Broadband spectra of seismic survey air-gun emissions, with reference to dolphin auditory thresholds

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Acoustic emissions from a 2120 cubic in. air-gun array were recorded through a towed hydrophone assembly during an oil industry 2-D seismic survey off the West Wales Coast of the British Isles. Recorded seismic pulses were sampled, calibrated, and analyzed post-survey to investigate power levels of the pulses in the band 200 Hz–22 kHz at 750-m, 1-km, 2.2-km, and 8-km range from source. At 750-m range from source, seismic pulse power at the 200-Hz end of the spectrum was 140 dB *re*: 1 μPa^2/Hz, and at the 20-kHz end of the spectrum seismic pulse power was 90 dB *re*: 1 μPa^2/Hz. Although the background noise levels of the seismic recordings were far in excess of ambient, due to the proximity of engine, propeller, and flow sources of the ship towing the hydrophone, seismic power dominated the entire recorded bandwidth of 200 Hz–22 kHz at ranges of up to 2 km from the air-gun source. Even at 8-km range seismic power was still clearly in excess of the high background noise levels up to 8 kHz. Acoustic observations of common dolphins during preceding seismic surveys suggest that these animals avoided the immediate vicinity of the air-gun array while firing was in progress, i.e., localized disturbance occurred during seismic surveying. Although a general pattern of localized disturbance is suggested, one specific observation revealed that common dolphins were able to tolerate the seismic pulses at 1-km range from the air-gun array. Given the high broadband seismic pulse power levels across the entire recorded bandwidth, and known auditory thresholds for several dolphin species, we consider such seismic emissions to be clearly audible to dolphins across a bandwidth of tens on kilohertz, and at least out to 8-km range. © *1998 Acoustical Society of America.* [S0001-4966(98)04004-1]

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LIST OF SYMBOLS

DAT   Digital Audio Tape
GPS   Global Positioning System
CTD   Conductivity, Temperature, and Depth
HPF   High Pass Filter
2-D   two dimensional

INTRODUCTION

One of the ''noise pollution'' issues of great concern in recent years is that of high levels of manmade noise introduced into the marine environment, and the effects this may have on marine life, especially higher organisms such as marine mammals. Much concern has focused upon the possible effect that increased noise levels may have on cetaceans (whales and dolphins). These concerns range from impairment of cetaceans' ability to communicate acoustically, due to overall increases in background noise levels, to the possibility of physiological damage to sensory and other body organs induced by the proximity of high energy sound sources. Maritime seismic surveying is perceived as one particular threat, the effects of which may span this range of possibilities.

Seismic surveys in the marine environment are generally one of the first stages in the exploration for oil and gas reserves beneath the seabed. Operational modes may vary, but the general methodology involves a large survey ship towing the sound source and receiver equipment. The sound source is generally an array of air guns which produce loud impulsive bursts of underwater sound from the release of compressed air, forming a rapidly expanding and contracting bubble. The bubble collapse causes a transient, of relatively slow rise time compared to chemical explosives, which is geared to the production of primarily low-frequency energy in the subkilohertz region. The characteristics of the sound pulse produced can be modified to a certain extent by the composition and geometry of the gun array. The receiver equipment is generally a long streamer behind the ship (often several kilometers in length) which houses an array of hydrophone elements. Sound energy radiating outward from the gun array propagates downward through the seabed and reflects from discontinuities in the underlying rock strata, such as oil and gas pockets. The reflected sound waves are received by the trailing hydrophone array and the data processed and archived aboard ship, ultimately to be used for mapping the subsurface topography.
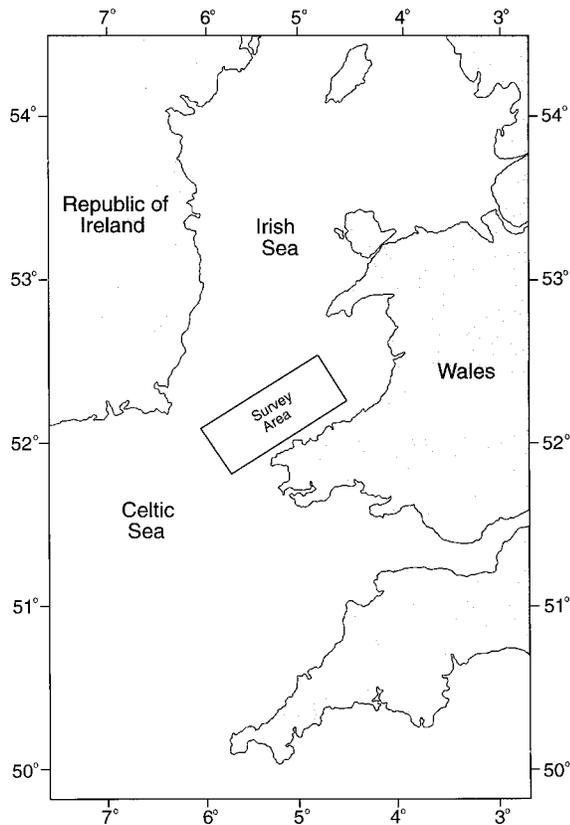
FIG. 1. Chart showing location of seismic/dolphin survey area in relation to the British Coastline. Degrees of latitude and longitude are north of the equator and west of Greenwich meridian, respectively.

