Quantitative measures of air-gun pulses recorded on sperm whales (*Physeter macrocephalus*) using acoustic tags during controlled exposure experiments

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The widespread use of powerful, low-frequency air-gun pulses for seismic seabed exploration has raised concern about their potential negative effects on marine wildlife. Here, we quantify the sound exposure levels recorded on acoustic tags attached to eight sperm whales at ranges between 1.4 and 12.6 km from controlled air-gun array sources operated in the Gulf of Mexico. Due to multipath propagation, the animals were exposed to multiple sound pulses during each firing of the array with received levels of analyzed pulses falling between 131–167 dB re. 1 μPa (pp) [111–147 dB re. 1 μPa (rms) and 100–135 dB re. 1 μPa^2 s] after compensation for hearing sensitivity using the M-weighting. Received levels varied widely with range and depth of the exposed animal precluding reliable estimation of exposure zones based on simple geometric spreading laws. When whales were close to the surface, the first arrivals of air-gun pulses contained most energy between 0.3 and 3 kHz, a frequency range well beyond the normal frequencies of interest in seismic exploration. Therefore air-gun arrays can generate significant sound energy at frequencies many octaves higher than the frequencies of interest for seismic exploration, which increases concern of the potential impact on odontocetes with poor low frequency hearing. *© 2006 Acoustical Society of America.*
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I. INTRODUCTION

A. Background

Seismic survey vessels fire towed arrays of air guns every 10–15 s to produce geo-acoustic profiles of hydrocarbon deposits in the seabed (Barger and Hamblen, 1980). The air-gun array creates a downward directed, low frequency pulse with most energy concentrated around 50 Hz and a back-calculated, broad-band source level (SL)[1] between 230 and 260 dB re. 1 μPa (0-peak) (Dragoset, 1990; Richardson *et al.*, 1995). The widespread use of this technique (Schmidt, 2004) and the ocean traversing potential of the low frequency, high powered pulses (Nieukirk *et al.*, 2004) have raised concern about the effects of air guns on marine life (Richardson *et al.*, 1995, NRC, 2000, 2005; Gordon *et al.*, 2004). A wide range of marine animal species might be affected by air-gun pulses (McCauley *et al.*, 2000, 2003) with possible negative consequences for human fisheries (Engås *et al.*, 1996). Effects of air-gun pulses on marine mammals may warrant particular concern (Richardson *et al.*, 1995; Gordon *et al.*, 2004, Caldwell, 2002), as many marine mammal species rely critically on sound for orientation, food finding, and communication (Tyack and Clark, 2000). While there are quite a few studies of the effects of seismic signals on baleen whales (Ljungblad *et al.*, 1988; Malme *et al.* 1984, 1985, 1986, 1988; Reeves *et al.*, 1984; Richardson *et al.*, 1986), data for toothed whales are limited (e.g., Goold and Fish, 1998; Stone, 2003) and have often been collected circumstantially (e.g., Madsen *et al.*, 2002).

Investigations of how noise may affect the behavior of marine mammals benefit from methods that can estimate reliably the received noise levels at the whale along with concomitant logging of relevant behavioral parameters (Richardson *et al.*, 1995; Tyack *et al.*, 2004). Although sound propagation models may be helpful in this context, animal movements in the sound field generated by directional air-gun arrays with complex radiation patterns can, together with

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site-specific sound propagation conditions, lead to uncertainties in forward modeling of the signals received by the whale. To overcome this problem, multisensor, acoustic recording tags (e.g., Dtags; Johnson and Tyack, 2003) have been developed to record sound and behavior from the exposed animal, and these have recently proven successful in logging the three-dimensional movements of tagged whales along with recordings of animal sounds and ambient noise (Johnson and Tyack, 2003; Nowacek *et al.*, 2004).

B. Quantification of air-gun pulses for geophysical exploration

In seismic profiling, good signal to noise ratios in echoes returning from geological features below the seafloor are achieved on the transmission side by generating high sound pressure levels (Dragoset, 1984, 1990). The back-calculated source level of an air-gun array is proportional to the firing pressure and the number of guns, whereas it only increases by the cube root of the gun volume (Caldwell and Dragoset, 2000). For this reason, arrays with 30 or more guns are common. The back-calculated source level is a number of convenience for rating the sound output of an array: at close quarters the array does not act as a point source and the highest actual sound pressure levels will be considerably smaller than the back-calculated source levels (Caldwell and Dragoset, 2000). Due to the directional nature of the array, most of the sound energy will be directed toward the seabed to serve the purpose of seismic profiling. Radiated levels in the horizontal plane will be at least 20 dB lower than the back-calculated on-axis level (Barger and Hamblen, 1980; Dragoset, 1990). The industry standard acoustic unit for source sound pressure back-calculated from a known range in the far field, where the array can be viewed as a point source, is the *bar-m*, which describes the peak pressure in a specified frequency band (Dragoset, 1990). A rating in *bar -m* (i.e., the received peak or peak-to-peak sound pressure in bars times the range of the receiver in meters from the source) can readily be converted to a source level expressed in dB re. 1 μPa (0-p) or (p-p) by adding 220 dB to $20 \log_{10}(bar\text{-}m)$ (Richardson *et al.*, 1995). The idealized signature of an air-gun pulse measured on the acoustic axis below the shallow (5–10 m deep) array is a single cycle transient with a duration on the order of 20 m followed by much weaker bubble pulses (Dragoset, 2000). The pulse is broadband with a peak-frequency around 50 Hz, and is normally characterized in a frequency band up to between 125 and 1000 Hz (Dragoset, 1990; Gausland, 2002). The distribution of power or energy in the pulse as a function of frequency (the acoustic spectral signature of the array) is typically given per 1 Hz band as power flux spectral density (conventionally described in dB re. 1 $\mu Pa^2/Hz$) or energy flux spectral density (dB re. 1 $J/m^2/Hz$) (Fricke *et al.*, 1985). Thus, industry standards rate arrays in terms of their theoretical back-calculated, band limited on-axis signature.

C. Marine mammal hearing and sensation

Understanding the effects of air-gun sounds on an animal species requires the determination of exposure thresholds at which physiological effects and behavioral responses are elicited. Peak or peak-peak pressure units characterizing the magnitude of an acoustic signal are merely a description of the instantaneous sound pressure. While these may be useful measures from the perspective of seismic profiling, they are not meaningful as stand-alone measures of how sound is processed by an animal from a detection or sensation point of view. Most biological receivers, the mammalian ear included, are best modeled as energy detectors, integrating intensity over a frequency-dependent time window of around 200 ms (Green, 1985). Air-gun pulses will usually be received by exposed animals off the axis of the array, and at ranges for which the pulse has a much longer duration (Greene and Richardson, 1988; Madsen *et al.*, 2002) and a different frequency spectrum (Goold and Fish, 1998) than the on-axis signature described in the previous section. It is therefore important when considering the potential impact of the sound on an animal not to use the on-axis signature of the air-gun pulse but to quantify the air-gun pulses as they are likely to be received by the animals using measures that relate to sensation levels of a biological receiver.

Sound levels radiated off the axis of an air-gun array may be an order of magnitude lower than the peak pressures generated on the acoustic axis (Dragoset, 1990), but, given the high on-axis pressures, the absolute levels of these by-products may still be considerable. So what may be considered a relatively low level horizontal acoustic by-product from an operational perspective in the geophysical exploration industry could have absolute pressure levels that, when weighted by the frequency-sensitivity characteristics of the ear of an exposed animal, could lead potentially to audition-mediated physiological effects, behavioral disruption, or masking.

This study examines the sound exposures received by deep diving toothed whales diving near operating seismic survey vessels in a deep water habitat. Acoustic data were recorded by archival tags on sperm whales (*Physeter macrocephalus*) during controlled exposures to air-gun arrays in the Gulf of Mexico. Results demonstrate that for each firing of the air-gun array, sperm whales receive several versions of the primary pulse that travel on different propagation paths and which have very different temporal and spectral properties. We explore how air-gun pulses can be quantified in a way that might be relevant to sperm whale sensation levels and to their potential for interfering with sperm whale acoustic activities, and we discuss analytical problems associated with the derivation of such measures. It is demonstrated that the received levels measured from sperm whales diving up and down in the water column at variable ranges from the array cannot be predicted by simple geometric spreading laws. We show that some air-gun pulse components carry significant energy at frequencies octaves above the frequency range generally modeled by geophysicists and discuss the implications for high frequency impacts of air-gun pulses on sperm whales and other toothed whale species.

