UNIVERSITY OF
BATH

Citation for published version:
Merchant, N, Witt, MJ, Blondel, P, Godley, BJ & Smith, G 2012, Long-term monitoring of sound exposure from shipping in coastal waters. in 11th European Conference on Underwater Acoustics 2012, ECUA 2012. Institute of Acoustics, St. Albans, pp. 1026-1033, 11th European Conference on Underwater Acoustics, Edinburgh, UK United Kingdom, 1/07/12.

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Link to publication

Reproduced here with permission from the IOA

University of Bath

LONG-TERM MONITORING OF SOUND EXPOSURE FROM SHIPPING IN COASTAL WATERS

ND Merchant   Department of Physics, University of Bath, Bath, UK
MJ Witt   College of Life & Environmental Sciences, University of Exeter, UK
Ph Blondel   Department of Physics, University of Bath, Bath, UK
BJ Godley   College of Life & Environmental Sciences, University of Exeter, UK
GH Smith   College of Engineering, Mathematics & Physical Sciences, University of Exeter, UK

1   INTRODUCTION

High-intensity, short-term acoustic events such as seismic surveys, pile-driving operations and military sonar activities have been the focus of considerable attention due to their potential to cause physical injury and temporary or permanent threshold shift in marine mammals (e.g. [1-3]). However, there is also growing recognition of the potential for long-term exposure to anthropogenic noise to induce chronic effects in a range of marine species [4, 5]. These effects may occur at levels below those necessary to induce short-term behavioural responses, and through mechanisms which are more difficult to observe. They include masking of biologically significant sounds [6, 7], chronic stress [8, 9], subtle long-term behavioural responses [10] and shifts in attention [11, 12]. *In situ* measurement of long-term exposure to anthropogenic noise both in absolute terms and relative to background levels is needed to inform further investigation in this area [13].

Noise from shipping is pervasive throughout the marine environment, especially at low (<300 Hz) frequencies [14, 15], and is therefore a key concern regarding the chronic effects on marine species [4]. Long-term observations have shown that background noise levels have been rising since at least the 1960s due to increases in (distant) shipping traffic and tonnage [15-17]. In coastal waters, noise levels exhibit high spatiotemporal variability [18] due partly to the greater dependence of acoustic propagation on local environmental factors, but also to a higher concentration of shipping, industrial activity, and biological noise sources. Since coastal shipping noise is both temporally dynamic and persistent, reliable measurement of sound exposure requires continuous monitoring.

We present a method of characterising sound exposure from shipping in coastal environments which combines continuous acoustic data from a single hydrophone with AIS (Automatic Identification System) shipping data. The broadband sound pressure level (SPL) is separated into intermittent and background components using an adaptive threshold, and the sound exposure level (SEL) of each component is calculated over periods of 24 hours. This allows assessment of both the total sound exposure and the contribution of intermittent shipping noise. Peaks in the intermittent ship noise are then linked to the closest points of approach (CPAs) of ships using AIS data, indicating the spatial distribution of intermittent ship noise sources. The method provides a detailed analysis of sound exposure levels and ship source distribution which can enhance coastal management of the marine environment with regard to ship noise pollution.

2   METHODS

2.1   Data acquisition

Falmouth Bay (see Fig. 5) is a large and deep natural harbour at the western entrance to the English Channel. The Channel is one of the busiest seaways in the world with around 45,000 ship transits annually [19]. Traffic within the Bay consists of commercial shipping into Falmouth Harbour to the north, recreational boating, and activity related to bunkering (refuelling) of large vessels. The latest published figures show total annual ship arrivals to Falmouth of 1,309 in 2009 [20]. An

Autonomous Multichannel Acoustic Recorder (AMAR; Jasco Applied Sciences Ltd) was deployed in the Bay for 20 days between July 24 and August 13, 2010, positioned on a seabed of sand to muddy sand 1.8 km offshore from Nare Head in waters ~30 m deep. The AMAR was mounted on a custom-fabricated frame containing an acoustically triggered pop-up buoy system, and was programmed to record continuously in 30-minute blocks, sampling at 16 kHz, using a GeoSpectrum M8E-132 hydrophone (effective bandwidth 5 Hz to 150 kHz). AIS data for the duration of the deployment period were provided by a Web-based ship-tracking network (http://www.shipais.com/). This covered the area 48.0-51.0ºN / 1.0-7.0ºW, and included good coverage of Falmouth Bay and the surrounding area (see below). Hourly wind speed and rainfall data from the Culdrose weather station, 14 km to the west of the deployment location, were provided by the UK Met Office.