Although the output of air gun arrays is usually ''tuned'' to produce a concentration of low-frequency energy, the impulsive nature of the bubble collapse inevitably results in a broadband sound characteristic. In addition there is considerable lateral spreading of sound energy from the gun array into the wider marine environment. Air gun array source levels at the low-frequency end of the spectrum below 100 Hz, are high, typically in the order of 220–240 dB re: 1 μPa @1 m (Barger and Hamblen, 1980; Greene and Richardson, 1988; Richardson $et\ al.$, 1995; Richardson and Wursig, 1997). Seismic pulses are often detectable >100 km from source (R. J. Morris, personal communication; Richardson and Wursig, 1997), and in deep water may be audible >1000 km from source (Richardson and Wursig, 1997). Indeed our own observations during Irish Sea seismic surveys revealed that pulses were audible on hydrophone recordings above the highly elevated background ship noise at least up to 20-km range. High-frequency energy in the seismic pulse spectrum (i.e., above 1 kHz) has generally been ignored in the literature, and in any case is of little interest to the seismic industry, being filtered from survey recordings as ''unwanted clutter.'' In this paper we examine the broadband output from a 2120 cubic in. air-gun array, used at sea during an oil industry 2-D seismic survey off the West Wales Coast of the British Isles in March 1996.

I. METHODS

A. Field recording

Seismic surveying was conducted in the southern Irish Sea off the West Wales Coast (Fig. 1), a shallow shelf area of between 50 and 100 m depth. Recordings of seismic emissions were made from the guard ship, a smaller vessel used in conjunction with the main seismic ship to keep other shipping traffic clear of the long survey streamers. The guard ship generally steamed just ahead of the seismic ship while ''shooting seismic'' was underway. Shooting along a single seismic survey line typically lasted some 2–3 h, with air-gun shots approximately every 10 s; the seismic survey lasted the entire month of March. The guard ship recording apparatus consisted of a 250-m towed stereo hydrophone assembly, with transducer–preamplifier elements positioned 180-m and 230-m aft of the guard ship during tow. The tow depth of the elements was undetermined, but probably within 10 m of the surface and definitely within 20 m as shallow obstacles at 20-m depth were cleared by the tow. Signal output from the rearmost hydrophone element was taken directly to the left channel input of a SONY TCD-D10 DAT recorder, and was used to record seismic pulses flat ± 2.5 dB re: 1 μPa in the band 200 Hz–22 kHz. The hydrophone–preamplifier units had integral first order 200-Hz HPF circuits attenuating the input signal below the 200-Hz threshold frequency. Signal output from the forwardmost hydrophone was fed through an additional external HPF stage, with filter break at approximately 6 kHz, and passed to the right channel input of the DAT recorder. The right channel recording (filtered at 6 kHz) was used for manual listening post survey to evaluate dolphin sounds in the area (see Goold, 1996). The left channel recording (filtered at 200 Hz) was used for the analysis of seismic pulses.

The seismic ship was fitted with a differential GPS navigation unit for accurate determination of position to approximately ± 2 m. The guard ship was fitted with nondifferential civilian GPS, and could fix its geographic position to approximately ± 100 m. Both vessels stored absolute time and position continuously from their GPS units on computer disk and these data were used post survey to determine source–receiver ranges. With the air-gun array (geometry illustrated in Fig. 2) towed 90 m behind the large seismic vessel, and the hydrophone receive element towed 230 m behind the much smaller guard ship, GPS center positions for both vessels were used to calculate the distance between sound source and receiver to a precision of ± 100 m.

