Final Report

Noise Source Level and Propagation Measurement of Underwater Detonation Training at the Silver Strand Training Complex, Naval Base Coronado, Coronado, CA

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14. ABSTRACT
On 13 and 14 May 2014, a team from the University of Washington conducted a set of measurements of the underwater sound generated by explosive charges as part of a naval training event conducted in the Silver Strand Training Complex off San Diego. Environmental measurements to support the acoustic research included measurements of sound speed versus depth showing a thermocline, and sea surface directional wave measurements. This team was joined by personnel from U.S. Pacific Fleet and HDR Inc., who conducted simultaneous observations of marine mammals.
Two underwater explosive charges (each 10 pounds [4.54 kg], C-4 explosive) were detonated each day, separated temporally by about 3 seconds, and spatially by about 450 m. These underwater detonations are referred to here and elsewhere as UNDETs. The resulting underwater sound was measured simultaneously by instrumentation aboard two vessels at differing locations. This arrangement provided a measurement range span of approximately 400 to 1,700 m, designed to obtain the key sound metrics of peak pressure and sound exposure level (SEL).
A mitigation zone is defined by a radius of 700 yards (640 m) centered at the UNDET source detonation site. One UNDET event was delayed owing to the presence of a California sea lion in the mitigation zone prior to detonation; however, operations resumed after a mandatory 30-min wait period, after which the animal was confirmed to be at a safe distance from the charge location.
Key finding emerging from this study are as follows:
1) Measurements of peak (absolute value) acoustic pressure ranged from a minimum of 209 dB re 1μPa recorded at 1,651 m to a maximum of 222 dB re 1 μPa recorded at 358 m.
2) Measurements of sound exposure level (SEL) ranged from a minimum of 184 dB re 1 μPa^2-s recorded at 1,651 m to a maximum of 191 dB re 1 μPa^2-s recorded at 358 m.
3) Both peak pressure and SEL depend on range from source and the above results are in reasonable agreement with

levels predicted by Soloway and Dahl 2014b.
4) Measurements of peak pressure as a function of depth at fixed range show levels varying by up to 4 dB over a 6 m depth span. This dependence on depth is likely associated with the observed thermocline, an effect that will undergo further study.
5) In terms of frequency content, it was found that 90 percent of the UNDET energy is contained in the frequency range from 50 to 2,500 Hz.
The May 2014 San Diego sound measurement trial measurements make an important contribution to the catalogue of measurements of underwater sound from small-charge underwater explosions made in shallow water, with this particular contribution also influenced by a thermocline. Future work on this dataset will include the analysis of the effects of the thermocline on peak pressure and SEL.

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EXECUTIVE SUMMARY

On 13 and 14 May 2014, a team from the University of Washington conducted a set of measurements of the underwater sound generated by explosive charges as part of a naval training event conducted in the Silver Strand Training Complex off San Diego. Environmental measurements to support the acoustic research included measurements of sound speed versus depth showing a thermocline, and sea surface directional wave measurements. This team was joined by personnel from Commander, U.S. Pacific Fleet and HDR Inc., who conducted simultaneous observations of marine mammals

Two underwater explosive charges (each 10 pounds [4.54 kg], C-4 explosive) were detonated each day, separated temporally by about 3 seconds, and spatially by about 450 m. These underwater detonations are referred to here and elsewhere as UNDETs. The resulting underwater sound was measured simultaneously by instrumentation aboard two vessels at differing locations. This arrangement provided a measurement range span of approximately 400 to 1,700 m, designed to obtain the key sound metrics of peak pressure and sound exposure level (SEL).

A mitigation zone is defined by a radius of 700 yards (640 m) centered at the UNDET source detonation site. One UNDET event was delayed owing to the presence of a California sea lion in the mitigation zone prior to detonation; however, operations resumed after a mandatory 30-min wait period, after which the animal was confirmed to be at a safe distance from the charge location.

Key finding emerging from this study are as follows:

1. Measurements of peak (absolute value) acoustic pressure ranged from a minimum of 209 dB re 1µPa recorded at 1,651 m to a maximum of 222 dB re 1 µPa recorded at 358 m.
2. Measurements of sound exposure level (SEL) ranged from a minimum of 184 dB re 1 µPa^{2}s recorded at 1,651 m to a maximum of 191 dB re 1 µPa^{2}s recorded at 358 m.
3. Both peak pressure and SEL depend on range from source and the above results are in reasonable agreement with levels predicted by Soloway and Dahl 2014b.
4. Measurements of peak pressure as a function of depth at fixed range show levels varying by up to 4 dB over a 6 m depth span. This dependence on depth is likely associated with the observed thermocline, an effect that will undergo further study.
5. In terms of frequency content, it was found that 90 percent of the UNDET energy is contained in the frequency range from 50 to 2,500 Hz.

The May 2014 San Diego sound measurement trial measurements make an important contribution to the catalogue of measurements of underwater sound from small-charge underwater explosions made in shallow water, with this particular contribution also influenced by a thermocline. Future work on this dataset will include the analysis of the effects of the thermocline on peak pressure and SEL.

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Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

a_o	charge radius of explosive with spherical geometry
C-4	composition 4 explosive
c	water sound speed (m/s)
dB	decibel(s) upper cutoff frequency for type II functional hearing group
E	energy flux density (Watt/m^2)
ESD	energy spectral density
f	frequency (Hz)
f_L	lower bound of frequency window containing 90% of the UNDET energy (Hz)
f_U	upper bound of frequency window containing 90% of the UNDET energy (Hz)
HOBO	water-depth data-logger
Hz	Hertz
kg	kilogram(s)
MINEX	Mine Neutralization Exercise
MMO	marine mammal observer
m	meter(s)
NAVFAC	Naval Facilities Engineering Command
P_{peak}	peak pressure (Pa)
Pa	Pascal(s)
R	measurement range in meter(s)
rms	root mean square
SEL	sound exposure level (dB re 1 $\mu Pa^2 s$)
SOCAL	Southern California
T	integration period for sound exposure level (s)
TNT	Trinitrotoluene explosive
UNDET	underwater detonation
USLM	underwater sound-level meter
VLA	vertical line array
W	charge weight (kg)
Z	detonation depth (m)
Z_o	hydrostatic depth (m)
ρ	material density (kg/m^3)
$\sigma_{P_{peak}}$	standard deviation of the peak pressure
σ_R	standard deviation of range
τ	bubble pulse period (s)

1. INTRODUCTION

Naval activities such as ordnance disposal, demolition, and a variety of training exercises can involve detonation of small explosive charges in shallow water (herein, underwater detonations [UNDETs]). On 13 and 14 May 2014, a team from the University of Washington, along with experienced field biologists from the Navy and HDR Inc., conducted a set of measurements of the underwater sound generated by sub-surface explosions during a naval training exercise. The measurement site was located in the near-shore waters of the Navy's Silver Strand Training Complex portion of the Southern California (SOCAL) Range Complex, off San Diego, California. SOCAL marine mammal observations were conducted simultaneously with the sound measurements.

The goals of this work are to measure and quantify the underwater sound produced during this UNDET training exercise; these measurements will in turn provide accurate ground-truth data to improve the modeling of such sound for assessing potential impacts on marine life. To meet these goals, underwater sound measurements of the UNDET events are presented with a focus on peak pressures, sound exposure levels (SEL), and how these metrics compare with empirical models. A summary of marine mammal observations during the UNDET events is also included.

A similar experiment was conducted on 11 September 2012 off the coast of Virginia Beach, Virginia (Mine Neutralization Exercise Sound Measurement Trial conducted off the coast of Virginia Beach, Virginia on 11 September 2012 [MINEX]). Results of this experiment are summarized in a report by Soloway and Dahl (2014a), and for the purposes of consistency across Navy training ranges, portions of that report are also presented here.

This report is organized into five sections. **Section 2** presents a brief overview of underwater explosion research, including semi-empirical equations for peak pressure from explosions, the calculation of the SEL, and the calculation of the bubble pulse period. **Section 3** presents a description of the UNDET events involved in this study, acoustic measurement and marine mammal monitoring methods. **Section 4** contains results, relevant discussion and application of these results (in a theoretical context) in terms of Navy criteria for acoustic effects on marine mammals. A summary of the work is in **Section 5**.

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2. BACKGROUND

Portions of the following section originally appeared in the report, “Mine Neutralization Exercise (MINEX) Sound Measurement Trial” Soloway and Dahl 2014a.

Chapman (Chapman 1985) provided a review and discussion of the general characteristics of underwater explosions. During the detonation of an underwater charge, the explosive material is transformed into a small sphere of gas at high temperature and pressure. As a result of the pressure differential between the gas sphere and the hydrostatic pressure in the water, a shock wave is radiated into the water. Following detonation, the gas sphere begins to expand outward resulting in a pressure tail behind the shockwave that exponentially decreases in magnitude. As the bubble expands, the pressure inside begins to decrease. When the pressure inside the bubble reaches the hydrostatic pressure of the water, the inertia of the moving gas causes the bubble to continue to expand. This continued expansion of the gas results in the pressure within the gas sphere falling below the hydrostatic pressure. Eventually the gas sphere ceases to expand. With the pressure inside the gas sphere now below the hydrostatic pressure, the bubble begins to contract thereby increasing the internal pressure. Similar to the expansion process, the inertia of the gas bubble causes the pressure within the sphere to increase past the hydrostatic pressure. This process of expansion and contraction, collectively referred to as the bubble pulse, continues until the energy within the gas sphere has been radiated into the water. A notional pressure history of the explosive waveform as it relates to the size of the gas sphere is shown in **Figure 1**. The time between the shock arrival, P_{peak}, and the peak pressure of the bubble pulse P_1, is referred to as the bubble pulse period, τ.

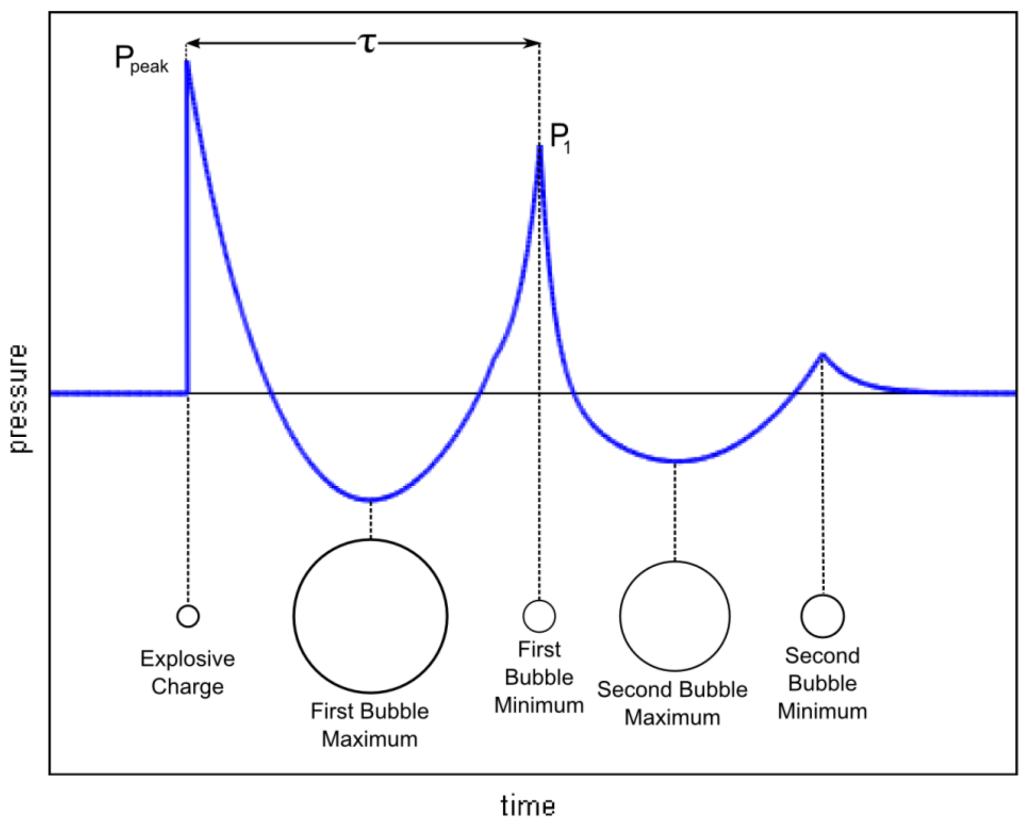

Figure 1. Notional pressure-time history for an underwater explosion with the size of the gas sphere is shown in relation to the explosion waveform (Figure adapted from Gaspin et al. 1979).

