Partial dereverberation used to characterize open circuit scuba diver signatures

Kay L. Gemba[a)] and Eva-Marie Nosal
Department of Ocean and Resources Engineering, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Honolulu, Hawaii 96822

Todd R. Reed
Department of Electrical Engineering, University of Hawai'i at Mānoa, Honolulu, Hawaii 96822

(Received 13 September 2013; revised 7 June 2014; accepted 11 June 2014)

The use of passive acoustics to detect self-contained underwater breathing apparatus (SCUBA) divers is useful for nearshore and port security applications. While the performance of a detector can be optimized by understanding the signal's spectral characteristics, anechoic recording environments are generally not available or are cost prohibitive. A practical solution is to obtain the source spectra by equalizing the recording with the inverse of the channel's impulse response. This paper presents a dereverberation method for signal characterization that is subsequently applied to four recorded SCUBA configurations. The inverse impulse response is computed in the least-square sense, and partial dereverberation of SCUBA is performed over the 6–18 kHz band. Results indicate that early reflections and late reverberation added as much as 6.8 dB of energy. Mean unadjusted sound pressure levels computed over the 0.3–80 kHz band were 130 ± 5.9 dB re 1 μPa at 1 m. Bubble noise carries a significant amount of the total energy and masks the regulator signatures from 1.3 to 6 kHz, depending on the regulator configuration. While the dereverberation method is applied here to SCUBA signals, it is generally applicable to other sources if the impulse response of the recording environment can be obtained separately.
[http://dx.doi.org/10.1121/1.4884879]

PACS number(s): 43.30.Xm, 43.28.We, 43.55.Br, 43.60.Pt [SAF] Pages: 623–633

I. INTRODUCTION

Protection of critical infrastructure is a priority for security agencies. About 90% of trade is accomplished with cargo ships globally (Kaluza *et al.*, 2010). Oceanic trade routes are connected to land-based transportation systems by ports, with some large regions supplied by a few major ports, such as the Port of New York or Los Angeles. Disruption of port traffic by a device, such as a dirty bomb, and the resulting contamination and loss of life and goods would have significant impact on these regions. In addition, military assets, such as nuclear submarines or aircraft carriers, use port facilities and require increased security.

Protection can be achieved using a layered approach of technological systems (Smookler *et al.*, 2005; Bruno *et al.*, 2010). Generally speaking, technologies are layered from wide range, low resolution systems to narrowly focused, high resolution systems. These layers overlap and ideally allow technologies to communicate with one other. In particular, the layers to protect ports might be arranged as follows: satellites, Automated Identification System, radar, high frequency radar, optical systems, automated underwater vehicles, and underwater acoustics. Most technologies used for harbor security do not penetrate the water surface, which limits a layered systems approach for self-contained underwater breathing apparatus (SCUBA) detection. Fortunately, acoustics can be used to monitor below the water surface.

Acoustic monitoring technologies can be broadly separated into active and passive systems. Several active acoustic systems are available for port security applications (Shaw *et al.*, 2005; Folegot *et al.*, 2008; Suchman and Meurling, 2010), which have the ability to detect low signal-to-noise ratio (SNR) sources, such as divers. In favorable multipath environments, SCUBA divers were detected at about 500 m (Suchman and Meurling, 2010) and intercepted at 350 m. However, the use of active systems can be limited in reverberant, nearshore environments (Gebbie *et al.*, 2011). An active system may falsely classify sources with similar scattering characteristics, it requires an operator and has a higher up front cost than a passive system. The problem of a high false alarm rate is magnified in a multipath environment (Borowski *et al.*, 2008). Passive acoustic systems can compliment some of these shortcomings and have no acoustic impact on their environment. This is an advantage in protected environments and when considering the bio-effects of noise to marine life (Nowacek *et al.*, 2007). A passive system can also improve source classification performance if the underlying signal is known. Unfortunately, port and nearshore environments are typically very noisy areas: pleasure boats, commercial vessels (Hildebrand, 2009), noise from shore, snapping shrimp (Legg *et al.*, 2007), breaking waves (Carey, 2000), as well as wind and rain (Wenz, 1962), all contribute to background noise levels, making acoustic detection of low SNR sources, such as SCUBA, difficult. Nevertheless, a well-designed passive acoustic system has potential to provide useful detection information, particularly when integrated with autonomous underwater and

[a)]Author to whom correspondence should be addressed. Electronic mail: gemba@hawaii.edu

surface vehicles (Bingham *et al.*, 2009) and/or active acoustic systems.

A passive acoustic system relies on an accurate characterization of the source signal. A few past studies have published information about SCUBA source characteristics. Recordings of several underwater breathing apparatus, such as SCUBA and rebreathers, were made by Radford *et al.* (2005) to quantify the effects of SCUBA noise during studies of mobile aquatic animals. Sound pressure levels (SPLs) and spectrum levels were reported for a window length of 10 s, which included at least one diver breath and bubble noise. Mean reported source levels (SLs) ranged from 164 to 158 dB re 1 μPa at 1 m for SCUBA using a bandwidth of 50 Hz–5 kHz. Depending on the environment, it was estimated that fish can detect SCUBA at over 200 m for noisy ocean conditions. The authors concluded that continuous broadband noise (up to 1.3 kHz) in their SCUBA recordings are due to exhaled bubbles. In another study, SPLs were reported for several unclassified SCUBA systems by Donskoy *et al.* (2008), ranging from 131 to 147 dB re 1 μPa at 1 m. Configurations varied in terms of equipment, tank pressure, kicking intensity, and breathing intensity.

Diver detection methods employing passive acoustics were analyzed for several environments in previous literature. A method to detect divers using a single hydrophone with a multi-band matched filter (Chen and Tureli, 2006) was investigated in a tank and an estuarine environment (Hudson River, New York). Results indicated detection distances of about 50 m in the estuary. Extensive work in the same estuarine environment was conducted by Stolkin *et al.* (2006), Stolkin and Florescu (2007), Bunin *et al.* (2007), Borowski *et al.* (2008), and Sutin *et al.* (2010), giving detection distance of more than 100 m for single hydrophone using a noncoherent envelope processor. Lennartsson *et al.* (2009), Johansson *et al.* (2010), and Lennartsson *et al.* (2010) conducted several sea trials with single hydrophones, a six hydrophone array, and electric underwater sensors. Detection distances for the port of Gothenburg (Sweden) were on the order of 30 m for a single hydrophone. Nearshore reef environments (Kilo Nalu, Island of Oahu, Hawai'i) were analyzed (Gebbie *et al.*, 2011) using two 24-element L-shaped hydrophone arrays, with resulting detection ranges of about 20–30 m. Integrated passive detection systems to detect underwater sources (Sutin *et al.*, 2010) have been investigated, as have systems to deter swimmers (Sutin and Sinelnikov, 2010).

To our knowledge, no spectrum levels or source signatures have been published for various SCUBA configurations in the open literature. This paper presents an analysis of different configurations of SCUBA diving equipment, including sound signatures, SPL, and spectrum levels. A method to remove reverberation due to the underwater recording environment (in this case, a pool) over a particular frequency band is presented and applied. SPLs are adjusted within a practical subband in the least-square sense using dereverberation techniques borrowed from speech processing.

This paper is structured as follows: First, an introduction to open circuit regulators is given. Section II discusses relevant SCUBA equipment followed by a short introduction to different SCUBA designs. The experimental setup is introduced in Sec. III and methodology of data analysis in Sec. IV. Signatures of different SCUBA systems are presented in Sec. V, including SLs and dereverberation results. The paper concludes with a discussion of the results, as well as several observations and recommendations.

II. SCUBA OPEN CIRCUIT MECHANICS

A SCUBA setup enables a diver to breathe a gas mixture autonomously below the water surface. "Open" refers to the state of the loop; in an open system, the diver exhales the gas while for a closed configuration (i.e., rebreathers), the gas is recycled. The gas mixture in an open SCUBA system is usually air, composed of 20.95% oxygen, 78.09% nitrogen, and small amounts of trace gases by volume (Heine *et al.*, 2004). However, divers may use different kinds of gas blends, depending on the application of the dive. Popular mixtures include enriched air commonly referred to as Nitrox 32% and Nitrox 36%. The amount of oxygen is increased (e.g., to 32% oxygen) to decrease nitrogen absorption in the blood and increase dive time (Heine *et al.*, 2004). The term "gas" will be used instead of air when addressing the internal flow through the SCUBA gear.