Although the two vessels generally remained close together for operational reasons, with the guard ship directly ahead of the seismic ship, the occasional opportunity was taken to perform ''walk-away'' tests where the guard ship increased speed and steamed ahead of the seismic ship. This procedure was used to increase the distance between the two ships during the 2–3 h of continuous seismic shooting per survey line. Assessment of received seismic power at extended distance from source was thereby possible, with GPS positions used to determine source–receiver ranges. Seismic pulses analyzed in this work were all recorded at bow aspect
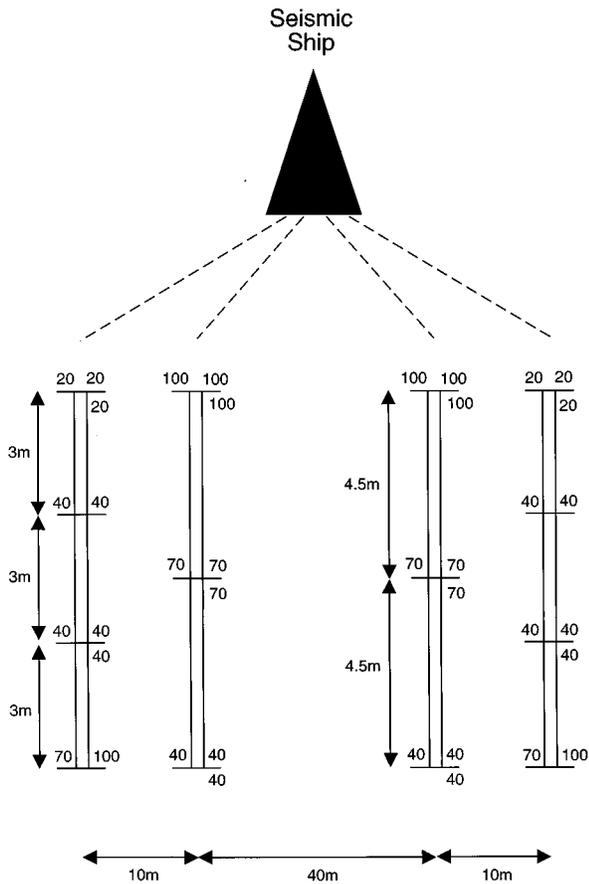
FIG. 2. Geometry of 2120 cubic in. air-gun array used during the seismic surveys. The survey vessel towed four elongated floats, shown as vertical bars, from which 14 gun clusters were suspended to 5 m depth. Numbers along the floats indicate position and capacity (in cubic inches) of each individual sleeve gun, totaling an array capacity of 2120 cubic in. Arrowed lines indicate the geometrical spacing of the various elements in meters.

to the seismic vessel, i.e., with the guard ship steaming directly ahead of, and on the same course as, the seismic ship.

B. Equipment calibrations

1. Hydrophone

The transducers used in the towed hydrophone were Benthos AQ-4 elements, and the preamplifiers were miniaturized transistor units with a gain of 30 dB. The composite hydrophone–preamplifier unit was calibrated against a precise reference transducer at the Sonar and Signal Processing Unit of the Loughborough University of Technology and shown to have a response of -172 dB re: 1 V/μPa$\pm$1.5 dB across the frequency range 4 kHz–24 kHz. The result is consistent with Benthos specifications for the AQ-4 element (plus 30-dB preamplifier gain). Although calibration could not be made below 4 kHz due to reverberation within the test tank, Benthos specifications indicate the element to have a flat response at least down to 200 Hz. As the preamplifiers had built in 200-Hz high pass filter circuits, the -172 dB re: 1 V/μPa voltage response of the hydrophone was taken to apply across the recorded bandwidth between 200 Hz and 22 kHz.
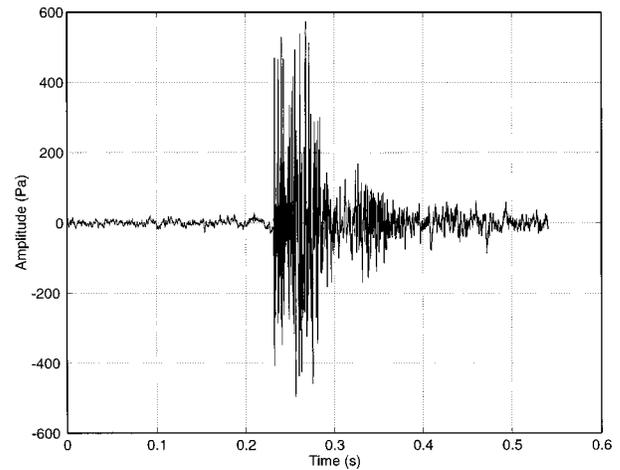

FIG. 3. Waveform trace showing a typical seismic pulse recorded through a 200-Hz High Pass Filter 750 m from the air-gun source at bow aspect.

2. Recording/sampling system

Recorded sounds were sampled from the DAT recorder analog line output onto computer disk using a Cambridge Electronic Design (CED) 1401 laboratory interface. These data were then imported into MATLAB version 4.2c for further analysis. The conversion factor from DAT recorder input to MATLAB data was measured by recording and replaying a series of 10-kHz sinewaves (a frequency in the center of the DAT recorder band) from 1 to 128 mV amplitude, with all recorder gain settings fixed from their fieldwork levels. A linear regression analysis on the MATLAB data versus DAT input voltage yielded the required factor. This factor together with the hydrophone calibration enabled the conversion of MATLAB data into acoustic pressure.