2.1 Peak Pressure

Peak pressure is a value indicative of the highest amplitude of a given sound and is a commonly used metric to quantify underwater noise. Using experimental measurements of UNDETs collected during and after World War II, a semi-empirical equation was developed for predicting the peak pressure from underwater explosions as a function of range (R) and charge weight (W) to the one-third power, or $R/W^{1/3}$ (herein referred to as scaled range). Historically, the term "semi-empirical" has been used to describe this peak pressure equation owing to the origins of this parameter in Kirkwood-Bethe propagation theory (Kirkwood and Wood 1968) and geometric similarity (Cole 1948). The peak pressure (Arons 1954) is given by

$$P_{peak} = 52.4\times10^{6}\left(\frac{R}{W^{1/3}}\right)^{-1.13} \tag{1}$$

where P_{peak} is the peak pressure in Pascal (Pa), R the measurement range in meters (m), and W is the charge weight in kilograms (kg) of 2,4,6-Trinitrotoluene (TNT). It is important to note that this equation was developed for TNT, due to its historical and continued use as the standard high explosive, and assumes a spherical TNT charge of density 1,520 kg/m^3 (Cole 1948). Using this equation, the peak pressure for other high explosives can be predicted through the use of TNT-equivalent weight. While originally formulated for spherical charges, the equation has been successfully employed for a wide array of charge geometries (Wakeley 1977; Chapman 1985; Murata et al. 2002; Santos et al. 2010).

Note that as applied in environmental statuary regulations established by the National Marine Fisheries Service, peak pressure is expressed in dB re 1 µPa. Therefore this conversion is carried out by $20\log_{10}(P_{peak})$ + 120 dB, where P_{peak} (in Pa) is taken directly from Equation (1).

While a full derivation of the Kirkwood-Bethe theory is outside the scope of this report, it has been shown that the pressure in the water decays exponentially with time, and is dependent only on the explosive material and the ratio of the range to the charge radius, R/a_o (Cole 1948). The peak-pressure equation assumes a spherical charge geometry where the charge weight is given by $W=\rho\frac{4}{3}\pi a_o^3$ where ρ denotes the density of the explosive material. With this in mind, the ratio R/a_o can be reformulated as

$$\frac{R}{a_o}=\frac{R}{W^{1/3}}\times\left(\rho\frac{4}{3}\pi\right)^{1/3} \tag{2}$$

In the peak-pressure equation $\left(\rho\frac{4}{3}\pi\right)^{1/3}$ is absorbed into the 52.4×10^6 factor. Additionally, the Kirkwood-Bethe theory supports the $R^{-1.13}$ decay of the peak pressure with range, which is a somewhat greater decay rate than the R^{-1} decay expected for spherical spreading of an acoustic wave (Cole 1948).

2.2 Bubble Pulse Period

Following the development of the peak-pressure equations, an analogous equation for the bubble pulse period as a function of charge weight and explosion depth was developed. Specifically, this equation predicts the time delay between the arrival of the shock wave and the first bubble pulse peak. Although originally formulated using measurements of deep underwater explosions (Slifko 1967), this equation has previously been applied successfully to shallow charges (Chapman 1985). The bubble pulse period is given by

$$\tau = 2.11 \times W^{1/3} Z_o^{-5/6} \tag{3}$$

where τ is the bubble pulse period in seconds (s) (**Figure 1**), and Z_o is the hydrostatic depth in meters (given by Z_o= Z+10.1 m where Z is the detonation depth measured from the water surface). Unlike the peak pressure equation, which is a function of scaled range, the bubble pulse period is a function of charge weight and detonation depth, and should be consistent for measurements collected simultaneously at multiple ranges.

2.3 Sound Exposure Level and Energy Flux Density

Sound exposure level is a measure of the sound energy accumulated over time, and is defined as the time integral of the squared acoustic pressure:

$$\mathrm{SEL} = 10 \log_{10}\left(\int_0^T P^2(t)dt\right) \tag{4}$$

Where SEL is in units of dB referenced to 1 $\mu Pa^2 s$. SEL has become a useful metric to assess cumulative noise exposure as it gives an indication of the total acoustic energy received by an organism and allows for the comparison of sounds with varying durations (Southall et al. 2009).

A common approach to calculating the SEL is the 90 percent energy approach. Using this methodology, the integration period, T, is the sample interval that includes 90 percent of the energy of the explosion's waveform. An example of this calculation is illustrated in **Figure 2**. When calculating the SEL in this report, the 90 percent energy approach is used exclusively.

Closely related to SEL is the energy flux density, E, which is defined as the time integral of the squared acoustic pressure divided by the density of the medium, ρ, and the sound speed in the water, c;

$$E = \frac{1}{\rho\, c} \int_0^T P^2(t)dt \tag{5}$$

where E is in units of $\mathrm{Watts/m^2}$, ρ is in units of $\mathrm{kg/m^3}$, c is in units of m/s, and P has units of Pa. Similar to the peak pressure, a semi-empirical equation has been developed for computing the energy flux density of the explosive shockwave as a function of R and W (Cole 1948):

$$E \propto W^{1/3}\left(\frac{R}{W^{1/3}}\right)^{-2.12} \tag{6}$$

Given the similarity of Equations (4) and (5), an empirical equation for SEL has been developed as a function of R and W using Equation (6) (Soloway and Dahl 2014b)

$$\mathrm{SEL} = 6.14\ \log_{10}\left(W^{1/3}\left(\frac{R}{W^{1/3}}\right)^{-2.12}\right) + 219 \tag{7}$$

where SEL is expressed in dB re 1 $\mu Pa^2 s$. Additional information on Equation (7) can be found in Soloway and Dahl 2014b.

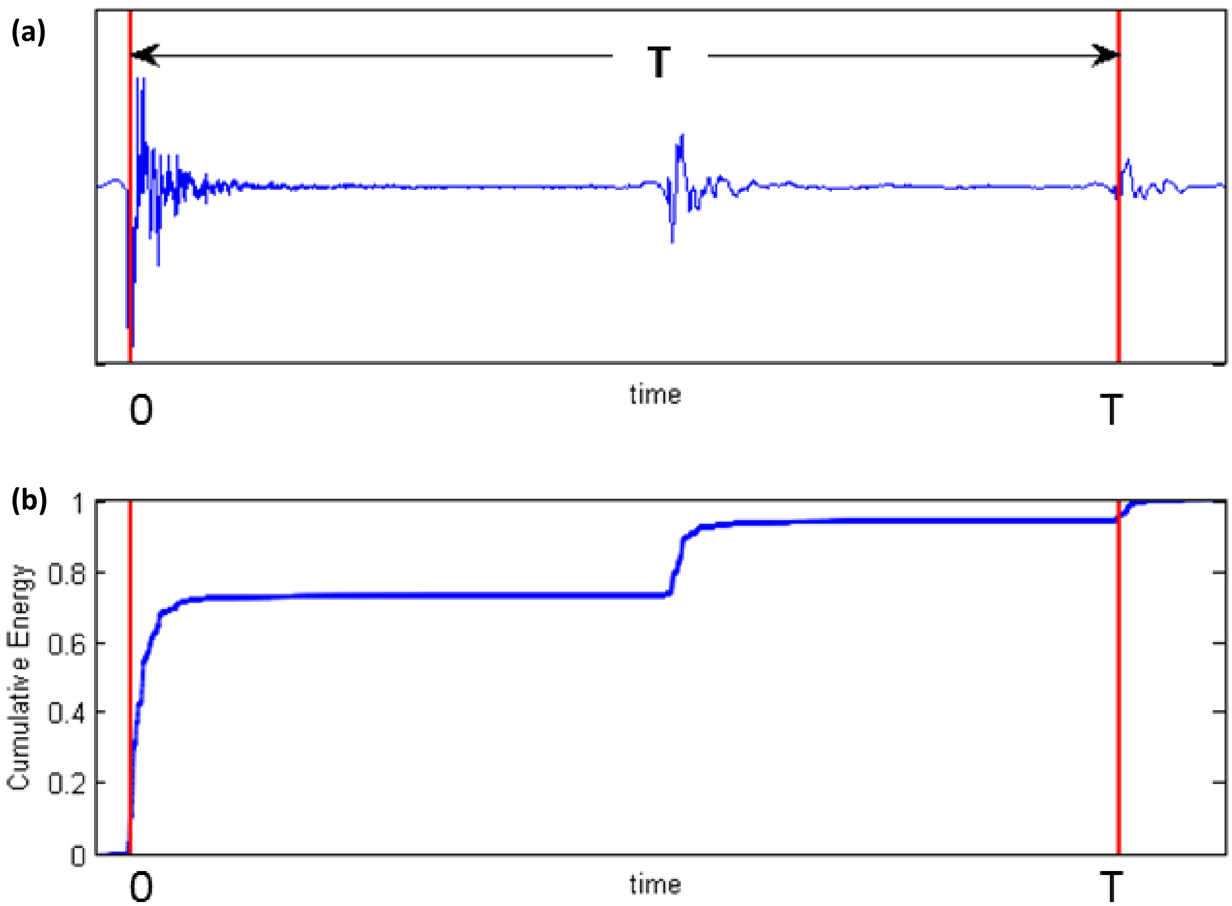

Figure 2. (a) Time history of an explosion and (b) the resulting time history of its cumulative energy. Red lines indicated the start and end times of the window containing 90 percent of the waveform energy. In the above (b) the first pulse at time 0 is from the direct water arrival, while the other two pulses are a results of the bubble pulses. Data shown here are from Soloway and Dahl 2014a.

3. MEASUREMENTS

3.1 UNDET Test Description and Acoustic Measurements

Measurements were conducted on 13 and 14 May 2014, at a site located two (2) kilometers from the beach in the Silver Strand Training Complex part of the U.S. Navy's SOCAL Range Complex. On each day, two UNDET events occurred in rapid succession, with a delay of approximately 3 seconds between detonations.

Acoustic measurements associated with these UNDETs were collected from two study vessels; the *F/V Alexes* and *El Gato Dos,* both chartered sport-fishing boats of length approximately 11 meters. *Alexes* was designated as the near vessel, positioned closer to the detonations (400–800 meters), and the *El Gato Dos* was designated as the far vessel, positioned 1,300–1,700 meters from the detonations. The *Alexes* was positioned approximately at the 22-meter isobath (notional depth from nautical charts) on both days, and the exact water depth was determined to be 23.7 meters using the depth sounder on *Alexes*. The *El Gato Dos* was also positioned on the same 22-meter isobath on 13 May, and on 14 May, it was positioned farther offshore on the 26-meter isobath. The detonation sites and vessel locations for 13 and 14 May are shown in **Figure 3** and **Figure 4**, respectively.

All four explosive charges detonated underwater consisted of 4.54 kg of composition 4 (C-4) explosive. The TNT-equivalence of C-4 is 1.34, thus each charge had an explosive equivalence of 6.08 kg of TNT. The delay between detonations on 14 May is readily seen in the data measured from the *El Gato Dos* using one of the acoustic measurement systems (the underwater sound-level meter [USLM]) that will be described shortly (**Figure 5**). This example clearly shows the time delay between the two UNDETs recorded that day with a similar relation applying to the measurements on 13 May.