Acoustically relevant parts of the gear are the first and second stages of the regulator and the pressure hose connecting the two. The first stage is the assembly that attaches to the tank valve and reduces high pressurized gas from the tank to an intermediate pressure. The intermediate pressure hose then delivers the gas to the second stage. The second stage, also called the primary regulator, is the part from which the diver breathes. Here, the intermediate pressurized gas coming from the first stage is reduced to ambient pressure that the diver can breathe (Heine *et al.*, 2004). The first and second stage are likely to have different acoustic signatures, but it is beyond the scope of this paper to analyze them separately.

The signature of the SCUBA signal can be decomposed into two components: the demand (or gas intake) and the exhale. The demand fluctuates during a normal breath (Riegel, 1976), which likely causes the signature to vary with time. The specific structure of the internal and moving mechanism of the regulator might also influence the demand signature. As the diver exhales, bubbles form and ascend to the surface; these create the exhale component of the SCUBA signature. Ideally both components would be recorded separately in order to quantify their individual signatures. However, bubbles take longer to reach the surface than the time needed between breaths even at shallow depths (i.e., several meters). Therefore, a separate recording of the inhale signature is impractical since any field experiment recording will have a mixed signature. In contrast, the exhale signature alone can be analyzed between two consecutive breaths.

As the diver demands gas, the first stage releases gas from the tank to its chamber. The pressure for an aluminum 80 cubic feet tank ranges up to ~3000 psia (pounds per square inch absolute, relative to a vacuum), while the intermediate pressure in the chamber is nominally 150 psig (pounds per square inch gauge, relative to atmospheric pressure), which may vary with equipment (Heine *et al.*, 2004). The first part of the demand signature depends on the mechanism within the first stage that opens the high pressure valve. The second part of the demand signature is dominated by the flow noise of the gas through the chamber, pressure hose, and primary regulator. As the gas demand ends, the intermediate pressure stabilizes and the high pressure valve closes. This is the third and final part of the demand signature. A complete analysis of SCUBA configuration must consider different mechanisms and designs.

Generally speaking, two different configurations of SCUBA systems are commercially available: diaphragm and piston design. Each system can be either balanced or unbalanced. Both the first and second stage of a regulator might be balanced or unbalanced and may have either a piston or diaphragm design (Heine *et al.*, 2004). A short introduction to each type is given in Secs. II A–II D.

A. Balanced diaphragm

The diaphragm is a flexible rubber disk attached to a bias spring (see top diagram in Fig. 1). The disk separates water at ambient and air pressure in the intermediate pressure chamber. Furthermore, the diaphragm connects to a lever piston, which opens or closes the high pressure (marked "HP" in the diagram) valve. The pressure valve is closed in its default position. As the diver demands gas, the pressure in the chamber decreases. The ambient water pressure pushes the diaphragm inward and opens the high pressure valve. The pressure difference required to open the high pressure valve is called the cracking pressure. The mechanism is reversed as the intermediate pressure increases when the diver stops demanding gas; the diaphragm moves to its resting position which closes the high pressure valve. This process is independent of tank pressure (hence the term "balanced" regulator), which means that the diver needs to produce the same pressure differential to start the breathing process regardless of tank pressure.

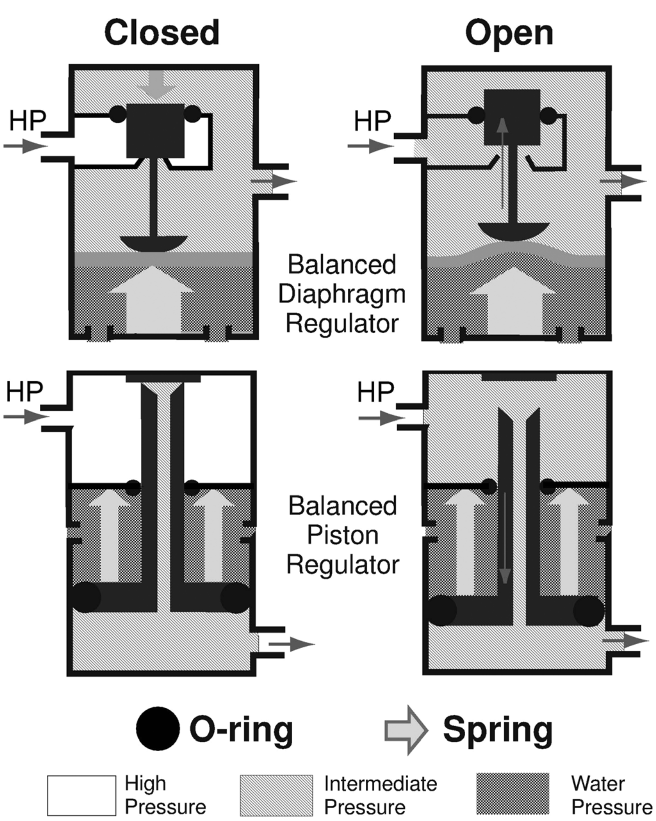

FIG. 1. Comparison of balanced diaphragm and balanced piston regulator. Figure published with permission from NAUI Worldwide.

B. Balanced piston

The mechanics of the balanced piston process are almost identical to those of the balanced diaphragm. The main difference is that the piston sits in a high pressure seat assembly in its resting position (see bottom diagram in Fig. 1). This assembly is attached to the chamber wall. When the diver inhales, the piston moves impulsively out of its seat. When the demand comes to a halt, the process is reversed; the piston slams back into the high pressure seat assembly rather than bending back. This process is also independent of tank pressure.

C. Unbalanced diaphragm

The main difference between the unbalanced diaphragm and the balanced configurations above is the force balance within the first stage. For a balanced configuration, the intermediate chamber pressure opposes the bias spring and ambient water pressure. For an unbalanced configuration, the intermediate chamber pressure and tank pressure oppose the bias spring and ambient water pressure. As the tank pressure is reduced, less force pushes the assembly into opening position. Therefore, the diver has to create a higher cracking pressure.

D. Unbalanced piston

Analogous to the difference between the balanced and unbalanced diaphragm, the unbalanced piston has a different force balance than the balanced piston does. The unbalanced piston mechanism uses the same configuration that the balanced piston does.

III. EXPERIMENTAL OVERVIEW

Several experiments were conducted in a swimming pool (diving well) at the University of Hawai'i at Mānoa in December 2011, July 2012, August 2012, and June 2013. Pool pumps elevated the overall background noise level in the lower frequencies, caused flow noise as water flushed out of the pool, and produced transients caused by movement of the plastic door mechanisms attached to the outflow areas. Background noise was minimized by shutting off the pool pumps in the 2012 trials. The dimensions of the pool were 22.9 m × 22.9 m with a depth of 5.18 m, corresponding to resonance frequencies of 65 Hz and 290 Hz, respectively. SCUBA setups were selected to represent one of the four design combinations (balanced or unbalanced, diaphragm or piston). A total of four sets of regulators were tested (with approximate free flow rates in parenthesis): (i) Apeks XTX

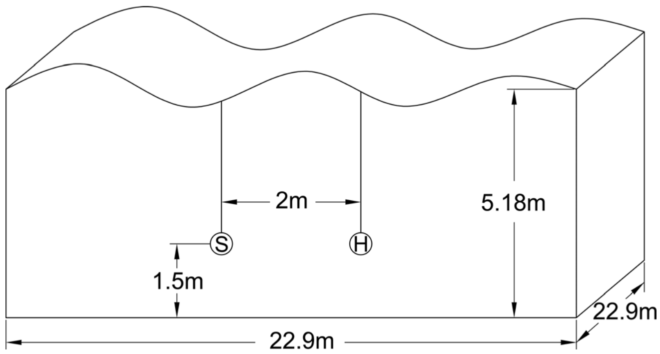

FIG. 2. Schematic diagram of the diving well. The source "S" represents either the diver or transmitting transducer and "H" represents the hydrophone.