A cursory check was also made of the DAT recorder frequency response, which was specified by the manufacturers to be flat ± 1 dB between 20 Hz and 22 kHz. A synthesized composite signal of eight sinewaves, each of equal amplitude and spanning the DAT recorder frequency range, was recorded through the line input and subsequently replayed and sampled to disk from the line output. The composite signal was imported to MATLAB, rescaled to true voltage using the DAT to MATLAB voltage conversion factor, and subjected to power spectral density analysis through a sliding 2048 point Hanning window. rms amplitude values from integration around the eight frequency peaks were found to be within ± 0.4 dB of the rms sinewave amplitudes, and the manufacturers specification of ± 1 dB was therefore considered adequate as a measure of frequency response flatness. The overall spectral analysis of seismic data, taking into account the hydrophone response, is considered to be flat ± 2.5 dB.

C. Seismic analysis

Seismic sounds were sampled to disk from the DAT recordings, with a sampling rate of 45.455 kHz, and the wave data units converted to sound pressure amplitude by application of the DAT to MATLAB conversion factor. Seismic pulse waveforms were selected from recordings taken at
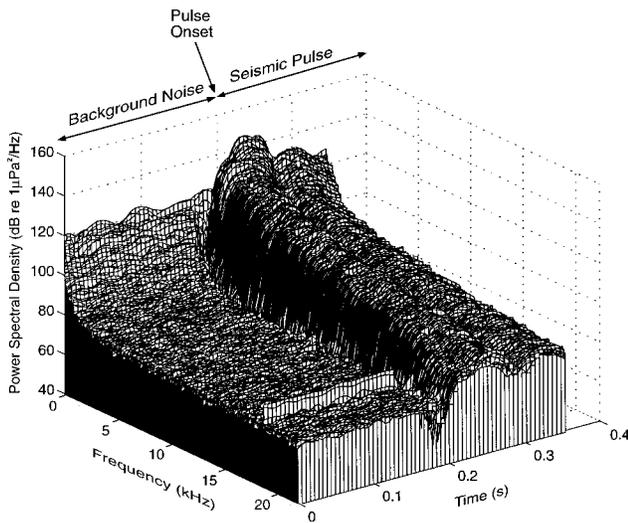
FIG. 4. Power-frequency-time matrix plot of average background noise preceding average maximum seismic pulse power at 750-m range from the 2120 cubic in. air-gun array. The seismic pulse onset occurs at 0.2 s in the plot, and there is clearly a surge in power across the entire bandwidth of 200 Hz–22 kHz.

source–receiver ranges of 750 m, 1 km, 2.2 km, and 8 km. Figure 3 shows a typical seismic pulse recorded 750 m from source. The waveform is a complex of high and low frequencies of uncertain duration, and a short-time Fourier transform method was employed to analyze the time-frequency structure of sequences of pulses. In analyzing any signal with a time-varying frequency content the choice of analysis window duration is important. Time and frequency resolution are inversely proportional, short windows giving good temporal resolution and poor frequency resolution and *vice versa* (Papoulis, 1984). To ascertain the window length giving the least spectral power estimate reduction resulting from time-frequency analysis in the onset region of the pulses, power spectral density analysis was performed on the pulse onset region (i.e., maximum energy region) through Hanning windows of various length, based on 2^n for computational efficiency. Power maximum occurred from application of a 2048 point (45 ms) windows across the initial section of the pulse, and analysis was therefore continued with this window. It should be noted that although the window duration is 45 ms the effective time resolution is better as a result of the tapering nature of the window. By simple calculation the 3-dB width of a 45-ms Hanning window is 16.4 ms, and 80% of the windowed signal energy is contained within this width.

An average power-frequency-time matrix of background noise power and seismic pulse power was constructed at each of the four source–receiver ranges. Power spectral density analysis was performed across 8192 waveform points, in advancing steps of 256 points, through 2048 point Hanning windows on (i) 11 sequential background noise waveform sections immediately preceding seismic pulses and (ii) the seismic pulses themselves. Background noise analysis, and construction of an average noise matrix at each source–receiver range, was performed prior to seismic pulse analysis. The average background noise matrix was then sub-

tracted from each individual seismic pulse matrix prior to pulse power averaging, in order to remove the contribution of incoherent background noise from the pulse power. Figure 4 is a composite plot of the average background noise matrix preceding the average seismic pulse power matrix 750 m from source, and illustrates the huge cross bandwidth power surge above the already elevated background noise at the seismic pulse onset.

Finally, for each source–receiver range, the maximum pulse power spectrum slice was extracted from the average matrix, and each of the average background noise matrices for the four different source–receiver ranges were averaged internally to a single power-frequency spectrum. Average background noise and average maximum seismic pulse power spectra were then smoothed using a 10 point running average (resulting in a 222-Hz resolution spectrum) to further reduce estimation noise, and plotted together on a logarithmic (dB) scale for each source receiver range.