2.2   Data Analysis

2.2.1   Acoustic data processing

Acoustic data were calibrated via the hydrophone sensitivity (-165 dB re 1 V µPa^{-1}) and the AMAR pre-amplifier gain (0 dB), then processed with custom-written MATLAB scripts. The power spectral density (PSD) was calculated using a 1-s Hann window with 50% overlap for each 30-minute measurement. 172 short (< 1 s) bursts of system noise with exceptionally high amplitudes below 10 Hz were purged using a frequency-sensitive noise gate. The mean PSD was then calculated in 60-s windows. The files were then concatenated to form a master file which was used as the source file for the subsequent calculations of SPL and SEL. A 9 day period from 16:30 on July 24 to 16:30 on August 2 was selected for analysis. The remaining data were discarded since the signature of a single vessel dominated the acoustic spectrum from around 17:00 on August 2 onward, precluding analysis of surrounding shipping. The vessel was identified from AIS data as a 55-m tug within ~1 km of the deployment site throughout the period from August 2 to (at least) August 13. Its presence may have been related to bunkering or other industrial activities in the Bay.

An integration time of 300 s was used to calculate the SPL over a frequency bandwidth of 0.01-1 kHz. This bandwidth covers the nominal frequency range of commercial shipping noise [21], and allowed comparison of recorded levels with relevant studies. The integration time was chosen such that the SPL varied over a similar timescale to the transmission rate of the AIS data (typically around 600 s). This also smoothed the signal in the time domain, meaning ship passages were more likely to produce unique local maxima in the SPL (rather than multiple maxima). This made it easier to identify ship passages from maxima in the SPL (see below). The SEL for each 24-hr period was also calculated, using an integration time of 300 s over the nominal frequency bandwidth of shipping (0.01-1 kHz) and the full recorded bandwidth (5 Hz – 8 kHz). The latter was included to assess the effect of higher frequency components on sound exposure levels.

2.2.2   Separation of intermittent and background components

Intermittent ship noise was identified using an adaptive threshold. The threshold adapts to long-term variations in the broadband SPL while distinguishing short-term, relatively high-amplitude events, enabling the relative level of shipping noise exposure above the background to be determined. The adaptive threshold works on the assumption that the minimum SPL within a window of duration W is representative of the background noise level within that period. A tolerance above the minimum SPL, the threshold ceiling, C [dB], is then defined. W and C may be tailored for the application. The time-dependent adaptive threshold level, $ATL(t)$, for a time-dependent SPL, $SPL(t)$, is then:

$$ATL(t) = \min \left[SPL(t) \right]_{t-\frac{W}{2}}^{t+\frac{W}{2}} + C$$

where $ATL(t)$ has units of dB re 1 µPa^2. In other words, $ATL(t)$ is C decibels above the minimum recorded SPL within a rolling time window of duration W centred on time t.

In this study, *W* was set to 3 hours and *C* to 6 dB. This value of *W* was necessary because of sustained periods of local shipping noise with durations approaching 3 hours. *C* was selected through experimentation (it was found to effectively distinguish background and intermittent contributions to the 24-hr SEL - see below) and for simplicity (as it is double the minimum SPL). Data above the threshold were classed 'intermittent', data below the threshold 'background'. Maxima in the intermittent SPL data were detected for subsequent comparison to AIS data. The intermittent and background SELs were then calculated for each 24-hr period. An estimate of the SEL in the absence of intermittent data was also made. This was calculated by substituting the intermittent data with the median background level computed with a rolling 3-hr window.

2.2.3 Spatial distribution of peak-generating ships

A graphical user interface (GUI) was designed in MATLAB to analyse each peak in the intermittent SPL with reference to figures displaying the tracks of AIS transmissions, the calibrated spectrogram, and the broadband SPL for a two-hour window centred on the SPL peak (example output shown in Fig. 4). Firstly, the distance of each AIS transmission from the hydrophone was calculated from its latitude and longitude coordinates. Transmissions within 50 km were plotted against time, linking data points from the same vessel. The closest points of approach (CPAs) of each vessel were then computed geometrically, assuming direct trajectories and constant speed between AIS transmissions. For each peak in the intermittent SPL, CPAs within a 15-minute window centred on the peak were considered. Finally, the spectrogram was consulted to confirm whether SPL peaks were due to ship signatures and not, for example, due to wind noise. These are readily distinguished by the tonal components present in ship signatures. Each SPL peak was then categorised as uniquely identified (one CPA), due to multiple possible sources (> one CPA), or unidentified (no CPA). The coordinates of each uniquely identified CPA were then recorded.