Acoustic measurement systems deployed from the near vessel *Alexes* consisted of a vertical line array (VLA), and a Loggerhead autonomous hydrophone recording device. The VLA elements consisted of nine hydrophones (ITC 1032), spaced 0.7 m apart, with receiving voltage sensitivity ranging from -204 to -208 dB re V/µPa depending on the position of the hydrophone. Data from the VLA were recorded on a multi-channel coherent data acquisition system (Astro-Med DASH-20) with each channel sampled at 62,500 samples per second. The autonomous Loggerhead system consisted of a self-contained data acquisition and storage system (Loggerhead Instruments DSG) and a single hydrophone (HTI-96-min) recording at 100,000 samples per second with a receiving voltage sensitivity of -220 dB re V/µPa. Additionally, a 3-channel geophone system was attached to the bottom of the VLA. This instrument was not part of the formal measurement plan and data from the geophone system are not included in this report, as they require further analysis and interpretation. The long-term goal of the geophone system is to examine acoustic particle velocity associated with UNDETs. Finally, the depths of the hydrophones were monitored continually using two HOBO® data loggers.

Acoustic measurement systems deployed from the far vessel the *El Gato Dos* consisted of an identical Loggerhead device, and a second single-hydrophone device that was assembled at the University of Washington, referred to here as the USLM. It consisted of a single HTI-96-minute hydrophone recording 50,000 samples per second, with receiving voltage sensitivity of -205 dB re V/µPa. The vertical measurement geometries associated with the *Alexes* and *El Gato Dos* are shown in **Figure 6**.

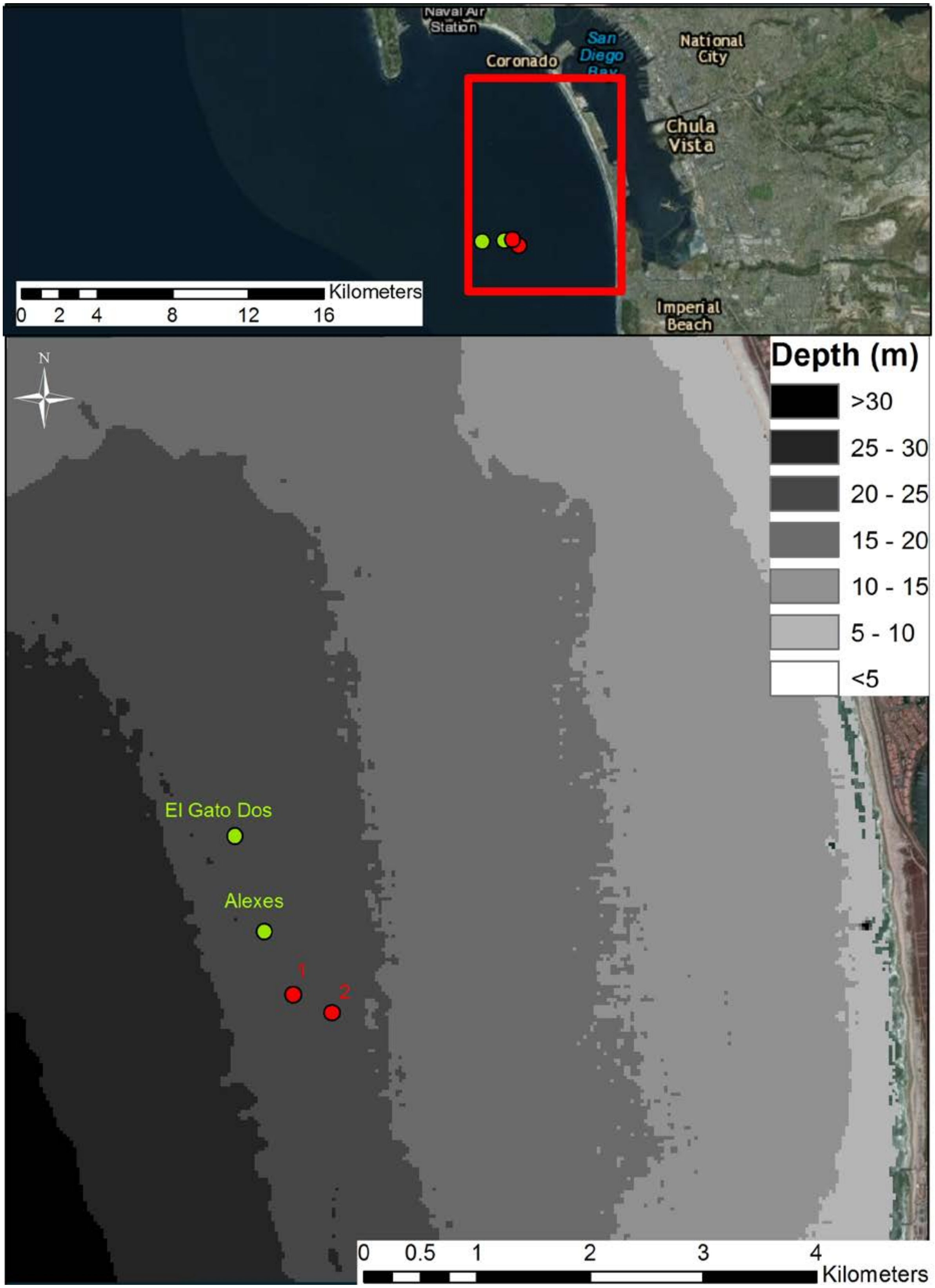

Figure 3. Map of test site for 13 May 2014, with the locations of *Alexes* and *El Gato Dos* (green, labeled) in relation to the two UNDETs (red, numbered). A large-scale view is shown in the top panel.

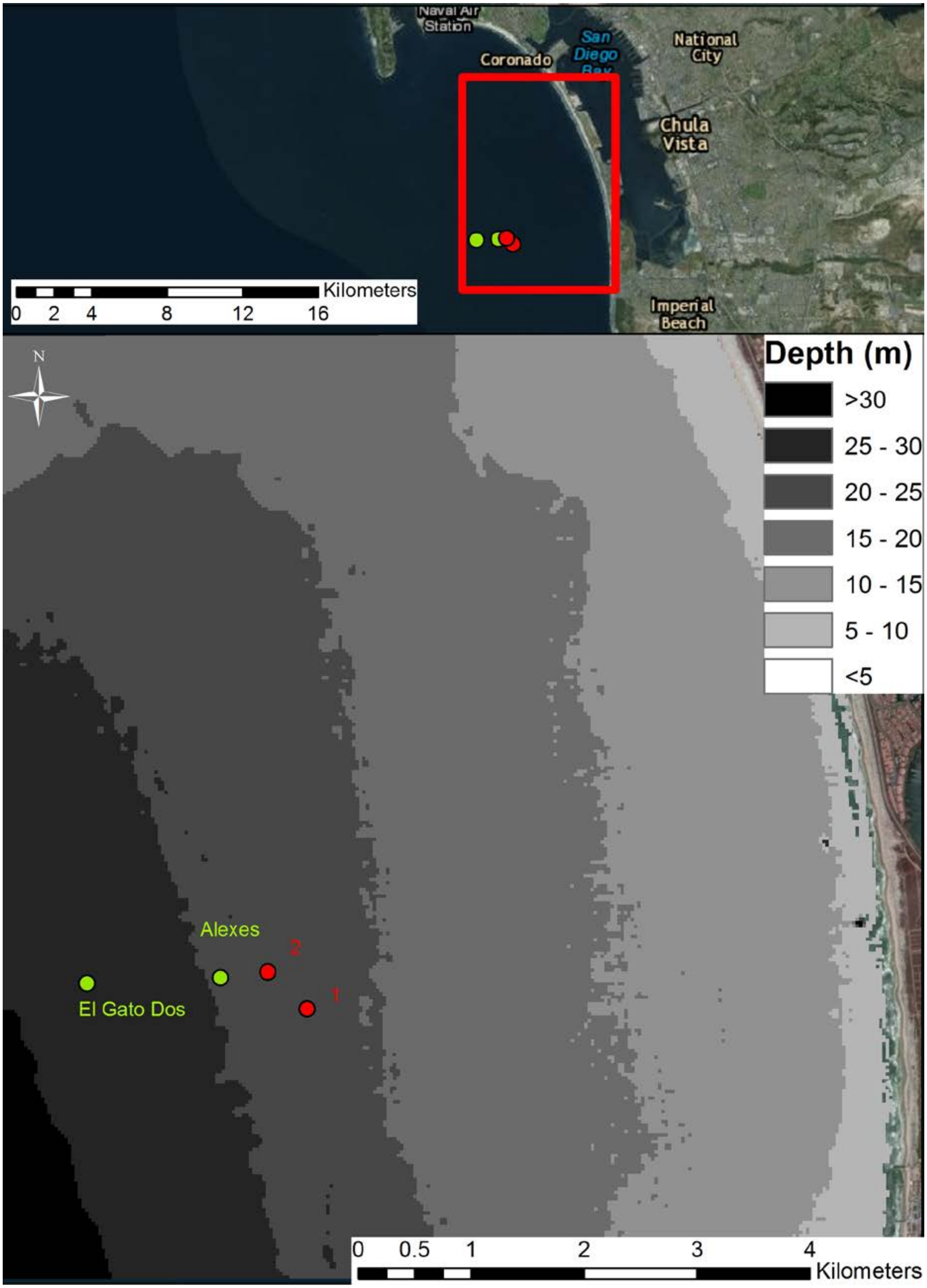

Figure 4. Map of test site for 14 May 2014, with the locations of *Alexes* and *El Gato Dos* (green, labeled) in relation to the two UNDETs (red, numbered). A large-scale view is shown in the top panel.

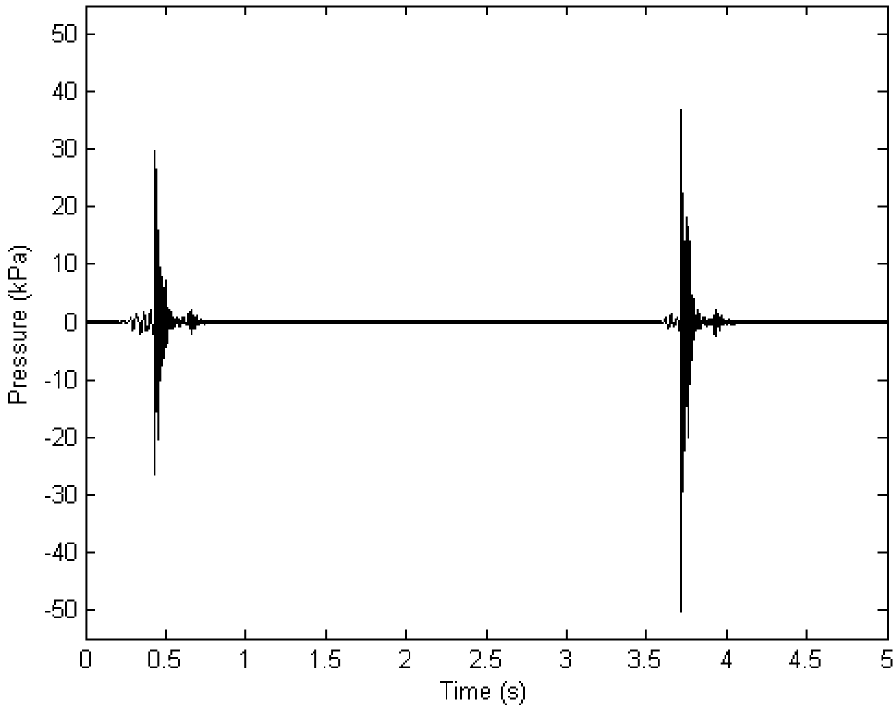

Figure 5. Time series of the two detonations on 14 May, separated by approximately 3 seconds, as measured by the USLM hydrophone system on the *El Gato Dos.*