II. RESULTS

The solid curves in Fig. 5(a)–(d) illustrate maximum seismic pulse power at the four source–receiver ranges of 750 m, 1 km, 2.2 km, and 8 km. It can be seen from Fig. 5(a) and (b) (750-m and 1-km range, respectively) that seismic pulse power is far in excess of even the highly elevated background ship noise levels across the entire recorded bandwidth 200 Hz–22 kHz. Seismic pulse power ranges from approximately 140 dB *re*: 1 μPa^2/Hz at the 200-Hz end of the spectrum to approximately 90 dB *re*: 1 μPa^2/Hz at the 20-kHz end. High-frequency sound is attenuated by absorption through molecular resonance in seawater more rapidly with distance than low-frequency sound, and at 2.2-km range [Fig. 5(c)] seismic pulse power merges with the background noise at approximately 20 kHz. It should be stressed that the background noise spectrum is highly elevated from ambient by mechanical and flow sources of the guard ship (and at close source–receiver ranges the seismic ship), and water flow over the towed hydrophone. A "quiet" ambient noise environment would produce a curve several tens of dB below those obtained here. Even given the elevated background noise levels, it is clear that even 2.2 km from source, seismic pulse power dominates virtually the entire spectrum. At 8-km source–receiver range [Fig. 5(d)] seismic pulse power merges with background noise at approximately 8 kHz. If similar recordings were made in a quiet ambient environment (e.g., such as a fixed listening post far removed from engine machinery, or perhaps the ear of a swimming dolphin) the gap between seismic power curve and noise power curve would be increased from the illustrated examples at equivalent ranges from the air gun array. Both high- and low-frequency energy is present in the pulses at considerable magnitude and will certainly be detectable tens of kilometers from source.

Since the spectra of the seismic pulses cover a wide frequency range over which the Dolphin's hearing sensitivity varies very significantly it was thought worthwhile to make use of the same kind of procedure used in human environmental noise assessment whereby the frequency components of the noise (in this case the seismic pulses) are weighted
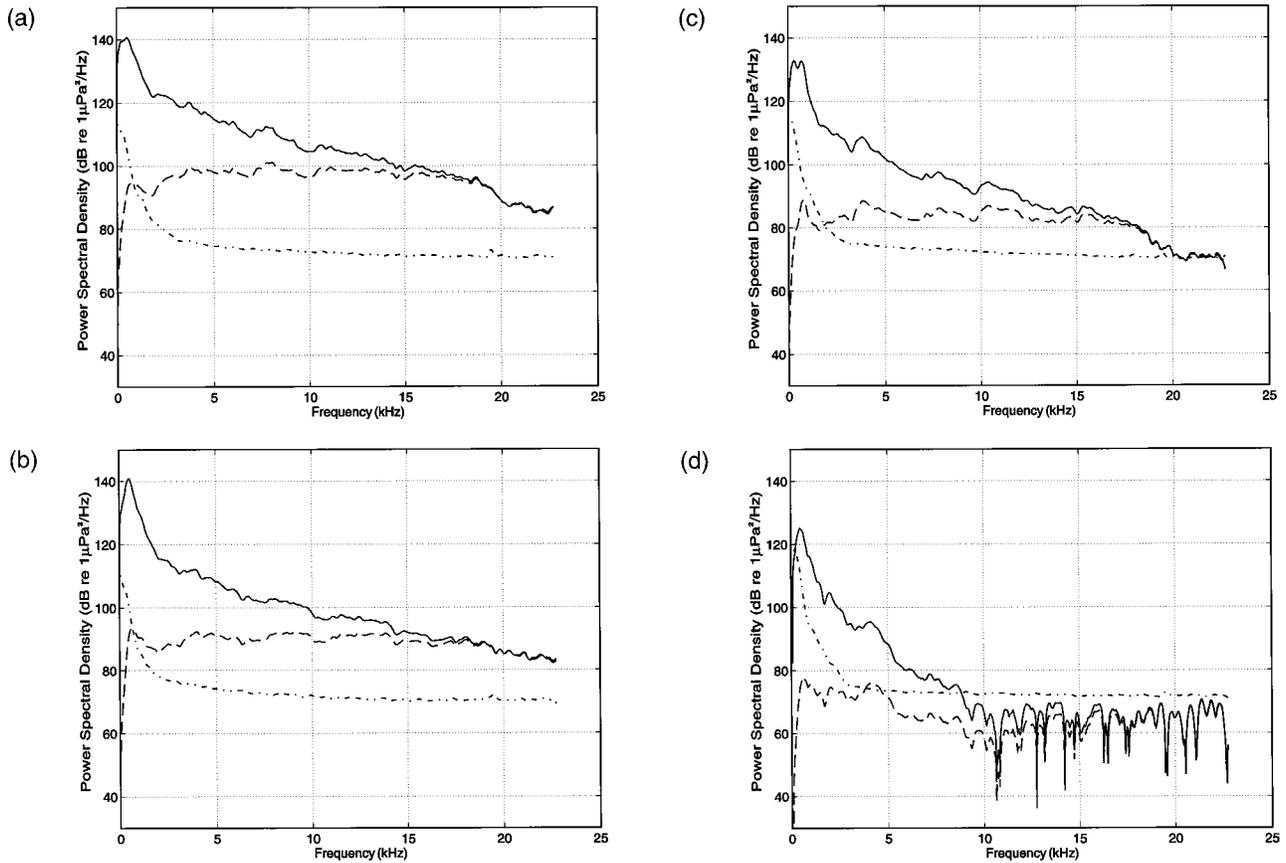
FIG. 5. Plots of maximum seismic power spectral density (solid line), spectral density normalized using dolphin threshold curve (dashed line), and average background noise, including high ship noise (dot-dash line) at four different source–receiver ranges: (a) 750 m; (b) 1 km; (c) 2.2 km; and (d) 8 km. Plots are shown on a logarithmic scale of power spectral density in dB *re*: 1 μPa^2/Hz.

