals with the second arrival at or near the clip level (±1). (Bottom) Short (110 ms) time series of second arrival shows signal distortion and elongation, but no apparent bubble pulses. Waveforms are time aligned with maximum peak pressure at 0 s.

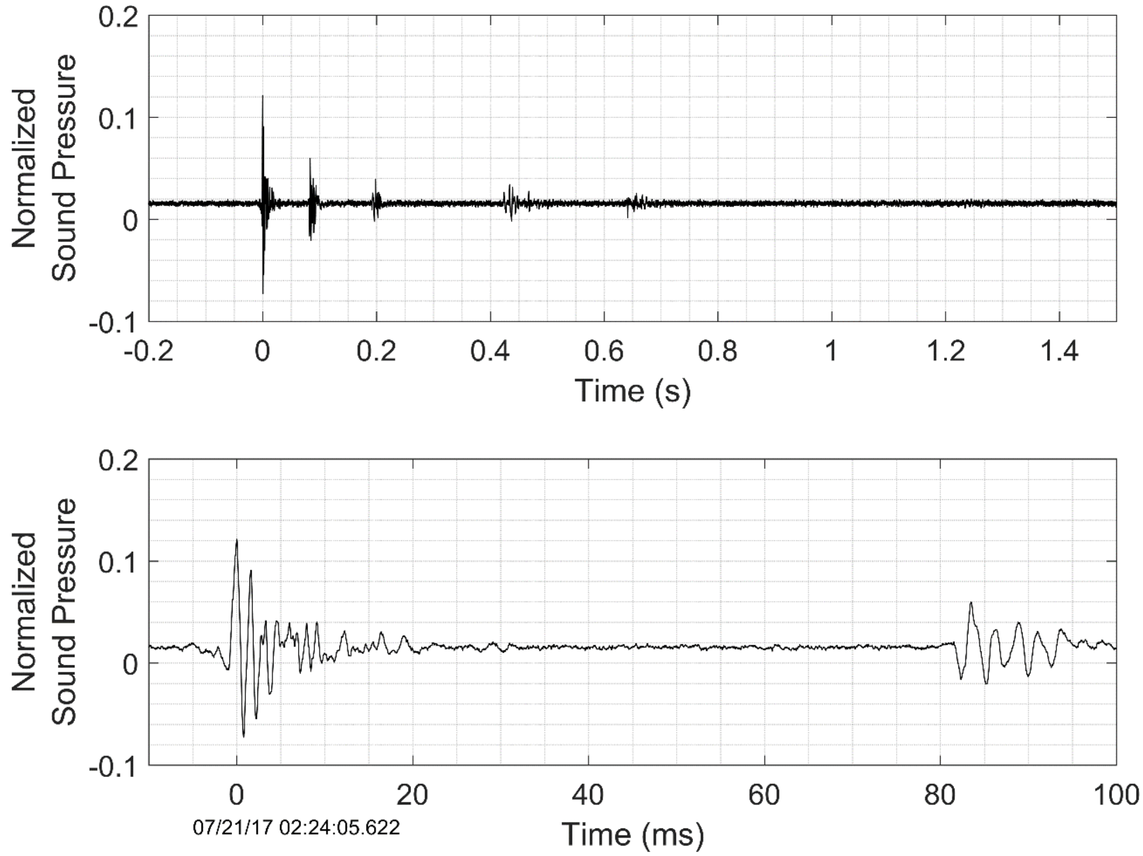

Figure 12. AGM-64 Maverick normalized sound pressure waveforms.
Explosion recorded at site H during exercise on SOAR subarea 3. (Top) Long (1.5 s) time series shows 5 arrivals. (Bottom) Short (110 ms) time series of first arrival shows no apparent bubble pulses. Waveforms are time aligned with maximum peak pressure at 0 s.