200 (Apeks, Blackburn, Lancashire, UK), balanced diaphragm (<300 Liter/min), (ii) Oceanic SP-5 (Oceanic, San Leandro, CA) unbalanced piston first stage, unbalanced 2nd stage (250 Liter/min), (iii) ScubaPro MK25 (ScubaPro, El Cajon, CA) balanced, flow-though piston first stage and balanced 2nd stage G250 (<300 Liter/min), and (iv) Royal Mistral (Vista, CA), unbalanced diaphragm, approximate manufacturing date 1962 (600–700 L/min).

SCUBA systems were recorded with a single 6050-C International Transducer Corporation (ITC, Santa Barbara, CA) hydrophone. Both hydrophone and SCUBA setup were suspended from the swimming pool surface to nominally 1.5 m above the pool bottom, facing each other 2 m apart. Figure 2 shows a schematic of the underwater recording environment including dimensions. The letter "S" denotes the source (either diver or transmitting transducer) and "H" denotes the hydrophone. A scientific diver descended with her own equipment and approached a suspended aluminum 80 cubic foot tank attached to one of the test regulators. She recorded the tank working pressure, switched primary regulators to use the test regulator, and started breathing for 2 min while the hydrophone recorded her breaths. The diver was advised to breathe as regularly as possible. After 2 min passed, the diver switched regulators and dumped pressure out of the suspended tank until it reached the next pressure of interest and recording continued. After three iterations, the suspended SCUBA equipment was replaced with a fresh tank and regulator. Table I shows the number of recorded breaths at each pressure.

Data were recorded on a single channel of a custom analog-to-digital converter (ADC; Fedenczuk and Nosal, 2011) with a sampling rate of 192 kHz, a 10 Hz high pass filter, and an antialiasing filter. The gain setting was chosen empirically such that the maximum amplitude of the recorded signal remained at ~0.6 V to avoid clipping. The response of the 6050-C ITC hydrophone used in the recordings is nearly flat at -158 dB re 1 V_{rms}/μPa at 2 m until ~30 kHz. Sensitivity increases in the 30–70 kHz band to ~-153 dB re 1 V_{rms}/μPa at 2 m. There is a resonance frequency at 50 kHz. The final band (70–96 kHz) is characterized by a steep roll-off.

To estimate the impulse response of the recording channel, the suspended SCUBA equipment was replaced with a Lubell speaker (Model LL916c, Lubell Labs, Inc., Columbus, OH). Just as the SCUBA equipment, the distance of the Lubell speaker to the hydrophone was 2 m with a height of 1.5 m above the floor. The Lubell speaker's channel was therefore the same as the recording channel of the SCUBA diver. The useful frequency range of the speaker ranged from 1 kHz to 18 kHz. Test signals included five 0.5 s linear frequency sweeps from 0.3 to 22 kHz followed by three 10 s of pink noise. This sequence of test signals was repeated three times.

TABLE I. Tank pressure and number of breaths recorded.

	Recording 1		Recording 2		Recording 3	
Regulator	[psi]	Breaths	[psi]	Breaths	[psi	Breaths
Apeks	2600	24	2200	28	1200	13
Oceanic	3000	20	2000	13	1000	28
ScubaPro	1200	19	750	24	500	18
Mistral	1800	13	—	—	—	—

IV. ANALYSIS OF DATA

A. Sound levels

Source spectrum levels (SSL) represent the acoustic pressure as a distance of 1 m away from the source. SSL are calculated using the passive sonar equations (1) as given by Urick (1967) and are a function of frequency in units of dB re 1 μPa^2/Hz at 1 m. First, the power spectral density (PSD, denoted by S_{xx}) is computed after convolving the extracted diver signal with the inverse of the channel's impulse response. Afterward, the PSD is adjusted for hydrophone sensitivity, $|M_h|$, and ADC gain, G. Calibration curves and measured amplitude responses are calibrated using $V_{p2p/2}$ (volts peak-to-peak divided by a factor of 2),

$$\mathrm{SSL}[f] = S_{xx} + |M_h| - 20\log(G) + 20\log(R) + \alpha(R), \quad (1)$$

$$\mathrm{SL} = 10\log_{10}\sum_f 10^{\mathrm{SSL}[f]/10}. \quad (2)$$

If recordings are made at a distance, $R > 1$ m, the PSD is further adjusted for spherical spreading and frequency dependent attenuation. The absorption coefficient, α, with units of dB/m, is calculated for fresh water (Francois, 1982) with a temperature $> 20\,^\circ$C, corresponding to a fresh water heated pool environment. To convert SSL to SL, computed SSLs (1 Hz bin width) are integrated using Eq. (2) and units are stated as dB re 1 μPa at 1 m, including the bandwidth of integration.

When the PSD is computed without the inverse, the terminology *spectrum levels* and *SPLs* is used, respectively (note that the same units are applicable). Spectrum levels and SPLs, therefore, represent the energy 1 m away from the acoustic source, including reverberation effects. To emphasize a particular comparison when not including the inverse, the adjective *unadjusted* (i.e., unadjusted SPL) will be used. On the other hand, to emphasize a particular comparison when the inverse is included, the adjective *dereverberated* (i.e., dereverberated SPL) will be used.

To compute SCUBA signals, samples of 1.5 s duration were extracted for analysis. Each sample contained a single diver breath (about 1.4 s long) preceded and followed by a brief period of background noise. To calculate PSD, the samples were windowed with a Kaiser window (Kaiser, 1974) using a β value of 6.5 and normalized by a broadband normalization factor (Havelock *et al.*, 2009) to account for window effects. Samples were not filtered. Spectrum levels were adjusted for hydrophone sensitivity, ADC gain, spherical spreading, and frequency dependent attenuation. Spectrum levels were integrated from 300 Hz to 80 kHz for SPL calculations. The lower frequency bound of 300 Hz was chosen to eliminate contributions from resonance frequencies of the pool. The upper bound of 80 kHz was selected to reduce system noise, allow for filter transitions near the Nyquist frequency, and reject samples with low SNR due to the roll-off of the hydrophone response.

B. Dereverberation of recorded signals

SCUBA signals were recorded in an environment subject to early reflections and late reverberations and, as a result, calculated SPLs are overestimated when calculated directly from the recorded signals. One way to remove additional energy in the recordings is to invert the acoustic impulse response (AIR) of the recording channel and correlate the recorded signal with the resulting inverse. The inverse of the single hydrophone mixed-phase AIR can be significantly improved using a delay (Neely and Allen, 1979; Mourjopoulos, 1994; Clarkson *et al.*, 1985) to render it casual and improve stability. However, Radlovic *et al.* (2000) found that equalization of AIR yields poor performance at offsets of fractions of a wavelength for a given channel, yielding incoherent dereverberation. Even though only approximate equalization can be achieved using single-channel least-squares (SCLS) methods (Miyoshi and Kaneda, 1988), this technique can be efficiently employed in practical applications (Mourjopoulos *et al.*, 2003); SCLS filters are more robust to measurement noise and only partially equalize deep spectral nulls (Naylor and Nikolay, 2010), hence, reducing narrow band noise amplification after equalization.

The first step in dereverberating a recorded signal is to choose an appropriate length for the AIR (or correspondingly, the applicable reverberation time), which is based on several factors. First and most importantly, the AIR should include all of the early reflections and most of the late reverberant energy to account for the overall additional energy in the recorded signal of interest. However, the reverberant energy decays below the noise floor and poor SNR samples in the AIR should not be considered. Second, a delay will be added to the AIR, which increases the dimensions of the matrix to be inverted. To minimize computational demand, the added delay and choice of decay time should be kept as short as possible.