TABLE I. Tag on and tag off times are local time. "*CEE dur*" gives the duration of the CEE in minutes. "*Analyzed*" denotes the number of first/second pulses analyzed.

Tag	Date	Tag on	Tag off	CEE start	CEE stop	CEE dur (min)	Analyzed
sw02_253a	10/9/02	16:38	20:58	17:59	19:15	104	112/74
sw02_254a	11/9/02	10:13	21.45	12:16	14:20	124[a]	55/13
sw02_254b	11/9/02	10:28	22.52	12:16	14:20	124[a]	14/8
sw02_254c	11/9/02	10:34	22.56	12:16	14:20	124[a]	39/22
sw03_164a	13/6/03	9:48	23.20	18:26	19:26	60	82/34
sw03_165a	14/6/03	13:35	06:19	17:01	19:01	120	150/79
sw03_165b	14/6/03	13:38	06:05	17:01	19:01	120	175/82
sw03_173b	22/6/03	14:46	20:38	17:23	19:23	120	383/379

[a]This CEE was paused for 19 min while dolphins passed close to the source vessel.

II. MATERIALS AND METHODS

A. Habitat and logistics

In 2002, experiments were performed from 19 August through 15 September in the Gulf of Mexico as a part of the 2002 SWSS (Sperm Whale Seismic Study) cruise. Visual and acoustic tracking was performed from the RV Gyre while the MV Rylan T., which was physically carrying a coastal survey vessel the MV Speculator, acted as the source vessel. Whales were located and tracked acoustically off the continental shelf of the northwestern Gulf of Mexico by means of a towed hydrophone array. While surfacing, the whales were tracked by visual observers with 25 magnification big-eye binoculars. In 2003, experiments were performed from 3 to 24 June 2003 in the Gulf of Mexico as a part of the 2003 SWSS cruise. In this year, the RV Maurice Ewing, operated by the Lamont-Doherty Earth Observatory, was the platform for acoustic and visual tracking and the MV Kondor Explorer was the source vessel. Procedures for localization and tracking of the whales in 2003 were the same as in 2002.

B. Controlled exposure procedure and air-gun arrays

After tagging, tagged whales were tracked acoustically and visually for at least 1–2 h before controlled exposures were initiated. The source vessel was initially positioned several kilometers from the tagged whale to ensure low initial received levels at the whale. At the beginning of the controlled exposure experiment (CEE), increasing numbers of the guns in the array were fired in a gradual ramp up following the regular procedure used by industry in an attempt to reduce the risk of a high level exposure to undetected nearby whales. The ramp-up procedure entailed starting with a single air gun, and then doubling the number of air guns firing every 5 min. The CEEs lasted between 1 and 2 h leaving the rest of the tag recording time for postexposure data logging.

In 2002, MV Rylan T. towed a small 20 gun array with 2000 psi (pounds per square inch) firing pressure and a volume of 1680 in.^{3} The far-field, vertical signature of the array had a back-calculated, wide-band (3–800 Hz) zero-to-peak SL of 41.1 *bar-m*, corresponding to 252 dB re. 1 μPa (0-peak). The array was fired every 15 s with a 30 min ramp up from 1 to 20 guns. In 2003, MV Kondor towed a larger 31 (28 in use) gun array with 2000 psi firing pressure and a volume of 2590 in.^{3} The far-field, vertical signature of the array had a back-calculated, zero-to-peak source level of 56.9 *bar-m* in the band 3–218 Hz, corresponding to 255 dB re. 1 μPa (0-peak). The array was fired every 15 s with a 30 min ramp up from 1 to 28 guns. In both years, a mitigation protocol was adopted to ensure that no animal sighted or detected acoustically in the study area was exposed to levels higher than 160 dB re 1 μPa (rms) stipulated by the federal permits under which the experiments were carried out (NMFS research permits 369-1440-01, 981-1578, and 981-1707 afforded to P. T.). Acoustic and visual watches for cetacean and turtles were performed from the seismic vessels from at least 1 h prior to the ramp-up and during the seismic emissions, with instructions to stop firing of the air guns in case of any encounter at <2 km range. On that basis, one CEE was paused for 19 min while two other CEEs were shortened due to lack of sufficient daylight to observe the mitigation zone (Table I).

C. Dtag specifications and deployment

A noninvasive, archival Dtag (Johnson and Tyack, 2003) was used to gather data on three-dimensional movements and sounds impinging on, or produced by, the tagged whale. Movements of the tagged whales were logged by a depth sensor and 3-axis magnetometers and accelerometers sampled at 47 Hz (2002) or 50 Hz (2003). In 2002, acoustic data were sampled at 32 kHz with a 12 bit ADC. A one-pole high pass filter (HP) at 400 Hz (−3 dB cut off) reduced flow noise and a four-pole Butterworth low-pass filter at 12 kHz countered aliasing problems. Saturation of the recorder occurred at received levels of 152 dB re. 1 μPa (0-peak). In 2003 a second version of the Dtag was used for three of the four whales tested. This tag version sampled sound with 16 bit resolution at 96 kHz again with a 400 Hz one-pole HP filter, and a saturation level of 193 dB re. 1 μPa (0-peak). This tag used a sigma-delta analog-to-digital converter with built-in anti-alias filtering and a flat (±1 dB) frequency response up to 45 kHz. The 400 Hz HP filter in both tags was corrected in postprocessing with a compensating filter yielding a well-characterized frequency response flat within ±1 dB from 0.045 to 12 or 45 kHz. Sperm whales selected for tagging were approached with a rigid hulled inflatable boat while logging at the surface. Tags were brought close to the whales with a 15 m pole cantilever mounted to the bow of the boat and were attached temporarily to the dorsal sur-

TABLE II. Columns "*Whale depth* (m)" and "*Vessel range* (km)" are the minimum-maximum values for which arriving pulses were analyzed. "*First pulse*" numbers give the received *m*-weighted levels for all first arriving pulses analyzed and "*Second pulse*" numbers give *m*-weighted received levels for second arriving pulses. "pp" means peak-peak sound pressure (dB re. 1 μPa, pp), rms is the root-mean-square sound pressure (dB re. 1 μPa, rms) and SEL is the sound exposure level (dB re. 1 $\mu Pa^2 s$).

			First pulse			Second pulse		
Tag	Whale depth	Vessel range	pp	rms	SEL	pp	rms	SEL
sw02_253a	8–658	8.4–12.6	142–162	120–144	106–127	146–159	130–146	118–129
sw02_254a	15–614	6.5–9	136–155	121–140	105–123	135–158	116–143	102–126
sw02_254b	6–611	5.7–9.5	136–152	121–135	108–118	145–158	131–142	113–128
sw02_254c	18–605	5–8.4	139–155	125–139	106–123	141–162	125–143	111–126
sw03_164a	20–500	11–12	140–157	125–146	112–129	141–164	125–140	112–124
sw03_165a	na	na	137–160	123–146	106–130	138–154	123–141	110–125
sw03_165b	na	na	135–160	119–147	105–130	135–151	119–137	104–123
sw03_173b	0–17	1.4–7.4	131–162[a]	111–147[a]	94–131[a]	131–153	114–135	104–125

[a]Some pulses were clipped in this recording.

face with suction cups. After a preprogrammed recording time, the tags released from the animals and floated to the surface for recovery by means of an attached VHF transmitter.