3   RESULTS

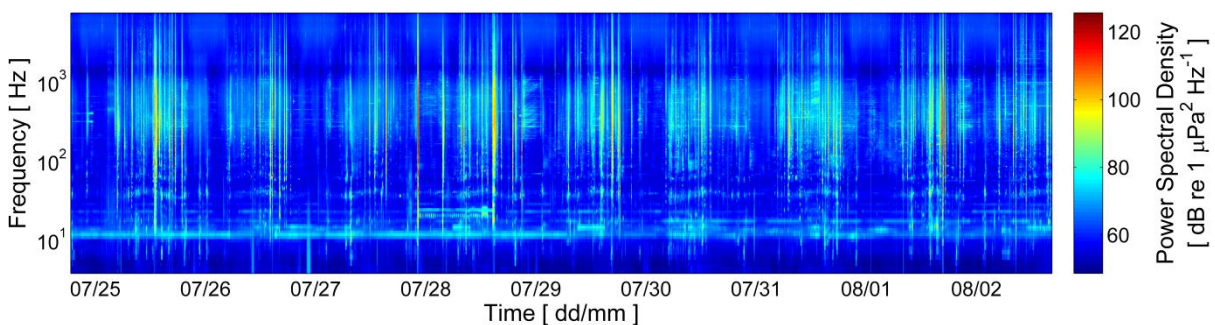## 3.1   Sound pressure levels and weather data

Fig. 1. Power spectral density for 9 days of continuous monitoring [22].

The ambient noise field was punctuated by wide bands of intermittent ship noise, some of which spanned the entire frequency range (Fig. 1). Overall, broadband (0.01-1 kHz) SPLs ranged from 86.1 to 148.6 dB re 1 μPa^2. The SPL was above the threshold level ('intermittent') 29% of the time, and below this level ('background') 71% of the time. SPLs from a representative day are presented in Fig. 2. The median threshold level was 96.2 dB re 1 μPa^2, with a range of 10.6 dB. Intermittent peaks in the SPL ranged from 92.8 to 148.6 dB re 1 μPa^2, and exceeded the threshold level by a median of 6.4 dB. In total, there were 314 peaks in the intermittent SPL (mean: 34.9 per day).

Mean hourly wind speeds at the Culdrose weather station ranged from 2 to 17 knots (1.0-8.7 m s^{-1}), with a maximum hourly increase of 6 knots (3.1 m s^{-1}). Wind speeds in this range have been associated with variations of up to around 20 dB in shallow water ambient noise levels [18]. Spectra characteristic of wind noise did not feature in the frequency spectrum of the intermittent component,

implying that any wind-generated noise was below the adaptive threshold, or was masked by local vessel activity. Rainfall was recorded at Culdrose in 12 hours of data over the 9 day period, with a maximum rate of 0.8 mm per hour. Since rain generates noise at frequencies above 1 kHz [23], it was not considered to contribute to the broadband (0.01-1 kHz) levels used for noise classification.
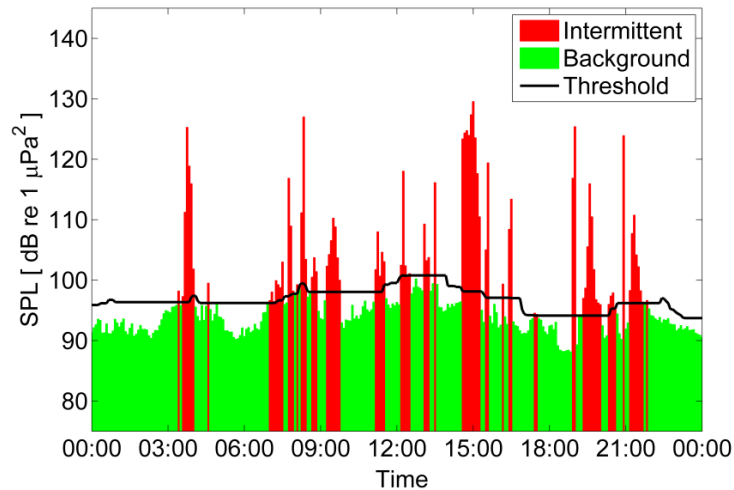

Fig. 2. Broadband (0.01-1 kHz) SPL for a representative day (28 July) showing classification of 'intermittent' and 'background' data. The solid line is the adaptive threshold level [22].