Usefully, methods developed for room acoustics can be modified for underwater recordings in enclosed spaces since the same physical principles apply. In room acoustics, the term "reverberation" describes the reflected energy within an enclosure (Kuttruff, 2000). After cutoff of a sound source, the energy that arrives at some point in the room decays due to attenuation. Plotting SPL against time gives decay curve. Reverberation time (T_{60}) is defined as the time it takes for the energy to reach one millionth of its initial value after the cessation of sound, and corresponds to a SPL drop of 60 dB. In practice, reverberation can be estimated by extrapolating the linear region of the decay curve to a 60 dB drop (Kuttruff, 2000).

A simple and intuitive way to obtain a single decay curve is by playing colored noise (Müller and Massarani, 2001) over a duration sufficiently long to allow the room to reach a steady state, after which it is suddenly turned off; the decay curve is estimated by plotting SPL against time after the cessation. Decay curves from multiple realizations can be averaged to minimize random fluctuations; we averaged over three realizations in this study.

A more sophisticated way to obtain the decay curve is known as the method of backward integration (Schroeder, 1965). Schroeder showed that the ensemble average of the squared signal decay, $\langle h^2 \rangle$, is equivalent to an integral over the squared impulse response, g,

$$\langle h^2(t) \rangle = \int_t^\infty [g(x)]^2\,dx = \int_0^\infty [g(x)]^2\,dx - \int_0^t [g(x)]^2\,dx. \tag{3}$$

In practice, the upper bound of the integral is chosen to minimize the effect of the noise tail. For a single realization, the method by Schroeder (1965) represents an improvement over the colored noise method because it gives the ensemble average of decay curves and is, consequently, insensitive to random fluctuations and more efficient (Kuttruff, 2000).

In the work presented here, the AIR is obtained by correlating the recorded linear frequency sweep with the original sweep, both extended with zeros to twice their original length before correlation. A line of best fit applied to the linear portion of the resulting ensemble averaged decay curve is used to estimate the reverberation time (Kuttruff, 2000). The tail of the AIR is subsequently truncated to reflect the reverberation time. The first arrival in the impulse response is set as the first sample point and the impulse response is scaled to unity.

Inversion of mixed-phased AIR is achieved using SCLS techniques (see Robinson and Trietel, 1980, for a good discussion on the related spiking filter and Naylor and Nikolay, 2010, for a general overview) and the inverse solution is given by

$$\hat{f} = [H^T H]^{-1} H^T z. \tag{4}$$

In Eq. (4), $\hat{f}$ is the optimum inverse of the AIR in the least-squares sense. H is the circulant matrix of the AIR and $z = [0,0,\ldots,1,\ldots,0,0]^T$, where the spike (of value 1) occurs at the position of the delay. Originally, Robinson and Trietel (1980) include a noise prior in Eq. (4). The prior can be used to render the inversion more stable, e.g., to improve conditioning under poor SNR recordings. Since our recordings are made well above the noise floor, the noise prior is not used in the analysis. The performance of the inverse for a particular delay in the frequency domain is evaluated using the

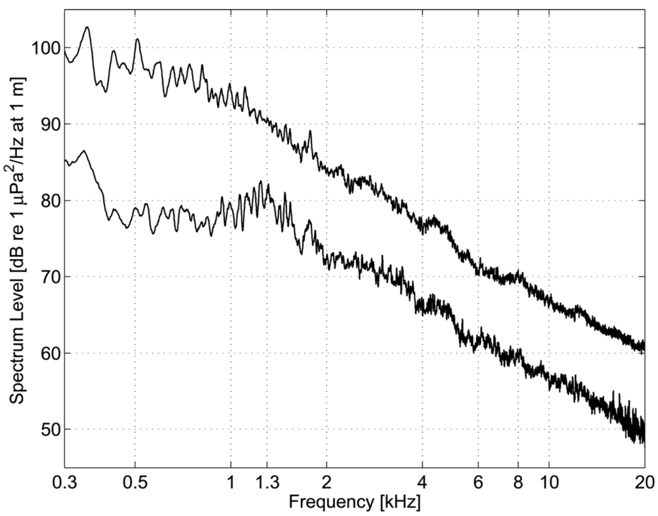

FIG. 3. Ensemble averaged noise due to exhaled bubbles (top) and control (bottom).

magnitude deviation (Naylor and Nikolay, 2010) of the equalized impulse response

$$\sigma = \left[\frac{1}{I} \sum_{k=0}^{I-1} \left(10 \log_{10} |\hat{D}(k)| - \bar{D} \right)^2 \right]^{-1/2}, \tag{5}$$

where

$$\bar{D} = \frac{1}{I} \sum_{k=0}^{I-1} 10 \log_{10} |\hat{D}(k)|. \tag{6}$$

In Eqs. (5) and (6), I corresponds to the length of the fast Fourier transform (FFT) with frequency bins, k, and Fourier coefficients, $\hat{D}$, of the inverted AIR. Magnitude deviation is invariant to the length of the FFT and, for ideal equalization, equates to zero. An appropriate delay is selected by plotting magnitude deviation versus delay and choosing a value corresponding to a minima. Afterward, the inverse, delayed AIR is windowed using a combination of a Kaiser and rectangular window: a half-Kaiser window of 0.005 s is applied to the beginning and tail of the inverse AIR, whereas all remaining coefficients are unaffected. Windowing the edges reduces undesired edge effects of the deconvolved signal. Deconvolution is achieved by convolving the SCUBA signal with the inverse impulse response in the time domain. The AIR is filtered before inversion over an appropriate subband, as discussed in Sec. V C. The filters have a ripple ratio of 0.1 dB, a stop-band attenuation of −60 dB, and transition bands of 500 Hz on both sides. After filtering, all signals are downsampled to reduce computational load.

V. RESULTS

In what follows, dB is used to abbreviate dB re 1 μPa at 1 m when reporting SPLs. For plotting, individual spectrum levels are smoothed (on the decibel scale) with a running average filter of 20 points unless otherwise noted.

A. Exhale signature

Exhaled bubbles are present in all recordings at all times when a diver is present in the pool. Since bubbles from the previous breath are present when the diver takes a subsequent breath, the demand signature is inseparable from the exhale signature. However, the exhale signature can be measured in the absence of a diver breath by calculating spectrum levels between diver breaths.

Figure 3 shows bubble spectrum levels and controls background spectrum levels (recorded before the diver entered the pool). Levels are ensemble averaged over 30 recordings from the Apeks regulator. Results indicate that the bubble signature is broadband and dominant below ∼1.3 kHz, with significant energy in higher frequencies as well. Spectrum levels of bubble signatures roll-off linearly past 1.3 kHz with a slope similar to that of the control. Bubble SPL is 127.8 dB in the 0.3–3.5 kHz band. 3.5 kHz is empirically determined (from Fig. 4) as the transition point between the exhale and the demand signature for the Apeks regulator.

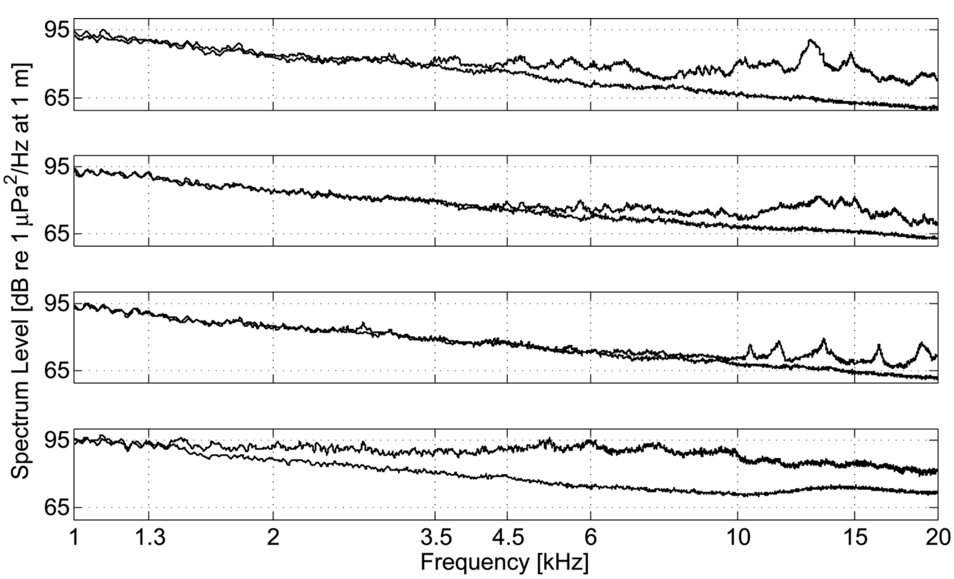

FIG. 4. Four regulator spectrum levels (Apeks, Oceanic, ScubaPro, and Mistral from top to bottom) showing transition from the exhale signature (bubble noise, bottom trace) at 3.5, 4.5, 6, and 1.3 kHz, respectively from regulator signature.