D. Data and analysis

1. Distance from sound source

In the 2002 and 2003 SWSS cruises, eight whales were tagged long enough under suitable conditions to perform controlled exposure experiments. The tag-on times and durations of the CEEs are summarized in Table I. In each cruise, an observation vessel, independent of the seismic source vessel, was maintained within about 2 km of the tagged whale. Whale surfacing locations were recorded by observers on this vessel whenever possible, and the whale position between sightings was later estimated using dead-reckoning (Johnson and Tyack, 2003; Zimmer *et al.*, 2005). The dead-reckoned track was computed as the time integral of an estimated velocity vector for the whale based on its orientation as a function of time, recorded by the tag, and an assumed constant swimming speed. The swim speed and a constant advection due to a net current were selected so that the dead-reckoned track would best match the visual observations during initial and final surfacings. A sample of the dead-reckoned tracks was checked against visually fixed locations for accuracy, with mean discrepancy of 370 m ± 223 m (95% CI, $N=16$ fixes). The error in the source-to-whale range estimates will only be as great as the location error when this is along the source-to-whale axis, which generally is unlikely as visual tracking was conducted from the independent observation vessel. Therefore, we conservatively consider ranges reported here to be accurate within ±0.5 km (Table II). Visual tracking was poor for two of the tested whales (sw165a and sw165b), so their position information is not included in this study. Range and depth intervals of the exposed whales are summarized in Table II along with the received sound levels (m-weighted, see section c).

2. Data offload and seismic pulse extraction

Data were offloaded from the tag via a high speed infrared port, and analyzed with custom programs in MATLAB 6.0 (*Mathworks*). Spectrogram and wave form representations of all pulses were inspected visually, and time cues for each pulse arrival were stored along with time cues for a nearby background noise segment. Seismic pulses for which sperm whale clicks occurred within a window of less than 100 ms were omitted. For each seismic pulse, three sound segments were extracted corresponding to the two maximum arrivals of the seismic pulse and a nearby noise sample. The stored window sizes were 100 ms for the first arrivals and 200 ms for second arrivals due to the longer time dispersion of the latter pulses perhaps due to reverberation in the sea floor. Some pulses had decaying tails that extended beyond the time windows, but the use of larger window sizes increased the rejection rates due to overlap with sperm whale clicks. Since the energy in the last part of the decaying tails is relatively small, we chose the indicated window sizes as a compromise between underestimating energy and rejecting too many pulses. To ensure reliable estimation of received levels, we introduced a second criterion for analysis based on signal-to-noise (SNR) ratio: pulses were only accepted for analysis if the SNR was greater than 10 dB (*sensu* McCauley *et al.*, 2000). SNR was calculated as the ratio of the broad band root-mean-square (rms) levels of each pulse and of the noise segment preceding the pulse.

3. Received level measures

Regulations for exposure of sounds to cetaceans currently specify acceptable received levels (RL) in terms of rms sound pressure (NMFS, 2003). For transients, this measure introduces the uncertainty of how to define the time window over which the squared pressure should be averaged, and it is poorly suited for predicting the level of impact of transients with high peak pressure or of long transients with high energy flux density (Finneran *et al.*, 2002; Madsen, 2005). For that reason, we have quantified the seismic pulses by three measures: peak-peak (RL_{PP}, dB re. 1 μPa, pp), rms

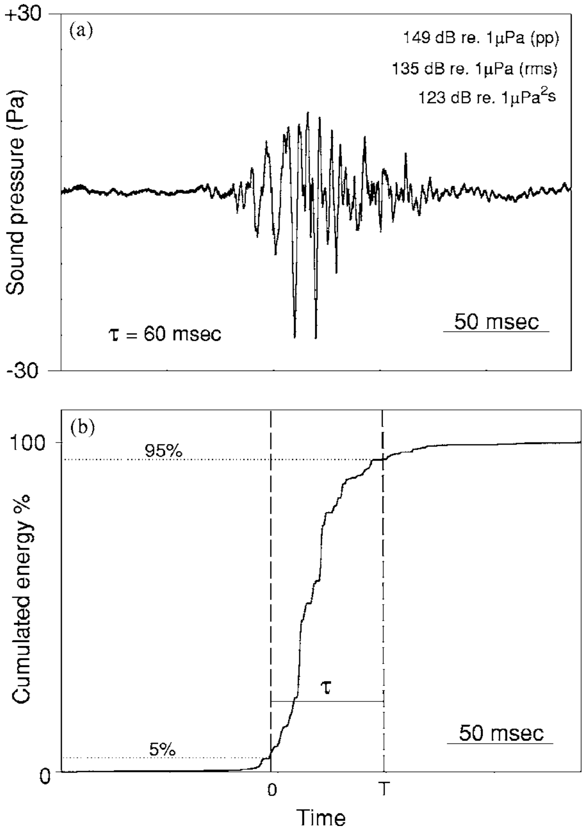

FIG. 1. (a) Wave form of the first pulse arrival from a firing airgun array showing the relationship between pp, rms, and SEL. (b) Relative cumulative energy as a function of time for the wave form shown in (a). The duration (τ) of the pulse in (a) is given by the time window containing 90% of the total relative energy of the window analyzed. τ is used as averaging time for derivation of the square root of the mean pressure-squared (rms) of the pulse and as integration time for computation of the sound exposure level (SEL).

(RL_{rms}, dB re. 1 μPa, rms) and sound exposure level (SEL, dB re. 1 μPa^2 s) (proportional to energy flux density for a plane wave propagating in an unbounded medium). This will facilitate comparison with other studies and provide measures that take into account both the peak pressure (RL_{pp}) and the sound exposure level (SEL) of the sound pulse (McCauley *et al.*, 2003). All analyses are based on the assumption of individual pressure measurements of a plane wave propagating in the far-field of the sound source.

For calculation of rms levels of a transient signal, we have adopted the 90% energy approach used by McCauley *et al.* (2000) and Blackwell *et al.* (2004). The relative energy is computed in a window around the seismic pulse [Fig. 1(a)], and the duration (τ in seconds) is defined by the smallest sample interval ($0{:}T$) in the analysis window containing 90% of the energy in the window [Fig. 1(b)]. This duration defines the sample interval over which the root-mean-square pressure level (RL_{rms}) is computed:

$$10\log\left(\frac{1}{T}\int_0^T p^2(t)dt\right) \quad [p(t) = \text{instantaneous pressure}]. \tag{1}$$

The SEL is given by the square of the instantaneous pressure integrated over the pulse duration T:

$$10\log\left(\int_0^T p^2(t)dt\right) \quad [p(t) = \text{instantaneous pressure}]. \tag{2}$$

Consequently, the SEL is given by rms sound pressure level (RL_{rms})+10 log(τ). To avoid small errors in the exposure measures due to ambient noise in the analysis window, the noise power of the preceding 100 ms noise window was subtracted from $p^2(t)$ when computing RL_{rms} and SEL.

Since the ear of most mammals, dolphins included, integrates low frequency sound over a window of around 200 ms (Johnson, 1968a; Au *et al.*, 2002), this duration was used as the maximum integration time for RL_{rms} and SEL (*sensu* Madsen *et al.*, 2002). For sound exposures high enough to generate temporary or permanent threshold shifts, the 200 ms integration window does not apply, and the entire duration of the exposure should be taken into account (Finneran *et al.*, 2002; Nachtigall *et al.*, 2004). However, the transient exposures in the present study are highly unlikely to cause TTS (Finneran *et al.*, 2002), so we feel that the use of a 200 ms maximum integration time is justified from a sensation perspective, especially considering that there is very little energy outside of this window in the pulses analyzed.

4. Frequency-weighting to approximate the frequency response of sperm whale auditory system

Seismic pulses are designed to have peak energy around 50 Hz, but there is significant energy both lower, and as will be shown, at significantly higher frequencies. The spectrally corrected Dtag recordings have a flat frequency response down to about 45 Hz, but at lower frequencies flow noise around the tag dominates the recording and received levels cannot be accurately determined. This leads to an underestimation of the low frequency energy in the pulses and thereby in the broad band sound pressure and sound exposure levels. However we argue that such low frequency components may have little relevance to sperm whales which seem to hear best at higher frequencies (Ridgway and Carder, 2001).