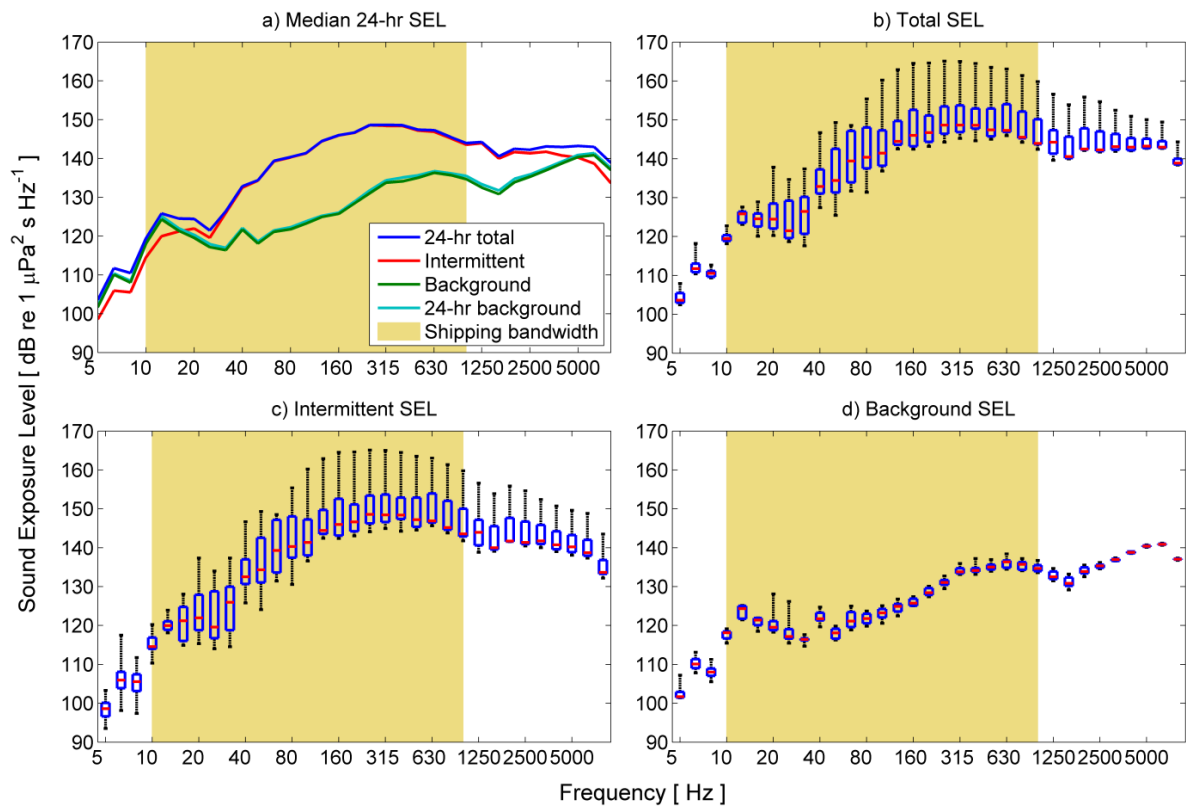## 3.2   Sound exposure levels

Fig. 3. a) Median 24-hr SEL in third-octave bands, calculated from 9 consecutive 24-hr periods. b), c), d): total SEL and SEL due to intermittent and background components. The centre lines of the boxes denote the median; box limits indicate the first quartile. The whiskers are the maximum and minimum values recorded. Shaded areas: nominal bandwidth of shipping noise (0.01-1 kHz) [22].

The broadband SEL for each 24-hr period between 16:30 on July 24 and 16:30 on August 2 was calculated over the frequency ranges 0.01-1 kHz (nominal shipping bandwidth) and 5 Hz - 8 kHz (full bandwidth). Over both frequency ranges, the total SEL was dominated by the contribution of the intermittent component. This was especially the case over the nominal shipping bandwidth where the median total SEL was 157.0 dB re 1 µPa^2 s, 14.4 dB greater than the estimated level in the absence of the intermittent events ('24-hr background'). The median 24-hr SEL was concentrated above ~100 Hz, with a broad peak at 315 Hz (Fig. 3a). The intermittent component was most dominant between around 30 and 2,000 Hz. The variability of the intermittent data (Fig. 3c) appears to account for the variability of the total 24-hr SEL (Fig. 3b) above ~30 Hz. In contrast, the 24-hr SEL of the background component was comparatively stable at all frequencies (Fig. 3d).