according to the listener's hearing sensitivity at that frequency (Kinsler *et al.*, 1982). In the human case the standard A-weighting (relative sensitivity) curve approximately mirrors the human ten phon equal loudness contour which gives the level of sound at each frequency having the same loudness as a 10 dB (*re*: 10^{-12} W m^{-2}) signal at 1 kHz. The signal, after such weighting, should have approximately the same loudness as a 1-kHz tone having the same power.

In order to gain further insight into the likely impression of the seismic pulses on dolphins the seismic pulse spectra were weighted using published data on the variation of auditory threshold with frequency in the bottlenose dolphin (Johnson, 1967; Au, 1993). The dolphin auditory threshold curve for continuous tones (Fig. 3.2 in Au, 1993) was increased by 5 dB to allow for the increase with reducing tone burst duration (Johnson, 1967) and is shown in Fig. 6(a). It is recognized that pulse duration tends to increase during propagation and that the threshold shift with pulse duration is slightly frequency dependent. However, for simplicity a fixed figure of 5 dB (figure for 50 ms at 20 kHz) was used but the sensitivity to duration and frequency in this tone duration region is small (within 1.8 dB of this figure for a pulse duration range 50–100 ms and frequency range 1–20 kHz). A weighting (relative sensitivity) curve appropriate for dolphins using a reference frequency of 20 kHz is shown in Fig. 6(b). Note that this has been obtained, as in the case of the human A-weighting curve, by mirroring the sensitivity

curve [Fig. 6(a)] in the sensitivity level at the reference frequency and setting this level to 0 dB. The choice of reference frequency is arbitrary and has been set, as in the human case, at approximately one-third of the frequency of maximum sensitivity. The dashed lines in the Fig. 5 plots are the seismic spectra with the weighting curve added. As in the human case the integral of each weighted spectrum (expressed in
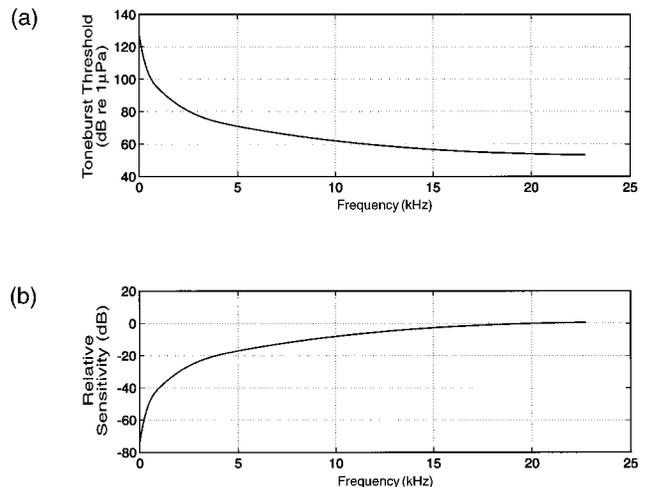

FIG. 6. (a) Dolphin hearing threshold curve for 50-ms tone bursts. (b) Relative sensitivity or weighting curve derived from (a).

TABLE I. Seismic pulse power at four source–receiver ranges corrected for sensitivity variation with frequency.

Range (km)	Power (dB$_{dt}$)
0.75	140
1.0	133
2.2	127
8	112

μPa^2/Hz) should have approximately the same loudness as a tone at the reference frequency having the same power and allows comparison with the dolphin hearing threshold at 20 kHz.