Mammalian auditory systems have differential spectral sensitivity with a gently sloping decrease in sensitivity toward low frequencies and a sharp cutoff in sensitivity at high frequencies (Fay and Popper, 1994). For humans it is common practice to apply spectral corrections when calculating noise exposures. The so-called A-weighting mimics the frequency dependence of sensation at moderate exposure levels while the flatter C-weighting is appropriate for transients at levels that might lead to damaging sound exposures (ANSI 1994; Harris, 1997). There is no reason to believe that marine mammals are different from humans in this respect (Finneran *et al.*, 2002) but it is a major challenge to determine suitable weighting functions for the diverse cetacean groups. Based on anatomy of the inner ear (Fleischer, 1976; Ketten, 1997, 2000), available audiograms (Au *et al.*, 1997) and the frequency ranges of vocalizations, it is believed [Richardson *et al.*, 1995; Southall *et al.* (unpublished)] that the auditory systems of toothed whales are less sensitive to low-frequency noise than those of baleen whales, who use low frequency sound for communication. In that light, different

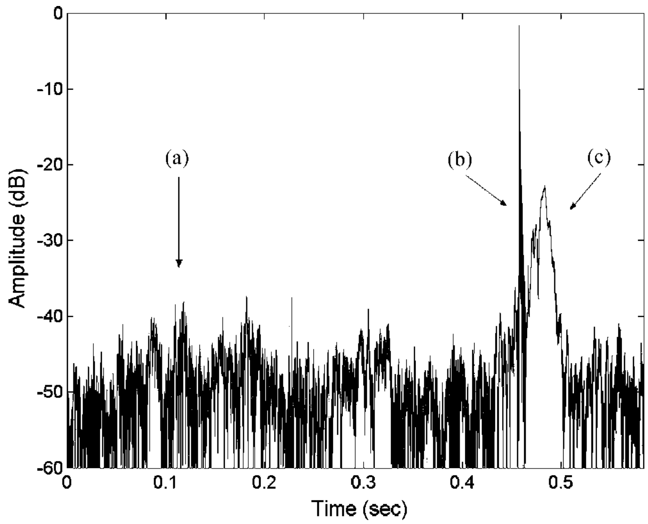

FIG. 2. Amplitude plot of the envelope (absolute value of the Hilbert transform) of the received wave form of a click and air gun pulses on a sperm whale. (a) Points to the first pulse arrival from the firing of an airgun array that is buried in noise. (b) Points to a usual click produced by the tagged whale that overlaps in time with the second pulse arrival from the firing airgun array (c). None of the pulses can be analyzed because of bad SNR (a) and overlap (c) with the sperm whale click (b).

weighting functions, called M-weighting akin to the C-weighting for human auditory systems, have been developed for different marine mammalian groups [Southall *et al.* (unpublished)].

Sperm whales have been included in the group of mid-frequency odontocetes (assuming that the effective hearing range is >150 Hz) that also includes most delphinids (Ketten, 1997). While it seems highly unlikely that the hearing curve of a sperm whale (Ridgway and Carder, 2001) equals that of a dolphin (Johnson, 1968b), we will use the M-weighting function for impact of transients on midfrequency odontocetes in the present study to avoid additional confusion, accepting that we may thereby underestimate the sensation levels of the pulses impinging on the sperm whales. The weighting function was implemented in the time-domain as a filtering operation prior to exposure calculation. The filter characteristic was realized by a two pole 200 Hz HP filter with a Q factor of unity [sensu. Southall *et al.* (unpublished)].

III. RESULTS AND DISCUSSION

A. Analysis of seismic pulses recorded with onboard tags

The advantage of using onboard, calibrated sound recording tags to make exposure measures is that the sound field quantified is very close to what is received by the whale. However, quantifying low frequency sounds with sound recording tags attached to a moving animal poses the difficulty that other recorded sounds interfere with and can mask the signals of interest. The two major sources of interference are flow noise generated by water movements around the tag and sperm whale clicks that overlap with the analysis windows of the seismic pulses. Figure 2 presents an example of such interference rendering analysis futile. The first arrival (a) is low enough in amplitude to be masked by the flow noise, and the second arrival (c) overlaps in time with a click from the tagged whale (b). Sperm whales produce usual clicks at interclick intervals of 0.4–1 s with click durations, as recorded by a tag attached to the body, of up to 50 ms. The interference duty cycle of some 5% from the tagged whale's own clicks, in concert with occasional high amplitude incoming clicks from other sperm whales, leads to the rejection of a significant number of air-gun pulses that otherwise have sufficient SNR for analysis.

The design and placement of the tag probably give rise to more flow noise around the recording hydrophone than the moving whale hears. The flow noise levels vary significantly over time depending on the activity of the whale and position of the tag. To avoid saturation of the recorder by low frequency flow noise, the Dtags have a built-in one-pole prewhitening filter (f_0=400 Hz), but this high-pass filtering attenuates low frequency sounds of interest below 400 Hz in the same way as it does the flow noise. Likewise, the postemphasizing filter used to flatten the spectral response of the tag down to 45 Hz does not improve the broadband SNR as all low frequency noise is amplified equally. As a result, a number of seismic pulses with low received levels compared to the flow noise could not be analyzed.

A primary goal of the SWSS CEE studies [Miller *et al.*, (unpublished)] was to study the effects of seismic pulses on sperm whales with a target range of received levels from 120 to 160 dB re. 1 μPa (rms). Given the largely unknown radiation pattern of the seismic array and the uncertainties in acoustic propagation, it was necessary to take a conservative approach in positioning the seismic vessel. An additional factor was the frequent presence of dispersed groups of sperm whales near the tagged whale which sometimes prevented close approaches to the tagged whale without the risk of exceeding permitted levels of exposure to other whales. Accordingly, none of the pulses received by tagged sperm whales exceeded the 160 dB re. 1 μPa (rms) limit (maximum of 147 dB re. 1 μPa (rms)) during the CEEs (Table II). The cautious exposure approach in combination with the complex acoustic propagation conditions in the Gulf of Mexico also meant that the received levels of many of the seismic pulses impinging on the whales were low enough to be masked by the flow noise around the tags, rendering analysis impossible. Table I gives the number of pulses analyzed and it is evident that some tag recordings had a high rejection rate due to overlap with sperm whale clicks and poor SNR. This does not necessarily imply that the whales were exposed to a lot of pulses at insignificant levels, only that we were unable to quantify the exposure in these cases.

With the changing levels of flow noise between and within tag attachments, the lowest received levels of pulses that warranted analysis varied between 111 and 125 dB re 1 μPa (rms) (Table II). The quantitative properties of the weakest receptions are therefore under-represented in our assessment of the total exposure. An exception from that caveat is whale sw03_173b, which rested near the surface without clicking or moving much for the entire CEE. During this CEE almost all pulses could be analyzed except for those received when the tag was out of the water during surfacings.