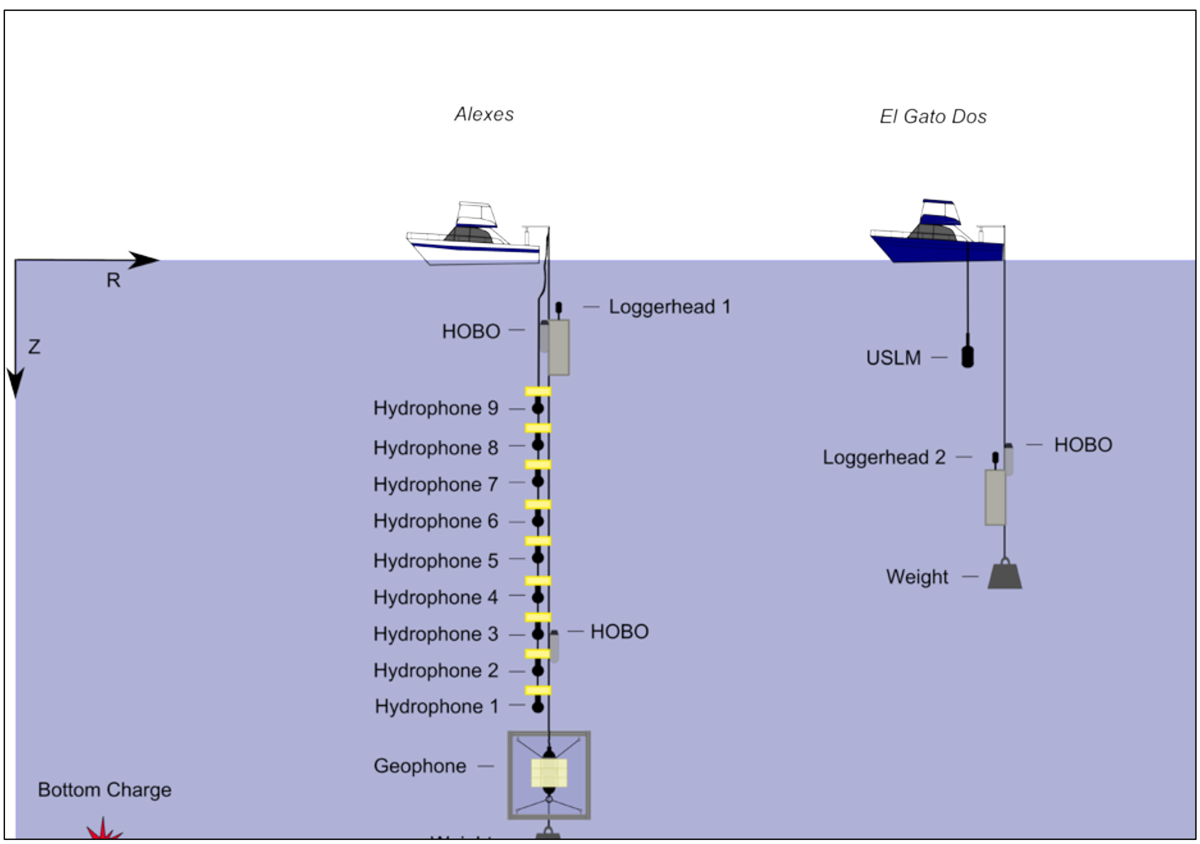

Figure 6. Measurement instrument geometries for the *Alexes* and *El Gato Dos*.

3.2 Environmental Conditions and Measurements

The seabed in the immediate vicinity of the measurements is composed of unconsolidated, sandy sediments (Merkel & Associates, Inc. 2013). Profiles of sound speed versus depth in the water column were recorded from *Alexes* using a YSI CastAway Conductivity, Temperature, and Depth instrument, which computes the sound-speed profile from direct measurements of conductivity (a surrogate for salinity) and temperature as a function of pressure (a surrogate for depth). The water column at the time of these measurements was characterized by a thermocline between the surface and approximately 15 m, resulting in a sound speed that varied from 1,510 m/s near the sea surface to 1,492 m/s near the seabed, with sound speed in the bottom 10 meters of the water column being approximately constant (**Figure 7**).

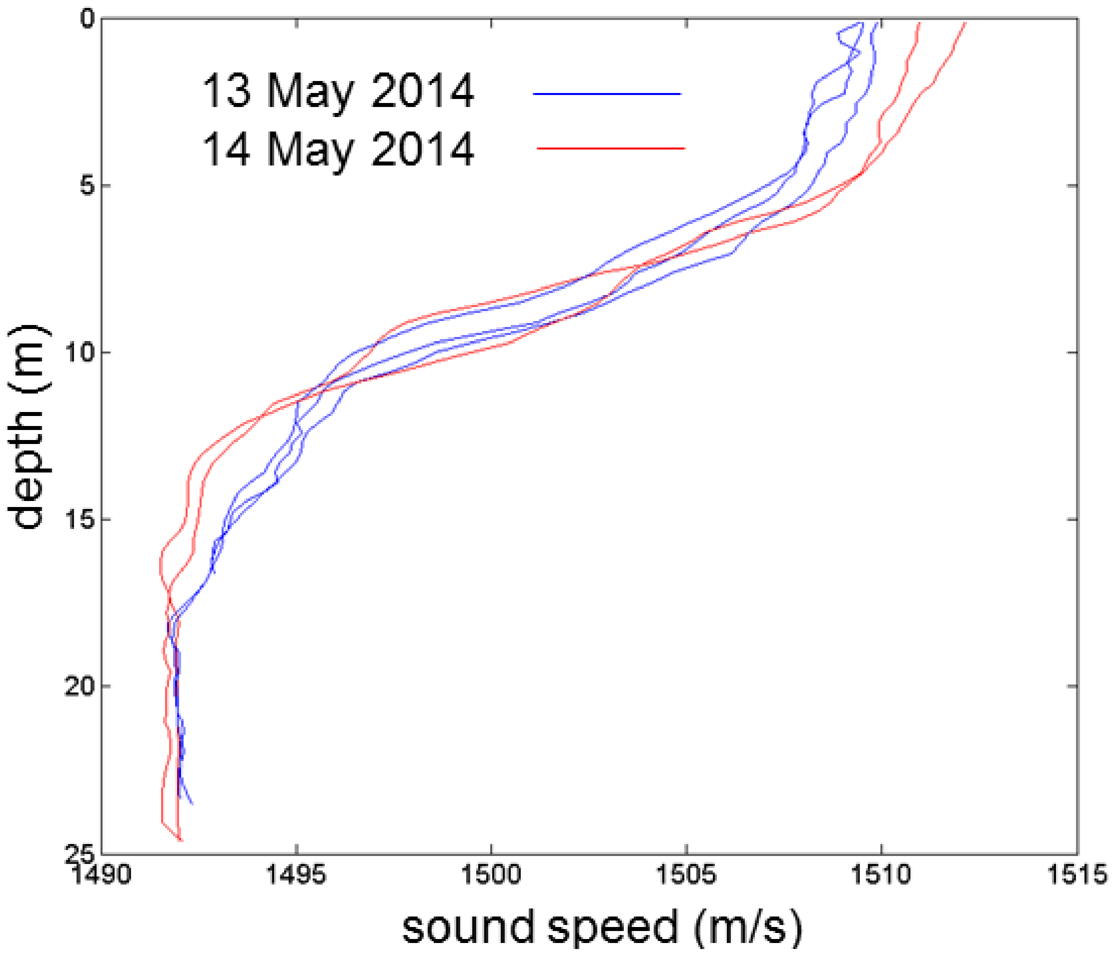

Figure 7. Sound-speed profiles collected from the *Alexes* 13 and 14 May, corresponding to the times of the acoustic measurements on these days.

Sea surface conditions were measured using a Datawell Directional Wave Buoy deployed each day from the *El Gato Dos*. Both days were generally characterized by relatively calm conditions, during which the root mean square (RMS) wave heights were 0.19 meter (13 May) and 0.16 meter (14 May). Directional wave measurements indicated that the dominant (low frequency) wave field originated from an offshore direction, approximately from the W to WNW. The sea-surface wave measurements are summarized in **Figure 8** and **Figure 9,** respectively, and may be used in conjunction with more refined acoustic modeling efforts in the future.

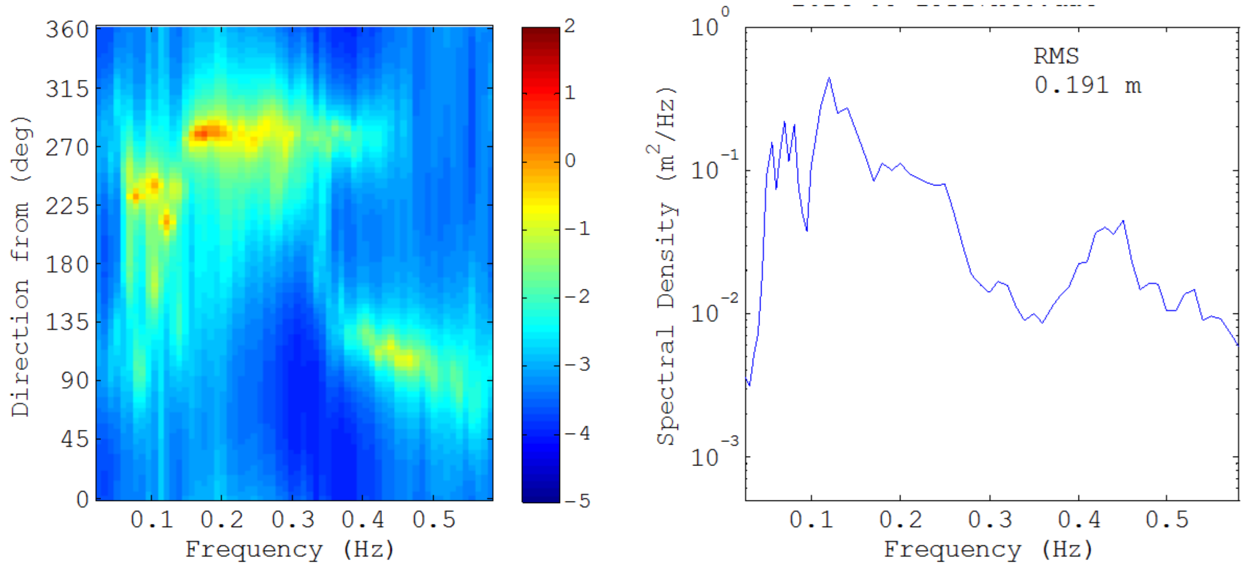

Figure 8. Surface wave conditions during the 13 May 13 tests (at 1030 local time). Left panel: directional wave spectrum showing the peak in the spectrum at 0.15–0.30 Hz originating from 270°. Right panel: directionally-averaged spectral density. The RMS wave height is 0.19 meters.