While the seal bomb experiment was conducted in shallower waters (San Diego Trough) than the Naval exercises on SOAR (San Nicolas Basin), the time delays of the multipath arrivals can still be used on the missile explosions to qualitatively compare source to receiver ranges such that shorter delays indicate farther ranges (Figure 4). Using this approach for the two examples above suggests that the Maverick missile explosion was at greater distance from the recorder than the Hellfire missile. Also, the received sound pressure was higher for the smaller explosive charge Hellfire missile than for the larger charge Maverick missile, further supporting that for this example, the Maverick explosion was at a greater range than the Hellfire explosion. As shown for the seal bomb experiment, at far ranges, the direct arrival signal becomes weak with low SNR (Figures 4, 5A, and 6A) due to ray path bending (refraction) caused by strong sound speed gradients found during the summer and fall offshore Southern California. At these ranges, the first seafloor-sea surface reflection (SSR) often shows the best SNR and appears as the first arrival instead of the direct path arrival. In the example above, the closer Hellfire explosion first arrival was the direct path arrival and the first SSR was the second arrival; whereas, the farther Maverick explosion first arrival appears to be the first SSR.

At even farther ranges than the example Maverick explosion, multipath arrival delays of the SSR's become shorter and the arrivals can overlap, distorting the waveform even further. Approximately 79 km southeast of site H was site N, which also recorded the same example Maverick explosion (Figure 13). The explosion signal arrived at site H ~26 s before site N, suggesting that it traveled about 39 km farther to site N than H, which is consistent with ranges for explosions occurring in the northwest corner of SOAR subarea 3, about 20 km from site H and 59 km from site N. The difference in peak-to-peak received sound pressures at the two sites is about 14 dB, which is ~6 dB more than spherical spreading would predict given straight propagation paths, but extra loss may be appropriate given the longer paths associated with multiple seafloor-sea surface reflections, losses at the seafloor during those reflections, and bathymetric obstructions between site N and SOAR subarea 3 (Figure 1).