Above around 2 kHz, the median background levels rose (Fig. 3d). This high frequency component was the least variable part of the background sound exposure, and consisted of impulsive noise exhibiting a diurnal periodicity with maxima during the night [24]. It is probable that this noise was produced by snapping shrimp: these decapods generate characteristic impulses with peak frequencies in this range [25]. Two species of snapping shrimp have been documented in coastal waters to the east of the deployment site: *Alpheus glaber* near Plymouth [26] and *Alpheus macrocheles* further east around Weymouth [26, 27]. There have also been unpublished reports of *Alpheus macrocheles* specimens caught by fishermen in Falmouth Bay.

3.3 Spatial distribution of peak-generating ships

Peak-generating ships were identified using a GUI which displayed AIS and acoustic data as shown in Fig. 4. Each of the peaks in the broadband SPL was categorised as 'uniquely identified', 'due to multiple ship sources', or 'unidentified', based on the number of CPAs within ± 7.5 minutes of the peak. For example, in Fig. 4 the intermittent peak at 01:50 was classed as uniquely identified and attributed to the vessel 212032000. The previous peak at 01:30 was unidentified as there were no CPAs within its 15-minute window.

The AIS coverage of the Falmouth Bay area was not continuous throughout the deployment, and data were unavailable for 126 of the 314 peaks recorded. Of the remaining 188 peaks, 59 (31%) were classed as uniquely identified, 61 (32%) as due to multiple possible sources, and 68 (36%) as unidentified. Inspection of each plot suggested that 18 of the uniquely identified peaks could not unambiguously be attributed to individual CPAs, and were instead attributed to multiple ship sources. These 'false positives' were typically due to substantial shipping activity closer to the deployment than the identified vessel. A further 5 peaks having two CPAs in the 15-minute window were clearly attributable to one of the CPAs. All 5 cases involved large (> 77 m length) commercial vessels close to the deployment. The classification of peaks was then 46 (24%) uniquely identified, 74 (40%) due to multiple ship sources, and 68 (36%) unidentified.

Of the uniquely identified vessels, 24 were cargo ships, 13 were tankers and the remaining 9 were small craft. Peak broadband (0.01-1kHz) SPLs attributed to these vessels ranged from 92.8 to 148.6 dB re 1 µPa^2, with CPAs between 0.18 and 34.1 km from the hydrophone. Potential sources of the unidentified peaks include vessels ≤299 GT not transmitting AIS signals, ship noise unrelated to the passage of ships (engine activity, manoeuvring, bunkering operations, etc.), and vessels outside the 50-km range considered.