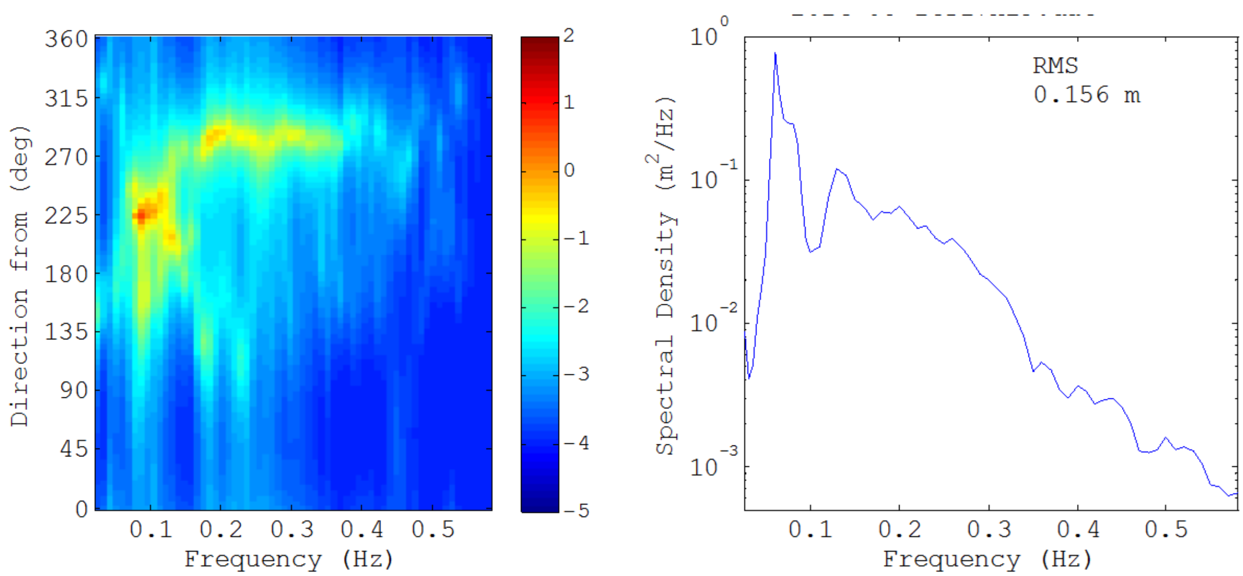

Figure 9. Surface wave conditions in effect during the 14 May tests (at 10:30 local time): (left side) directional wave spectrum showing the peak in the spectrum at frequency of approximately 0.1 Hz originating from 250°, (right side) directionally-averaged spectral density. The RMS wave height is 0.16 meter.

3.3 Marine Mammal Monitoring

Marine mammal observers (MMOs) were positioned on each acoustic monitoring vessel and conducted visual monitoring for marine mammals and sea turtles during all four UNDET events on 13 and 14 May. The MMOs monitored a 640-meter mitigation zone around the detonation locations to ensure that no marine mammals or sea turtles were present in this zone 30 minutes before each UNDET event (**Figure 10** and **Figure 11**). Four California sea lions *(Zalophus californianus)* were observed over the course of both days, one on 13 May and three on 14 May (**Table 1**). The UNDET events on 14 May were delayed by the presence of a California sea lion in the mitigation zone prior to detonation (**Figure 10**). Operations resumed after a mandatory 30-minute wait period, after which the animal was confirmed to be at a safe distance from the charge location. Two gray whale *(Eschrichtius robustus)* sightings were made, one on the 13th and another on the 14th. It is unknown if these were two different animals, or the same animal both days. Given the very nearshore location, and the relatively small-sized individual observed during each sighting, it is suspected that the sightings represented a single juvenile gray whale both days. The gray whale sightings were approximately 5-7 km north of the UNDET locations. Common dolphins, most likely long-beaked common dolphins (*Delphinus capensis*), were also sighted both days near Point Loma and Coronado. A small sub-pod of common dolphins transited the mitigation zone on 14 May, but this event occurred two hours prior to the UNDET that day.

Table 1: Marine mammal sightings in conjunction with UNDET monitoring, 13-14 May off San Diego, California.

Date	Time	Common Name	Scientific Name	Number of Animals
5/13/2014	0904	Gray whale	*Eschrichtius robustus*	1
5/13/2014	0920	California sea lion	*Zalophus californianus*	1
5/13/2014	1110	Unidentified common dolphin	*Delphinus spp*.	26
5/14/2014	0835	Gray whale	*Eschrichtius robustus*	1
5/14/2014	0903	Unidentified common dolphin†	*Delphinus spp*.	32
5/14/2014	0930	California sea lion	*Zalophus californianus*	2
5/14/2014	1030	California sea lion*	*Zalophus californianus*	1
5/14/2014	11:32	Unidentified common dolphin	*Delphinus spp.*	15

† Sighting occurred in the mitigation zone but nearly 2 hours before the UNDET events occurred

*Animal initially sighted in mitigation zone, operations delayed by 30 mins

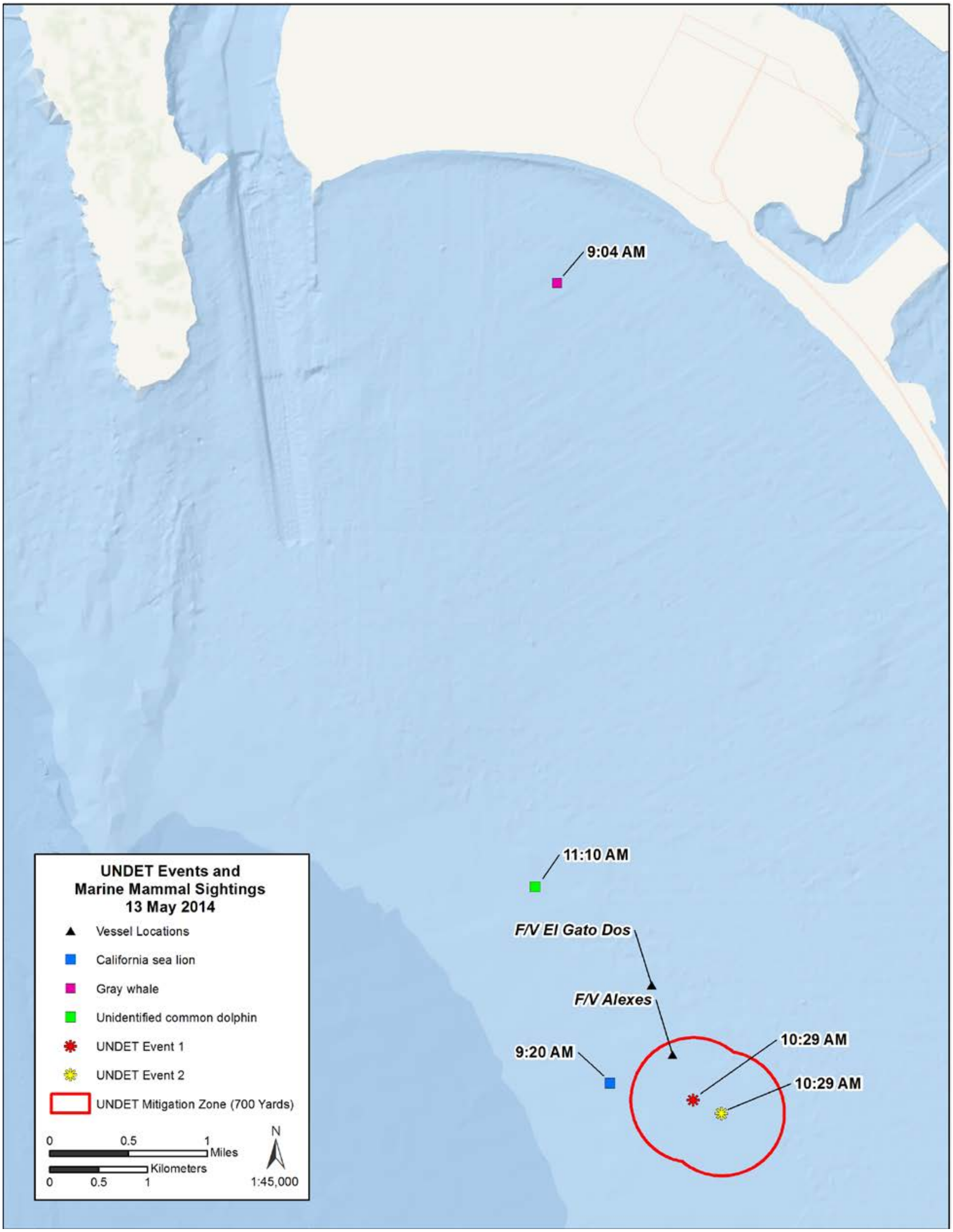

Figure 10. Summary of marine mammal observations on 13 May. A 600-meter mitigation zone (red line) was maintained around the detonation locations to ensure no marine mammals or sea turtles were present in this zone 30 minutes before each UNDET event.

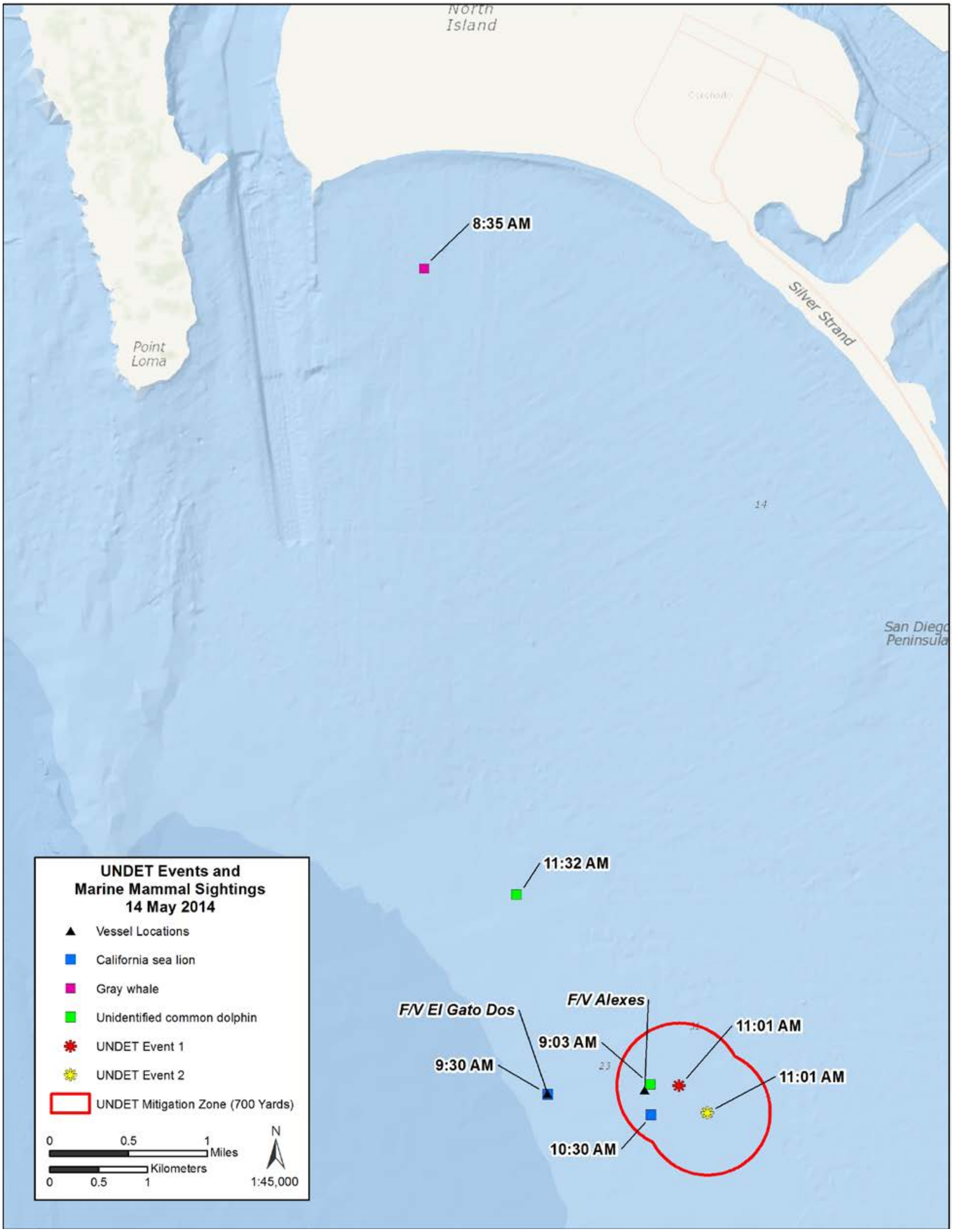

Figure 11. Summary of marine mammal observations on 14 May. A 600-meter mitigation zone (red line) was maintained around the detonation locations to ensure no marine mammals or sea turtles were present in this zone 30 minutes before each UNDET event.