Table I shows this integral, expressed in dB re: 1 μPa. Continuing the comparison with the methodology of human noise measurement and noting that this figure is equivalent to the dB figure used for A-weighted sound levels adjusted for the human frequency response we term this the dolphin dB figure for sensitivity-weighted transient signals or dB$_{dt}$. It is recognized that there may be a slight underestimate in this figure for the 750-m, 1-km, and 2.2-km ranges as a result of the exclusion of signal components above the upper cutoff frequency of 22 kHz and below the lower cutoff frequency of 200 Hz. However, the error resulting from the exclusion of frequencies above 22 kHz will not be greater than 1 or 2 dB since the spectral density is falling and the dolphin sensitivity variation is leveling off. The spectral density estimation at the 8-km range is unreliable above 10 kHz, the variation shown resulting from random errors in the background noise subtraction. At this range absorption is an important factor, ensuring a rapid decrease in signal power at high frequencies and the true spectrum will continue to decrease above 10 kHz. Integrating the spectrum up to 10 kHz leads to a figure within 1 dB of that quoted. The exclusion of frequencies below 200 Hz is potentially more serious since the spectral density is still rising with reducing frequency at this point and will reach a peak below 200 Hz. However the dolphin's hearing sensitivity is still reducing and the excluded bandwidth is small. Assuming that the tendency for the reduction in sensitivity to compensate for the increase in spectral power resulting in the approximately flat adjusted spectra seen in Fig. 5(a)–(d) continues below 200 Hz, then the excluded frequencies below 200 Hz lead to errors of less than 1 dB at all distances. An alternative approach to error estimation is to take the upper figure of the typical range for air-gun outputs (240 dB re: 1 μPa @ 1 m), assume inverse square law power reduction (note that the figures in Table I follow this law approximately), and that all this power is concentrated below 200 Hz. Using the hearing threshold figure at 100 Hz to adjust for hearing sensitivity again leads to errors in the dB$_{dt}$ figures due to this excluded power of less than 1 dB at all distances.

III. DISCUSSION

It was mentioned in the Introduction to this paper that seismic survey recordings were conducted in conjunction with an acoustic dolphin survey, using passive listening for dolphin vocalizations. During the March 1996 seismic survey, on which the sound analyses in this paper are based, natural dolphin population densities were so low that it was impossible to assess any effect on their distribution. The paucity of dolphin encounters was likely the result of a seasonal offshore migration the previous Autumn (Goold, in press), which meant that there were very few dolphins in the area at the time of the seismic survey. However some 18 months previous to the seismic survey described in this paper, in the Autumn of 1994, an identical seismic operation had been conducted by the same operators in adjacent prospect blocks, and using the same air-gun array. The 1994 seismic operation was conducted at a time when common dolphin population density was much higher (Goold, 1996), and acoustic dolphin surveying carried out in conjunction with seismic operations at that time suggested a localized disturbance of dolphins. For example, during the first week of seismic surveying only 4% of dolphin contacts occurred when air-gun shots were in progress, the remaining 96% occurring when the guns were silent between shot lines. However, there was also an observation during the 1994 survey of common dolphins close to the guard ship hydrophone for approximately 2 h while air-gun shots were in progress at an average distance of 1.34 km. The closest approach between the two ships during this encounter was 1070 m (both vessels fitted with differential GPS) and common dolphin sonar clicks could be heard very clearly through the guard ship hydrophone, causing intermittent record level overload. The inference was therefore drawn that (i) common dolphins were close to the guard ship hydrophone and (ii) that seismic energy from this particular air gun array under the prevailing conditions was therefore tolerable to common dolphins at a radius from the gun array of 1 km. No observations were made of dolphins at closer range to the gun array while firing was in progress. Figure 5(b) shows seismic pulse power at 1 km from the gun array in the same waters, and this plot may well be representative of a broadband threshold at which dolphins will tolerate seismic pulses.

Although it would be useful to present analyses of the seismic pulses recorded through the guard ship hydrophone during the aforementioned encounter, such analyses are precluded due to the recorder setup at the time. During the 1994 seismic survey, seismic pulses were recorded merely as a by-product of the acoustic dolphin survey, which was a new venture in itself. Gain levels were set high to capture faint dolphin whistles, and both recorder channels were 6-kHz high pass filtered. As a result of the high gain setting, seismic pulses recorded at source–receiver ranges of less than 2.5 km exceeded the DAT recorder dynamic range as configured at the time, resulting in clipped signals on tape. We can therefore only assume that the seismic power level presented in Fig. 5(b) is closely representative of that to which dolphins were exposed during the aforementioned encounter. This is a reasonable assumption given that both seismic operations were conducted in essentially the same shallow sea area, and that the same air-gun array (indeed the same contractor) was employed in both instances. Although propagation conditions in the sea may vary considerably, both surveys were conducted in a perpetually mixed shelf sea region, thereby eliminating any complications of thermal stratifica-

tion. Thermal stratification would not have occurred at the time of year in which these surveys were conducted in any case, and a CTD cast during the 1996 seismic survey confirmed a homogeneous vertical temperature-salinity profile. It should be noted at this point that sound pressure level estimates for the air-gun array at 5 km, quoted merely as ''rough cut estimates'' in Goold (1996), were based on an erroneous assumption of the high pass filter performance particularly at the low-frequency end of the spectrum. Some time after the 1994 survey work the filter unit was tested and found to have a much shallower attenuation slope than the design specified. Sound pressure level measures below 6 kHz quoted in Goold (1996) were overcompensated, resulting in estimates that were too high. The power spectral density measures made in the current work, however, are based essentially on a flat ± 2.5-dB bandpass recording between 200 Hz and 22 kHz, and a total system through-put calibration.