The coordinates of uniquely identified CPAs were distributed within Falmouth Bay and further south into the English Channel (Fig. 5). The largest cluster of CPAs to the east of the deployment corresponds to the paths of vessels entering and leaving Falmouth Harbour and the Bay. A second cluster ~15 km south of the deployment site corresponds to paths of vessels navigating along the coast past the headland at Lizard Point. Small vessels were distributed within the Bay close to the deployment, while the main shipping routes were populated by tankers and cargo ships. The tanker furthest east in the English Channel appears to have been falsely identified as the coast obscures the line of sight to the hydrophone. Error in the position of the CPA could also be the cause, since these were calculated assuming constant speed and direct trajectories between AIS transmissions.
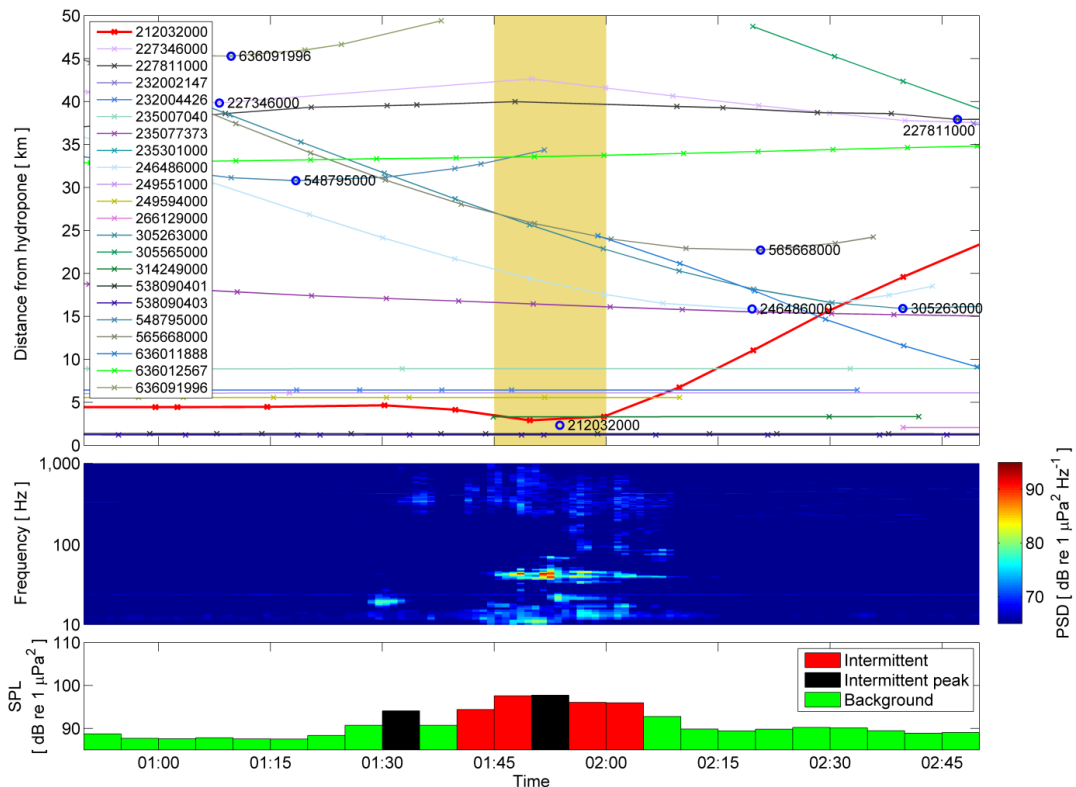
Fig. 4. Example of ship identification using AIS. *Top*: Range from hydrophone vs. time. Crosses denote individual AIS transmissions; circles show closest points of approach labelled with MMSI numbers. Shaded area is 15-minute time window around SPL peak at 01:50; heavy line indicates track of vessel identified as source of peak. *Middle*: PSD of concurrent acoustic data. *Bottom*: Broadband (0.01-1 kHz) SPL, showing 'background', 'intermittent', and 'intermittent' peaks [22].
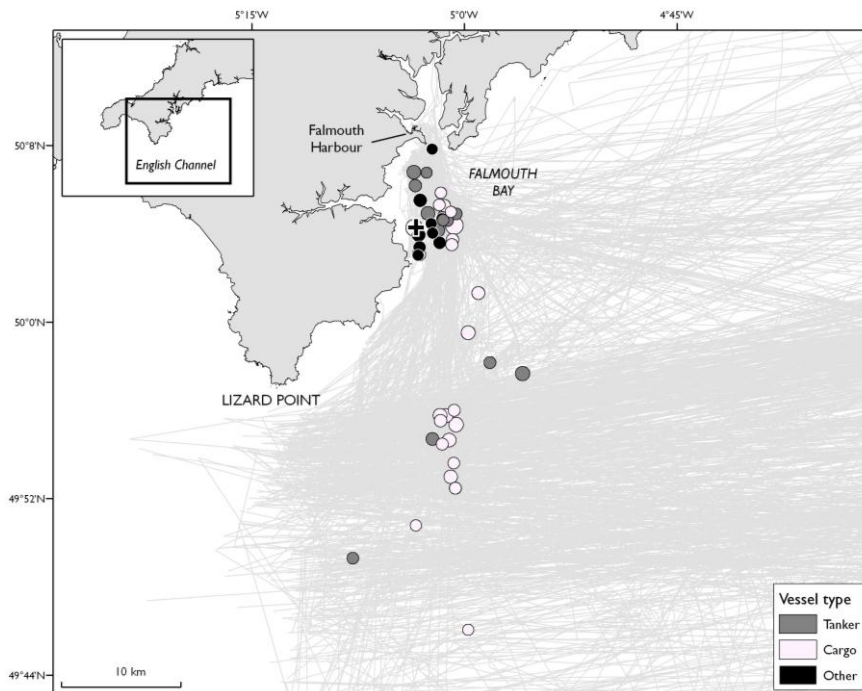

Fig. 5. Uniquely identified CPAs categorised by vessel type. The size of each circle corresponds to the magnitude of the associated SPL peak, ranging from 92.8 to 148.6 dB re 1 µPa^2 [22].