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4. RESULTS AND DISCUSSION

Results and discussion relating to the measurements of energy spectral density (**Section 4.1**), peak pressure (**Section 4.2**), Experiment and Measurement Error (**Section 4.3**), bubble pulse period (**Section 4.4**) and SEL (**Section 4.5**) will be presented with comparisons to predicted values discussed in Section 2.

Note that the peak pressure and SEL (**Table 2**) from the VLA are currently not available for measurements made 13 May, because of signal interference recorded on the VLA associated with the generator on the vessel Alexes. This effect was reduced on 14 May by using an AC to DC power inverter (Kisae Technology) connected to the engine battery that was purchased on the evening of 13 May. The peak pressures from the VLA on 14 May were recovered and are presented in this report; however, additional work needs to be done to recover the SEL. The 13 May data may be recoverable; however, not before this report is finalized. The temporary absence of the peak pressure and SEL on 13 May and the SEL on 14 May made from the VLA does not alter any conclusions due to redundancy in the data from other recording systems operating simultaneously.

4.1 Energy Spectral Density

Given the transient nature of the explosion pressure signal, the signal's spectral content is appropriately conveyed by an ESD. **Figure 12** shows the ESD for measurements made on 13 and 14 May using the Loggerhead systems on Alexes and El Gato Dos.

The narrow spectral peaks revealed in the narrow band estimates (spectral resolution of 1 Hz) are related to the time interference of the bubble pulses, and the overall ESD levels are highly dependent on explosive charge weight and measurement range (Weston 1960; Kibblewhite and Denham 1970). An analysis based upon the cumulative integration of each ESD over frequency shows that 90 percent of the UNDET energy is contained within the approximate frequency range 50 to 2,500 Hz (**Table 3**).

4.2 Peak Pressure

Measurements of peak (absolute value) acoustic pressure ranged from a minimum of 209 dB re 1µPa recorded at 1,651 m to a maximum of 222 dB re 1µPa recorded at 358 m. A measurement uncertainty of +/- 3 dB has been estimated for peak pressure values, the derivation of which is discussed in the next section. These results are compared with those predicted by Equation (1) in **Figure 13** and are found to have an RMS deviation of 3.4 dB. For additional context, data from the MINEX Sound Measurement Trial are also included for comparison.

To better illustrate how the measured data compare to predictions, the SOCAL data can also be considered in the context of historical measurements (**Figure 14**) including experimental results from studies by Arons (1954), Cole (data presented in Temkin 1988), Murata et al. 2002, as well as the more recent MINEX measurements (Soloway and Dahl 2014a). While the measurements from previous studies correspond to varying charge weights, explosive materials, and measurement ranges, there is good agreement between results from the various studies and the levels predicted by the peak pressure equation. The historical data, not including the MINEX or SOCAL results, has an RMS deviation of 2.4 dB with respect to Equation (1). Although the value is slightly lower than that originating from the SOCAL measurements, in part due to sample size, overall, there is generally good agreement between the levels from both the new and historical studies and the levels predicted by the peak pressure equation.

Table 2: Measurement range and depth summary for acoustic measurements from two vessels on 13 and 14 May 2014 off San Diego, California, along with summary of acoustic measurements expressed in peak pressure and SEL. SEL not currently estimated from the VLA on 14 May 2014 until a noise interference issue can be resolved.

Date	Vessel	Test Charge	Measurement System	Depth (m)	Range (m)	Peak Pressure (dB re 1 µPa)	SEL (dB re 1 µPa2 s)
13-May-14	Alexes	1	Loggerhead*	12.3	512	216	189
		2	Loggerhead*	12.3	784	218	188
	El Gato Dos	1	Loggerhead*	15.7	1255	215	186
			USLM**	7.0	1255	215	187
		2	Loggerhead*	15.7	1499	212	185
			USLM*	7.0	1499	212	186
14-May-14	Alexes	1	Loggerhead*	11.6	685	215	187
			VLA***	13.1	685	218	-
				13.8		218	-
				14.5		218	-
				15.2		218	-
				15.9		219	-
				16.6		219	-
				17.3		219	-
				18.0		219	-
				18.7		220	-
		2	Loggerhead*	11.6	358	218	191
			VLA*	13.1	358	217	-
				13.8		218	-
				14.5		219	-
				15.2		219	-
				15.9		219	-
				16.6		219	-
				17.3		220	-
				18.0		220	-
				18.7		222	-
	El Gato Dos	1	Loggerhead*	19.9	1651	213	184
			USLM**	7.0	1651	209	184
		2	Loggerhead*	19.9	1353	215	185
			USLM**	7.0	1353	214	187

* Self-contained data acquisition and storage system (Loggerhead Instruments DSG)

** Universal Sound Level Meter

*** 9-hydrophone vertical line array

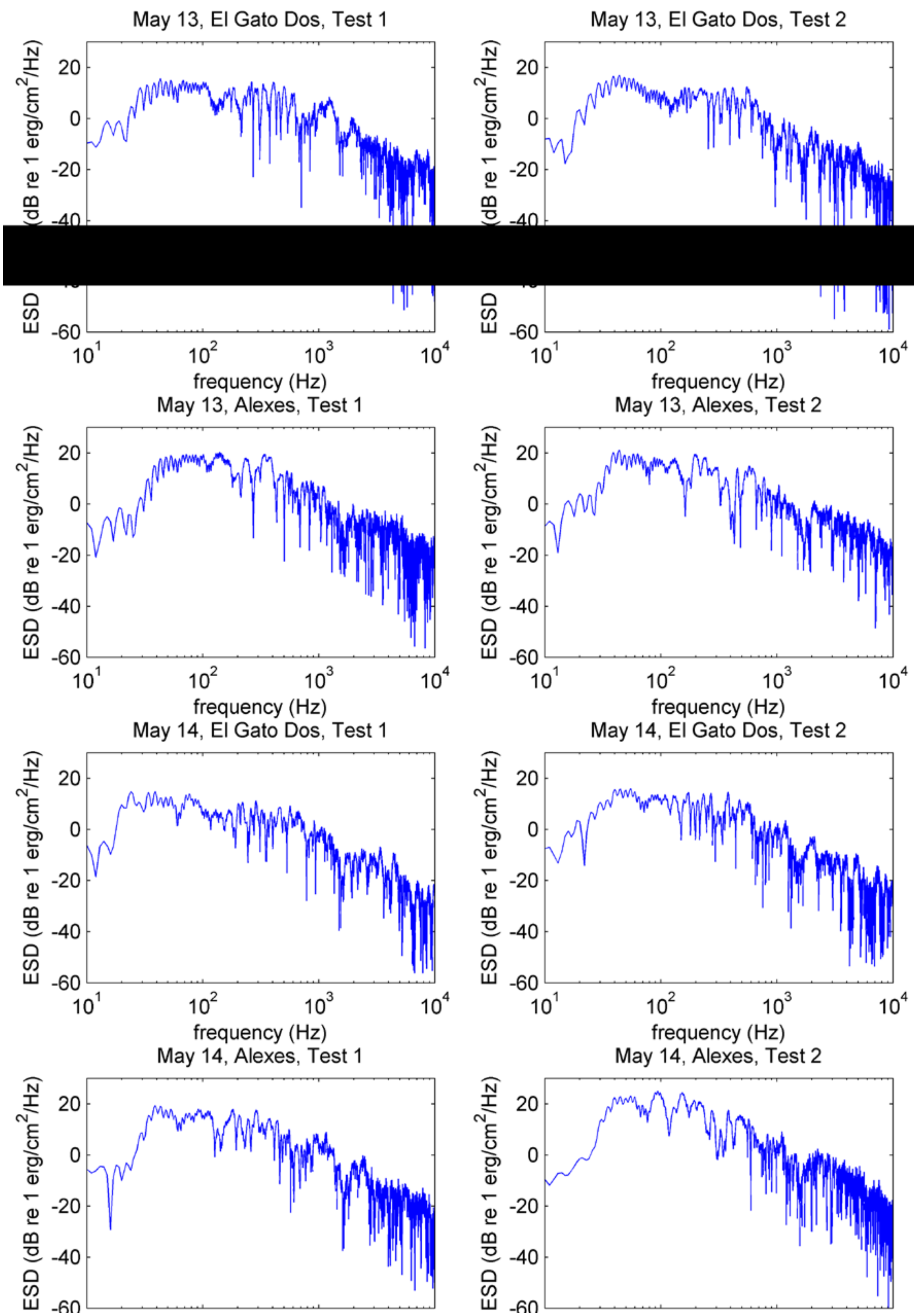

Figure 12. Energy spectral density for 13 and 14 May calculated from the Loggerhead system on Alexes and El Gato Dos. Spectral resolution is 1 Hz.

Table 3: Lower and upper frequencies (f_L and f_U respectively) within which 90% of the UNDET energy is contained.

	90% Energy Range	
Test and Vessel	**FL (Hz)**	**FU (Hz)**
13 May, Test 1 Alexes	69	2192
13 May, Test 2 Alexes	70	1251
13 May, Test 1 El Gato Dos	70	2087
13 May, Test 2 El Gato Dos	57	1963
13 May, Test 1 Alexes	74	1296
13 May, Test 2 Alexes	74	1421
13 May, Test 1 El Gato Dos	59	1842
13 May, Test 2 El Gato Dos	53	2563

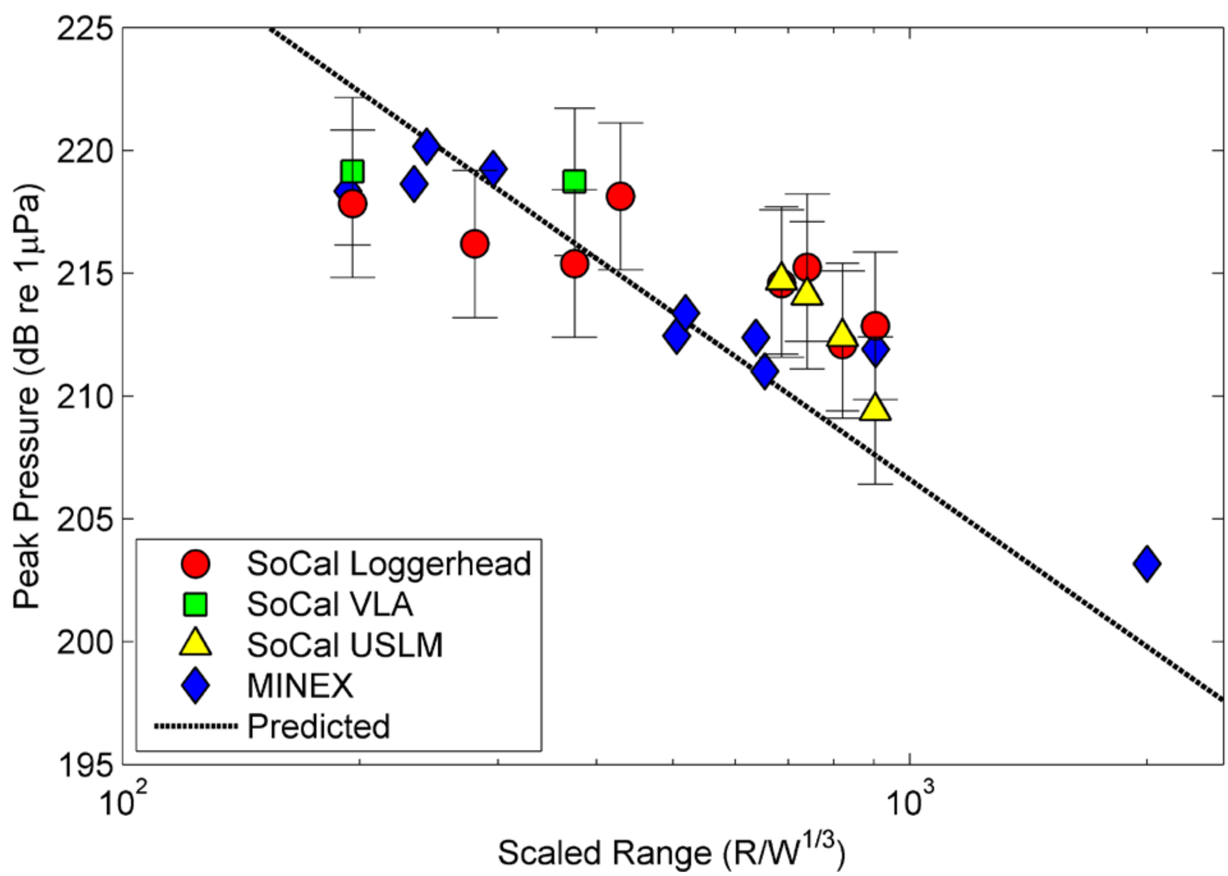

Figure 13. Peak pressure measurements plotted against scaled range (R /W$^{1/3}$) for UNDETs recorded from *Alexes* and *El Gato Dos* are shown with the predicted peak pressures from Equation 1 (black line).