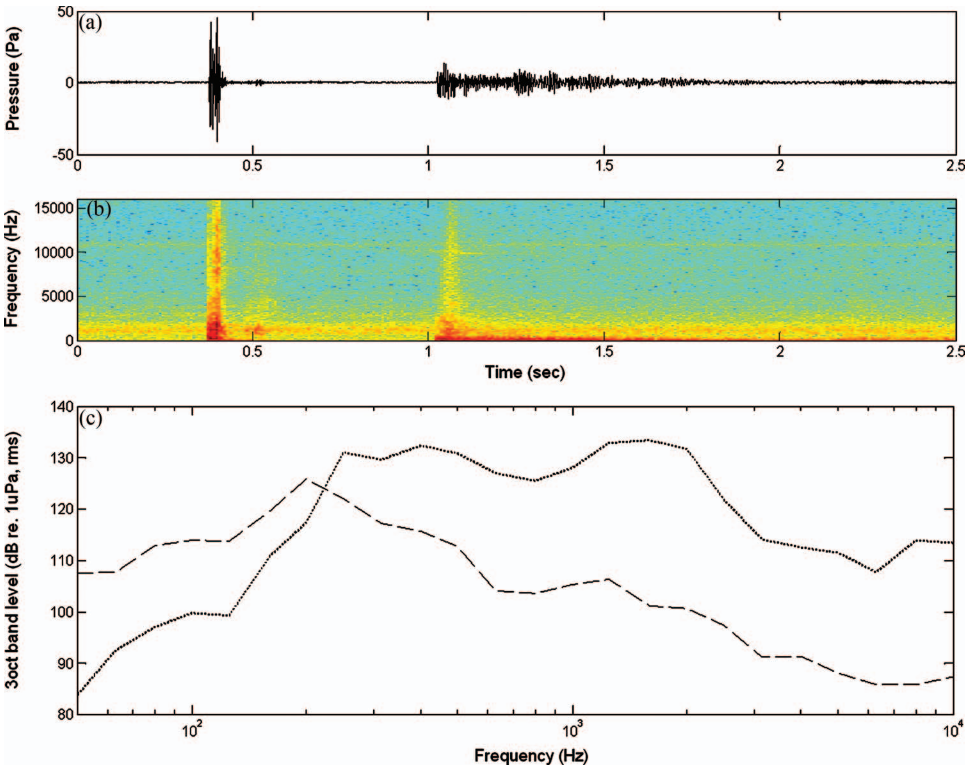

FIG. 3. (a) Wave form of an airgun exposure of whale sw03_173b at a range of 3 km and a depth of 15 m. (b) Spectrogram of the wave form in (a) (FFT=1024, 50% overlap). Note how the first pulse arrival has energy all the way up to the Nyquist frequency at 16 kHz, whereas the second arrival has little energy above 1 kHz. (c) 1/3 octave rms sound pressure levels of the two pulses displayed in (a) and (b). First arrival has a dotted line and the second arrival has a dashed line. The rms levels for these pulses can be converted to 1/3 octave SELs (dB re 1 μPa^2 s) by subtracting 13 dB (54 ms duration) for the rms levels of the first pulse and 7 dB (200 ms max integration time) for the rms levels of the second pulse.

Some of the pulses in this exposure actually clipped the tag. In general, however, it is not meaningful to provide an average exposure level for a CEE or to argue that the range of received levels that could be calculated is representative of the overall acoustic exposure, since pulses of low amplitude are rejected more often than are high level receptions. Nonetheless, the absolute levels that we are able to provide are indisputably close to those received by the whale at a given depth and range from the array and so provide a point characterization of the exposure. It should be recalled that the actual broadband exposure will in some cases be significantly underestimated compared to the true broadband received levels due to the exclusion of energy below 45 Hz and the M-weighting filter that starts at 200 Hz.

A second potential way in which received sound levels may be underestimated relates to the effect of body shading. The mismatch in acoustic impedance between seawater and sperm whale tissue, bone and airways in particular, means that the sound levels at the tag will be attenuated whenever the body of the whale is placed between the source and the tag. This effect will be most severe at high frequencies for which the wavelengths are small compared to the size of sperm whale body parts (Medwin and Clay, 1998). Body shading will therefore lead to a frequency-dependent underestimation of some received levels. The constantly changing geometry between the moving source vessel and the diving whale renders body shading effects inseparable from the effects of changing propagation conditions, but body shading is likely to be range independent and will if anything only lead to an underestimation of the received levels. Resonances in air volumes held within a diving animal might also influence the spectral emphasis of pulses recorded on the animals, but we have no means of testing such a conjecture or of assessing if such resonances would also effect the sound heard by the whale. Nonetheless, this effect can be considered second order compared to changes in whale position and multipath propagation.

B. Received levels and the effects of depth and range

Air-gun arrays are designed to produce a single downward-directed impulse that propagates through the water column and into the seabed. Unavoidably, some sound energy also radiates horizontally from the array creating a complex radiation pattern. The presence of multiple propagation paths involving surface and bottom bounces as well as the re-radiation of sound reverberating within subbottom layers increases the complexity of the received signal and can give rise to long reverberant wave forms of several seconds at long ranges (Greene and Richardson, 1988; Madsen *et al.*, 2002). At the shorter ranges of interest here ($<$13 km), the question is whether sperm whales are effectively exposed to a single impulse with properties akin to those of the on-axis pulse from the array or if a more complex multipulsed exposure is occurring [DeRuiter *et al.* (unpublished)].

To answer this question with an example, Fig. 3(a) shows the wave forms of pulses received by a sperm whale at a range of 3 km and at a depth of 15 m. The first arrival consists of a short, well-defined transient followed some 500 ms later by a reverberant second arrival with a long decaying tail. This pattern of multiple arrivals was observed in all exposures that could be analyzed and it is evident that, with each firing of the array, the whale may receive several pulses with differing temporal and spectral properties. An immediate consequence is that acoustic exposure of animals by air-gun arrays should not be modeled by a single well-defined pulse arrival for each firing of the array. Detailed modeling of the acoustic propagation that leads to this arrival pattern is beyond the scope of the present paper and is treated in detail by DeRuiter *et al.* (unpublished). Here we focus only on the two strongest arrivals, since the remaining pulses carry relatively little energy.

The CEE involving whale sw03_173b which rested near the surface throughout the exposure provides an opportunity to examine the relationship between range and RL at shallow depths. Figure 4 displays how the received levels in the first and second arrivals changed over time as the source vessel approached the whale and moved away from it again. The first arrivals actually saturated the recorder during the closest approach at a range of 1–2 km and the levels in that period of time are therefore underestimated (Fig. 4). The first arrivals have short durations from 15 to 30 ms whereas the second arrivals have durations up to and beyond the 200 ms maximum analysis window due to multipath spreading. The second arrivals therefore have higher SELs and lower rms levels for a given peak pressure due to the longer integration (SEL) and averaging times (rms) [Figs. 3(a) and 4]. While the levels of both arrivals increase with reducing range to the source vessel, the variation in received levels of the first arrivals is much larger than for the second which, given their time delay with respect to the first arrivals, are likely bottom reflections. While the received levels are highest for the second arrivals at the beginning of the CEE when the source was about 5 km from the whale, the received levels of the first arrival quickly dominate in terms of p-p and rms pressure as the source approached. There is less variation over the course of the exposure when the received levels are quantified as SEL because the longer durations of the weaker second arrivals tend to compensate for their reduced peak pressure (Fig. 5).

Since almost all of the pulses received by whale sw03_173b could be analyzed, the entire exposure history of this animal throughout the CEE could be estimated. We use SEL as the measure of acoustic exposure. The cumulated SEL experienced by sw03_173b as a function of time is displayed in Fig. 5. It is seen that the second pulse arrivals dominate the exposure during the first 15 min, and that the first pulse arrivals contribute little to the overall exposure in this time interval. As the source vessel approaches, the SEL of the first arriving pulse increases rapidly and the first pulse arrivals become the determining factor for the overall exposure. The implication is that the second pulse arrivals may be more important for a near-surface whale that is distant from the source whereas direct arrivals will dominate at shorter ranges but both pulse arrivals must be considered to avoid underestimation of the combined acoustic exposure.

We argue that the overall acoustic exposure, calculated as in Fig. 5, should be considered as an exposure metric along with the maximum received sound pressure levels and SELs of individual pulses, when assessing the impact of transient noise sources on marine mammals. However, cumulated energy cannot serve as a stand alone measure for mitigation since an overall exposure of 151 dB re. 1 μPa^2 s like the one displayed in Fig. 5 could be achieved with a single 200 ms tone with a rms sound pressure level of 158 dB re. 1 μPa (rms) $[151=158+10\log(0.2\text{ s})]$ or with a single or a few ultrashort transients of very high sound pres-