There is some difficulty in determining how loud the seismic pulse seems to a dolphin at different ranges. This stems from the fact that hearing threshold measurements have been carried out using long (quasi-continuous) tones and tone bursts of varying duration but not for more complex signals such as the seismic pulses and isophon (equal loudness) curves have not been measured at all. Noise masking measurements have been used to determine the bandwidth of the constant Q filters by which it is suggested the dolphin's auditory system can be modeled. The critical ratio and critical bandwidth methods indicate the filter Q to be 12.3 and 2.2, respectively (Au and Moore, 1990; Johnson, 1968). It is fairly clear that the dolphin can hear the seismic pulse even at the maximum range (8 km) considered. Taking the narrowest bandwidth case ($Q = 12.3$) at the frequency of peak spectral density 466 Hz, the power within the filter bandwidth is [from Fig. 5(d)] approximately $125 + 10 \log_{10}(466/12.3) = 141$ dB re: 1 μPa, well above the threshold of 105 dB re: 1 μPa at this frequency and this is not even taking into account the contributions from other spectral components. This conclusion is also clearly not critically dependent on the bandwidth estimation used. The question of how the seismic pulses affect the dolphin at different ranges is less easily answered. It is known that the dolphin adapts to environmental noise during echo location by increasing its emitted click amplitude. Peak energy in the dolphin click spectrum in a quiet environment occurs around 50 kHz, however this peak shifts to higher frequency along with increasing click amplitude in response to noise (Au, 1980, 1993) and is in the range at which the seismic spectral density is very low and decreasing and the dolphin hearing threshold is beginning to increase again. It is likely therefore that the predominant interference is with the dolphins' communication which takes place at lower frequencies (5–30 kHz). In order to have some idea of how loud the seismic signal might appear to the dolphin, it is necessary to take into account their dependence of sensitivity on frequency and to weight the spectrum before calculating an effective power.

Use of the low level threshold curve is likely to lead to an underestimate of the dolphin dB_{dt} figure since it will reduce the contribution of low-frequency components if the equal loudness contours become flatter with increasing

acoustic pressure as in the human case. Table I shows the ''dB_{dt}'' figures for the four source distances, all clearly exceeding the threshold at 20 kHz.

In order to determine the potential for interference with dolphin communication typical levels for these signals are required. Unfortunately the literature is sparse on this subject; although a figure of 155 dB re: 1 μPa at 9 kHz at source (1-m range) has been ascertained for common dolphin (Hall, 1997). At a range of 10 m (assuming predominately inverse square law attenuation) the power level would be 135 dB re: 1 μPa which is equivalent to 125 dB at 20 kHz using the same normalization curve. The range of 10 m has been used as a typical distance between dolphins in the same pod. Comparing this figure of 125 dB with those in Table I it is seen that the seismic pulse has comparable response-adjusted level (perceived as comparably loud) as this typical communication signal at an air-gun-to-dolphin distance of 2.2 km. At the closer distances of 750 m and 1 km the pulse will appear much louder. Bearing in mind the assumptions and approximations made the figures in Table I are not inconsistent with the observation that dolphins find the seismic signal levels at 1 km and closer distressing and that this distress may be due to interference with communication. It should be remembered, however, that these power levels occur within only a 50–100 ms period repeated at 10-s intervals. This low duty-cycle signal would not seem to be a serious potential interruption of echo location or communications. However, it is known that, in humans, loud sounds cause a temporary threshold shift (permanent for very loud and sustained sounds) within approximately 0.5 ms of the start of the sound (acoustic reflex) and recovery may take several minutes (Kinsler $et\ al.$, 1982). This protection mechanism may well exist in dolphins and, if it is present, would lead to reduced hearing sensitivity even during the interpulse intervals.

A recent publication (Ridgway $et\ al.$, 1997) describes experiments in which the thresholds for behavioral changes and temporary threshold shifts in captive dolphins were measured at sound levels of 181 dB and 193–196 dB re: 1 μPa, respectively, for a 1-s tone burst at 20 kHz. Even allowing for uncertainty in our distance estimation it is clear that our observation of dolphins exhibiting behavioral changes (avoidance) at distances less than 1 km together with our estimate of a sensitivity-weighted sound level referenced to 20 kHz of 133 dB at this distance suggests a far greater sensitivity to environmental noise than that presented in the Ridgway report. One possible explanation is that the threshold for the observed behavioral changes in captive dolphins is far higher than that for avoidance behavior in free ranging dolphins. Captive dolphins cannot swim away and may be more tolerant through necessity!

The dolphin is a inquisitive animal and will tolerate fairly loud engine and propeller noise in order to investigate ships at close quarters. However, there must be a distance from a source of loud noise at which the desire to investigate is balanced by auditory distress. Further work needs to be done to determine ''safe'' distances at which high source level sounds are tolerable to cetaceans. Our best estimate at present for dolphins and the 2120 cubic in. air-gun array in a shelf sea environment is 1 km.

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