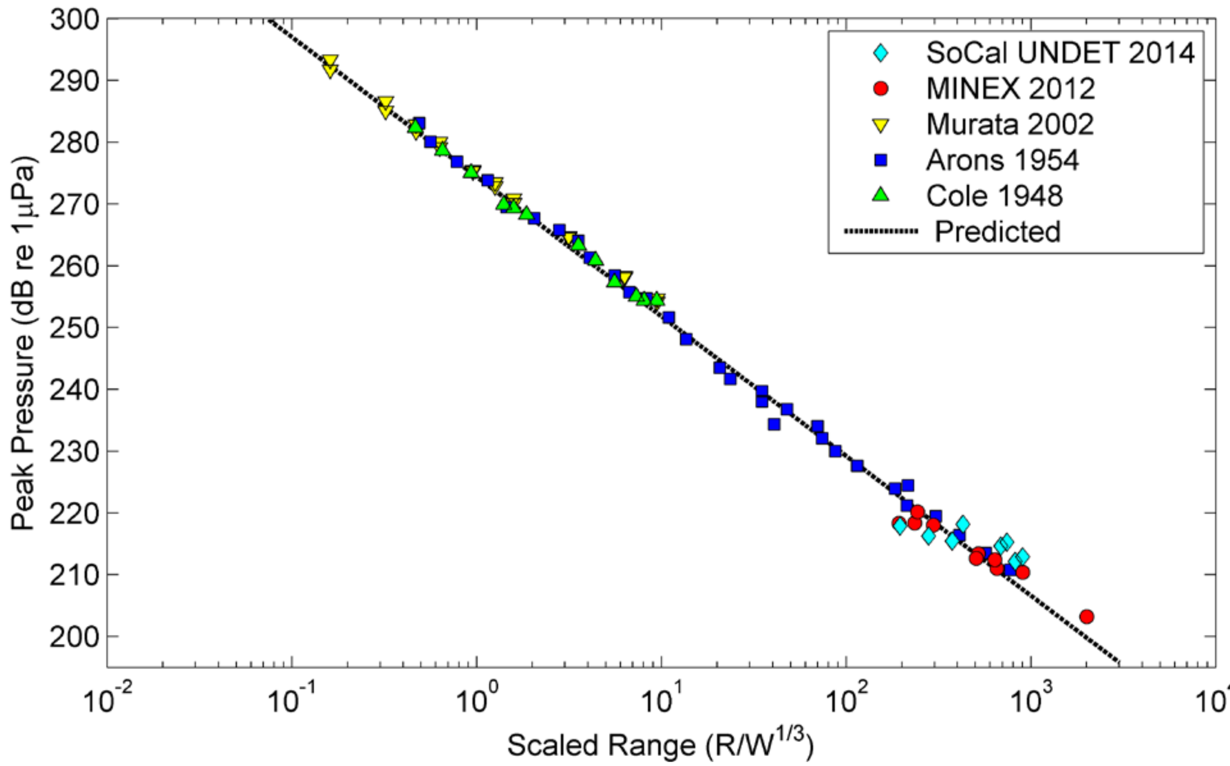

Figure 14. Peak pressures from May 2014 San Diego measurements (SD UNDET), September 2012 Virginia Beach MINEX Sound Measurement Trial (Soloway and Dahl 2014a), and previous measurements of Arons 1954, Cole (data presented in Temkin 1988), and Murata, Takahashi, and Kato 2002 with predicted peak pressure from Equation 1 (black line).

It is also of interest to determine how the peak pressure varies with depth in the water column. The peak pressure data (expressed in dB re 1μPa) recorded on the Loggerhead and VLA from the Alexes on 14 May are shown with respect to depth in **Figure 15** For both tests 1 and 2, the peak pressure appears to increase with depth. The variation between the highest and lowest recorded peak pressure for tests 1 and 2 is 4 dB, exceeding what is expected to be variation owing to hydrophone calibration (discussed in the next section). We thus postulate that this variation is a result of the effects of the waveguide and in particular, the sound velocity gradient associated with the thermocline (**Figure 7**). This effect was identified in a previous study by Brockhurst et al. (1961). A future analysis of the data will involve a detailed study of the acoustic propagation conditions in order to quantify this effect.

4.3 Experimental Errors

We identify two types of errors that establish error bars or the degree of uncertainty in our results when expressed in decibels. The first (or component of variance) is the basic uncertainty associated with the hydrophone calibration. Although all our systems are calibrated multiple times, this error must still be assumed for any underwater acoustic measurement that depends on calibration. Using the 9-hydrophone VLA as test data for purposes of an in-situ evaluation this error we assume that nearest-neighbor hydrophones are sufficiently co-located such that they effectively receive the same signal and we can eliminate propagation effects. We find that the standard deviation of the difference of measurements made from the set of paired-hydrophones is approximately 1 dB and take this value as our estimate of this component of variation.

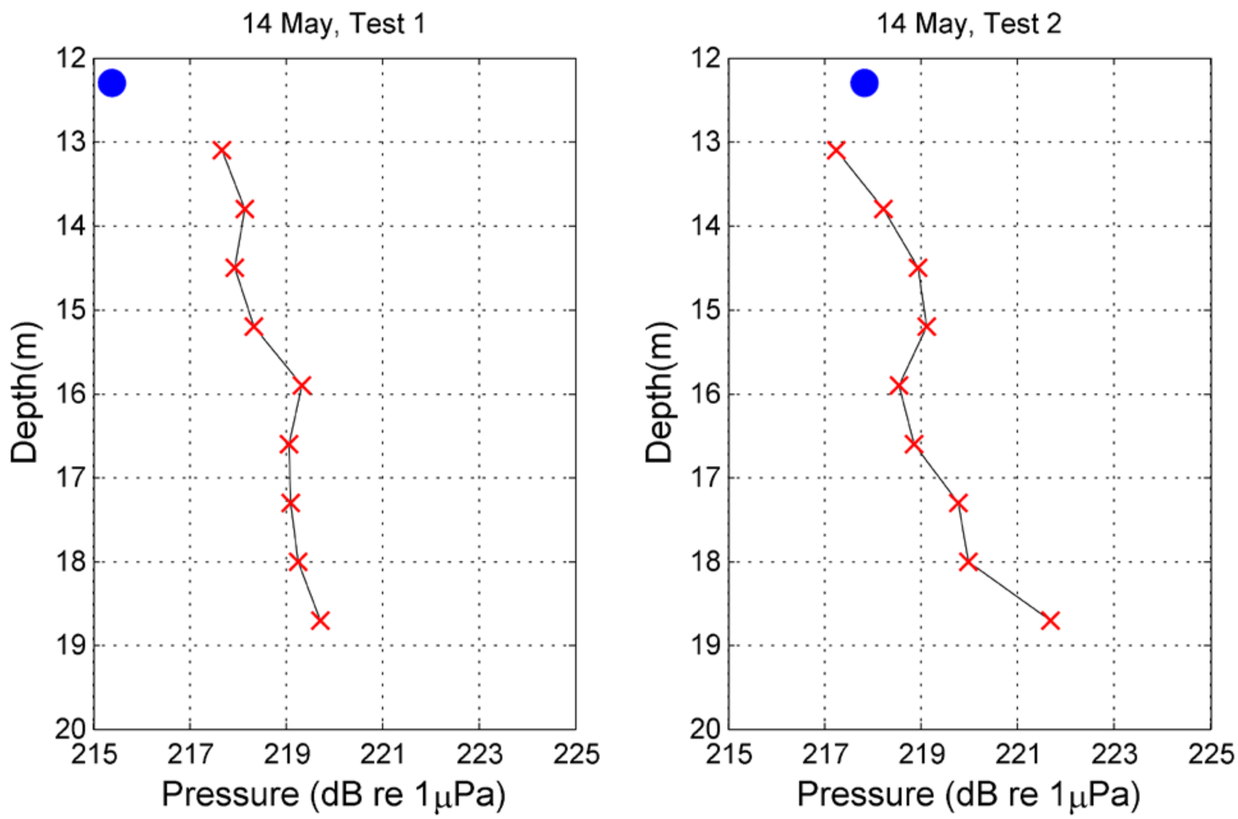

Figure 15. Depth dependence of the peak pressure measured on 14 May from Alexes on the Loggerhead system (blue circle) and the 9 hydrophones of the VLA (red x).

The second component of variance arises from the case of repeated measurements (of peak pressure and SEL) from what we presume are identical explosive charges that detonate with equal efficiency. The detonations in this case all arose from 4.54 kg charges; however, all from different ranges. By way of Equation (1) we can scale measurements made at these different ranges to a constant reference range. For this purpose, we use a reference range of 1,000 meters, and find a standard deviation of about 3 dB using the results from the El Gato Dos, which was positioned closer to this reference range. Note that scaling to another range using Equation (1) introduces additional uncertainty. This effect is evaluated using standard techniques based on functions of random variables which in this case requires the partial derivative of Equation (1) with respect to the variable range (R), taking absolute value, and multiplying result by an expected standard deviation for R or σ_{R} which we take as 20 m, gives

$$\sigma_{P_{peak}} = 1.13\left(52.4 \times 10^{6}\left(\frac{R}{W^{1/3}}\right)^{-2.13}\left(\frac{1}{W^{1/3}}\right)\right)\sigma_R \qquad (8)$$

where $\sigma_{P_{peak}}$ is the standard deviation in peak pressure in Pascals. This uncertainty (which assumes no variation in weight, W) translates to about 0.5 dB near range 1,000 meters and increases with decreasing range. Thus, we view the estimate of 3 dB obtained from the range-scaling approach as an upper bound to be associated with component of variance linked to detonation efficiency, and weight, of presumably identical charges.

These two components of variance are clearly independent and thus combined by summing their squared values and taking square root of the result yielding a value of 3.16 dB for which we settle on 3 dB in view of the upper bound nature of the second component.

Thus, error bars corresponding to +/- 3 dB are used for the measurements of peak pressure that are expressed in dB in this report. Furthermore, a similar error analysis on the SEL data, and corresponding Equation (7) for purposes of scaling, also yielded a final estimate close to 3 dB; therefore error bars of +/- 3 dB will be applied to the SEL measurements.

4.4 Bubble Pulse Period

The bubble pulse period was determined from the auto-correlation of the measurement time series, where the bubble pulse period was the time between the first and second peak values of the auto-correlation function. The measured and predicted bubble pulse periods (from Equation 3) are compared in **Table 4**. The results indicate good agreement between the measured and predicted bubble pulse periods, with errors lower than four percent.

Table 4: Predicted and measured bubble pulse period.