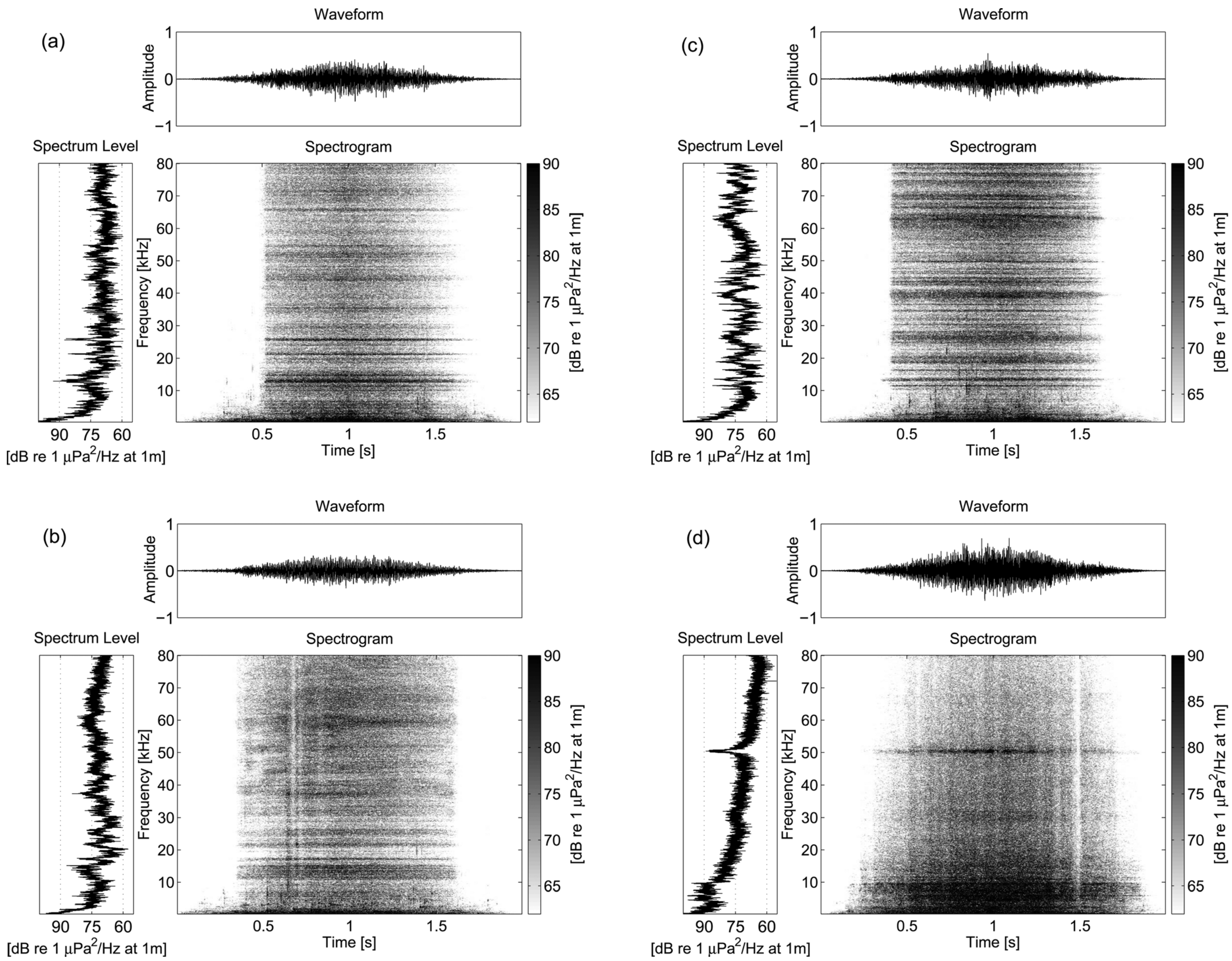

FIG. 5. Spectrogram (2048 frequency bins at 50% overlap) of SCUBA signals: (a) Apeks XTX 200, (b) Oceanic SP-5, (c) Scuba Pro MK25, and (d) Royal Mistral.

Figure 4 shows spectrum levels of all four regulators against respective exhale bubble spectrum levels. Thirty samples were used to compute regulator ensembles, except the Royal Mistral for which only nine samples were used. As above, the exhale signatures are computed using samples taken between diver breaths. At lower frequencies, all regulator ensembles closely follow the exhale signatures. The demand signature diverges from the exhale signature at ~3.5 kHz for the Apeks regulator, 4.5 kHz for the Oceanic regulator, 6 kHz for the Scuba Pro regulator, and 1.3 kHz for the Royal Mistral. Above 6 kHz, no bubble noise is present for any of the regulators.

B. SPLs and signatures

Unadjusted signatures (waveforms, spectra, and spectrograms) of all four regulators are presented in Fig. 5. All signals are broadband and likely extend beyond the 80 kHz limit of our recording system. A single breath can easily be identified; the sudden onset is abrupt over the whole band as the diver begins to inhale. Several bands display dominant energies throughout the breath, which vary from one regulator to another. All multi-stage regulators show narrowband energy peaks between 10 and 20 kHz and some energy peaks at higher frequencies (e.g., ScubaPro at 40 kHz and >60 kHz). These peaks can be exploited for detection and classification purposes. The Mistral contains a significant amount of energy between 4 and 10 kHz and a narrowband energy peak at 50 kHz (although the 50 kHz peak could be caused by the ITC resonance at this frequency, this is unlikely since the other regulators did not exhibit a peak at 50 kHz despite containing high-frequency energy). SPLs are presented in Table II. Mean unadjusted levels computed over the whole band are almost identical for all regulators, showing a 0.2 dB variation in SPL for the first three modern regulators (Apeks, Oceanic, and ScubaPro). For these three regulators, total mean levels are 130.3 ± 0.1 dB. The SPL of the Royal Mistral is >4 dB higher than that of the other regulators. The minimum computed SPL is 125.0 dB and the maximum is 135.9 dB. The 6–80 kHz band levels exclude the contribution from bubble noise and are computed to compare demand levels only. Mean levels for the first three regulators are 127.5 ± 0.5 dB. The SPL of the Mistral in this band is 3.9 dB higher than that of the other regulators.

TABLE II. SCUBA system SPLs (dB re 1 μPa at 1 m). Parentheses indicate the number of recorded breaths. Top left: Total SPL (demand plus exhale signatures). Top right: Demand signature integrated over the 6–80 kHz band. Bottom left: Unadjusted recordings integrated over the 6–18 kHz band. Bottom right: Dereverberated recordings integrated over the 6–18 kHz band.