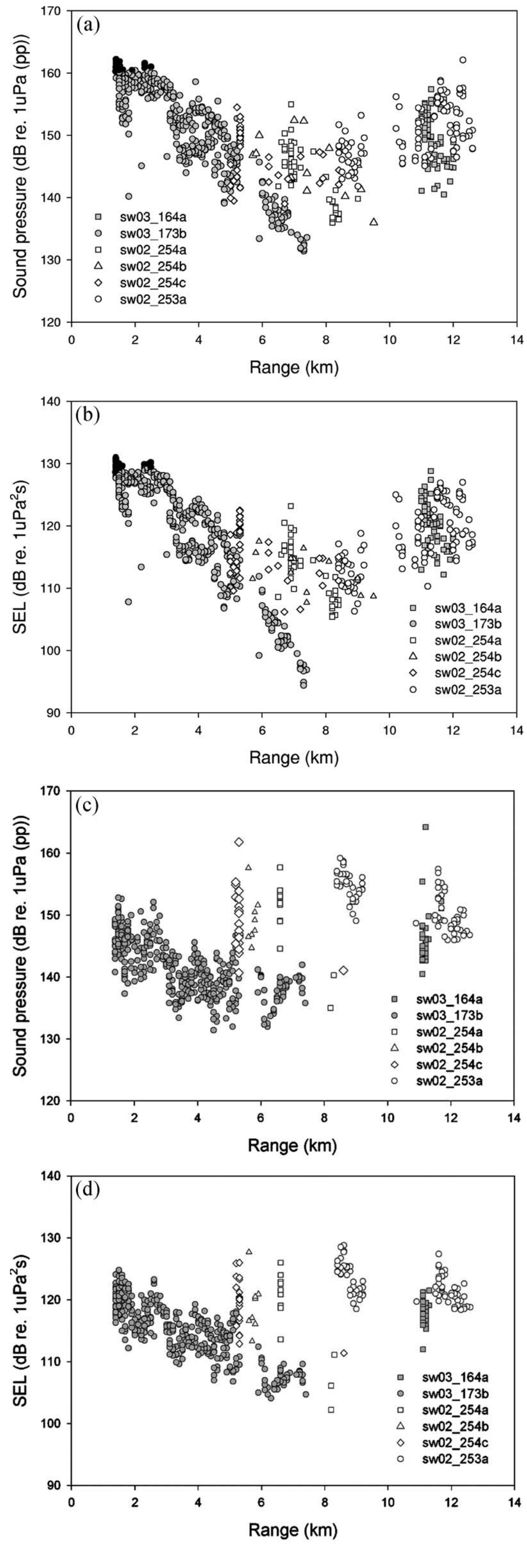

FIG. 4. (a) Received peak-peak sound pressure levels of the first arrival for each airgun pulse that could be analyzed as a function of range from all CEEs where range to the whale could be derived. The highest levels closest to the source were clipped (closed dark circles). The data are from six different whales during two seasons using two different seismic arrays. Note how the received levels reach a minimum between 5 and 9 km, after which the received levels increase again with range. (b) sound exposure levels (SEL, dB re. 1 μPa^2 s) for the same pulses as displayed in (a). (c) Received peak-peak sound pressure levels of the second arrival for each airgun pulse that could be analyzed as a function of range from all CEEs where range to the whale could be derived. Note how the received levels of this pulse component actually increase with range beyond 5 km. (d) Sound exposure levels (SEL, dB re. 1 μPa^2 s) for the same pulses as displayed in (c).

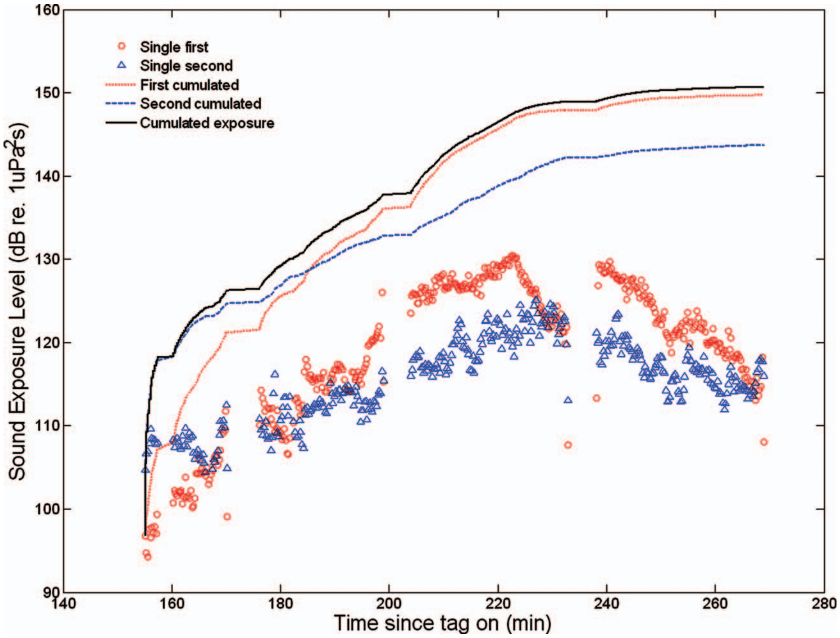

FIG. 5. Acoustic exposure of whale sw03_173b during the entire CEE with the exception of pulses impinging on the whale when surfaced. Circles denote received sound exposure levels (SEL, dB re. 1 μPa^2 s) of first arriving pulses as a function of time (min). Triangles denote received SELs of second arrivals as a function of time. Dotted line shows cumulative SEL of the first arrivals and the dashed line shows cumulative SEL of the second arrivals over course of time. The solid line shows the overall accumulating exposure as a function of time. The full acoustic M-weighted exposure during this CEE amounted to 150.7 dB re. 1 μPa^2 s. Some pulses received at the shortest distance between the array and the whale were clipped, leading to an underestimation of the overall sound exposure level.

sures above 200 dB re 1 μPa (pp) (or any combination in between). While the former may only lead to short term behavioral disruption, the high level transient exposure could perhaps induce stronger effects. Similarly, a few sound pulses may only evoke little or no behavioral response, whereas a long sequence of the same pulses could have negative effects through sensitization (Richardson *et al.*, 1995).

In contrast to sw03_173b, most of the exposed whales continued to perform foraging dives throughout the exposure. Data from these animals provide an indication of the way that the sound exposure varies with distance over the normal range of depths traversed by sperm whales. Figure 4 plots all received levels for whales for which the range to the array could be determined. It is evident that there is no simple relationship between received levels of the first pulse arrivals and the range to the seismic array no matter whether RLpp (4a) or SEL (4b) are considered. Rather, the received levels fall to a minimum between 5 and 9 km and then start increasing again at ranges between 9 and 13 km. It must be emphasized that these received levels as a function of range are generated from six different whales during two field seasons with different seismic arrays. Nevertheless, the pattern is consistent across both seasons, and within individual experiments. It must be concluded that the received level of first pulse arrivals can be just as high (160 dB re. 1 μPa, pp) at 12 km as at a range of 2 km from the array. When looking at the secondary arrivals [Figs. 4(c) and 4(d)], it is seen that they have higher received levels at 5–12.6 km than at ranges closer to the seismic sources. It is therefore clear that sperm whale exposure to different pulse components at ranges from 1 to 13 km from the seismic sources does not necessarily attenuate with increasing range. Rather, both received sound pressures and SELs may actually increase if the whales move from say 7 to 12 km (Fig. 4). Similar results have also been reported from recordings of air-gun arrays operating in the Gulf of Mexico and off California in 1995, where shallow hydrophones (10–100 m) received sound pressure levels with several range-dependent local maxima up to 170 dB re 1 μPa (pp) from 3 to 10 km (Lepage *et al.*, 1995; 1996).

These exposure patterns emerge because the received levels from different pulse components in this range interval and in this location do not conform to simple geometric spreading laws such as 20 log(Range) (Urick, 1983). In fact whales diving in a stratified water column at variable ranges are exposed to a much more complicated sound field due to multipath propagation [Lepage *et al.*, 1995; 1996; DeRuiter *et al.* (unpublished)].

Acoustic shadow and convergence zones are generated by downward refracting sound speed profiles such as are found in the summer months in the Gulf of Mexico. Since such situations are common, and this type of profile results in distinct, robust "shadow zone-convergence zone" characteristics of the acoustic waveguide, it can be useful to make some general approximations for the extent of these zones, both for scientific and regulatory purposes. We derive such rules here, using standard results from ocean acoustics. See DeRuiter *et al.* (unpublished) for in-depth analysis and modeling of the sound propagation leading to the observed exposures.