Test and Vessel	Range	Bubble Pulse Period (s)		Error (%)
		Predicted*	Actual	
13 May, Test 1 Alexes	512	0.2093	0.2076	0.81%
13 May, Test 2 Alexes	784	0.2093	0.2055	1.80%
13 May, Test 1 El Gato Dos	1255	0.2093	0.2076	0.81%
13 May, Test 2 El Gato Dos	1499	0.2093	0.2055	1.84%
13 May, Test 1 Alexes	685	0.2093	0.2089	0.22%
13 May, Test 2 Alexes	358	0.2093	0.2019	3.52%
13 May, Test 1 El Gato Dos	1651	0.2093	0.2082	0.54%
13 May, Test 2 El Gato Dos	1353	0.2093	0.2018	3.61%

*Predicted from Equation (3)

The bubble pulse period has been used in previous studies to estimate the detonation depth for a given charge of known weight using Equation (3) (Chapman 1988). Applying this approach to the measured bubble pulse periods, the calculated detonation depths are in excellent agreement with the 23.7-meter water depth measured from the Alexes, and have a standard deviation of 0.5 meter.

4.5 Sound Exposure Level

The SEL measured from this experiment ranged from a minimum of 184 dB re 1 $\mu Pa^2 s$ recorded at 1,651 m to a maximum of 191 dB re 1 $\mu Pa^2 s$ recorded at 358 m. These results are compared with those predicted by Equation (7) in **Figure 1**6. For additional context, data from the MINEX Sound Measurement Trial at Virginia Beach have also been included. Comparing the measured (SOCAL) data and predicted values gives an RMS error of 2.3 dB. Overall, we believe that Equation (7) is an effective tool for predicting the SEL. Furthermore, the predictive capability of Equation (7), a result of an empirical fit to MINEX data, can be possibly be improved upon incorporating the SOCAL data set provided that propagation effects (such as suggested in **Figure 16**) can be quantified.

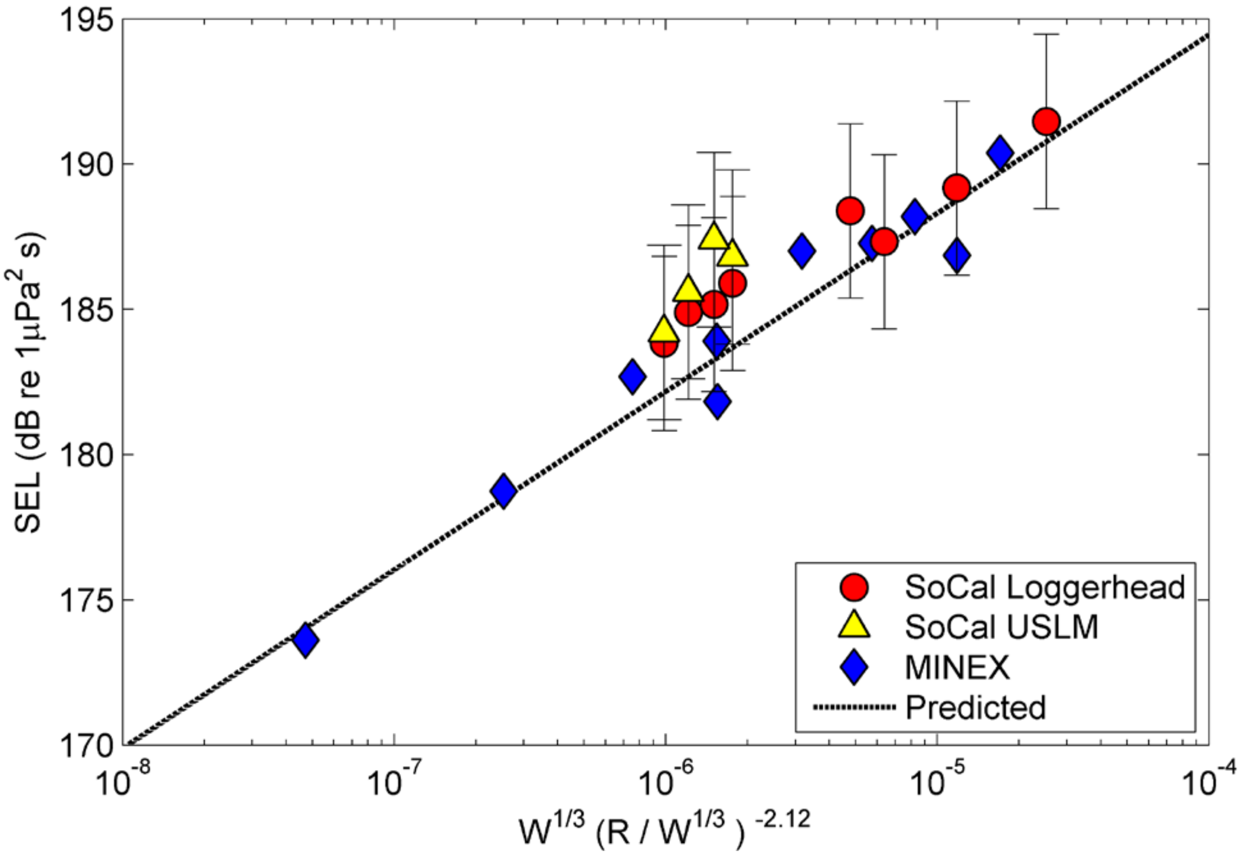

Figure 16. SEL measurements from the 2014 UNDET test (SD) and the 2012 Virginia Beach MINEX trial plotted against the energy scaling parameter $W^{1/3}\left(R/W^{1/3}\right)^{-2.12}$, compared with the levels predicted by Equation (7) (black line). Measurements from VLA are not included because of signal interference recorded on the VLA associated with the generator on the vessel Alexes.

5. SUMMARY

On 13 and 14 May 2014, a team from the University of Washington conducted a set of measurements of the underwater sound and key environmental parameters as part of Navy underwater detonation training in the Silver Strand Training Complex portion of the SOCAL Range Complex.

Two underwater explosive charges were detonated (UNDETs) each day, both consisting of 4.54 kg of C-4 explosive. Measurements of the four UNDETs were collected at ranges between 360 and 1,650 m from two vessels, *Alexes* (positioned closer to the detonations) and *El Gato Dos* (positioned farther from the detonations), giving a total of eight locations (two locations for each UNDET).

Acoustic data were recorded from the *Alexes* using a 9-hydrophone VLA and a single-hydrophone autonomous recording device, and from *El Gato Dos* using an identical single-hydrophone autonomous device as well as a second single-hydrophone device, referred to as the USLM, that was assembled at the University of Washington. Sound speed profiles of the water column were collected from *Alexes* on 13 and 14 May during the measurement period. The water column was characterized by a thermocline resulting in a sound speed that varied from approximately 1,510 m/s near the sea surface to 1,492 m/s near the seabed. Sea surface directional wave measurements were also collected (RMS wave heights between 0.16 and 0.19 m) and will be employed for future modeling efforts.

The peak pressures measured during this experiment ranged from a minimum of 209 dB re 1µPa recorded at 1,651 m to a maximum of 222 dB re 1 µPa recorded at 358 m. The SEL ranged from a minimum of 184 dB re 1 $\mu Pa^2 s$ recorded at 1,651 m to a maximum of 191 dB re 1 $\mu Pa^2 s$ recorded at 358 m. These results are in reasonable agreement with the levels predicted by Soloway and Dahl 2014b. Measurements from VLA show the peak pressure increases with depth and varies by up to 4 dB for approximately 6 m depth span of the VLA. This depth dependence is likely an effect of the waveguide and in particular, the sound velocity gradient associated with the thermocline. Additionally, analysis of the energy spectral density of the measurements shows that 90 percent of the UNDET energy is contained within the approximate frequency range of 50 to 2,500 Hz. During and immediately prior to all UNDET events on 13 and 14 May, no marine mammals were observed within the mitigation zone, defined by a radius of 640 m centered at the UNDET source detonation site.

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6. REFERENCES

Arons, A. B. 1954. "Underwater Explosion Shock Wave Parameters at Large Distances from the Charge." *The Journal of the Acoustical Society of America* 26 (3): 343–46. doi:10.1121/1.1907339.

Brockhurst, R. R., J. G. Bruce, and A. B. Arons. 1961. "Refraction of Underwater Explosion Shock Waves by a Strong Velocity Gradient." *The Journal of the Acoustical Society of America* 33 (4): 452–56. doi:10.1121/1.1908689.

Chapman, N. R. 1985. "Measurement of the Waveform Parameters of Shallow Explosive Charges." *The Journal of the Acoustical Society of America* 78 (2): 672–81. doi:10.1121/1.392436.

Chapman, N. R. 1988. "Source Levels of Shallow Explosive Charges." *The Journal of the Acoustical Society of America* 84 (2): 697–702. doi:10.1121/1.396849.

Cole, R. H. 1948. *Underwater Explosions.* Princeton: Princeton Univ. Press.

Department of the Navy (Navy). 2013. 2012 Expanded Benthic Habitat Mapping for the U.S. Navy's Silver Strand Training Complex (SSTC) Boat Lanes, Coronado, California. Prepared for: U.S. Pacific Fleet, Pearl Harbor, HI. Prepared by: Merkel & Associates, Inc., San Diego, CA. Under Naval Facilities Engineering Command Southwest Contract Number: N62473-10-D-0805 Contract Delivery Order: 26. February 2013.

Gaspin, Joel B., Jean A. Goertner, and Ira M. Blatstein. 1979. "The Determination of Acoustic Source Levels for Shallow Underwater Explosions." *The Journal of the Acoustical Society of America* 66 (5): 1453–62. doi:10.1121/1.383539.

Kibblewhite, A. C., and R. N. Denham. 1970. "Measurements of Acoustic Energy from Underwater Explosions." *The Journal of the Acoustical Society of America* 48 (1B): 346–51. doi:10.1121/1.1912134.

Kirkwood, John Gamble, and William W Wood. 1968. *Shock and Detonation Waves*. New York: Gordon and Breach.

Murata, Kenji, Katsuhiko Takahashi, and Yulio Kato. 2002. "Measurements of Underwater Explosion Performances by Pressure Guage Using Fluoropolymer." *Journal of Material Processing Technology* 85 (1-3): 0924–0136.

Santos, Manuel E. dos, Miguel N. Couchinho, Ana Rita Luis, and Emanuel J. Goncalves. 2010. "Monitoring Underwater Explosions in the Habitat of Resident Bottlenose Dolphins." *The Journal of the Acoustical Society of America* 128 (6): 3805–8. doi:10.1121/1.3506378.

Slifko, John F. 1967. *Pressure-Pulse Characteristics of Deep Explosions as Functions of Depth and Range*. NOLTR 67-87. United States Naval Ordnance Laboratory.

Soloway, A.G., and P.H. Dahl. 2014a. *Mine Neutralization Exercise (MINEX) Sound Measurement Trial*. under Contract No. N62470-10-3011, Task Order CTO 03, issued to HDR Inc. Norfolk, Virginia: Naval Facilities Engineering Command (NAVFAC) Atlantic.

Soloway, A.G., and P.H. Dahl. 2014b. "Peak Sound Pressure and Sound Exposure Level (SEL) from Underwater Explosions in Shallow Water." *Accepted to J. Acoustical Soc. America Express Letters*

Southall, Brandon L., Ann E. Bowles, William T. Ellison, James J. Finneran, Roger L. Gentry, Charles R. Greene Jr, David Kastak, et al. 2009. "Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations." *The Journal of the Acoustical Society of America* 125 (4): 2517–2517. doi:10.1121/1.4783461.

Temkin, S. 1988. *A Review of the Propagation of Pressure Pulses Produced by Small Underwater Explosive Charges.* Memorandum NRL-MR-6181. New Brunswick, NJ: Rutgers University.

Wakeley, Joseph. 1977. "Pressure-Signature Model for an Underwater Explosive Charge" 27 (2): 445–49.

Weston, D. E. 1960. "Underwater Explosions as Acoustic Sources." *Proceedings of the Physical Society* 76 (2): 233. doi:10.1088/0370-1328/76/2/307.

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