4   DISCUSSION

The assessment of shipping noise in coastal waters is complicated by the presence of both intermittent noise from local vessel traffic and ambient noise from distant shipping. We have shown that these two components are clearly distinguished by the nature of their contribution to the 24-hr SEL, and can be separated by applying an adaptive threshold to the sound pressure level. Intermittent ship noise produced a variable, high amplitude component (Fig. 3c) which determined the magnitude and variability of the total 24-hr SEL (Fig. 3b). A lower amplitude 'background' component remained stable over the 9 days analysed (Fig. 3d). Analysing the sound exposure in this way makes it possible to assess both the absolute sound exposure at the deployment location and the contribution of intermittent shipping noise relative to background levels. In the frequency 0.01-1 kHz, we recorded a median 24-hr SEL of 157.0 dB re 1 μPa^2 s compared to an estimated 142.6 dB re 1 μPa^2 s in the absence of intermittent shipping noise.

It is important to note that background levels are likely to be heightened by shipping noise below the level of the adaptive threshold. This background level should therefore be understood as the estimated level in the absence of significant local shipping activity, not in the absence of shipping noise *per se*. In this study the 24-hr SEL was determined by the intermittent component which constituted 29% of the time series. This component may be less dominant in areas with a lower density of local shipping, and where there are fewer large commercial vessels.

By relating the acoustic data to the CPAs of AIS-transmitting vessels, it was possible to account for 64% of peaks in the intermittent SPL for which AIS data were available as being due to shipping. 24% of peaks appeared to be uniquely attributable to individual vessel passages. The spatial distribution of uniquely identified vessels (Fig. 5) indicates that the majority were large commercial vessels transiting either along the northern side of the English Channel or into Falmouth Bay. Although relatively few small vessels were identified, these may constitute only a small proportion of the overall small vessel fleet operating in the Bay, since AIS transceivers are only mandatory for vessels over 299 GT. The absence of these vessels from the AIS data may partially account for the 36% of acoustic peaks which remained unidentified.

The shipping noise recorded in Falmouth Bay was predominantly within the nominal frequency range of shipping (0.01-1 kHz; Fig 3, Fig. 3c). However, the peak frequency of sound exposure from intermittent ship noise (315 Hz) was considerably higher than that of reported source spectra for large commercial vessels, which are typically around 100 Hz or below [28-30]. Propagation of sound in shallow water is subject to high attenuation at both high and low frequencies [31], and favourable propagation at mid-frequencies may partly explain the observed spectral composition. A more significant factor is likely to be the composition of the shipping fleet contributing to underwater noise, which may have included more small vessels than were indicated by the AIS data.

ACKNOWLEDGEMENTS

REFERENCES

1.   Lucke, K., et al., 'Temporary shift in masked hearing thresholds in a harbor porpoise (Phocoena phocoena) after exposure to seismic airgun stimuli'. J. Acoust. Soc. Am., 2009. **125**(6): 4060-4070.
2.   Bailey, H., et al., 'Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals'. Marine Pollution Bulletin, 2010. **60**(6): 888-897.

3.   Evans, D.L. and G.R.E. England, Joint interim report Bahamas marine mammal stranding event of 15-16 March 2000. 2001, US Dept. of Commerce and Secretary of the Navy. 59pp.

4.   Slabbekoorn, H., et al., 'A noisy spring: the impact of globally rising underwater sound levels on fish'. Trends in Ecology & Evolution, 2010. **25**(7): 419-427.

5.   Tyack, P.L., 'Implications for marine mammals of large-scale changes in the marine acoustic environment'. Journal of Mammalogy, 2008. **89**(3): 549-558.

6.   Clark, C.W., et al., 'Acoustic masking in marine ecosystems: intuitions, analysis, and implication'. Marine Ecology Progress Series, 2009. **395**: 201-222.

7.   Popper, A.N. and M.C. Hastings, 'The effects of human-generated sound on fish'. Integrative Zoology, 2009. **4**(1): 43-52.