	Total SPL (0.3–80 kHz)			Regulator SPL (6–80 kHz)		
Regulator	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Apeks (47)	130.4	127.8	133.3	127.2	124.5	131.1
Oceanic (51)	130.2	125.0	133.5	128.0	112.4	132.2
Scubapro (44)	130.4	125.5	133.6	127.3	110.4	132.5
Mistral (9)	134.9	133.6	135.9	131.4	129.8	132.3
	SPL before dereverberation (6–18 kHz)			SPL after dereverberation (6–18 kHz)		
Regulator	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Apeks (47)	122.4	119.8	124.7	116.1	113.2	119.0
Oceanic (51)	119.4	109.6	128.5	113.9	101.9	123.0
Scubapro (44)	116.0	108.2	120.0	109.6	101.6	114.4
Mistral (9)	129.7	128.1	131.1	122.9	121.0	124.3

Several significant lower outliers in SPL were identified in the second recordings of the Oceanic (2 breaths) and ScubaPro (10 breaths) regulators, with a minimum of 110 dB. It is believed that these outliers were a result of unusually weak breaths made by the scientific diver. Overall, variations in SPL of the demand signature (i.e., 22 dB for the ScubaPro) are much larger than the difference computed over the whole band (i.e., 8 dB for ScubaPro).

The experiment in 2013 was conducted to investigate the relationship between breathing intensity and SCUBA SPL. It used the Apeks regulator only. Results were integrated over the full bandwidth of 0.3–80 kHz. Computed SPLs range from 116.3 to 131.7 dB. The difference between peak demand and quiet breathing is 15.4 dB. Results integrated over the 6–80 kHz band (regulator signature only) range from 110.5 to 130.7 dB (a 20.2 dB difference).

C. Dereverberated signatures

The SPLs for the pink noise recordings are 25 dB above the noise floor and range from 104 to 129 dB. The decaying signal reached the noise floor in ~0.255 s, giving a reverberation time (T_{60}) estimate of 0.55 s. In comparison, backward integration method by Schroeder (1965) yields a reverberation time close to 0.4 s. A 0.25 s AIR length (corresponding to an energy decay of 37.5 dB) is used for the inversion procedure; the AIR included most of the reverberant energy, it was kept as short as possible for inversion, and reduced low SNR contributions from the tail (at ~ 0.25 s, mean regulator SPLs generally fell below the noise floor). 0.25 s corresponds to a filter length of 9250 taps. To select the appropriate delay for AIR inversion, magnitude deviation of the equalized AIR is plotted as a function of inversion delay, using Eq. (5) (Fig. 6). A delay of 226.5 ms (corresponding to a logarithmic deviation of 0.68 dB) is selected for the inverse; further performance improvement is minor and costly in terms of matrix inversion.

Figure 7 shows the recording channel AIR, AIR inverse, and equalized AIR. Sparse early reflections are present in the first 10 ms of the AIR, while the later response becomes more diffuse. The pool-floor reflection arrives at ~ 2 ms after the direct arrival, while the first wall and surface reflections

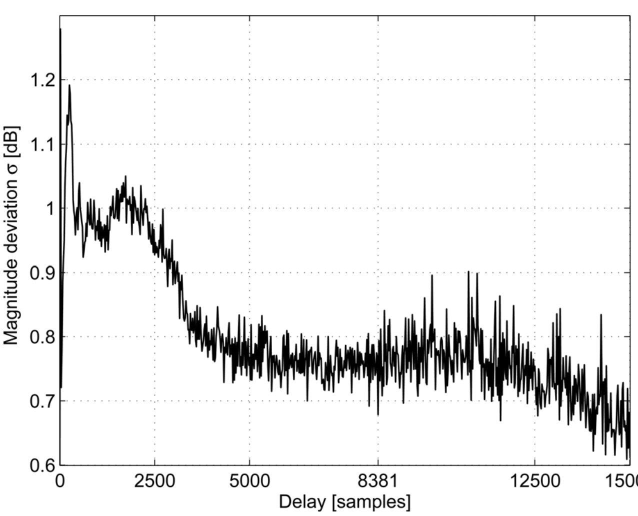

FIG. 6. Magnitude deviation of equalized AIR versus delay.

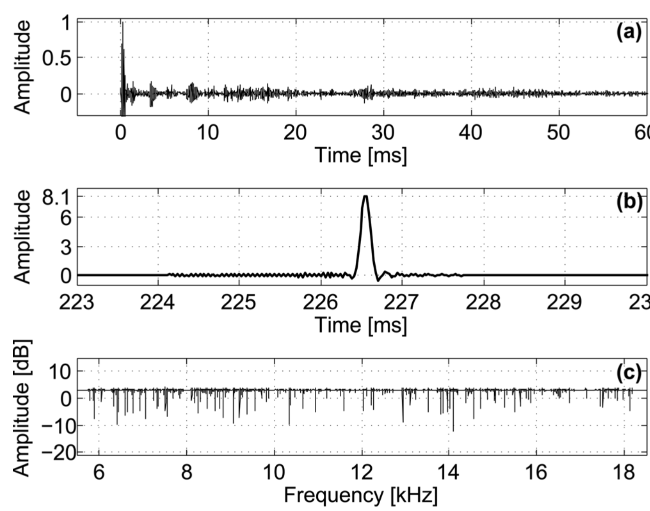

FIG. 7. (a) AIR, (b) AIR inverse, and (c) equalized AIR.

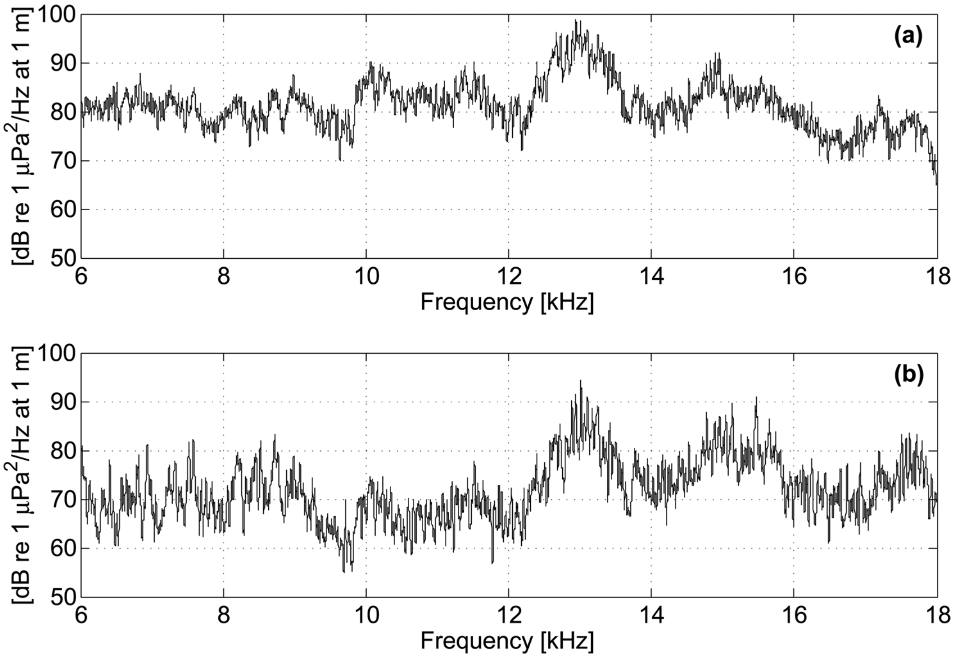

FIG. 8. (a) Apeks unadjusted spectrum levels and (b) SSLs.

arrive 6 ms after the first arrival. The inverse of the AIR is shown in Fig. 7(b), centered and zoomed in at the point of delay. The equalized AIR in the frequency domain is shown in Fig. 7(c). Several frequencies are not perfectly equalized and deviate from the mean by >10 dB. The dereverberation technique is only applicable for a fixed channel, whereas the exhale signature is not fixed; the bubbles do not stay within the recording channel, but ascend to the surface. Consequently, the dereverberation method cannot be applied to the part of the acoustic signature in which the exhale signature is dominant. 6 kHz is the highest transition frequency between bubble and regulator signature for all regulators and is selected as the lower frequency bound for the dereverberation procedure (see Fig. 4). The usable frequency range of the speaker limits the upper bound to 18 kHz. The SCUBA signals and the AIR are bandpass filtered between 6 and 18 kHz and downsampled to 37 kHz to reduce complexity of the system for dereverberation. SLs are given in Table II. SLs are between 5.5 dB (Oceanic) and 6.8 dB (Mistral) lower than the SPLs before dereverberation. The new minima is 101.6 dB and the new maxima is at 124.3 dB.