Consider the simplified geometric situation depicted in Fig. 6. A near-surface source transmits sound in a downward

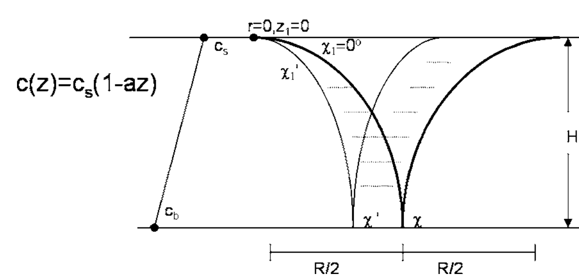

FIG. 6. Geometry for downward refracting rays and their convergence/shadow zones.

refracting waveguide of depth H with a linearly decreasing sound speed profile:

$$c(z) = c_s(1 - az). \tag{3}$$

The ray with a launch angle of zero degrees ($\chi_1 = 0$) with respect to the water surface will travel the farthest before being refracted down toward the bottom, and so defines the upper limit of the ensonified zone surrounding the source. The ray that hits the bottom at the critical grazing angle ($\chi' = \theta_{\mathrm{crit}}^{\mathrm{grazing}}$) will define the nearer limit of the second ensonified zone following the shadow zone, as rays hitting the bottom at steeper angles will transfer most of their energy into the substrate. As depicted in Fig. 6, rays with launch angles between χ_1 and χ_1' define the extent of the subsequent ensonified zone. Here we will focus on the zero degree launch angle ray, since it loses the least amount of energy due to having the lowest bottom grazing angle (bottom loss generally increases with increasing angle of interaction with the seabed).

Following the method of Brekhovskikh and Lysanov (2003), we define r and z as the horizontal range and depth, respectively, and place the source at $r_1 = 0$ and $z_1 = 0$. The reception point, i.e., the whale, is at position r, z. For an infinitesimal segment of the raypath, $dr = |dz/\tan\chi|$ where χ is the local grazing angle of the ray. Integrating this between source and receiver depths gives the relation:

$$r = \left| \int_{z1}^{z} \frac{dz}{\tan\chi} \right|. \tag{4}$$

Applying Snell's law, the grazing angle $\chi(z)$ can be expressed in terms of the launch angle, χ_1, as

$$\cos\chi = (1/n)\cos\chi_1, \tag{5}$$

where $n = n(z) = c_1/c(z)$ is the index of refraction. Using these equations, Eq. (4) can be rewritten:

$$r = \cos\chi_1 \left| \int_{z_1}^{z} [n^2(z) - \cos^2\chi_1]^{-1/2} dz \right|. \tag{6}$$

Equation (4) can be used to define the ensonified zones by substituting the launch angles $\chi_1 = 0$ for the longest range ray or $\chi_1 = \chi_1^{\mathrm{crit}}$, the solution of Eq. (5) for $\chi = \theta_{\mathrm{crit}}^{\mathrm{grazing}}$, for the shortest ray. For $\chi_1 = 0$ and the linear sound speed profile, $c(z)$, defined in Eq. (3), we get from Eq. (6):

$$r = \left| \int_{0}^{H} [(1 - az)^{-2} - 1]^{-1/2} dz \right| \tag{7}$$

For the locations and times of year for which data are reported here, the difference between the surface and bottom sound speed at 800 m depth was 50 m/s, so that $a \approx 0.00004\ \mathrm{m}^{-1}$ from Eq. (3), i.e., a is a very small number. Thus the integrand of Eq. (7) can be well-approximated by a binomial expansion truncated at the linear term. Since $(1 - az)^{-2} \approx 1 + 2az$, we obtain

$$r \approx \left| \int_{0}^{H} (2az)^{-1/2} dz \right|, \tag{8}$$

which can be readily evaluated to give the solution for r:

$$r = \sqrt{\frac{2H}{a}}, \tag{9}$$

which is the horizontal distance traversed by the longest traveling ray before reaching the bottom, a distance denoted as $R/2$ in Fig. 6 (R is the total ray cycle distance, so the bottom reflection point is one half of this). For the CEEs examined here, $R/2 \sim 6.3$ km, in reasonable agreement with the received level patterns over two years from different whales (Fig. 4).

An even simpler estimate of the ray half cycle distance can be derived by replacing the grazing angle $\chi(z)$ by a constant angle defined as one half the difference between the launch angle and the bottom grazing angle of impact. Likewise, the sound-speed profile can be replaced by the average sound-speed over the waveguide height in an "isovelocity" approximation. With these approximations, $R/2$ can be estimated with straight-line geometry as

$$R/2 \approx \frac{H}{\tan\theta^{\mathrm{average}}}. \tag{10}$$

Using even this crude estimate gives $R/2 \sim 8.1$ km, which is also in reasonable agreement with our data (Fig. 4). Straightforward ray tracing models therefore seem to be

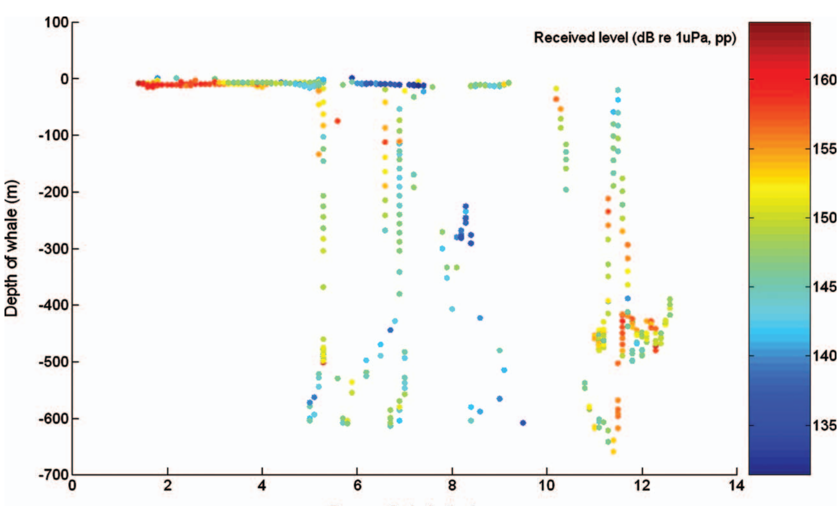

FIG. 7. Received peak-peak sound pressure levels (dB re. 1 μPa, pp) for all pulses that could be analyzed and for which depth and range could be derived. A few pulses close to the source were clipped. Note that the received levels can be as high at 12 km range (450 m depth) as at a range of 2 km. There is an important gap in the data set with no measurements on whales with depth greater than 20 m at ranges shorter than 4 km to the air gun source.

useful for predicting sound exposure levels as a function of receiver depth and range from the source. Moreover, these results appear to be fairly robust between years in the Gulf of Mexico (Fig. 4).

The variability in received levels of both pulse arrivals to the tagged whales as a function of both depth and range is summarized in Fig. 7. It is seen that whales, while ascending or descending during foraging dives, move in and out of the acoustic convergence and shadow zones, where the received sound pressure levels and SELs can change rapidly. It is also clear that at times during the CEE, the whales would have been exposed to much lower levels than those depicted in Fig. 4, which only includes pulses with a SNR of more than 10 dB. The collected data show that none of the sperm whales were exposed to sound levels higher than 162 dB re. 1 μPa (pp) (147 rms and 131 SEL) when diving more than 2 km from the seismic sources (Figs. 4 and 7). These received levels match fairly well with the findings of Tolstoy *et al.* (2004),[2] but the findings of Lepage *et al.* (1996) reporting broadband received level maxima of more than 170 dB re 1 μPa (pp) out to ranges of 7 km emphasize that broadband received levels are likely higher than reported for the M-weighted pulses in the present study. It is important to note that no data were obtained from deep-diving whales within 4 km of the source, as the only whale that was approached closely made shallow dives while the array was firing. Clearly the highest received levels will be experienced within the downward-projected beam of the airgun array where we were unable to collect data.

It is not the intention of this paper to evaluate the possible effects of sound on the behavior of exposed whales [see Miller *et al.*, (unpublished)]. However, if pulses with received levels in the range 140–165 dB re. 1 μPa (pp) (115 to 135 SEL) are found to have negative effects on sperm whales (as seen for bowhead whales (Richardson *et al.*, 1986; Ljungblad *et al.*, 1988), then animals in the Gulf of Mexico could be impacted at ranges of more than 10 km from seismic survey vessels, well beyond the ranges predicted by geometric spreading laws and beyond where visual observers on the source vessel can monitor effectively. We have shown that if whales wish to reduce their exposure then horizontal displacement away from the seismic survey vessel may not be the correct strategy. Rather, in the 5–9 km range, they may, depending on the acoustic propagation conditions, reduce their exposure by moving closer to the array or by vertical rather than horizontal displacement. Such movements, while reducing received levels in the short-term, might end up prolonging the overall exposure time and the accumulated SEL. This observation is of particular relevance when employing ramp-up procedures under the untested assumption that these will lead to horizontal displacement of animals away from the array.