8.   Wright, A.J., et al., 'Do Marine Mammals Experience Stress Related to Anthropogenic Noise?' International Journal of Comparative Psychology, 2007. **20**(2): 274-316.

9.   Rolland, R.M., et al., 'Evidence that ship noise increases stress in right whales'. Proc. of the Royal Society B: Biological Sciences, doi:10.1098/rspb.2011.2429, 2012.

10.   Picciulin, M., et al., 'In situ behavioural responses to boat noise exposure of Gobius cruentatus and Chromis chromis living in a Marine Protected Area'. Journal of Experimental Marine Biology and Ecology, 2010. **386**(1-2): 125-132.

11.   Chan, A., et al., 'Anthropogenic noise affects risk assessment and attention: the distracted prey hypothesis'. Biology Letters, 2010. **6**(4): 458-461.

12.   Purser, J. and A.N. Radford, 'Acoustic Noise Induces Attention Shifts and Reduces Foraging Performance in Three-Spined Sticklebacks'. Plos One, 2011. **6**(2): e17478.

13.   Ellison, W.T., et al., 'A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds'. Conservation Biology, 2012. **26**(1): 21-28.

14.   Richardson, W.J., et al., Marine Mammals and Noise. 1995, San Diego: Academic Press.

15.   Chapman, N.R. and A. Price, 'Low frequency deep ocean ambient noise trend in the Northeast Pacific Ocean'. J. Acoust. Soc. Am., 2011. **129**(5): EL161-EL165.

16.   Andrew, R.K., et al., 'Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast'. Acoustics Research Letters Online, 2002. **3**(2): 65-70.

17.   McDonald, M.A., et al., Increases in deep ocean ambient noise in the northeast pacific west of San Nicolas Island, California. J Acoust Soc Am, 2006. **120**(2): p. 711-718.

18.   Urick, R.J., Principles of Underwater Sound. 3rd ed. 1983, New York: McGraw-Hill. 423pp.

19.   McQuinn, I.H., et al., 'A threatened beluga (Delphinapterus leucas) population in the traffic lane: Vessel-generated noise characteristics of the Saguenay-St. Lawrence Marine Park, Canada'. J. Acoust. Soc. Am., 2011. **130**(6): 3661-3673.

20.   Department for Transport, Maritime Statistics 2009. 2010, DfT, London.

21.   Tasker, M.L., et al., Marine Strategy Framework Directive – Task Group 11 Report Underwater noise and Other Forms of Energy. EUR 24341 EN, 55pp, 2010.

22.   Merchant, N. D., Witt, M. J., Blondel, P., Godley, B. J., Smith, G. H., 'Assessing sound exposure from shipping in coastal waters using a single hydrophone and Automatic Identification System (AIS) data'. Marine Pollution Bulletin (In Press).

23.   Nystuen, J.A., 'Listening to raindrops from underwater: An acoustic disdrometer'. Journal of Atmospheric and Oceanic Technology, 2001. **18**(10): 1640-1657.

24.   Merchant, N.D., et al., Ambient Noise In The Western English Channel: Temporal Variability Due To Shipping And Biological Sources. Proc. of the IOA, 2011. **33**(5): 27-29.

25.   Au, W.W.L. and K. Banks, 'The acoustics of the snapping shrimp Synalpheus parneomeris in Kaneohe Bay'. J. Acoust. Soc. Am., 1998. **103**(1): 41-47.

26.   Holme, N.A., 'The bottom fauna of the English Channel. Part II'. Journal of the Marine Biological Association of the United Kingdom, 1966. **46**(02): 401-493.

27.   Hinz, H., et al., 'Temporal differences across a bio-geographical boundary reveal slow response of sub-littoral benthos to climate change'. Mar Ecol Prog Ser., 2011. **423**: 69-82.

28.   Arveson, P.T. and D.J. Vendittis, 'Radiated noise characteristics of a modern cargo ship'. J. Acoust. Soc. Am., 2000. **107**(1): 118-129.

29.   Wales, S.C. and R.M. Heitmeyer, 'An ensemble source spectra model for merchant ship-radiated noise'. J. Acoust. Soc. Am., 2002. **111**(3): 1211-1231.

30.   McKenna, M.F., et al., 'Underwater radiated noise from modern commercial ships'. J. Acoust. Soc. Am., 2012. **131**(1): 92-103.

31.   Jensen, F.B., et al., Computational Ocean Acoustics. 2011, New York: Springer. 794pp.