Figure 8 shows a comparison between the unadjusted Apeks spectrum levels and the dereverberated SSLs. Mean SLs are 6.3 dB lower (6–18 kHz band) for the Apeks regulator. The outstanding energy spike at 13 kHz seems to be invariant to the dereverberation procedure and, therefore, seems to be a property of the acoustic signature of the regulator rather than an artifact of reverberation.

VI. DISCUSSION

SPLs are similar for all modern regulators with an overall mean close to 130 dB for the unadjusted level with a SCUBA diver breathing normally. The higher mean SPL of ~4.5 dB for the Mistral regulator might be due to higher flow rate, a single stage design, or because a different scientific diver performed that particular test (increased breath length within a typical interval of integration or more bubbles in the water column). Variations due to the mechanical design could not be observed and might require an in depth investigation using higher time-frequency resolution techniques.

Comparing the combined and inhale-only parts of the signature leads to several observations. The lower frequency band (0.3–6 kHz) carries about half the acoustic energy in comparison to the full band (0.3–80 kHz). Second, SCUBA SPL (without exhale contribution) changes as much as 22 dB (ScubaPro, 6–80 kHz). The diver can (at least partially) control this range in SPL by varying breathing intensity. The combined signature (0.3–80 kHz) changes by 8.1 dB (ScubaPro, 0.3 kHz–80 kHz). The diver does not have much control over this part of the signature and bubble noise is a significant part of the energy <6 kHz (but note that the position of this bound depends on the regulator under consideration). A diver who wants to reduce his/her SPL would, therefore, choose a system that reduces the amount of acoustic energy due to the bubble signature to avoid detection by a sensor or aquatic species.

The mean unadjusted SPLs reported here are 1 dB lower than the lowest SPLs recorded by Donskoy *et al.* (2008) (131–147 dB re 1 μPa at 1 m), while the upper end of SPL ranges reported here fall well within their range. Donskoy *et al.* (2008) made measurements in a small tank (312 ft long, 12 ft wide, and 6 ft deep), and it is possible that additional energy due to reverberation and resonance might have elevated their levels. Their bounds of integration for SPL calculations are unknown and it is possible that additional energies < 300 kHz significantly changed their results. Donskoy *et al.* (2008) cited a range of ~16 dB caused by intentional change in demand intensity by the diver. Results in Table II show a SPL range of 10.9 dB in the full band (0.3–80 kHz) and 22 dB in the subband (6 kHz–80 kHz), however, the diver was breathing as regularly as possible for these recordings. Our 2013 recording for the Apeks regulator gives a SPL difference of 15.4 dB, which is very close to the 16 dB difference reported by Donskoy *et al.*

The SPLs reported by Radford *et al.* (2005) are ~30 dB higher than mean unadjusted levels measured here over the full band. The factors contributing to this difference cannot be confirmed, however, their experiment setup differed significantly from ours, as did the objective of their work, which was to estimate the distance at which SCUBA can be detected by aquatic animals. Radford *et al.* (2005) made recordings in a 20 m water column that could have resulted in higher levels of bubble noise due to a longer water column. The lower frequency bound for calculating SPL in our experiment is 300 Hz, while Radford *et al.* (2005) used 50 Hz; it is likely that considerable additional energy exists in the low frequencies [indeed, the spectrograms presented by Radford *et al.* (2005) show a significant amount of energy <2 kHz]. Their observation that bubble noise is dominant until ~1.3 kHz is consistent with our results (see Fig. 3).

Our results indicate that dereverberation of recorded underwater, stationary point-sources can be achieved in a controlled environment if the AIR of the channel can be estimated. Reverberation time is estimated using two methods that produced significantly different results [0.4 s with the method by Schroeder (1965) and 0.55 s with the pink noise decay]. The method by Schroeder is an ensemble average of all individual decay curves and eliminates random fluctuations so that resulting reverberation time estimates are more reliable.

The inversion procedure given by Eq. (4) resulted in a square, recursive Toepliz matrix on the order of 15 000 by 15 000. Such large matrices can be computationally problematic for moderately long AIR using high sampling rates. In addition, the method used here is sensitive to differences in position between the control source (used to measure the AIR) and test source. The method is only applicable to fixed sources because it requires that the channel is fixed. In addition, particular care must be taken for mobile sources (such as divers) to ensure that the test source is in the same location as the control source. Constant frequency signals exceeding the length of the AIR are less sensitive to exact alignment. Additional errors arise since most sources are not point-sources and have different directionality characteristics than the transducer. Figure 7(c) shows that perfect equalization is not achieved because several frequencies are not equally attenuated. The drawback of the dereverberation method used here is the ill-conditioned inverse of the SCLS solution, yielding inaccurate equalization performance.

VII. SUMMARY

The SCUBA SPLs and spectrum levels reported here represent a first step toward designing a passive acoustic SCUBA detector for nearshore and port security applications. Our results suggest that past published levels overestimate the energy of SCUBA regulators. For the three modern regulators tested, mean unadjusted SPLs were close to 130 dB re 1 μPa at 1 m. Given the transition between exhale and demand signature (1.3–6 kHz), it may be possible to exploit the characteristics of the bubble signature for classification purposes (e.g., SCUBA versus non-SCUBA). Since bubbles lag the diver position, their signature might be exploited to produce an additional vector for short duration tracking.

A method to remove reverberation for the use of underwater passive acoustic experiment was presented and used to remove additional energies due to reflections of the pool, accounting for as much as 6.8 dB over the 6–18 kHz band. The method can be used (and extended) for any type of recording environment to characterize a source. Since SCUBA and, especially, rebreathers (Radford *et al.*, 2005) have low SPL and the ambient noise field can be unpredictable, it seems plausible to focus on detection rather than tracking. To increase gain, a linear array analog to a tripwire (Johansson *et al.*, 2010) seems to be the optimum solution to detect divers in a noisy harbor or nearshore environment.

VIII. FUTURE DIRECTIONS

The dereverberation procedure can be improved in terms of robustness while keeping simplicity in mind. Such a method will be applicable for a wide range of underwater pool experiments, which could be used for sources such as autonomous underwater vehicles or similar. It is desirable to quantify equalization mismatch using different signals for transfer function estimation and different decay times. The SCLS filter can then be applied to control signals, yielding objective performance results.

ACKNOWLEDGMENTS

The authors thank research divers Troy Heitmann, Lauren Tuthill, and Keo Lopez. John Allen and Tyler Hee Wai contributed the Lubell speaker and recording support for experiments conducted in 2012. Volker Roeber helped with the experimental setup. Guidance from Margo Edwards, Director of the National Center for Island, Maritime and Extreme Environmental Security, helped to direct the study. Keoki Stender and David Pence from University of Hawai‘i Diving Safety Office helped with diving related questions. This paper is dedicated to Kevin Flanagan, our SCUBA instructor and friend. This material is based upon work supported by the U.S. Department of Homeland Security, Science and Technology Directorate, Office of University Programs, under Grant No. 2008-ST-061-ML0002. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.

Bingham, B. S., Prechtl, E. F., and Wilson, R. A. (**2009**). “Design requirements for autonomous multivehicle surface-underwater operations,” Mar. Technol. Soc. J. **43**, 61–72.

Borowski, B., Sutin, A., Roh, H.-S., and Bunin, B. (**2008**). “Passive acoustic threat detection in estuarine environments,” Proc. SPIE **6945**, 694513.

Bruno, M., Chung, K. W., Salloum, H., Sedunov, A., Sedunov, N., Sutin, A., Graber, H., and Mallas, P. (**2010**). “Concurrent use of satellite imaging and passive acoustics for maritime domain awareness,” in *2010 International WaterSide Security Conference*, IEEE, Marina di Carrara, Italy, pp. 1–8.

Bunin, B., Sutin, A., and Bruno, M. S. (**2007**). “Maritime security laboratory for maritime security research,” Proc. SPIE **6540**, 65400S.