The propagation conditions over ranges of kilometers in a deep water habitat like the Gulf of Mexico are incompatible with the zones of exposure method for rating potential impacts outlined by Richardson *et al.* (1995), which is based on the assumption that received levels decrease with range in a simple fashion with less and less impact on the exposed animals further from the noise source (NRC, 2005). If the received levels measured here in the range from 1 to 13 km have no significant effect on marine life, the effects of multipath propagation can be ignored from an environmental mitigation perspective. However, if received levels in this dB range are impactful as seen for some baleen whale species (Malme *et al.*, 1985; Richardson *et al.*, 1995), we face the challenge of how to mitigate under such conditions, where animals can dive in and out of high exposure levels at considerable ranges from the air-gun array (see also Lepage *et al.*, 1996).

C. Spectral properties and high frequency by-products

Noise transients produced by seismic survey vessels are designed to have maximum sound energy at around 50 Hz (Dragoset, 1990; Barger and Hamblen, 1980) and their impact on toothed whales, which are considered to be less sensitive to low frequency sound (Au *et al.*, 1997), could accordingly be assumed small (NRC, 2005). Dissenting data, reported by Goold and Fish (1998), showed that dolphins can be exposed to noise above ambient levels from air-gun pulses at frequencies of up to 8 kHz and at ranges up to 8 km. Resolution of this issue is important since the impact in terms of masking, physical damage and sensation levels on different cetaceans will relate to the frequency content of the noise pulses in question (Harris, 1997). The present data set provides an opportunity to test these contentions by measuring the absolute band levels of pulses impinging on sperm whales.

The spectral distribution of noise is often defined in terms of power spectral density (dB re. 1 $\mu Pa^2/Hz$) or energy flux spectral density (dB re. 1 $\mu Pa^2 s/Hz$) with both measures using an analysis bandwidth of 1 Hz. In contrast, the mammalian ear integrates energy over much broader bandwidths. It is common practice in describing noise exposure to approximate the way noise is integrated by the auditory system of mammals by measuring the rms noise power in 1/3 octave bands (third octave levels (TOL), dB re. 1 μPa, rms) (Richardson *et al.*, 1995). As an example, Fig. 3(b) presents the spectrogram of a seismic signal [Fig. 3(a)] received on sw03_173b while the whale was resting close to the surface and so well away from the axis of the sound source. The energy in the first arrival extends to the Nyquist cut-off frequency at 15 kHz, whereas the energy in the second arrival is concentrated below 500 Hz. To quantify the frequency distributions of these two arrivals, we performed a TOL analysis on the wave forms correcting for the HP filter of the tag but without the M-weighting. The result displayed in Fig. 3(c) shows that, despite the flat recording response to 45 Hz, the first arrival carries little energy below 300 Hz where the energy of an on-axis airgun pulse would be concentrated (Dragoset, 1990; Caldwell and Dragoset, 2000). Instead the energy is concentrated in the third octaves from 300 Hz to 3 kHz where the TOLs experienced by the whale 3 km from the array are around 130 dB re. 1 μPa rms. In contrast, the energy in the second arrival is concentrated at low frequencies around 200 Hz. This pattern was consistent over the entire CEE involving sw03_173b and was observed with less regularity in all other CEEs.

The observation that sperm whales are exposed to significant levels of high frequency energy from air-gun arrays is consistent with the report of Goold and Fish (1998). This high frequency energy is a by-product of the air-gun sound source and is beyond the frequency range within which air guns are usually characterized. Although its relative contribution to the overall output of the source is likely small (Tolstoy *et al.*, 2004), the relevant parameter for assessing the impact of seismic pulses on marine mammals is the absolute received levels at frequencies where the exposed animals have good hearing sensitivity. While it may not be surprising that a powerful impulsive sound source like an air gun could generate by-products with considerable energy at higher frequencies, this has not been addressed quantitatively before and the observation warrants further measurements and modeling as started by Tolstoy *et al.* (2004).

High SL emission of energy at midfrequencies has the potential to affect animals with apparent less sensitive low frequency hearing such as dolphins and beaked whales which are normally not considered in assessments of impacts from seismic surveying (Tolstoy *et al.*, 2004). Here we document that a whale more than 1400 m from the air-gun array received more than 162 dB re. 1 μPa (pp) (147 rms, 131 SEL) from pulses with essentially no energy below 300 Hz emphasizing that the potential for negative effects of this high frequency by-product on marine mammals should not be dismissed lightly. That predominantly high frequency pulses were received by whales near the surface is consistent with their radiation from grating lobes in the source array beam pattern. The combination of the Lloyd's mirror effect attenuating low frequency energy by destructive interference, and a high-frequency surface duct in the warm stratified summer water of the Gulf of Mexico will lead to high pass filtering of the signal [Deruiter *et al.*, (unpublished)]. All air-breathing mammals are forced to spend significant time near the sea surface to ventilate their lungs between dives. Deep diving marine mammals, such as sperm whales and beaked whales, will enter the high frequency exposure zone from air-gun arrays, when oceanographic conditions support it, whenever returning to the surface to recover from deep dives. Some species, such as pelagic dolphins, will likely be more exposed to the high frequency components, because they spend more time traveling and socializing near the surface.

The presence of significant energy at high frequencies in some air-gun pulses not only implies that the sensation levels are likely higher than previously expected for toothed whales, but also that the potential for masking should be considered. Masking occurs when the noise power is increased in one or more critical bands that overlap in the frequency domain with a signal of interest (Richardson *et al.*, 1995). Some sperm whale click types (e.g., coda, slow, and calf clicks) that are believed to serve a communicative purpose have most of their energy below 5 kHz (Madsen, 2002) and so overlap in frequency with the high frequency energy in some air-gun pulses. While masking of sperm whale communication sounds accordingly could occur, the short duration and low duty cycle of the high frequency air-gun transients renders the masking power very small as compared to comparable continuous noise, for example, from ship traffic (Aguilar *et al.*, 2006) So despite the presence of high frequency energy in some air-gun pulses, the low duty cycle of air-gun noise suggests that the pulses are not likely to pose a significant masking problem for sperm whale acoustic communication or echolocation.

IV. CONCLUSION

Onboard acoustic recording tags have been used to quantify the sound field impinging on sperm whales from air-gun arrays during a series of controlled exposure experiments in the Gulf of Mexico. We have demonstrated that, due to multipath propagation, sperm whales are exposed to several pulses for each firing of the array with very different temporal and spectral properties. Noise exposure estimates should consider these different pulse components and their potential combined impacts. Sperm whales diving at ranges between 4 and 13 km were exposed to pulses with received levels of up to 162 dB re 1 μPa (pp) (127 dB re. 1 μPa^2 s). The relative strength of pulses arriving on different paths vary with range and depth of the diving whales, but the absolute received levels can be as high at 12 km as they are at 2 km. We conclude that simple geometric spreading models cannot be used to establish impact zones when assessing potential effects on marine mammals in a deep water habitat like the Gulf of Mexico. We have also shown that air-gun arrays can generate high absolute levels of sound energy at frequencies octaves higher than that used for seismic profiling. Some pulse components have the bulk of their energy at frequencies above 300 Hz, and the relatively high received levels of such pulses at ranges of kilometers from the operating array is a cause for concern for toothed whales, including smaller species such as dolphins and beaked whales, not normally considered when assessing the impact of seismic surveys on marine life. The current study did not provide exposure measurements for sperm whales diving deep closer than 4 km from the array, and this lack of data should be addressed in further experiments. The different exposures experienced by whales while diving as compared to resting near the surface emphasize that sound exposure as a function of depth and range should not be extrapolated between habitats with varying sound velocity profiles and bottom properties.

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[1]Sound level back-calculated to 1 m range on the acoustic axis of the source (Urick, 1983).

[2]Tolstoy *et al.* used much longer fixed averaging times for derivation of rms levels and their levels were not M-weighted.

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