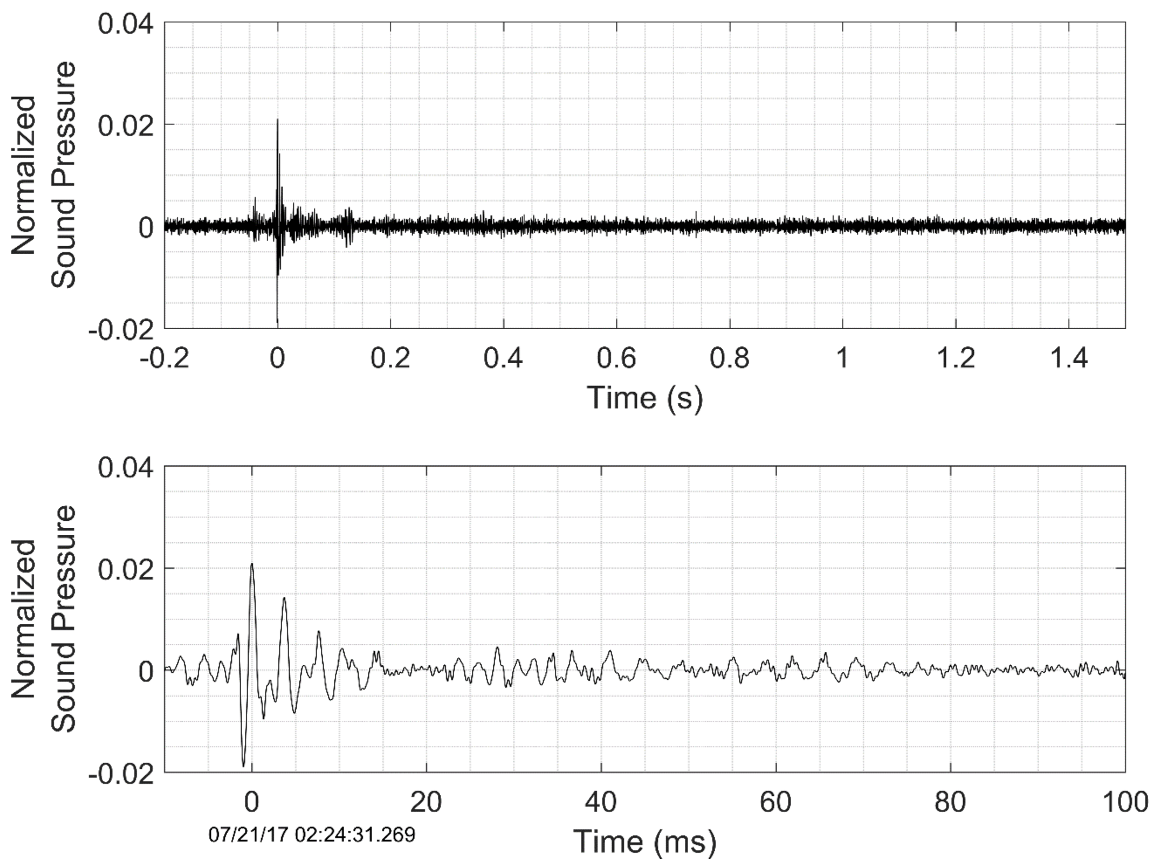

Figure 13. AGM-64 Maverick normalized sound pressure waveforms.
Same explosion recorded at site H (Figure 14) also recorded at site N during exercise on SOAR subarea 3. (Top) Long (1.5 s) time series shows short delay multipath arrivals. (Bottom) Short (110 ms) time series highest sound pressure arrival shows no apparent bubble pulses. Note the relatively low sound pressure of the signal required that a bandpass filter (200 – 2,000 Hz) be applied to improve SNR.

Seal Bomb and Navy ordnance waveform comparison

Both seal bomb and Naval missile explosions are more likely to originate at long distances (>10 km) from the recorder. Both types will exhibit multipath arrivals dependent on the bathymetry along the sound propagation path. As noted above, delay times of multipath arrivals can be used to estimate range to the explosion, especially when acoustic propagation is modeled properly; however, the long (1.5 s) multipath arrival waveforms displayed above inherently provide little information for distinguishing between the two types of explosions. On the other hand, short (~100 ms) waveforms of individual arrivals from the Naval examples and the seal bomb experiment show differences between the two explosion types with seal bombs consisting of a primary pulse followed by multiple bubble pulses and Naval explosions typically containing only a single pulse. This difference is attributed to seal bombs exploding a few meters underneath the sea surface and Navy missiles likely exploding at or very near the sea surface.

The Hellfire and Maverick missiles from site H and the seal bomb experiment explosions (detailed above) were high quality examples of recordings with good SNR and unobstructed propagation path waveforms. In practice, typical explosion recordings have more complex waveforms than these examples, mostly due to complexity and variability in acoustic propagation path. For example, the waveform from the direct path mid-water column seal bomb recording (Figure 3) does not include the seafloor reflection that is incurred by having a hydrophone near the seafloor as with typical HARP recordings (Figure 6B). Furthermore, objects near or between the explosion source and hydrophone receiver, such as ships and bathymetric features, can distort the waveform, reducing source identifying features. Appendices A – C show additional examples of explosions recorded by seafloor HARPs during Naval exercises using Hellfire missiles, Maverick missiles, and periods without Navy acoustic activity with presumed seal bomb sources, respectively. If the sources of 12 examples in the Appendices were not known, sorting them into explosion type based solely on their waveform would be difficult, even by a well-trained analyst. Additional information or techniques are needed to better sort these types of signals.

Conclusions

Since 2009, long-term monitoring of underwater sounds in the SOCAL Range Complex revealed large numbers of explosive events, with the majority of these sounds correlated with commercial fishery use of seal bomb deterrent devices. Navy-supplied periods of missile ordnance use on SOAR shows smaller numbers of explosions with different signal characteristics than those measured in a controlled experiment using seal bombs.

The characteristic difference of seal bombs with multiple bubble pulses following a primary pulse versus only a primary pulse for Naval missile explosions suggested a straightforward approach for explosion type differentiation. However, further investigation into the nature of these impulsive signals revealed that in practice, acoustic propagation can greatly alter waveforms such that signal type differentiation is made more difficult.

Future work on separating explosion type could include the use of machine learning to separate different signal types though clustering techniques, propagation modeling of impulsive sounds including bathymetry and temporally varying sound speed profiles, and better understanding of Naval ordnance use such as precise explosion locations, quantities, and event times.