Carey, W. (**2000**). “Oceanic low frequency ambient noise,” in *OCEANS 2000 MTS/IEEE Conference and Exhibition*, Providence, RI, Vol. 1, pp. 453–458.

Chen, X., and Tureli, U. (**2006**). "Passive acoustic detection of divers using single hydrophone," in *2006 Fortieth Asilomar Conference on Signals, Systems and Computers*, IEEE, Pacific Grove, CA, pp. 554–558.

Clarkson, P., Mourjopoulos, J., and Hammond, J. (**1985**). "Spectral, phase, and transient equalization for audio systems," J. Audio Eng. Soc. **33**, 127–132.

Donskoy, D. M., Sedunov, N. A., Sedunov, A. N., and Tsionskiy, M. A. (**2008**). "Variability of SCUBA diver's acoustic emission," Proc. SPIE **6945**, 694515.

Fedenczuk, T., and Nosal, E.-M. (**2011**). "Hawaii experimental acoustics range (HEAR) for shallow water applications," Mar. Technol. **45**, 69–76.

Folegot, T., Martinelli, G., Guerrini, P., and Stevenson, J. M. (**2008**). "An active acoustic tripwire for simultaneous detection and localization of multiple underwater intruders," J. Acoust. Soc. Am. **124**, 2852–2860.

Francois, R. E. (**1982**). "Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulfate contributions," J. Acoust. Soc. Am. **72**, 896–907.

Gebbie, J., Siderius, M., and Allen, J. S. (**2011**). "Passive acoustic array harbor security applications," Mar. Technol. Soc. J. **45**, 103–110.

Havelock, D., Kuwano, S., and Vorländer, M., Eds. (**2009**). *Handbook of Signal Processing in Acoustics* (Springer, New York), pp. 1–1500.

Heine, J., Bookspan, J., and Oliver, P. (**2004**). *NAUI Master Scuba Diver*, 2nd ed. (Naui Association of Underwater Divers, Riverview), pp. 1–290.

Hildebrand, J. A. (**2009**). "Anthropogenic and natural sources of ambient noise in the ocean," Mar. Ecol. Prog. Ser. **395**, 5–20.

Johansson, A. T., Lennartsson, R. K., Nolander, E., and Petrovic, S. (**2010**). "Improved passive acoustic detection of divers in harbor environments using pre-whitening," in *OCEANS 2010 MTS/IEEE SEATTLE*, IEEE, Seattle, WA, pp. 1–6.

Kaiser, J. F. (**1974**). "Nonrecursive digital filter design using the Io-sinh window function," in *IEEE Int. Symp. Circuits and Systems (ISCAS74)*, San Francisco, pp. 20–23.

Kaluza, P., Kölzsch, A., Gastner, M. T., and Blasius, B. (**2010**). "The complex network of global cargo ship movements," J. R. Soc. Interface **7**, 1093–1103.

Kuttruff, K. H. (**2000**). *Room Acoustics*, 4th ed. (Taylor and Francis, London), pp. 1–368.

Legg, M. W., Duncan, A. J., Zaknich, A., and Greening, M. V. (**2007**). "Analysis of impulsive biological noise due to snapping shrimp as a point process in time," in *OCEANS 2007—Europe*, IEEE, Aberdeen, Scotland, pp. 1–6.

Lennartsson, R. K., Dalberg, E., Johansson, A. T., Persson, L., Petrovic, S., and Rabe, E. (**2010**). "Fused passive acoustic and electric detection of divers," in *2010 International WaterSide Security Conference*, IEEE, Marina di Carrara, Italy, pp. 1–8.

Lennartsson, R. K., Dalberg, E., Persson, L., and Petrovic, S. (**2009**). "Passive acoustic detection and classification of divers in harbor environments," in *OCEANS2009, MTS/IEEE Biloxi—Marine Technology for Our Future: Global and Local Challenges*, IEEE, Biloxi, MS, pp. 1–7.

Miyoshi, M., and Kaneda, Y. (**1988**). "Inverse filtering of room acoustics," IEEE Trans. Acoust., Speech, Signal Process. **36**, 145–152.

Mourjopoulos, J. (**1994**). "Digital equalization of room acoustics," J. Audio Eng. Soc. **42**, 884–900.

Mourjopoulos, J., Clarkson, P., and Hammond, J. (**2003**). "A comparative study of leastsquares and homomorphic techniques for the inversion of mixed phase signals," in *ICASSP'82, IEEE International Conference on Acoustics, Speech, and Signal Processing*, IEEE, Paris, France, Vol. 7, pp. 1858–1861.

Müller, S., and Massarani, P. (**2001**). "Transfer-function measurement with sweeps," J. Audio Eng. Soc. **49**, 443–471.

Naylor, P., and Nikolay, D. G., Eds. (**2010**). *Speech Dereverberation* (Springer, London), pp. 1–406.

Neely, S. T., and Allen, J. B. (**1979**). "Invertibility of a room impulse response," J. Acoust. Soc. Am. **66**, 165–169.

Nowacek, D. P., Thorne, L. H., Johnston, D. W., and Tyack, P. L. (**2007**). "Responses of cetaceans to anthropogenic noise." Mammal Rev. **37**, 81–115.

Radford, C. A., Jeffs, A. G., Tindle, C. T., Cole, R. G., and Montgomery, J. C. (**2005**). "Bubbled waters: The noise generated by underwater breathing apparatus," Mar. Freshw. Behav. Physiol. **38**, 259–267.

Radlovic, B., Williamson, R., and Kennedy, R. (**2000**). "Equalization in an acoustic reverberant environment: Robustness results," IEEE Trans. Speech Audio Process. **8**, 311–319.

Riegel, P. (**1976**). "Breathing resistance in scuba regulators," in *OCEANS*, IEEE, Washington, DC, Vol. 1976, pp. 556–561.

Robinson, E. A., and Trietel, S. (**1980**). *Geophysical Signal Analysis* (Prentice-Hall, Englewood Cliffs, NJ), pp. 1–466.

Schroeder, M. R. (**1965**). "New method of measuring reverberation time," J. Acoust. Soc. Am. **37**, 409–412.

Shaw, K., Scott, R., and Holdanowicz, G. (**2005**). "Sonar sentinels on guard for submerged swimmers," Jane's Navy Int. **110**, 10–18.

Smookler, M., Clark, B., and Ostrander, J. (**2005**). "Underwater detection and surveillance technology for commercial port and vessel security. Who is going to pay for it," in *Proceedings of OCEANS 2005 MTS/IEEE*, IEEE, Washington, DC, pp. 935–940.

Stolkin, R., and Florescu, I. (**2007**). "Probabilistic analysis of a passive acoustic diver detection system for optimal sensor placement and extensions to localization and tracking," in *OCEANS*, IEEE, Vancouver, BC, Vol. 2007, pp. 1–6.

Stolkin, R., Sutin, A., Radhakrishnan, S., Bruno, M. S., Fullerton, B., Ekimov, A., and Raftery, M. (**2006**). "Feature based passive acoustic detection of underwater threats," Proc. SPIE **6204**, 620408.

Suchman, D., and Meurling, T. (**2010**). "Integrated underwater intruder detection system," in *2010 International WaterSide Security Conference*, IEEE, Marina di Carrara, Italy, pp. 1–8.

Sutin, A., Bunin, B., Sedunov, A., Sedunov, N., Fillinger, L., Tsionskiy, M., and Bruno, M. S. (**2010**). "Stevens passive acoustic system for underwater surveillance," in *2010 International WaterSide Security Conference*, IEEE, Marina di Carrara, Italy, pp. 1–6.

Sutin, A., and Sinelnikov, Y. (**2010**). "Time reversal acoustic approach for non-lethal swimmer deterrent," in *2010 International WaterSide Security Conference*, IEEE, Marina di Carrara, Italy, pp. 1–5.

Urick, R. J. (**1967**). *Principles of Underwater Sound for Engineers* (McGraw-Hill, New York), pp. 1–342.

Wenz, G. M. (**1962**). "Acoustic ambient noise in the ocean: Spectra and sources," J. Acoust. Soc. Am. **34**, 1936–1956.