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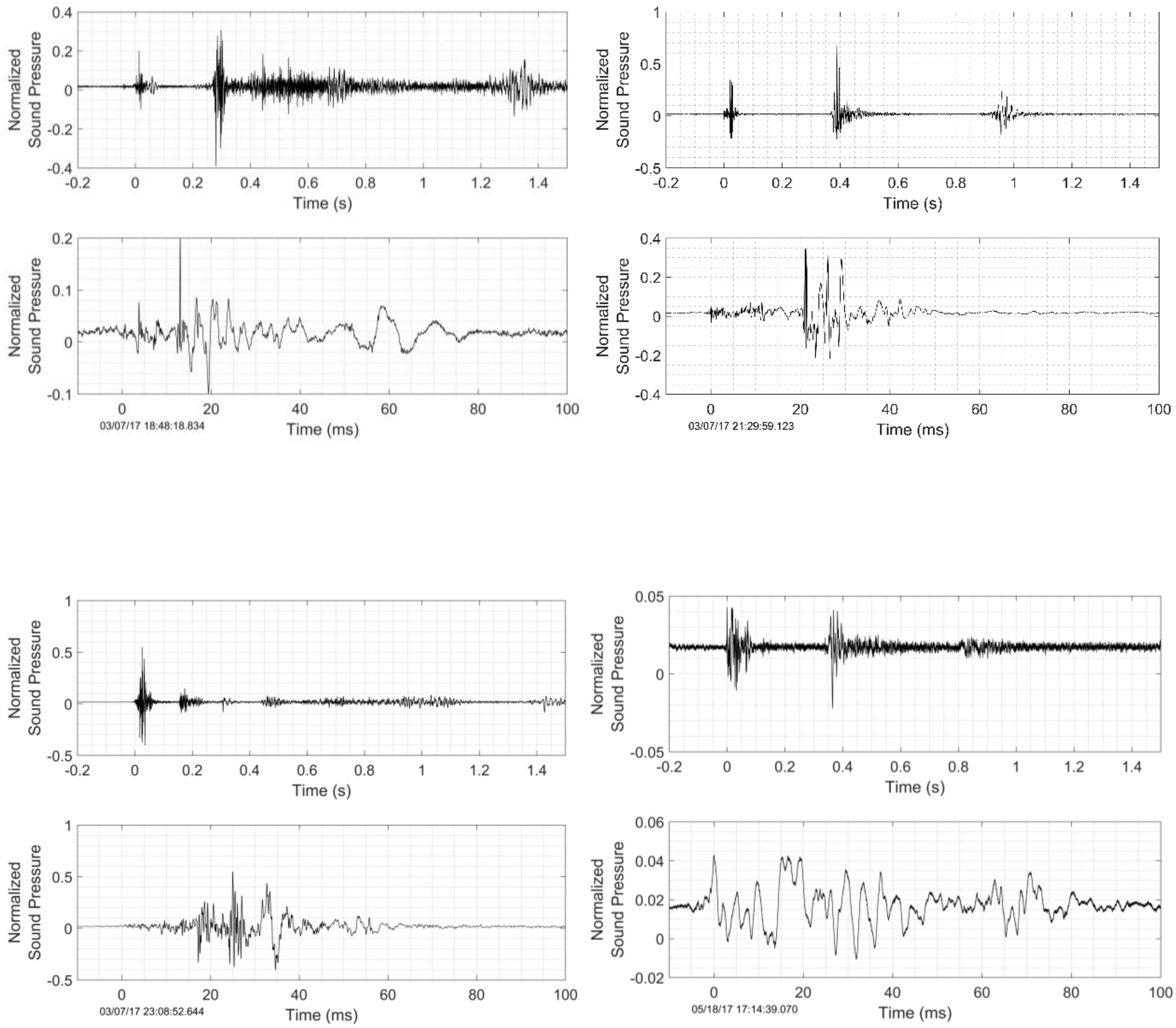
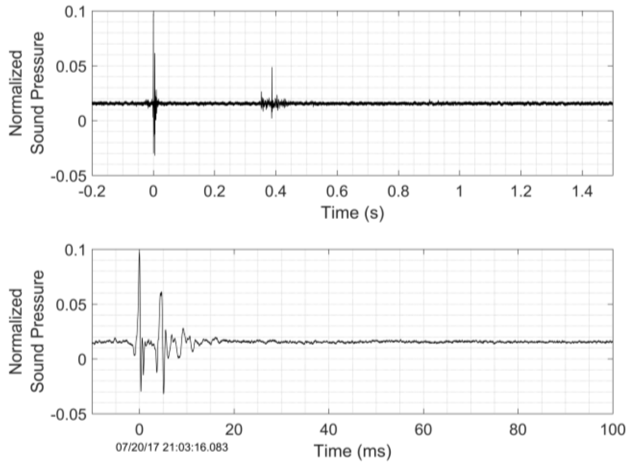
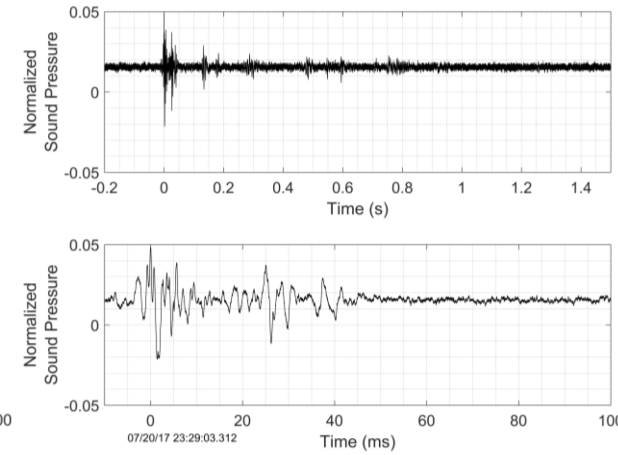
Appendix

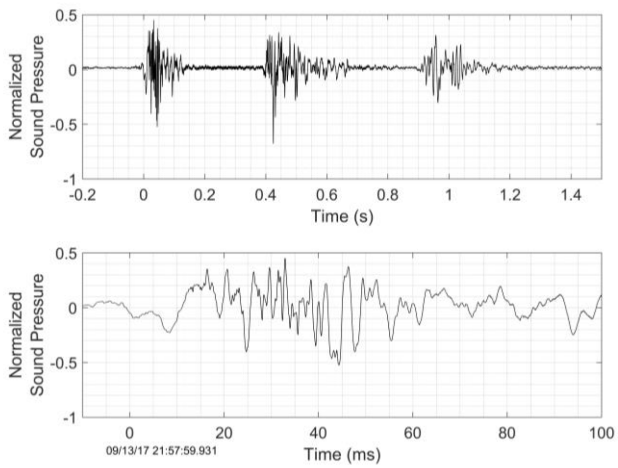
A. AGM-114M Hellfire normalized sound pressure waveforms recorded at site H.

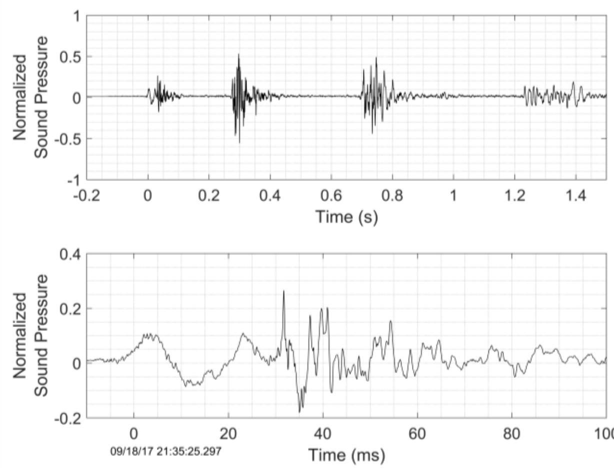


B. AGM-64 Maverick normalized sound pressure waveforms recorded at site H.









C. Seal bomb normalize sound pressure waveforms recorded at site H.